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

A thesis submitted in fulfillment of the requirements for
the award of the degree of

Master of Science (Honours)

from the

University of Wollongong

by

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1997

Certification:

This is to certify:

(i) that this thesis is solely the work of the candidate;

(ii) that this thesis has not been submitted for a degree to any other university or institution.

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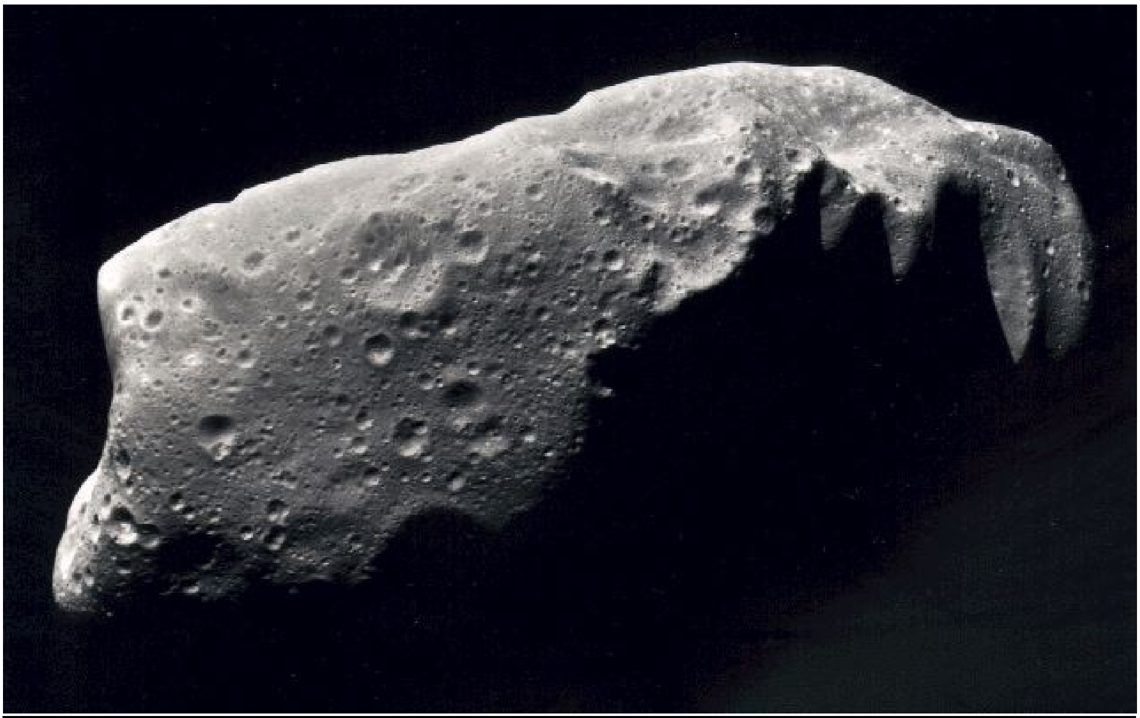

Frontispiece: Asteroid 243 Ida, a Main Belt S-type asteroid, photographed at a distance of 2400 km by the Galileo Jupiter probe on 28th August 1993.

Acknowledgments:

I wish to acknowledge the interest and support of my supervisors, Dr Bill Zealey, Head of the Department of Physics, and Prof Raghu Singh, Head of the Department of Civil and Mining Engineering, University of Wollongong.

I also wish to acknowledge the assistance of Dr John Lewis, Co-Director, Space Engineering Research Center for the Utilization of Local Planetary Resources, Lunar and Planetary Laboratory, University of Arizona, who provided my initial contacts with colleagues in the US.

Most importantly, I wish to thank my wife Wendy for her faith, support and many hours of help; and my daughters Katrina and Samantha for their help and affection.

Mark Sonter

Abstract

Future space industrialization will prompt the search for in-space resources, for construction and propellant mass.

This thesis reviews the literature regarding space resources, and notes the tremendous expansion in knowledge of the Near-Earth asteroids over the last decade (up to 1997), in regard to their population, compositions, and accessibility, making them primary targets of interest.

The literature highlights, and this thesis addresses, the need to consider details of potential mining and processing methods.

The literature also highlights the need for rigorous ways of comparing alternative hypothetical projects and deciding between competing targets, and competing mining, processing, propulsion, and power system choices, which all interact in complex ways.

This thesis identifies that the most useful high-level design-driver for assistance in making these choices and comparisons is the project Expectation Net Present Value, and produces flow diagrams, equations, and a calculation process enabling easy NPV calculation for various target orbit types, mission types, and system choices.

Examples are worked, using reasonable numbers for equipment mass and throughput, and basic celestial mechanics constraints. The conclusion is reached that robotic resource recovery from NEAs is technically feasible in the near term, and that the returned product can potentially be highly profitable, given an in-space market of some thousands of tonnes per year, in competition against Earth-launch costs of several hundred dollars per kilogram.

Glossary

apollo asteroid	asteroid with perihelion $q < 1.017$ AU and semi-major axis $a > 1.0$ AU
amor asteroid	asteroid with perihelion 1.017 AU $< q \leq 1.3$ AU
aten asteroid	asteroid with semi-major axis $a < 1.0$ AU and aphelion $Q > 0.983$ AU
aphelion	Q; the point on an orbit that is most distant from the Sun
carbonyl	a compound of a metal with carbon monoxide
hyperbolic velocity	the velocity of an object relative to a planet (in this thesis, the Earth) when it is outside that body's gravity well.
Hohmann transfer orbit	the most energy-efficient transfer trajectory between two coplanar orbits: it is an ellipse, tangent to the two orbits between which the body is transferring.
impulsive	a change in velocity that is imparted in a short period of time relative to the total trajectory duration
kerogen	the solid hydrocarbon in oil-shale
perihelion	q; the point on an orbit which is closest to the Sun
pyrolysis	generation of chemical species by thermal decomposition
regolith	surface fragmented rocky debris blanketing the Moon and small solar system objects
synodic period	period of a body with respect to the Earth
transfer orbit	trajectory from one body to another
trojan	an object which is trapped in a stable orbit 60 degrees ahead of or behind the primary body as it orbits the Sun.
volatiles	gases that can be released from comet cores by heating: (and hypothetically, from asteroids which are analogues of carbonaceous chondrites) water, carbon dioxide and monoxide, methane, ammonia, and hydrogen cyanide.

Abbreviations

AN	Ascending Node
AU	Astronomical Unit, equals the semimajor axis of Earth's orbit
DN	Descending Node
ELEO	Equatorial Low Earth Orbit
FOM	Figure of Merit
GEO	Geostationary Earth Orbit
HEEO	Highly Elliptical Earth Orbit
ISPP	In-Situ Propellant Production
IRR	Internal Rate of Return
LEO	Low Earth Orbit
LOX	Liquid Oxygen
LH_2	Liquid Hydrogen
MPBR	Mass Payback Ratio
NEA, NEO	Near-Earth Asteroid, Near-Earth Object
NPV	Net Present Value
NiFe	Nickel-Iron
PGM	Platinum Group Metals
ppm	parts per million
SSPS	Satellite Solar Power Station
SSTO	Single Stage to Orbit
SNC	Shergottite-Nakhlite-Chassignites: meteorites of likely Mars origin
VTOL	Vertical Takeoff and Landing

Mathematical Symbols

a	semi-major axis (of orbit)
e	eccentricity (of orbit)
i	inclination to the ecliptic (of orbital plane)
q	perihelion (of orbit)
Q	aphelion (of orbit)
Δv	velocity change
I_{sp}	specific impulse of rocket exhaust (seconds)
v_e	exhaust velocity (of rocket)
Δv_{DS}	deep-space rendezvous velocity
C_3	hyperbolic departure velocity squared (km^2/s^2)

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

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Chapter 1: Introduction

This thesis reviews the literature and concepts relating to mining the Near-Earth Asteroids for supply of resources to future in-space industrial activities. It develops a standard approach for carrying out Preliminary Feasibility Studies on proposals for asteroid resource recovery projects.

1.1 Background to the Concept of Space Mining.

1.1.1 The Desirability of Space Development

Any considerations of the long-term prosperity and indeed survival of humanity must take into account possible cosmic catastrophes, such as impact by asteroid or comet (Gehrels, 1994; and Chapman & Morrison, 1994). The need to develop a capability to deflect such potential impactors strongly suggests that mankind needs to be a space-capable, or in fact a space-colonizing species, rather than a species restricted in its ecological range only to the Earth.

Similarly, considerations of access to the almost unlimited energy and material resources of the solar system also point towards space colonization, focussing initially on the plentiful and diverse material resources in the asteroids (Lewis & Lewis, 1987).

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

The effect on the popular consciousness of realising that our species' range is not restricted to the surface of the Earth, but potentially extends throughout the Solar System, will be profound. The "Limits to Growth" paradigm will be replaced by an optimistic view of an increasingly prosperous, capable, and widespread, and therefore more secure humanity colonizing the Moon, the asteroids, Mars, and the moons of Jupiter and Saturn, and utilizing their resources. This clearly needs to be tested against technical and economic principles as to its achieveability.

1.1.2 Potential Commercial 'Drivers' for Space Industrialization

The future industrialization, settlement, and utilisation of space is likely to be brought about primarily by increasing commercial activities in space. In the near term (e.g. the next 20 years) the following reasonably predictable space commercial activities could develop.

Commercial space operations presently provide 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. Space based personal communications is imminent with the introduction of low earth orbit (LEO) satellite based mobile phone systems: "world-phones" such as Motorola's Iridium system. Capital expenditure for the Gates / McCaw Teledesic system, with a constellation of some 290 satellites, is in the order of $10 billion. (2012 update: market did not expand as predicted.)

At present, each satellite investment is rendered useless when it runs out of stationkeeping propellant. "The present annual consumption of propellant to boost communications satellites from low earth orbit (LEO) to geostationary orbit (GEO) is about 250 tonnes. At the present cost of lifting propellant to LEO of about $8000 per kilogram, this amounts to about $2000 million dollars per year." (Kuck, 1995). Thus, in-space refuelling and refurbishment of this enormous investment is a likely near-term development, using some sort of remote controlled in-orbit refueller.

It has been speculated that in-space industry may include commercial space-based production of high value pharmaceuticals, semiconductors, ultra-pure crystals, and exotic alloys. Although work has been done on the Russian “Mir” space station (in orbit since 1986) and on various Shuttle Flights, commercialization has been severely delayed by problems of restricted and costly access to space via the Space Shuttle, particularly after the Challenger disaster.

A more speculative, but technically sound driver for commercial space based activities, is the concept of large orbiting satellite solar power stations (SSPS), initially proposed by Dr Peter Glaser of Arthur D Little in the late 1970s. (For a good review of early work, see Glaser, 1982).. Such satellites would collect solar power, convert it to microwaves, and beam it to receiving antennae on Earth where the energy would be rectified, converted to AC power, and fed into the electricity grid.

This concept is again receiving active consideration, after a decade of disinterest: the Japanese are carrying out formal studies into an equatorial orbit SSPS pilot plant, titled SPS2000, to orbit at 1100km altitude (Nagatomo, 1996). A full-scale Geosynchronous orbit Solar Power Station (of say 5GW) would mass many thousands of tonnes. An SPS constructed using non-terrestrial materials, sourced from the Moon or the asteroids, could save up to 99% of the earth-launched mass, and hence earth-launch cost, with concomitant total increased mass of less than 8% (Space Studies Institute, 1986).

Another speculative, but again technically sound proposal for large scale activity in orbit is the work on the feasibility of space tourism by Patrick Collins, of University of Tokyo Research Centre for Advanced Science and Technology. The Japanese Rocket Society, with support from major industrial organizations, is planning a 50 - passenger, vertical take off and landing, single stage to orbit rocket - the “Kankoh-maru” - with a gross lift off mass of approx 550 tonnes (Isozaki et al, 1994). Their cost target is to get down to $200/kg, believing that at this cost, the space tourism market will grow rapidly to several billion dollars per year, and require hotels in orbit, to cater for 10 000 person accommodation after some years (Collins et al., 1994; Collins & Isozaki, 1996).

Thus there will be a market for construction metal, and for both stationkeeping and deorbit propellant.

1.1.3 The potential future market for mass-in-orbit

As a result of the activities described above, it is possible to hypothesize a conceptual post-2010 market for mass in low-earth-orbit (i.e. metals for construction, propellants, ceramics, life-support volatiles, and unprocessed mass for ballast and shielding against cosmic radiation). It is thought that the main early demand for mass in orbit will be for volatiles for propellant, closely followed by nickel-iron for construction material. The size and rate of development of this future in-orbit market for materials is not clear at the moment, but 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".

All these developments are presently stalled by the cripplingly high "airfreight" cost to lift anything into orbit. Present launch systems cost from \$10,000 to \$20,000 per kilogram to place mass in low earth orbit (LEO - 300km altitude), and about \$40,000 per kilogram to place mass in high geosynchronous earth orbit (GEO - 35,000km altitude). (Figure 1.1 on next page, from Stuart & Gleave, 1991).

This high launch cost is the result of the "throwaway" nature of present launch vehicles, low flight frequency and utilization, and extreme manpower demands of present operations. Totally reuseable, low maintenance, fast turnaround, high utilization airline style vehicles and operations would probably reduce cost to launch by a couple of orders of magnitude, to something like \$500 per kilogram to low earth orbit, still a rather high figure. As noted above, market studies suggest that at about \$200/kg there will be a multi-billion dollar space transportation market, driven initially by tourism. Large reduction in launch cost will prompt a huge growth in the market.

Thus, space commercialization is presently held back by the high entry cost, and, conversely, the development of low cost launch systems will be slow until there is an indication of a growing demand for transportation into space.

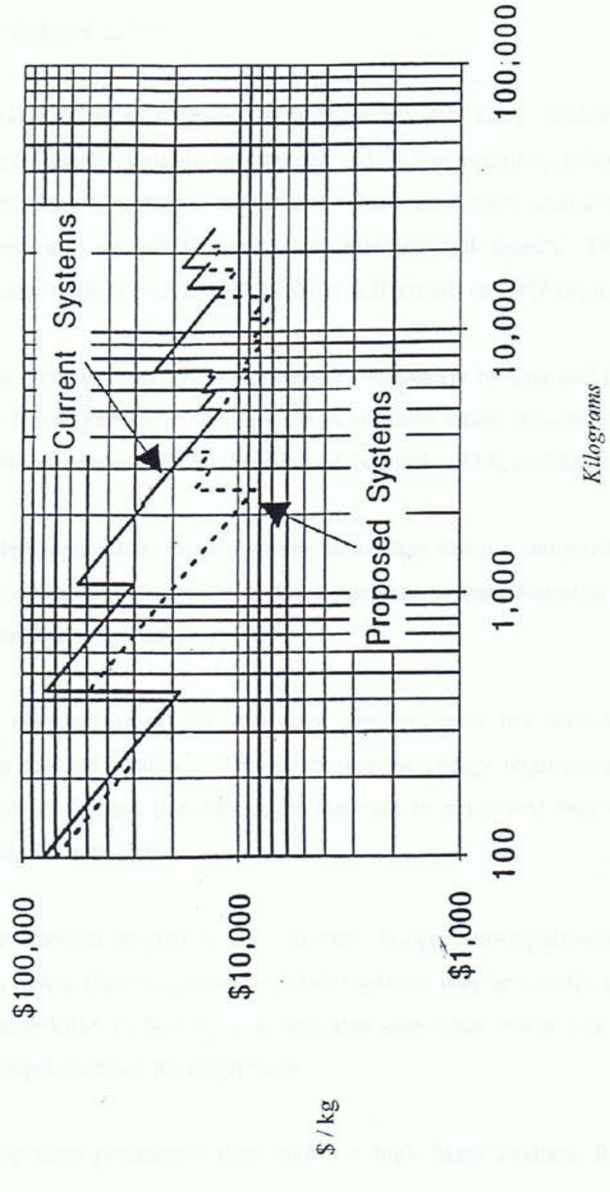


Figure 1.1 Launch Cost per kilogram vs Mass
(160 km orbit - US launch systems)
(Stuart & Gleave, 1991)

Kilograms to 100 mile Reference Orbit, i = minimum
Kilograms to 100 mile Reference Orbit, i = minimum

1.1.4 The Accessibility and Competitiveness of Non-Terrestrial Resources

Activities in orbit will require mass in orbit: metals for structural materials, oxygen, hydrogen, hydrocarbons, and ammonium compounds for fuels, and nonmetals for insulation and radiation shielding.

There are natural resources in space: metallic nickel-iron alloy, ilmenite, silicate minerals, hydrated minerals, bituminous material, and various volatiles, including water, ammonia, carbon dioxide, methane, and others. These have been identified either in meteorites, in lunar soil, or spectroscopically in asteroids and comets. There is also nonstop solar power at the rate of about 1.3 kW/sq m (thermal) or 100W/sq.m electrical.

The idea of mining the asteroids was first discussed in concept by Cox and Cole, 1964, and in detail by Brian O'Leary in “Mining the Apollo and Amor Asteroids”, in 1977. Other early writers are Herrick (1979), Morrison & Niehoff (1979), and Kuck (1979).

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 these possible target asteroids is much less than the energy requirement to launch from Earth.

In addition, the freedom to deliver the velocity change non-impulsively, over an extended period, means that low power propulsion systems may be considered, and this opens up the possibility of choosing a system that uses solar power and derives its return-journey propellant from the target body.

This *in situ propellant production* then allows a high Mass Payback Ratio **(mass multiplication).**

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.

Accessibility of Space Resources: 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.

From consideration of velocity increments for different transfers, it can be seen that it is 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 (see table 1.1 below).

Table 1.1 Mission Velocity Requirements (Δv)

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 orbits to Earth transfer	approx	1.0 km/s
LEO to Phobos / Deimos		7.0 to 8.0 km/s

Likely low Δv 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 Earth-Trojan asteroid (1986TO being the first such discovered); any of the Earth-orbit-hugging "Arjunas"; and the Moon itself. (Trojan asteroids are bodies which share the same orbit as a major planet, are gravitationally trapped in that orbit, and lead or lag the planet by 60 degrees in its orbit around the Sun.) These asteroid types are defined in Chapter 3.

1.1.5 In-Situ Propellant Production

The mission velocity Δv needed to reach these "near earth" low Δv targets is not significantly greater than that needed to place a communications satellite in geosynchronous earth orbit (GEO). The Δv required to return material from these targets is in some cases *very much less than that required to lift mass into orbit from the surface of the earth*, and it does not necessarily have to be provided impulsively. It 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, or propellant, 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. **Mass multiplication factors above 100 must be the initial aim.**

The effect of the very low energy requirement to return some asteroidal material to earth orbit, together with the possibility of using asteroid-derived mass for propulsion, is that some asteroidal material may be able to be delivered into Earth orbit for a cost which is very much less than the cost to launch the same mass of material from the Earth.

1.2 Purpose and Outline of Thesis

The intent of this thesis is 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) a development of a market for the products

(ii) adequate spectral data to suggest the body will contain the desired materials

(iii) identification of the range of orbital parameters that give reasonable accessibility and mission duration

(iv) development of feasible retrieval concepts (via In-Situ Propellant Production)

(v) development of feasible concepts for mining & processing

(vi) "adequate" Mass PayBack Ratio, and most importantly, positive Net Present Value, using chosen handling, processing and retrieval concepts.

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

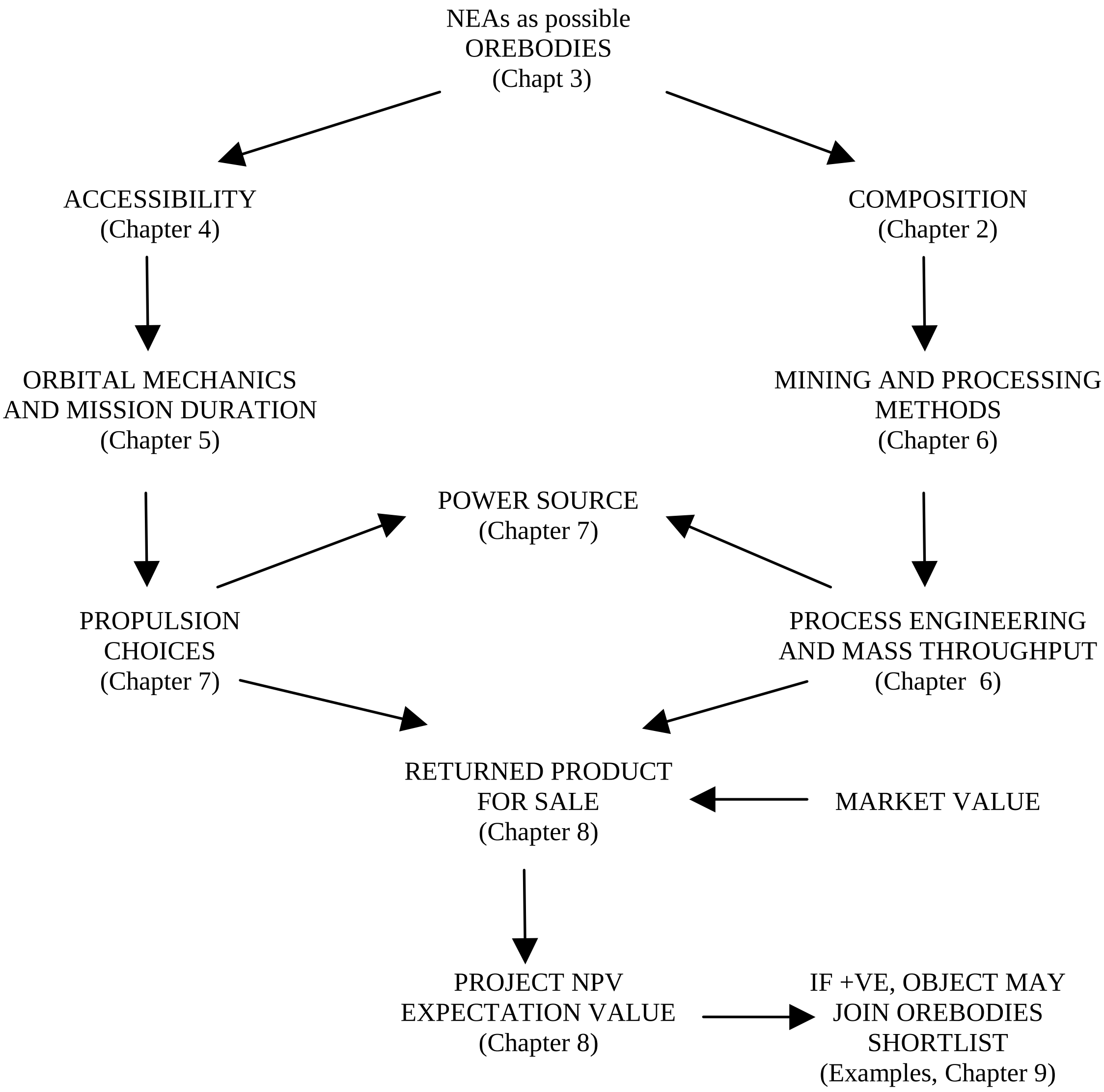


Figure 1.2 Concepts Flowchart

The above flowchart is a simple description of the methodology which is developed in this thesis for determining the technical and economic feasibility of any hypothetical asteroid mining project. It also shows the dissection of the topics into their respective chapters.

A brief review of the Chapter contents follows.

1.2.1 Review of Asteroid Geology & Resources

Astronomical work over the last fifteen years has increased the number of known Near Earth Asteroids (NEAs) from about 30 (Wetherill, 1979) to about 380 (see Asteroid Listings, page 195). 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 many 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 subset of the NEAs is more accessible than the Moon, in terms of required mission velocity (Δv) for outbound and return trips.

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

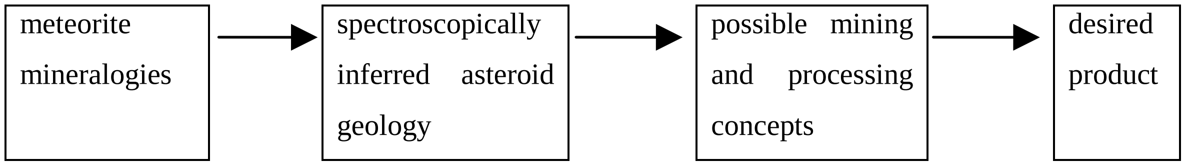


Table 1.2 Matrix of spectral type, inferred mineralogy, and potential products.

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)

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 possible sources of volatiles for future space industry.

Asteroid "geography": NEAs are classified by orbital parameters into Apollos, Amors, and Atens. The "Arjunas" are a group of small objects in very Earth-like orbits. The discovery rate of NEAs is now quite high, about 50 per year. (Asteroids with their orbits entirely within Earth's – ie., with Q < 1 AU - are called 'Atiras'.)

1.2.2 Asteroid Accessibility and Mission Profiles

Accessibility is defined in terms of Δv, total velocity change required, for outbound and for return trajectories. Approximately 10% of NEAs are more accessible than the Moon and at least 50% of these are likely to be potential orebodies.

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 the *means of comparison of mission concepts* are not well-developed.

This thesis develops methods for comparison of different asteroid mining concepts, and for choosing between various trajectory, mission, and engineering alternatives, so as to maximize project economic feasibility.

Application of the concepts of celestial mechanics show that

(i) simple estimates of "global minimum" delta-v can be made, by several methods;
(ii) the launch windows for these "global minimum" opportunities are infrequent, but somewhat more expensive local minima occur at approx 2-yearly intervals, for most NEAs;
(iii) good outbound opportunities do not generally fit with good return opportunities;
(iv) long synodic periods and phasing requirements militate against multiple-return mining missions;
(v) Earth-return hyperbolic velocity should be kept low (lunar flyby capture may be useful).
(vi) high-e targets require Hohmann transfers out and back, and a short (3 to 6 months) mining season at aphelion;
(vii) low-e targets may use continuous-thrusting propulsion, and short mining season.
(viii) missions appear to be classifiable by trajectory type and linkage with target type

Missions appear to be classifiable into 5 distinct types.

Despite the above constraints, there is a growing subset of targets that appear to be intermittently accessible for an outbound Δv of under 6 km/s, and offering return departure Δv under 2 km/sec.

1.2.3 Concepts for Mining, Processing, Power, and Propulsion

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. Process options are:

in-situ fluidization (now rejected due to risk of loss of circulation)
mechanical collection and thermal dehydration
mechanical collection and magnetic separation
carbonyl process.

Table 1.3 Possible Products and Sources

Type	Product and Process	
	Volatiles	Metal
"cryptocometary"	H_2O, CO_2 in-situ fluidization	----------
carbonaceous	H_2O, CO_2 thermal dehydration	NiFe magnetic separation
ordinary chondrite	----------	NiFe magnetic separation
metallic	----------	NiFe, Platinum Group Metals carbonyl process

For reasons of simplicity, risk minimisation, and near-term achievability, as well as achievability of economic viability, various <u>choices</u> would have to be made, and this thesis will expand only on some of these in further detail rather than all alternatives:

Product and Engineering Choices (those to be expanded on are underlined):

product : <u>water</u>; metal; other gases; silicates; PGMS

process : <u>drilling with insitu melting and extraction;</u> electrostatic / magnetic extraction ; carbonyl extraction; <u>heat, volatilize, and condense</u>

target type : overtly cometary; <u>extinct or dormant comet; overtly carbonaceous or hydrous asteroid</u>; S-type asteroid; overtly metallic asteroid.

trajectory and mission type : <u>"Apollo type"</u>; <u>"Aten- type"</u>; "<u>Arjuna type</u>"; <u>"Amor type"</u> <u>SP comet type</u>; <u>low-e, plane-change-dominated.</u>

power : <u>solar thermal</u>; nuclear thermal; photovoltaic;

propulsion : mass driver; arcjet; <u>steam rocket</u>

control : manual : <u>telepresence</u>; <u>machine autonomy</u>

Propulsion and power choices are linked; only a subset is technically viable. *In-situ production at the asteroid of the propellant required for materials return is an important* *"enabling" concept.* Sensible system choices are given below and further discussed in Chapter 7.

Table 1.4 Propulsion and Power Choices

		Propulsion		
		steam rocket	arcjet	mass driver
Power	solar thermal	Yes	No	No
	solar PV	No	Yes	Yes
	nuclear	Yes	Yes	Yes

1.2.4 Project Feasibility and Selection Criteria

The intent of this study is to develop a robust approach to defining the selection criteria which will determine the choice of preferred prospective target orebodies within the population of Near-Earth-Objects. It will be necessary to develop a logical way of comparing competing project concepts; ie a “Figure of Merit” for comparing asteroid mining concepts. Most of the (relatively fragmentary) literature to date has concentrated on Mass Payback Ratio, but it is clear that Net Present Value (NPV) is a more basic criterion for determining economic viability. The formula for NPV can be readily expanded so as to explicitly reference the astrodynamical parameters that define various asteroid missions.

The concepts discussed here involve the design for the simplest, minimum mass and cost product return system possible, which precludes a crewed mission. It assumes a remote controlled or automated mining and processing plant and assumes initial in-orbit market will be for volatiles for fuel.

1.3 Conclusions

This thesis provides the outline, plan, or generic methodology for performing Feasibility Studies for the asteroid mining projects of the early years of the next century.

Chapter 2: Asteroidal Resources

2.1 Attractiveness of the Near-Earth Asteroids versus other targets.

This Section reviews the Near-Earth Asteroids as potential resource sources in comparison with the other more-generally proposed alternatives, which are the Moon; and Phobos or Deimos, the moons of Mars.

2.1.1 The Moon

The Moon's relatively deep gravity well calls for an impulsive (i.e. rapidly applied) velocity change of approx 1 km/sec to transfer from lunar orbit to lunar surface or vice versa; and approx 2.4 km/sec either to perform a soft landing from a direct-from-earth trajectory or to take off on a direct to LEO (low Earth orbit) trajectory. The orbit to surface and surface to orbit transfer impulse requirements demand a large thrust-to-mass ratio rocket motor. This is a severe constraint on propulsion system and on propellant type; it means that the rocket must be either chemical or nuclear thermal, and the propellants of choice either hydrogen and oxygen, or hydrogen, respectively.

Electromagnetic launchers are not a near-term option because their emplacement demands very high level engineering capability and significant on-surface infrastructure. In addition, their inflexibility in launch azimuth and ultra-high g-force regime renders them much less useful than other launch systems.

There are simple schemes available for extraction of oxygen from lunar soils; and there are substantial quantities of water as ice (permafrost?) in permanently-shadowed craters at the North and South poles, as discovered recently by the Lunar Prospector probe. These discoveries profoundly improve the prospects for economic developments on the Moon.

These substantial water ice deposits make the Moon potentially a very easy place to get to and return from, despite its gravity well, because of the insitu availability of hydrogen and oxygen for fuel, and a very easy place to colonize.

It must be noted also that the Moon is the only non-terrestrial body humans have actually visited; there is certain knowledge of the composition of the soil at some dozen locations on its surface. It is known with certainty how the soil might be processed to recover free metal (Ni-Fe) fines (Agosto, 1981), or iron and oxygen from its ilmenite, or aluminium and oxygen from the feldspar. In addition, solar beamed microwave power may be an exportable commodity, if solar cells can be manufactured on-site (Criswell, 1995).

The relatively high gravity means that structure design and materials handling will not be dissimilar to earth based solutions; stable foundations and gravity imply easy civil engineering; there is an extensive literature regarding possible mining techniques for the Moon (see e.g. US Army Corps of Engineers, 1990).

An important advantage of the Moon over other targets is that communications are nearly instantaneous, and therefore real-time remote control from Earth is possible. However, any polar ice mining activity will need several communications satellites in lunar polar orbit.

In summary, the arguments (post-Lunar Prospector) against the Moon as a source of resources include: hardly any free metal, substantial impulsive Δv requirements; two weeks of imposed darkness out of every four, hence need for energy storage of heroic proportions, or for 50% downtime, or for nuclear power; and very severe temperature cycling. There is however a small spot near the lunar South Pole which appears to have near permanent sunlight.

2.1.2 The moons of Mars

Phobos and Deimos are potential resource targets. There is already high resolution photography of their surfaces, showing a well developed soil or regolith layer; and they are thought to be captured D-type asteroids. If this is so, they may contain both recoverable volatiles and extractable metal. The Russian Phobos 2 probe detected a shock front near Deimos, indicating either a magnetic field or evidence of outgassing (pers. comm., D. Kuck, 1996). However, spectral signatures for hydrated silicates have not been seen. It has been calculated (Fanale & Salvail, 1990) that deep primordial ice may persist in Phobos and Deimos, at depths of (approx) 20 metres (polar) to 100 metres (equatorial). This being so, these moons could be highly prospective as ice orebodies. However, Kuck notes that the highly fractured nature of Phobos makes it unsuitable for an in-situ fluidization - mediated approach to resource volatiles recovery (because of the threat of loss of circulation).

The velocity change needed to rendezvous with these minor planets is not great. It is the same as that needed to launch out of earth orbit onto a Mars transfer ellipse, i.e. approx 3.5 km/s, plus the Δv to circularize at the satellite's altitude. This assumes a zero-fuel-requirement aerocapture at Mars to match with Mars's heliocentric velocity, and to drop into an elliptical orbit with its highest point at the altitude of the target satellite. The satellite chosen should be Deimos because it is the higher, and hence a smaller circularization velocity will be required (700 m/s). Also, the velocity required for the later launch of valuable material back to earth orbit will be less than would be the case if it were to be launched from Phobos.

Phobos and Deimos are natural bases from which to conduct manned exploration and colonization of Mars.

There is a very significant drawback with the choice of the moons of Mars, however. This is that the navigational demands for successful aerocapture by close fly-through of the very thin Martian atmosphere are extreme, and are not demonstrated to be within the present state of the art. Spacecraft control during aerocapture must necessarily be autonomous, because telemetry time-of-flight time delay is many minutes, longer in fact than the entire aerocapture manoeuvre.

In the absence of aerocapture, an additional Δv of about 3.5 km/s is needed to kill hyperbolic velocity and drop into Mars orbit. In addition, the post-Mars-capture Δv needed to circularize at Deimos of 700 m/sec is similar to or greater than the total deep space Δv for certain Apollo asteroid rendezvous manoeuvres. Additionally, some 2 tonnes of chemical fuel would be needed to lift a 1000 tonne payload off Deimos (assumes rocket I_{sp} -Specific Impulse- of 270 sec).

2.1.3 The Near-Earth Asteroids

The Apollo, Amor, and Aten asteroids are the three classes of Earth-approaching asteroids or Near Earth Asteroids. The NEAs are quite small objects, generally about 1 km in diameter, and may be metallic, silicate, or "primitive" carbonaceous chondrite, inwhich case, water-bearing, i.e., hydrated in composition.

Apollos are asteroids which cross the Earth's orbit; they <u>do represent a collision threat</u>, and are now known to be the origin of some of the regular named meteor showers (Morrison (1993), Olssen-Steel (1987)). Amors do not cross Earth's orbit, but approach it to within 0.3 Astronomical Units (AU). Atens are Earth crossers which have the larger part of their orbit within Earth's orbit, i.e., their orbital semimajor axis is less than that of the Earth's orbit. Atens therefore also represent a collision threat.

The mission velocity to depart LEO for the most accessible of the Apollo-Amor-Aten asteroids is of the order of 5 to 6 km/s, with a ‘deep space’ rendezvous (orbit matching) velocity increment of 1 km/s or less for the most favourable outbound trajectories. The required velocity for departure to return to Earth is generally small, also of the order of 1 km/s, and it can be imparted slowly, over a period of many months if necessary, and hence *is suited to a propulsion system that is power-limited but continuous, and has available to it a large amount of reaction mass.*

Table 2.1 Targets Comparison Matrix

target	propulsion requirements	resource type	timetabling constraints	comments
Moon	6.3 km/s out; 2.4 km/s back	silicates giving aluminium and oxygen; polar ice	none	both out and back must be impulsive, high thrust
Phobos or Deimos	~4 km/s out, 3 km/s back; using aerobraking at Mars; ~8 km/s out without aerobraking at Mars	silicates, possibly NiFe, volatiles, deep buried ice	2 year synodic period	lunar gravity assist may be used both out and back; Mars aerocapture needs autonomous guidance
subset of NEAs	5 km/s out, 1 km/s back; low thrust non impulsive return acceptable	water, metal, carbon dioxide, silicates	irregular, NPV is important constraint	lunar gravity assist may help especially on return

The propulsion needs for a subset of NEAs are lower than for either the Moon or for Phobos/Deimos.

Thus some NEAs are very easy to reach and to return from; they appear to contain a wide range of potential resources (not all necessarily in one body); it is becoming evident that a total gradation exists between comets and asteroids; solar power is available; on-asteroid production of return propellant is possible, which enhances (by orders of magnitude) the potential mass return; it is known that at least some asteroids have regoliths; metallurgical recovery of metals and volatiles will clearly be much easier than from lunar soils, because of the very much higher grades in asteroidal regoliths.

Note that a number of E and M type asteroids, previously thought to be anhydrous, are now shown to have spectral indications of hydrated silicates: this greatly enhances their potential value as resource objects (Williams &Tedesco, 1995). Platinum Group Metals are valuable enough to return to Earth for sale (Kargel, 1994), albeit in the case of near term and small scale operations, probably only as a byproduct.

There are however several serious technical challenges associated with remote-controlled operations on the asteroids. One is that the radio signal time of flight may be anything from 5 to 30 minutes; thus a remote miner must be designed to be "smart"; it must use machine intelligence to operate semi autonomously, with only high-level human operator support.

A second problem is that we do not know how to land on, or more correctly, dock with, a slowly rotating asteroid (average rotation period about 6 hours) the gravity of which is 0.001 of Earth's, or less. There is also the necessity to secure equipment during mining operations, against various reaction forces; and there is the need to design processes which will run in zero-gravity.

The third major problem is that there is at present only inadequate geological knowledge; and detailed spectra exist for only very few of the NEAs. This can be easily addressed by support for low-cost astronomical studies.

A further interesting observation is that as mining projects, many asteroids appear to be “one season” mines, because of synodic or phasing constraints on launch and return arrival times.

2.1.4 The Resource Attractiveness of the NEAs:

Despite these drawbacks, i.e., ‘one-season’ mines, inadequate present geological knowledge, and necessity to develop autonomous mining equipment, the NEAs still appear to represent the most attractive orebodies for supply of water or ‘celestial stainless steel’ to facilities in LEO. The purpose of this thesis is to define more clearly the requirements that need to be met to achieve technical and financial feasibility, for any hypothetical asteroid mining project.

“... the Near Earth Asteroids are compositionally diverse, ... with km-sized chunks of natural stainless steel, the cores (possibly ice-rich) of extinct comets, primitive unmelted planetary materials, and differentiated rocks similar to lunar basalts....”. (There are also, it is now known, asteroids containing water-bearing clays and carbonaceous oil-shale-like materials ...)

"The panoply of materials is vastly broader and richer than those known to be present on the Moon. At least one-fifth of NEAs are volatile-rich, ... and almost all the others are metal-rich. Also, about one fifth are energetically more accessible than the surface of the Moon .....*Schemes are already known by which spacecraft dispatched on round-trip missions to the best of these asteroids could return over 100 times their own mass of asteroidal resources to near-earth-space*" -Lewis and Hutson, 1993.

Thus, the asteroids may be a veritable cornucopia of resources for the industrialization of space. The NEAs are good -probably the best- prospects for early extraterrestrial resource recovery ventures.

2.2 Asteroidal and Cometary Geology and Mineralogy

The geology and mineralogy of asteroids can only be interpreted from visible and IR spectral studies by astronomers, by attempting to correlate information from meteorite samples, from photographs taken during the two asteroid flybys of Gaspra and Ida by the Galileo probe, and the flyby of Mathilde by the NEAR spacecraft, and radar studies using radio telescopes.

Asteroids Gaspra and Ida, both S-types, photographed by Galileo during its flybys of them in 1991 and 1993, and Mathilde, a C-type, photographed by the NEAR probe in 1997, all show a well developed regolith despite the negligible gravity (Sullivan et al, 1995). There had been speculation that asteroids would necessarily lose any fines and be reduced to bare rock or metal. Ida was found to have a moon, named Dactyl, which, despite being only 1.5 km in diameter, itself retains a regolith.

Two Apollo asteroids, 1986DA and 3554 Amun, are known from radar reflection studies to be solid metal (Ostro et al, 1991). Others are suspected to be so from spectroscopic studies.

There are radar images of only three asteroids, Castalia and Toutatis, which both appear to be contact binaries, and very irregular, and Geographos, which is "the most elongated body in the solar system" (Ostro et al., 1995). See images on page 24.

Photometric and spectroscopic studies appear to show a wide variety of compositions, including metallic nickel-iron, silicates, hydrated silicates, and bituminous.

All of our assumptions about the makeup of asteroids depend on spectroscopic and photometric information and on implied linkages with meteorites. *Meteorites are the only "ground truth" available, and selection biasses are large and not well known*. For example, not all lumps of material entering the upper atmosphere will survive to reach the ground: volatile and structurally weak or friable objects will generally not survive to end up in museum display cases or meteoricists' laboratories. (An interesting exception is the recent recovery of an apparent ice meteorite in China! -Wang & Zhang, 1995.)

There is also selection bias at work in asteroid discovery rates and proportions: darker asteroids are clearly more difficult to discover than lighter asteroids.

Thus in order to review asteroid taxonomy and assumed mineralogy, meteorite mineralogy and taxonomy must first be discussed.

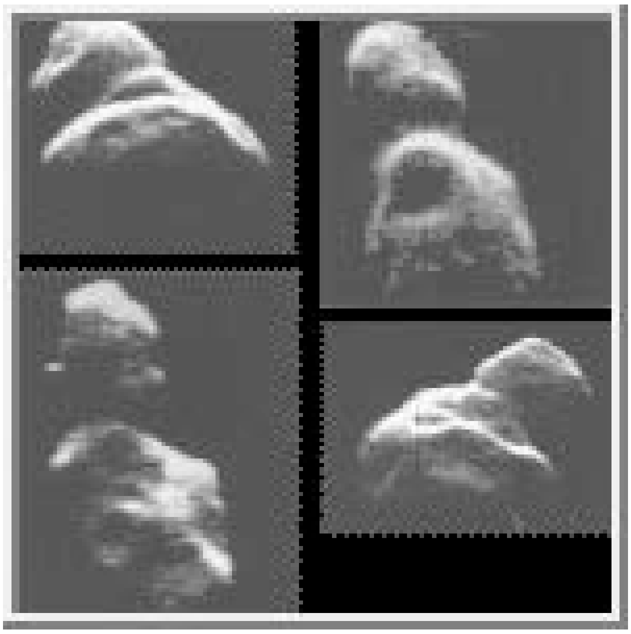


Figure 2.1 Near-Earth Asteroid Toutatis radar images (from JPL)

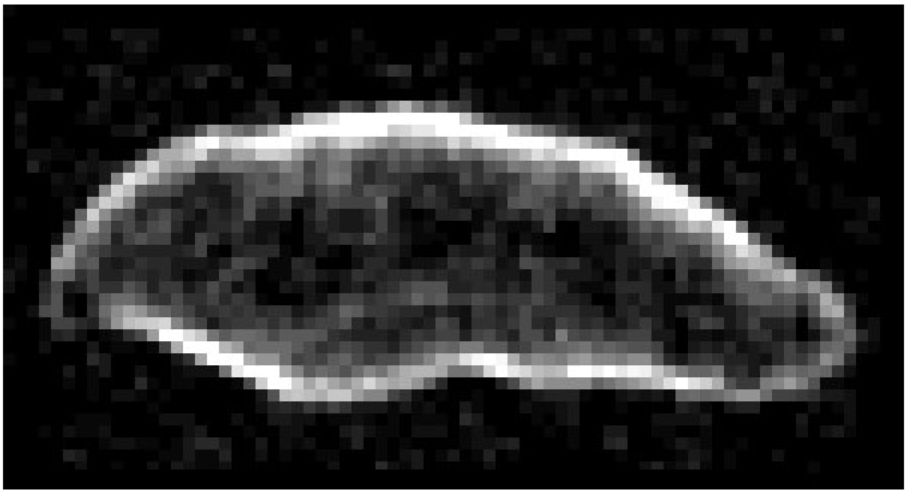


Figure 2.2 NEA 1620 Geographos radar image (from Ostro et al)

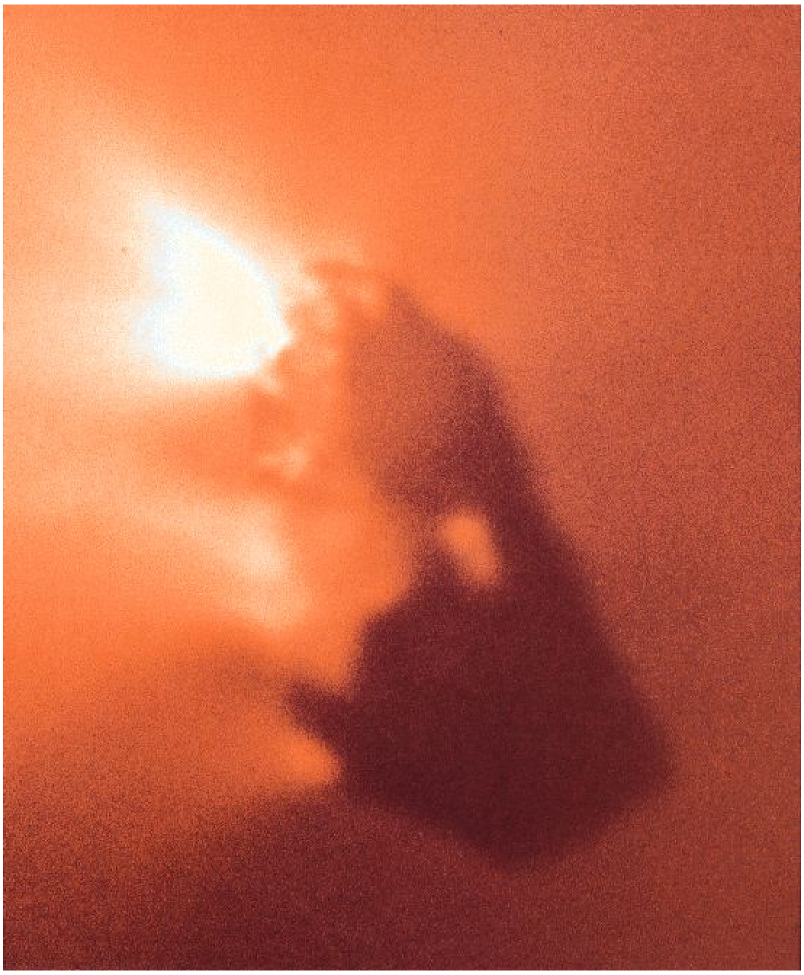


Figure 2.3 Comet p/Halley image from Giotto probe (from Max-Planck Institut)

2.2.1 Meteorite Mineralogy and Taxonomy

Meteorites are classified into Stones, Stony-Irons, and Irons.

The Stones comprise two subclasses, the chondrites and the achondrites. The Chondrites appear to be samples of primitive solar system accretion bodies with zero to low metamorphism, possibly with some aqueous alteration, and possibly some metasomatism. These are believed to be “never melted” bodies, dating from the origins of the solar system, and to be compositionally unchanged since their condensation from the presolar nebula, with composition correlating with mean radius of formation from the Sun. Chondrites are further subdivided into Enstatites, Ordinary Chondrites (these contain “abundant” free metal), and Carbonaceous Chondrites (these contain “no free metal, but autoreduction of magnetite and other iron oxides by carbon permits extraction of up to 40% by weight of total HCNO volatiles” - Lewis and Hutson, 1993).

The second classification within the Stones, the Achondrites, are igneous, basaltic, and show clear evidence of having been differentiated from a melt.

The Stony irons and the Irons are even more heavily differentiated and are interpreted to be fragments from the metallic core or the mantle-core boundary of an igneously differentiated planetesimal which suffered disruption in a cataclysmic impact.

Table 2.2 Meteorite Taxonomy

Primary	Secondary	Tertiary	Comments & analogs
Stones (96% of all falls)	Chondrites (88% of all falls)	Enstatites (3% of all falls)	$MgSiO_3$; high iron EH, or low iron EL
	primitive, zero to low metamorphism; aqueous alteration, metasomatism	Ordinary Chondrites (77%)	"abundant" free metal; high iron H, low iron L, or low-low iron LL
		Carbonaceous Chondrites (8%)	"no free metal, but autoreduction of .... iron oxides by carbon permits extraction of up to 40% w/w of total HCNO volatiles" (ref Lewis & Hutson)
	Achondrites (8% of all falls)	Eucrite, Howardite, Diogenite:	asteroids 1980PA, 1983RD, 1985DO2, are likely analogs
	igneous, basaltic, differentiated; not attractive for resources	Ureilite	C-rich
		Enstatite Achondrite or Aubrite	1982BB
		Lunar & Martian (SNC)	
Stony Irons (1%)	Pallasites Mesosiderites		olivine grains in metal matrix
Irons (3% of all falls)	Hexahedrites, Octahedrites, Ni-rich Ataxites		asteroids 1986DA & 3554 Amun are likely analogs

Ordinary Chondrites

The identity of the source asteroids for Ordinary Chondrites is a major puzzle of meteorite/ asteroid studies, because despite their abundance in meteorite collections, the only spectral matches are apparently to 1864 Apollo and to 3628 Boznemcova (Bell, 1995).

Theories and possibilities are:

1. Some S-type asteroids may be source objects for Ordinary Chondrites but regolith weathering processes may have enhanced the metal content of the surface and hence reddened their spectra. However Clark, Fanale, and Salisbury, 1992, argue convincingly against this hypothesis in "Meteorite - Asteroid Spectral Comparison - the Effects of Comminution, Melting, and Recrystallization".
2. Ordinary chondrite source bodies may have all attritioned to sizes too small to detect by telescope.
3. Regolith processes (gardening, radiation exposure) may have darkened the surfaces of the origin bodies to the point that they now have quite different spectra and get identified (erroneously) as C-type asteroids.
4. Ordinary chondrites may come not from asteroids but from comets.
5. Maybe all come from Boznemcova, which is close to Kirkwood gap, and has matching spectrum.
6. It has been suggested that commentators are mistaken in applying a time - constant "Uniformitarianist" model to the type-distribution information, and the proportions of 'falls' do in fact change over time. "There is no reason why we *should* expect meteorite type-abundances to be in line with source population abundances, over intervals of less than (say) 10 Myrs." (Gaffey, 1995) -present author's italics.

The implication of this conclusion for asteroid mining is that the spectroscopic evidence suggests a much higher abundance of volatiles in asteroids than might be interpreted from the falls proportion for carbonaceous chondrites in the total recovered meteorite population. If the spectroscopic evidence is more reliable, and in particular taking into account the observational bias against easy detection of C, D class asteroids, then there may be much greater availability of volatiles orebodies in space than meteorite falls indicate.

Carbonaceous Chondrites

Carbonaceous chondrites give the only ‘ground truth’ there is for composition of the most likely asteroidal source for volatiles, the C, D, P, F, and G class asteroids. The Carbonaceous Chondrite classifications are: CI, CM, CO, CV, CR.

CI (Ivuna - type; Orgueil is most-studied example)	=	C1
CM (Mighei - type; also Murchison, Murray)	=	C2
CO (Ornans - type)	}	
CV (Vigarano - type; Allende is most-studied)	=	C2 + C3
CR (Renazzo - type)	}	

The numbers refer to a **petrological scale**, ranging from 1 to 6, where 1 = maximum aqueous alteration (e.g. to hydrated salts or clays); 3 = unaltered (most primitive texturally), and very friable; and 6 = maximum thermal alteration (well cemented; diagenesis); chondrules totally absorbed.

There is an implicit identification of C-type asteroids with meteorites of classes C1/C2 (being relatively pristine chemically -but not texturally- with high proportion of clays) and with meteorites of classes C3/C4, which exhibit some thermal and aqueous alteration, metasomatism, and metamorphism. All such “identifications” must be treated with suspicion and care.

Note that ~ 70% of the carbon in CM-type carbonaceous chondrites is present as “insoluble, macromolecular” material. This material is described by Hayatsu 1977, 1980 thus: “Macromolecular carbon (in carbonaceous chondrites) is composed of condensed aromatic, heteroaromatic, and hydroaromatic ring systems in up to 4-ring clusters, cross-linked by short methylene chains, ethers, sulphides, and biphenyl groups”. He notes its similarity with vitrinite macerals of low-volatile bituminous coals, or with type III kerogens from oil-shales. Cronin et al, 1988, state "macromolecular carbon with H, N, O and S ... has been called 'kerogen-like" and an "organic polymer", but is different from both; it is acid resistant and in this regard fits the formal definition of kerogen ---". The stoichiometry has variously been given as

$C_{100}\ H_{71}\ N_3\ O_{12}\ S_2$ or $C_{100}\ H_{48}\ N_1\ O_{12}\ S_2$

Various researchers have investigated pyrolysis of carbonaceous chondrites and release of volatiles from this "polymer/kerogen" matrix material: Kerridge, 1985; Robert and Epstein 1982; Levy et al.,1973; Studier et al 1972. From the reports of these workers, stepwise heating of carbonaceous chondrite meteorites gives sequential volatiles release, as follows:

initially: CO, CO_2, H_2O; all at low temperature (~100C) in "large" quantities; (unfortunately not measured)

then C_2H_4, CH_4, C_3H_6 etc in "increasingly smaller quantities" at higher temperatures;

finally more CO released at $T \cong 600°C$ (possibly due to autoreduction of FeO?)

The implication of these findings is that asteroids having the composition of carbonaceous chondrites are legitimately able to be considered as orebodies for extraction of water and /or hydrocarbon volatiles.

Unfortunately, quantitative yields are not given, nor is there information to indicate required heating times for volatiles release. There is a need for simple experimental work on carbonaceous chondrites to determine lowest ultimate temperature for efficient volatiles extraction, and fastest heating rate for volatiles extraction, so as to be able to begin design of extraction processes.

2.2.2 Asteroid Taxonomy and Inferred Compositions

Asteroid classification schemes have been based on identifying groupings of photometric and spectroscopic characteristics. Below are listed the various techniques:

Table 2.3 Asteroid Observation Methods

Technique	**Information derived and interpretations**
Reflectance spectroscopy and multicolor photometry	Asteroid Classification; inferred surface mineralogy [Requires broad spectral coverage, high resolution, and high signal-to-noise ratio: knowledge of albedo improves characterization] Detection of water-bearing materials
Visible photometry and lightcurve photometry	Size [Requires knowledge of albedo] Albedo [Requires knowledge of size] Rotation period [Requires a sequence of closely spaced observations over several nights] Approximate shape [From analysis of lightcurves] Orientation of spin axis [From variation of lightcurve form with viewing geometry]
Visible polarization	Albedo [Requires observations over a range of phase angles] "there is an empirical reln. between albedo and polarization of reflected light, and phase angle"
Occultations	Diameter [Dependent on obtaining accurate durations from several sites]; existence of satellites
Infrared photometry	Size [Knowledge of albedo improves determination] Albedo [Derived in combination with visible photometry] Relative emissivity [Model-dependent indication of metal abundance or surface texture]

Table 2.3 (continued)

Technique	**Information and Interpretations**
Radar	Surface conductivity or metal abundance [Model depends on assumptions of surface porosity] Diameter [From duration of returned signal] Rotation rate [From frequency spread] Shape [From temporal variation of frequency spread]
Passive microwave radiometry (incl IRAS) and spectroscopy	Near-surface temperatures Temperature gradients, conductivities, and thermal inertias; cross-sectional area and albedo
Space telescope images	Moderate resolution images [Approximately 30-km resolution in middle of asteroid belt]

From the accumulated meteoritics knowledge and from the classication efforts of Tholen & Barucci (1989), and others, based on photometric and colorimetric properties, there has developed a tentative concensus regarding asteroid class-meteorite class match (eg Gaffey and McCord 1982, Lagerkvist & Barucci, 1992).

Barucci's classification is based on 7 spectrophotometric colours and on IRAS-derived albedos, and shows that the population can be statistically split into 9 classes, denoted B, E, G, C, M, D, S, A. Subclasses are numbered 0, 1, 2, etc with increasing value for higher albedos. This is described more fully in Tholen & Barucci (1989). Inferred mineralogies are in Table 2.4 below.

<u>Asteroid Taxonomy and Inferred Compositions</u>

Despite the tentative identifications below, meteorites are an *incomplete and misleading analogue of asteroidal material*: they do not cover the D, P type asteroids at all, and they tell us effectively nothing about regolith mechanical properties. They do indicate mineral assemblages, but incompletely, and only of the surface material.

A major discovery of the last several years is that approximately two-thirds of Main Belt C-type asteroids show spectral evidence of water of hydration. (Jones, 1990, quoted in Davis et al., 1993). Rivkin & Lebovsky 1995 found that "over 70 asteroids have been studied in the 3μm region for hydrated minerals, and these minerals have been found in roughly half of asteroids surveyed. Recent years have seen hydrated minerals discovered on asteroids of the E and M classes, previously thought to be anhydrous." In addition, the NEAs appear to exhibit the full diversity of compositions found thoughout the Main Belt, not being bound by the compositional gradation with solar distance that one finds within the Main Belt (Figure 2.4).

Table 2.4 Asteroid Taxonomy (modified from Nelson et al, 1993)

Type	**Interpreted mineralogy**	**Meteorite analog**
V	pyroxene, feldspar	howardite, eucrite, diogenite
A	olivine, olivine-metal	brachinite, pallasite
S	metal, olivine, pyroxene (1)	pallasite, mesosiderite
K*		carbonaceous / ordinary chondrites
M	metal, enstatite	irons, enstatite chondrites?
R*	pyroxene, olivine	
Q*	olivine, pyroxene, metal	ordinary chondrites
E	enstatite	enstatite achondrites
T*, D, P*	organic-rich silicates, carbon	
B,C,F*,G (2)	hydrated silicates, carbon, organics, opaques, shock or radiation-darkened silicates	CI, CM chondrites, black, gas-rich chondrites?

(*) Asterisked letters do not appear in Barucci's scheme, but are used in some other classifications

(1) N.B. The density of Ida, an unambiguous S-type, as revealed by Dactyl's period, is such that it cannot contain much iron (unless its porosity is greater than 50%), hence pallasite meteorites should no longer be considered derived from S-type asteroids.

(2) "P, D, RD, T, F, G, and B are all C-type subclasses, and hence are probably rich in carbon and volatiles." - Nichols, 1993.

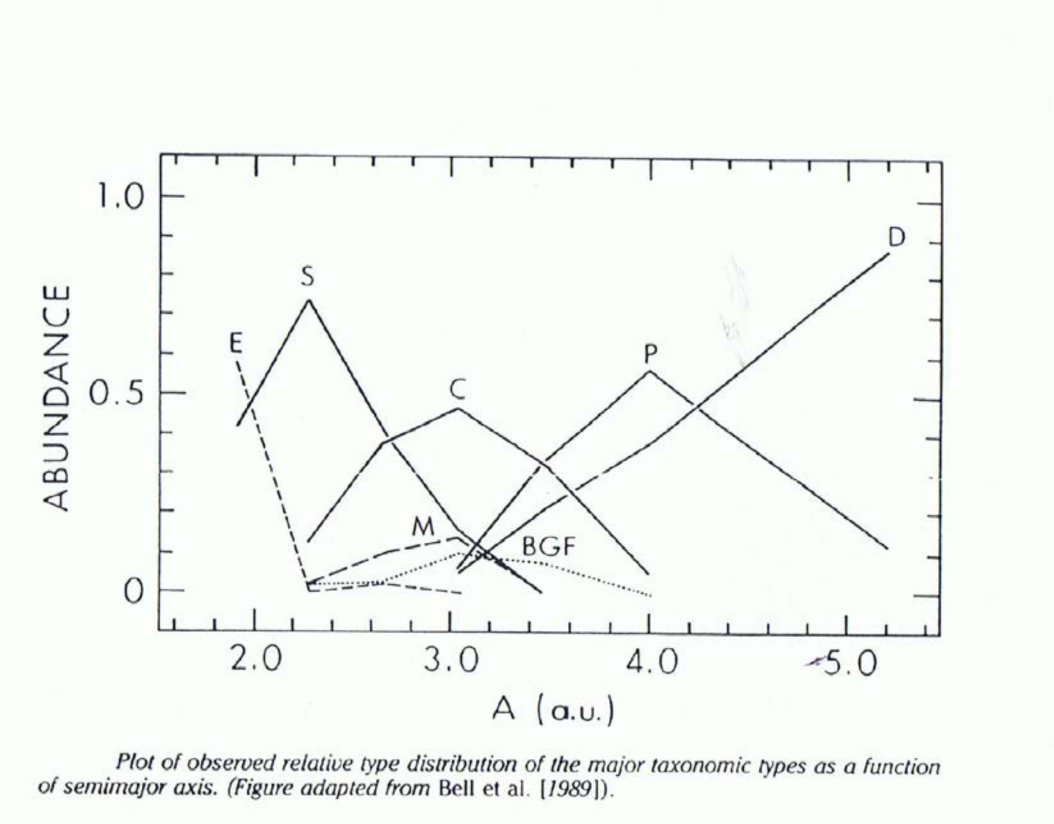


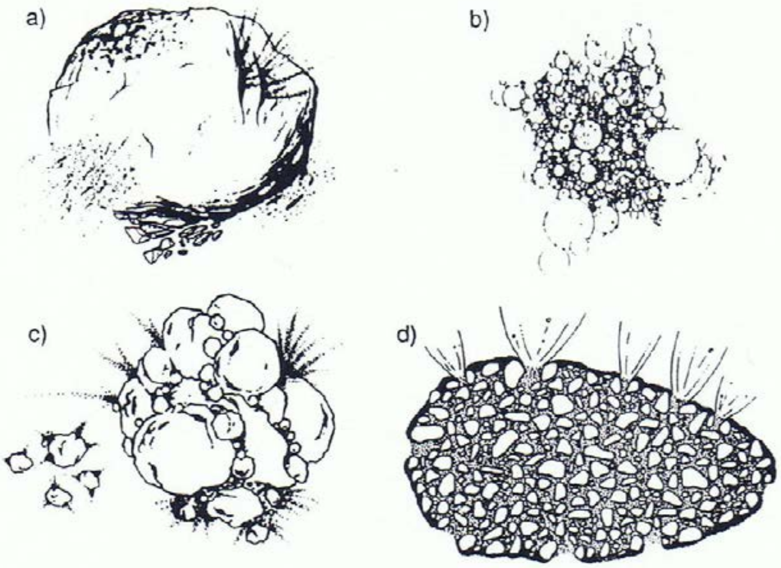
Figure 2.4 Compositional Gradation with Semimajor Axis (from Lewis, 1991)

Also, approximately half of the NEAs are believed to be derived from, or consist of, extinct comets. (Indeed, Steel suggests that a sizeable proportion are genetically related to p/Encke as apparent members of the Taurid Complex (Steel, 1995). Shoemaker suggests that comet - origin NEAs are up to 70 % of the total. (pers.comm. JS Lewis). In fact, it appears to be now accepted that there will be objects which fit into an evolutionary progression from blatant comet to rocky asteroid devoid of gases. (See image of p/Halley, on page 24; this is the most detailed image of a comet yet obtained.)

Thus the majority of NEAs appear to contain at least some water, even if only present as water of hydration or chemically bound in clay minerals, and at least some readily extractable metal; they also appear to contain at least some CO_2 source materials, either C-polymer together with FeO, or calcite/dolomite.

Thus our targets have characteristics ranging from frozen mudballs or gravel-clad snowballs to strengthless gravel-banks, solid rocky mountains with or without detrital cover, to flying lumps of stainless steel, coal, or oil-shale!

Asteroidal regolith, where present (believed never to be present on bodies less than 2 km in diameter, until the discovery of Dactyl) is believed to be of very low strength, e.g., like dry sand or soil, very loose, high porosity, and very poorly sorted, ranging from micron-sized particles to boulders.



Four suggested models for the structure of cometary nuclei: (a) the icy conglomerate model (Whipple 1950; drawing from Weissman and Kieffer 1981); (b) the fractal model (Donn et al. 1985); (c) the primordial rubble pile (Weissman 1986); and (d) the icy-glue model (Gombosi and Houpis 1986). All but (d) were suggested prior to the Halley spacecraft encounters in 1986.

Figure 2.5 Comet Models (from Weissman 1994):
clockwise from top left: icy conglomerate (Whipple); fractal (Donn);
priordial rubble pile (Weissman); icy glue (Gombosi & Houpis)

This apparent resource richness and apparent surface ‘tractability’ tempts one to consider that which most metallurgists would seek to avoid, namely, a plant designed to extract two or more products; but which the mining engineer loves: a multiproduct mine!

Further discussion is given in Chapter 6, Engineering Choices, Mining and Processing.

2.2.3 Comet Origin of Some Asteroids

There are strong indications that many asteroids are extinct or dormant comets (either because of the shape of their orbit, or because of telescopic/spectroscopic evidence), and thus potential sources of volatiles. Asteroid 4105 1979VA is known from its orbit to have been identified as comet p/Wilson-Harrington with a visible coma on its discovery apparition in 1949 (see e.g. Zuppero, Whitman, & Sykes, 1993). Asteroid 1986TF is identified as comet p/Parker-Hartley 1989. Asteroid 2060 Chiron shows irregular outgassing and coma formation confirming a cometary nature. Lewis & Hutson identify 1983SA (DonQuixote) as an “apparent extinct comet core”.

Other probable and possible comet-origin asteroids are (Weismann and Campins, 1993):

Table 2.5 Suspected comet-origin asteroids

probable comet origin	**possible**
944 Hidalgo	1580 Betulia
2101 Adonis	1620 Geographos
2201 Oljato	1685 Toro
2212 Hephaistos	1862 Apollo
3200 Phaeton (1983TB) in same orbit as Geminids	1866 Sisyphus
3552 DonQuixote (1983SA) - a D-type Apollo	1917 Cuyo
1984 KB	1981 Midas
	2062 Aten

Kuck has identified possible comet-origin asteroids from their Tisserand parameter; they include: 1986JK, 1987QB, 1994AB1, 1994JF1. The Tisserand parameter is defined in Chapter 3 and gives an indication of whether the orbit is under the influence of Jupiter (thus indicating likely membership of the family of “Jupiter comets”).

In his use of the Tisserand parameter Kuck follows Hartmann, Tholen, and Cruickshank, 1987. Their listing is as follows:

strongest candidates:	Hidalgo
	1983SA
	1984BC
	Chiron (now proven)
weaker candidates:	Griqua
	Hilda
	Thule
	Chicago
	Normannia
	1979VA (now proven)

As noted by Duncan Steel, asteroids which are associated with meteor streams are more likely to be derived from, or to be remnants of, disintegrated comets, or may themselves be dormant or extinct domets (Steel, 1995).

2.2.4 Comet Mantle Model

Cometary material is probably of high porosity. Britt, Kring, & Bell, 1995, suggest asteroidal material is probably also of high porosity, say 40% void spaces (e.g., like snow). This may arise as a result of very poor size sorting, lack of compaction forces, and also relates to the very skeletal structure of Interstellar Dust Particles.

Cometary material (and at least some asteroidal material) is probably of very low strength (say 100 to 1000 N/m^2) - a tiny fraction of the strength of ordinary rock. This is indicated by the evidence of comets which have broken apart, particularly during perihelion passage, and by the crater chains seen on various solar system bodies.

Shoemaker -Levy - 9 was a recent spectacular instance of breakup under gravitational tidal forces. The details of the breakup of S-L-9 suggest that it was a zero-strength body, i.e., a "rubble-pile", of density much less than 1 gm/cc..(Asphaug & Benz, 1995).

Density is estimated to be approx 0.6 g/cc by McKinnon & Benner, 1995 from considerations of crater chains on Callisto and Ganymede.

Those asteroids which are "extinct comets" (1979VA Wilson-Harrington being apparently one) are believed to have various volatiles trapped at depth, such as water ice, frozen carbon dioxide, ammonia, and hydrogen cyanide ices, with silicates and hydrocarbons, under an insulating layer of remnant nonvolatile hydrocarbon and silicate detritus, called a "lag deposit" (Prialnik & Mekler, 1991).

Prialnik & Mekler's model proposed a porous dust mantle and a dense sub-mantle ice crust overlying a core of porous ice.

If the dust mantle is "too thin" then sublimation occurs rapidly and the surface ice layer evaporates faster than any inward-advection-produced ice crust can build up. If dust mantle is "too thick", then the mantle quenches vapour production, and you get an extinct or dormant comet. For $\rho = 0.2$ and 0.5 g./cc and dust mantles 5mm and 1 mm thick, an ice crust forms, and expands to depth of ~ 1.3 m and 2.2 m respectively (after 10 orbits).

With the build up of crust, sublimation rate drops, decreasing by "many orders of magnitude". Dust impedes outflow of vapour and hence enhances inward flow - which densifies the deeper ice layer, but also warms it.

As ice sublimes and vapour streams away from comet surface, it entrains dust particles below a critical aerodynamic diameter, leaving coarser grains as a detrital layer.

Their model suggests ice temperature (under mantle, at perihelion) of 100 K to 233 K. (most likely ~ 200 K).

The implication of this model is that it is reasonable to believe that ices could survive for many orbits at depth under an insulating mantle.

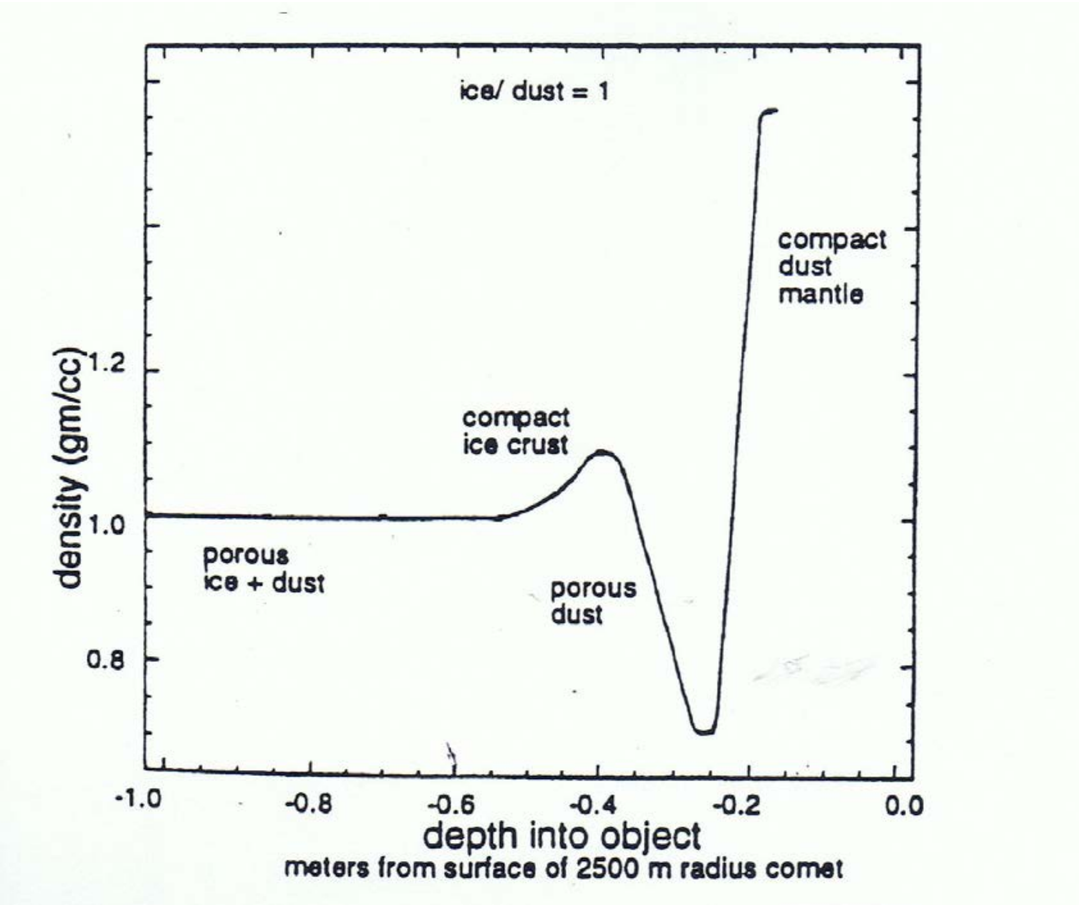


Figure 2.6 Density Profile of a Dormant Comet (from Zuppero et al, 1993)

2.3 Conclusions

The new view of asteroids now emerging is that there appears to be a continuum in types from cometary through highly carbonaceous coal-like or oil-shale - like to hydrated silicates, anhydrous silicates, and metal. Unexpectedly, even the smallest of objects appear to be capable of developing a regolith.

Chapter 3: Asteroid "Geography"

3.1 Introduction

Most asteroids orbit the Sun in the Main Asteroid Belt, between 2 and 3.2 AU (Astronomical Units) from the Sun (Earth-orbit radius is 1 AU, approx 150 x 10^6 km). Also, most asteroids have their orbits inclined only slightly to the general orbital plane of the solar system. The objects of interest in this thesis are the Earth-approaching asteroids.

3.2 The Earth-approaching or Near-Earth Asteroids.

The Near-Earth asteroids (NEAs) are classified into the Apollos, Amors, and Atens, as follows:

Apollos:	$q < 1.017$ AU
	Q unconstrained
	$a > 1.0$ AU
	e, i unconstrained
Amors:	$q > 1.017$ AU
	Q unconstrained
	$a > 1.0$ AU
	e, i unconstrained
Atens:	$q < 1.0$ AU
	$Q > 1.0$ AU
	$a < 1.0$ AU
	e, i unconstrained

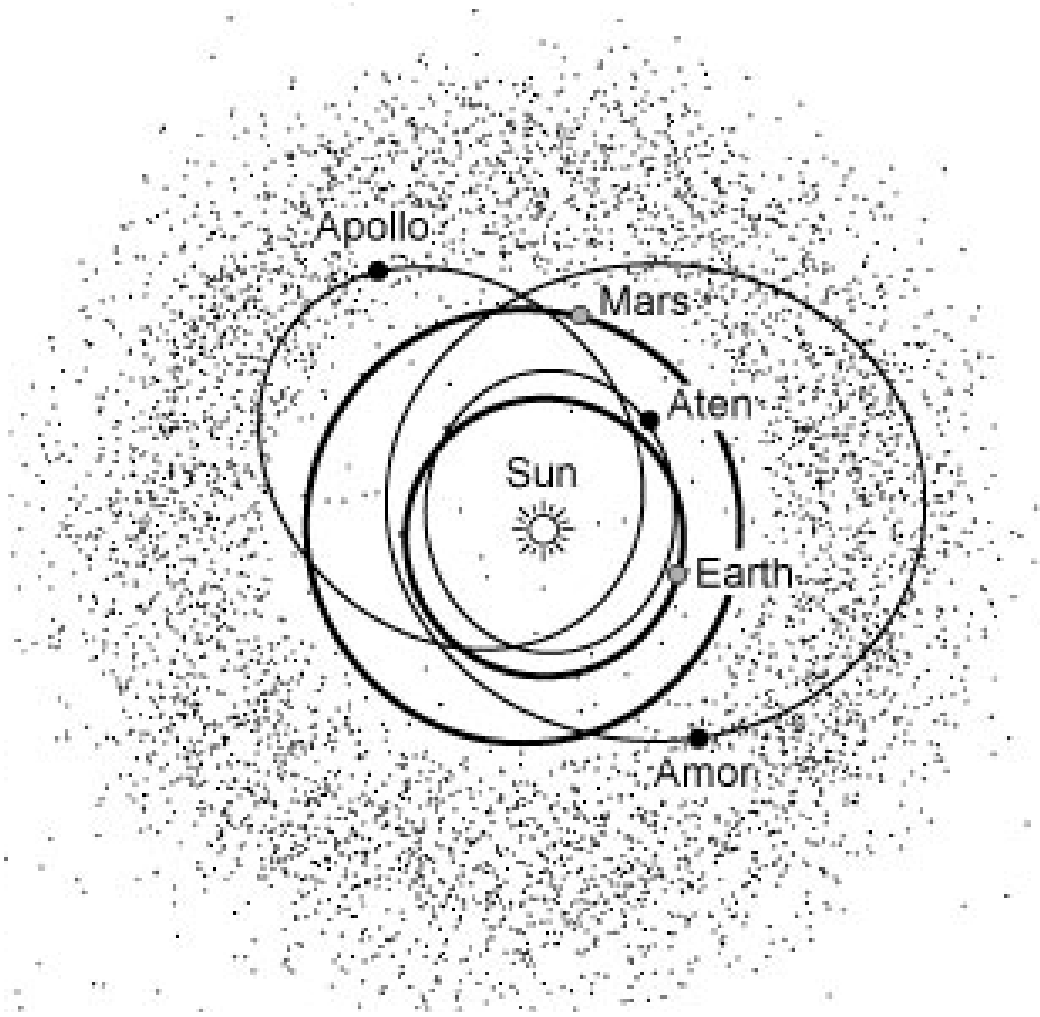


Figure 3.1 Apollos, Amors and Atens

The population of the NEAs is known to be continually depleted by collision with the inner planets, by gravitational boost out of the solar system following close encounter with Jupiter, and by impact with the Sun following gravitational perturbation by Jupiter (Farinella et. al., 1994).

There must be mechanisms for delivering new bodies into the NEA population, otherwise there would by now be none left over from the initial population emplaced at the time of origin of the solar system. The required mechanisms for maintaining the NEA population are not known but are believed to include capture into lower orbit and gradual decline in activity of short period comets, until they no longer show any cometary properties; and collision between large main belt asteroids injecting fragments into lower orbits either directly or via the Kirkwood gaps.

3.3 Databases

The Steward Observatory Asteroid Relational Database (SOARD) and the Planetary Data System Small Bodies Node (PDSSBN) are intended to provide up to date information on the orbital parameters of all known asteroids, and are available on Internet (see Appendix: Internet Addresses, p194). The total number of discovered Near Earth Asteroids is now about 480 and is increasing at about 50 per year. The table and graph below indicate the likely total population of the NEAs, as estimated by Shoemaker and updated by Lewis. (Lewis, 1993)

"Asteroid Listings", in the Appendices, at page 195, gives a recent listing of all low inclination Near Earth Asteroids. Also included is a listing of all NEAs with an orbital plane inclination less than 15 degrees, higher inclinations being essentially inaccessible with near-term propulsion systems.

Table 3.1 NEAR-EARTH ASTEROID POPULATION (from Shoemaker, updated by Lewis, 1993; further updated by present author in 1997)

Asteroid Class	No. Known	Projected D > 1 km	Projected D>0.1 km	No. Easier to reach than Moon (delta V out < 6 km/s from LEO)	
				Projected D > 1 km	Projected D>0.1 km
Aten (a<1.0)	26	250	45,000	50	20,000
Apollo (q<1.017)	198	2000	300,000	400	100,000
Amor (q<1.3)	196	1500	220,000	400	100,000
TOTAL	420	3750	565,000	850	220,000

As seen from the table above, and from the graph overpage, the statistically predicted population of Near-Earth objects of diameter bigger than 100 metres, and even 500 metres, is very large indeed.

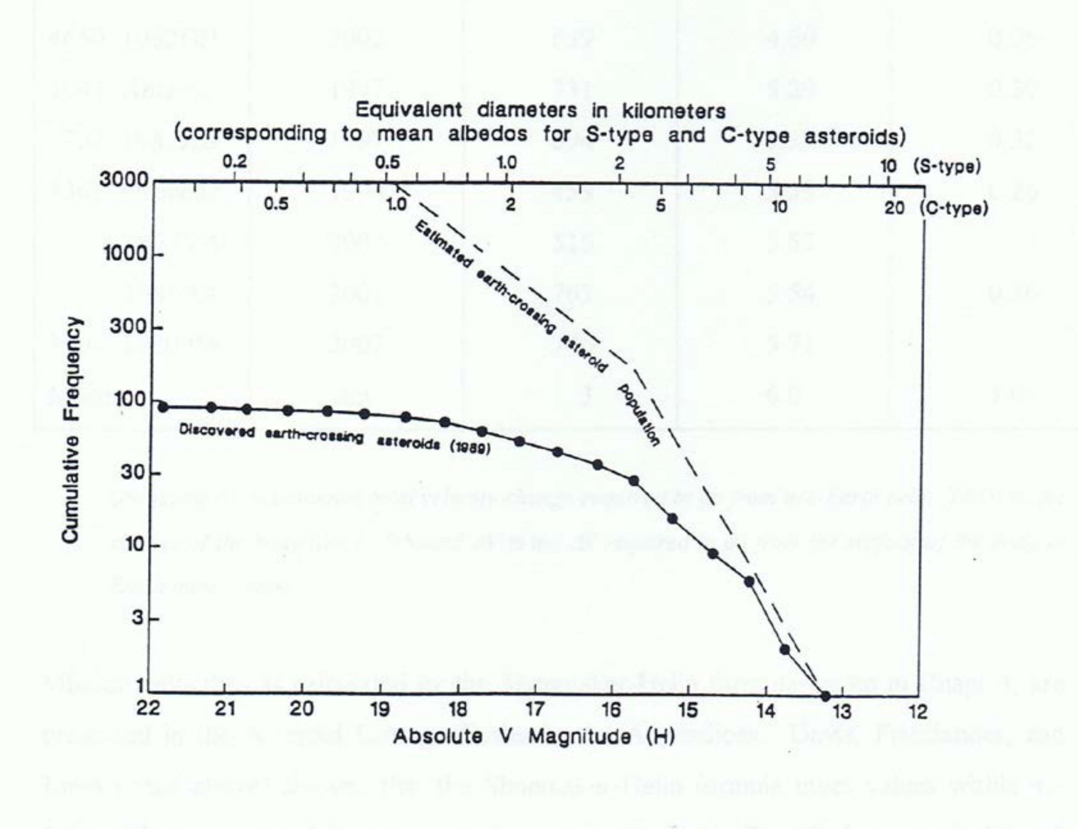


Figure 3.2 Size-Frequency Distribution (from Davis et al, 1993)

3.4 Accessibility

Discussion of target choice and of global minimum Δv calculations is given later. However, asteroids 4660 Nereus (previously 1982DB) and 1989ML both have minimum Δv's less than 5 km/s, and as of 1991 there were 22 NEA's with minimum launch Δv's under 6 km/s. Table 3.2 below gives accessibility of various NEAs compared with the Moon.

Table 3.2 Accessibility of Near-Earth Asteroids (from Lewis, 1991)

Target	Launch Year	Flight Time (days)	Outbound ΔV (km/sec)	Inbound ΔV (km/sec)
1989ML	2006	264	4.25	?
4660 1982DB	2002	639	4.50	0.06
1943 Anteros	1997	731	5.29	0.39
3757 1982XB	1997	694	5.37	0.22
3361 Orpheus	1994	453	5.39	0.26
1977VA	2000	515	5.53	
1980AA	2001	703	5.54	0.36
3908 1980 PA	2007	746	5.71	
Moon	any	3	6.0	3.0

Outbound ΔV is minimum total velocity change required to go from low-Earth orbit (LEO) to the surface of the body listed. Inbound ΔV is the ΔV required to go from the surface of the body to Earth intersection.

Mission velocities as calculated by the Shoemaker-Helin formula, given in Chapt 4, are presented in the Asteroid Listings Tables in the Appendices. Davis, Friedlander, and Jones (cited above) showed that the Shoemaker-Helin formula gives values within +/- 20% of those calculated for actual missions. (*see Fig 3.3.)* The filled squares in Fig 3.3 are calculated total Δv for actual specific launch opportunities. The dotted line is the Shoemaker-Helin calculation, which is intended to estimate a realistic 'global minimum'. As can be seen, Shoemaker-Helin is reasonably accurate, as a general formula, overestimating by about 0.5 km/s for 1989ML and 1982DB.

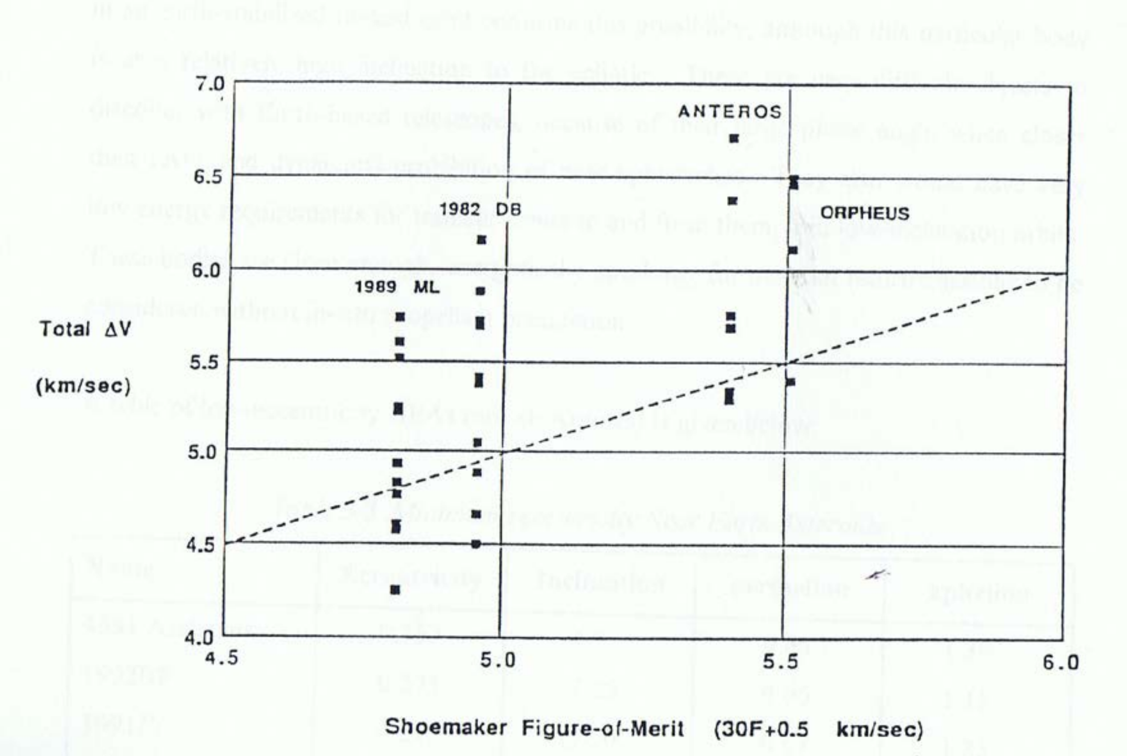


Figure 3.3 Shoemaker Figure of Merit c.f. specific missions (from Davis et al, 1993)

3.5 The Arjunas

Rabinowicz et al. have shown that there is an excess of small objects in nearly circular very "Earth-like" orbits, a near - Earth belt, which they have named the "Arjunas", less clearly defined as follows:

Arjunas: q, Q, a ~ 1.0 AU
e very small
i unconstrained
(this specification also holds for hypothetical Earth-Trojans)

The hyperbolic Δv for transfer to or return from these objects is likely to be under 1 km/sec. Dunbar has considered the possibility of Earth-Trojans and of bodies in Earth-stabilized "horseshoe" orbits (Dunbar, 1979). The discovery of asteroid 3753 Cruithne (1986 TO) in an earth-stabilized locked orbit confirms this possibility, although this particular body is at a relatively high inclination to the ecliptic. These are very difficult objects to discover with Earth-based telescopes, because of their large phase angle when closer than 1AU, and dynamical prohibition of near approaches. They also would have very low energy requirements for transfer orbits to and from them, **if** in low-inclination orbits. **These bodies are close enough, energetically speaking, for material return missions to be considered without in-situ propellant production.**

A table of low-eccentricity NEAs (not all Arjunas) is given below:

Table 3.3 Minimum eccentricity Near Earth Asteroids

Name	Eccentricity	Inclination	perihelion	aphelion
4581 Asclepius	0.357	4.9	0.66	1.39
1992BF	0.271	7.25	0.66	1.15
1991JY	0.295	49.00	0.67	1.23
1989UQ	0.265	1.3	0.67	1.16
1989UR	0.356	10.34	0.70	1.47
3554 Amun	0.281	23.4	0.70	1.25
2062 Aten	0.182	18.9	0.79	1.14
1982HR Orpheus	0.322	2.68	0.82	1.60
1991JW	0.118	8.7	0.915	1.161
1994UG	0.246	4.5	0.925	1.527
1991VG	0.049	1.5	0.975	1.077
1992JD	0.032	13.5	1.002	1.067
1993DA	0.094	12.4	0.85	1.02

(1991VG is the most accessible NEA presently known)

Of these objects, those with minimum inclination will be extremely accessible. The listing is far from complete, and as shown earlier, is being expanded on all the time. A one-year round trip to Arjuna 1991JW is shown in Figure 3.4.

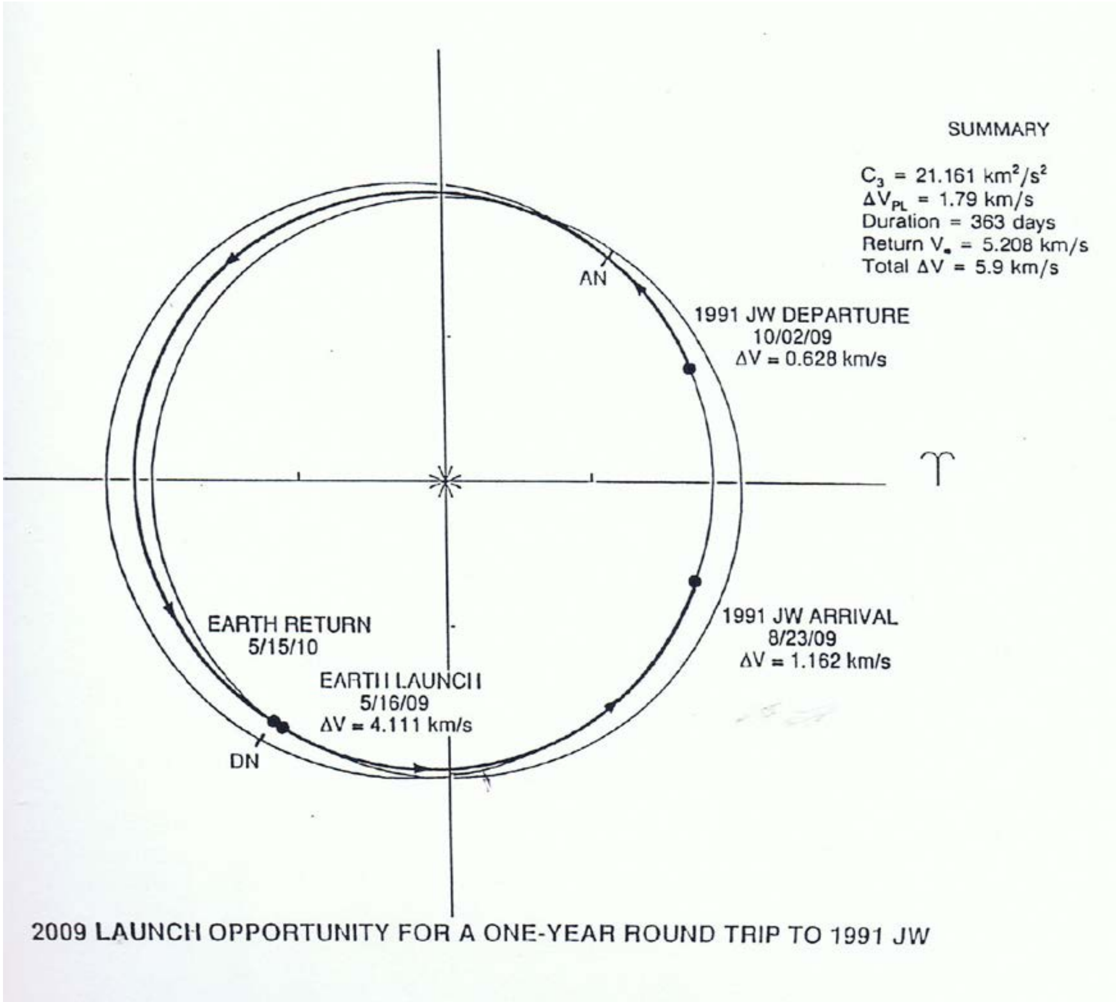


Figure 3.4 Round Trip to 1991 JW (from Davis et al)

(n.b. inclination to ecliptic is 8.7 degrees)

3.6 Short-period comets

Given that there appears to be a genetic link between at least some of the NEAs and short period comets, it is appropriate to include some consideration of them as potential targets. Kuck has done this, and notes that very long trip times for ballistic aphelion-rendezvous missions may be so disadvantageous financially that fast perihelion missions to short-period comets (with almost-guaranteed volatiles return) may be preferable, despite much higher delta-v requirement.

Table 3.4 Kuck's list of short-period comet targets

Name	Perihelion (q) AU	Aphelion (Q) AU	inclination (degrees)	Period (years)	eccent -ricity	Tisserand parameter
Boethin	1.147	9.065	4.2			
Churyumov-Gerasimenko	1.292	5.722	7.1	6.56		
du Toit-Hartley	1.201	4.814	2.9	5.21	0.61	2.92
Finley	1.034	6.110			0.71	2.60
Haneda-Campos	1.274	5.626	4.9	6.41		
Hartley 2	1.034	5.871	13.5	6.41	0.70	2.78
Honda-Myrkos-Pajansakova	0.528	5.514	4.3	5.25		
Howell	1.406	4.882	4.4	5.57		
Kopf	1.584	5.351	4.7	6.46		
Kushida	1.367	6.202	4.2	7.36		
Schwassman-Wachmann 3	0.937	5.185	11.4	5.36	0.69	2.95
Tuttle-Giacobini-Kresak	1.052	5.124	9.2	5.43	0.66	2.83
Wild 2	1.583	5.302	3.2	6.39		
Wirtanen	1.059	5.132	11.7	5.44	0.66	2.64
Wilson-Harrington	1.0003	4.287	2.8	4.3	0.62	3.08
1986 JK	0.896	4.704	2.1	4.68	0.68	2.93
1987 QB	1.135	4.468	3.5	4.69	0.59	3.04
1994 AB1	1.159	4.524	4.5	4.79	0.59	3.02
1994 JF1	1.317	3.763	3.5	4.05	0.48	3.27

Kuck used the Tisserand variable as an indicator of likely membership of the group of "Jupiter family comets", in his review of asteroidal targets.

$$T = \frac{a_j}{a} + 2\left(\frac{a}{a_j}\left(1 - e^2\right)\right)^{0.5} \cos i$$

where a_j = Jupiter's semi-major axis, and T < 3 indicates likely cometary origin.

As discussed in Chapter 9, only the objects with the smallest aphelia can really be considered to be prospective targets, because time duration will render an aphelion mission infeasible, and velocity requirement will render a perihelion mission infeasible.

3.7 Conclusion

The number of discovered NEAs is increasing rapidly. Many remain to be found. A substantial proportion are likely to be prospective "orebodies". The Arjunas in particular are very accessible.

Chapter 4: Orbital Mechanics

This Chapter describes solar system orbit parameters and discusses various approaches for calculation of mission velocities for transfer between different heliocentric orbits.

4.1 Orbital Geometry

The position and orientation of an orbit with reference to the rest of the solar system is given by its semi-major axis, a; the inclination of the orbit's plane to the plane of the ecliptic (i.e., to the plane of Earth's orbit), i; the orbit's eccentricity, e; the longitude of the ascending node, Ω; and the argument of the perihelion, ω.

The longitude of the ascending node of an object's orbit is the angular distance, measured anticlockwise looking from the north, from the radius vector giving the Earth's position at vernal equinox (i.e., Earth's position on 21st Sept) to the position at which the object passes from below (south of) the earth's orbital plane to above (north of) the Earth's orbital plane. The argument of perihelion ω is the angular distance around the object's orbit from its ascending node to its perihelion, measured in the direction of rotation. *(see figure 4.1*)

4.2 Delta-v (or mission velocity) as a measure of accessibility

To depart from one orbit on a transfer trajectory to intersect another orbit requires application of a velocity change; and to *rendezvous* with the target body, i.e. to match velocity with it when the transfer trajectory intersects or is tangent to its orbit, also requires application of a velocity change. *It is thus the total velocity change required to reach a body, rather than its distance, which is the true measure of the body's physical accessibility.*

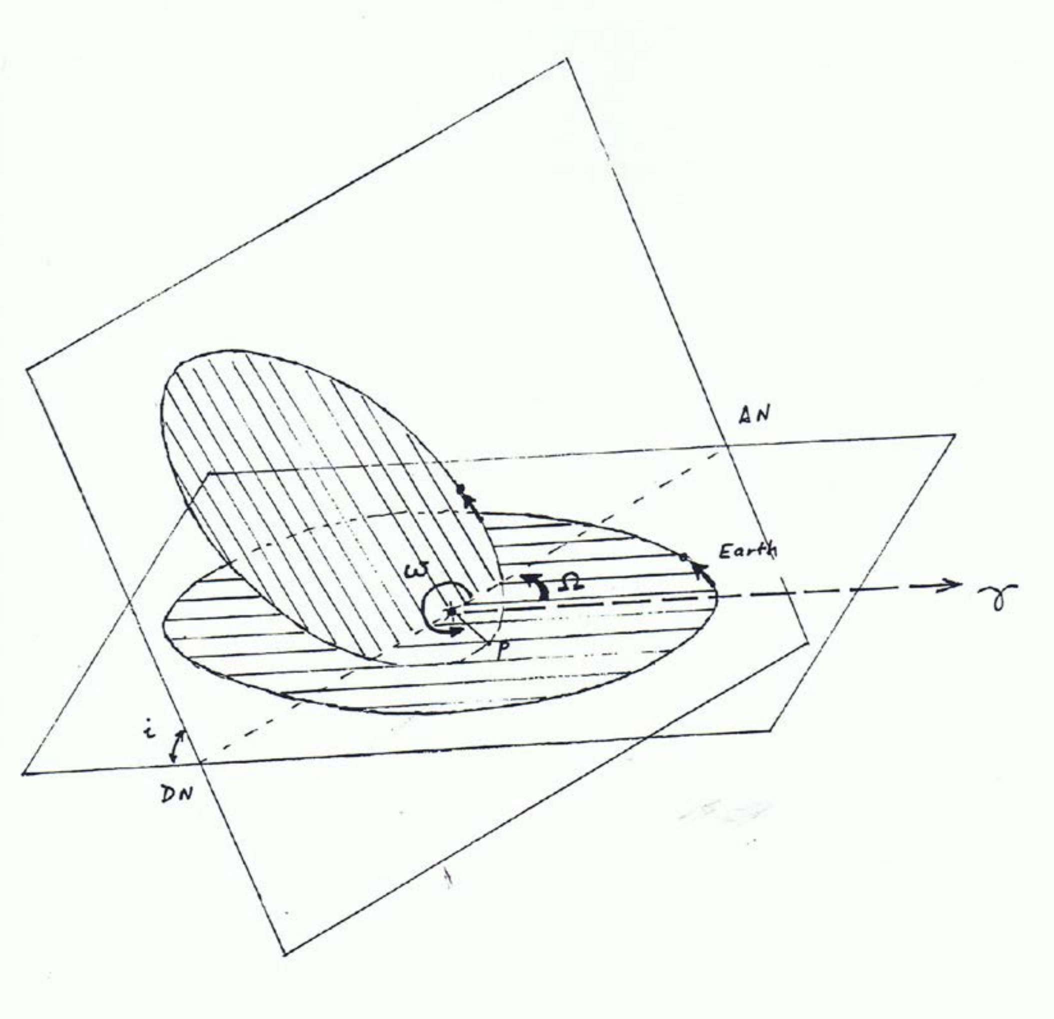


Figure 4.1 Geometry of Solar System orbits

4.3 Delta-v Calculations

There are several approaches to estimating a general velocity requirement for any particular target, without zeroing in on a particular launch window. The most often referenced in the literature is the system of formulae presented by Shoemaker & Helin in 1978. An alternative is to use “first principles” calculations and this is described in Section 4.4.1. Time-specific calculations are more accurate, but are beyond the “proof-of-concept” requirements of this overview.

Both eccentricity (and orbit semimajor axis) and target orbit inclination are critical as determinants of required mission velocity, as seen in Figure 4.2, from Davis et al..

4.3.1 Calculation of Delta-v according to the formulae of Shoemaker & Helin

Shoemaker and Helin (1978) presented formulae for calculating Δv to enter a transfer orbit to an NEA; they used an intermediary “Figure of Merit”, F, where

$$\Delta v = (30\ F + 0.5)\ \text{km/s}.$$

Their formulae are as follows:

(1) Figure of Merit, $F = U_L + U_R$, where U_L is the impulse required to inject the spacecraft into the transfer orbit from LEO; and U_R is the impulse required to rendezvous with the asteroid The authors note that low Δv trajectories are achieved by rendezvous at or near aphelion or perihelion of the asteroid’s orbit. Minimum Δv missions to Apollos and Amors are achieved by rendezvous at aphelion.

(2) With some qualifications, $U_L = \sqrt{U_t^{\,2} + s^2} - U_o$, where s is earth-escape velocity (11.2 km/s), and U_o is low-earth-orbital velocity (8.0 km/s), and

Note that U_t^2 is more generally designated in space mission literature as C_3 the *hyperbolic departure velocity squared (in km^2/s^2).*

Thus, U_L is more normally given as

$$U_L = \sqrt{C_3 + (11.2)^2} - 8.0 \text{ km/s} .$$

$$U_t^{\,2} = 3 - \frac{2}{Q+1} - 2\sqrt{\frac{2Q}{Q+1}} \times \cos\frac{i}{2}$$

where Q is aphelion of the asteroid in AU, and *i* is inclination of its orbital plane to the ecliptic. They reference this equation to Opik, 1951.

U_R , the required impulse at rendezvous, is given as

$U_R = \sqrt{U_c^{\,2} - 2U_rU_c\cos\frac{i}{2} + U_r^{\,2}}$ where, for both Apollos and Amors,

$U_c^{\,2} = \frac{3}{Q} - \frac{2}{Q+1} - \frac{2}{Q}\sqrt{\frac{2}{Q+1}}$ and $U_r^{\,2} = \frac{3}{Q} - \frac{1}{a} - \frac{2}{Q}\sqrt{\frac{a}{Q}\left(1-e^2\right)}$; the present author has deleted, for simplicity, a plane-change term, $\cos\frac{i}{2}$, which multiplies with the surd in the $U_c^{\,2}$ term for Amors, and with the surd in the $U_r^{\,2}$ term for Apollos. This is reasonable for the cases of interest in this thesis, because for $i < 10$ degrees, cos(*i*/2) is still almost unity.

For Atens, minimum Δv missions are achieved by rendezvous at perihelion. Shoemaker and Helin do not however present formulae for perihelion rendezvous, but only for "short mission" aphelion rendezvous trajectories.

These are, $U_t^{\,2} = 2 - 2\sqrt{2Q - Q^2}.\cos\frac{i}{2}$; and $U_c^{\,2} = \frac{3}{Q} - 1 - \frac{2}{Q}\sqrt{2-Q}$, with the other formulae above still applying.

Shoemaker and Helin note that “a characteristic of special importance about rendezvous missions at aphelion with low Δv Amors and Apollos is that rendezvous impulse is very low, typically of the order of 1 km/s. Under optimum conditions, the departure Δv for return to Earth is about the same.”

Lau and Hulkower (1985) found that 10% of known NEAs had total Δv ≤ 6 km/s. They found that reasonable low Δv launch opportunities occur for NEAs with a period of about 2 years for each object.

They claim that global minimum total Δv is a “viable measure of accessibility”. Unlike earlier more pessimistic assessments, they “demonstrated that asteroids (which) ranked high in the (accessibility) classification actually had more mission opportunities requiring less total Δv than those ranked low.”

4.3.2 Empirical formulae

Cutler (1987) plotted C_3 , Δv_{DS} , and total Δv values for “ideal” opportunities given in Lau and Hulkower (referenced above), and produced “least squares” empirical formulae for predicting global minimum energy requirements. He found good correlation for C_3 and for total Δv (i.e., departure Δv plus deep space (rendezvous) Δv), with the following formulae:

$$C_3 = (34.615 \times a) - (9.0231 \times e) - (27.204 \times p) + (1.9280 \times i) \qquad (r^2 = 0.951)$$

$$\text{total } \Delta v = (2.1161 \times a) - (1.6508 \times e) - (1.5273 \times p) + (0.19506 \times i) \qquad (r^2 = 0.940)$$

These least squares fits are surprisingly good, for an empirical, “sledgehammer” approach, and may therefore allow easy preliminary screening of candidate asteroids.

Cutler also plotted Δv_{out} versus Δv_{return} for various targets from Lau and Hulkower’s specific mission data, and found “there is a general trend for.....many of the “best” mission opportunities to form a line of negative slope that defines an excluded region near the origin in which no mission opportunities lie.” This behaviour implies that ideal minimum Δv's are not achieveable on both outbound and return trajectories for the same mission.

4.4 Hohmann Transfer Orbits

The lowest energy transfers are elliptical transfer between coplanar, semi-major axis-aligned, elliptical orbits, tangent to the inner and outer orbits at perihelion and aphelion, respectively. The mathematics of these transfers is given in Section 4.4.1.

However, these "best case" situations are generally not available because the orbits

(i) do not have collinear semi-major axes and do not have their respective perihelion and aphelion 180 degrees apart; and/or

(ii) are not coplanar.

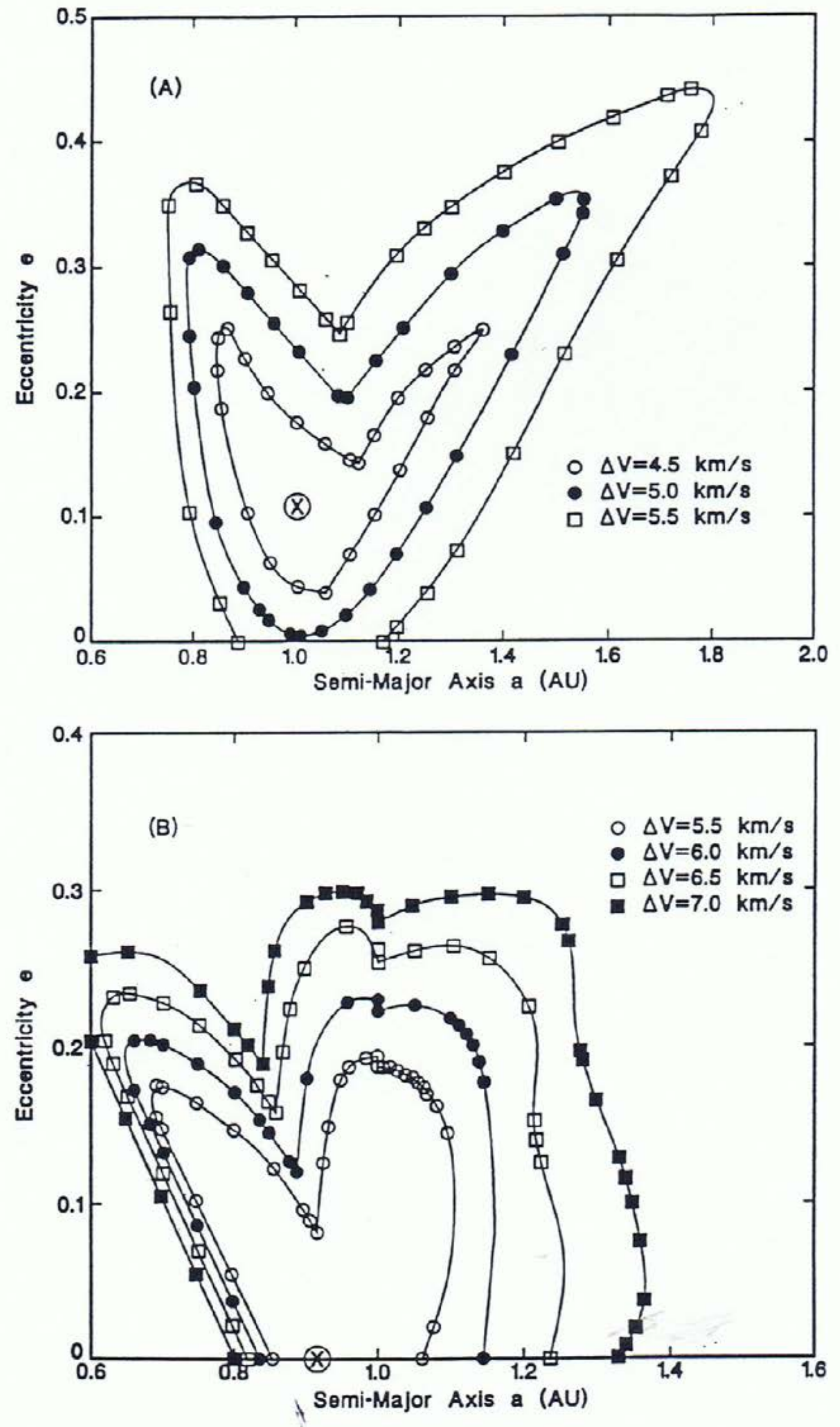
For the more general transfer situation, to/from an inclined elliptical orbit from/to a circular orbit, not in the same plane, the minimum energy transfer occurs when perihelion or aphelion is near ascending or descending node.

The Δv for plane change is additive to that for aphelion and perihelion change. The addition is vector addition, if both energy change and plane change occur simultaneously; but is arithmetic addition, if the two impulses have to occur at separate times.

At its simplest, Δv for inclination change is 0.5 km/s times i (degrees), when change is made at 1 AU, at Earth's circular velocity. It is "cheaper", however, if the velocity change can be made at the asteroid's aphelion.

Figure 4.2 shows the combined effects of eccentricity and semimajor axis on minimum mission velocity. It implies that one should search for objects that meet the following criteria:

$0.05 < e < 0.15$; and $0.9 < a < 1.2$ AU .



ΔV contours in a–e space for $i = 5$ deg. Part (A) is for minimum-energy rendezvous, while part (B) is for fast trip rendezvous.

Figure 4.2 Mission Velocity contours on Eccentricity - Semi-major Axis plot (from Davis et al)

Hohmann Transfer Calculations

The "first principles" calculation of velocity increments for carrying out a transfer from one elliptical orbit to another, coaxial, coplanar elliptical orbit is given below.

The minimum energy transfer from the lower (inner) orbit to the outer commences with a Δv (increase in velocity) at the periapse of the inner orbit, $\Delta v_{p,1}$. This velocity increase must be of enough magnitude to raise the apoapse of the transfer orbit to be equal to the apoapse of the outer orbit.

At the point where the transfer orbit contacts the outer orbit, a second Δv impulse is required (again in the forward direction) to increase velocity to match that of the higher orbit, i.e., raise the periapse to that of orbit 2.

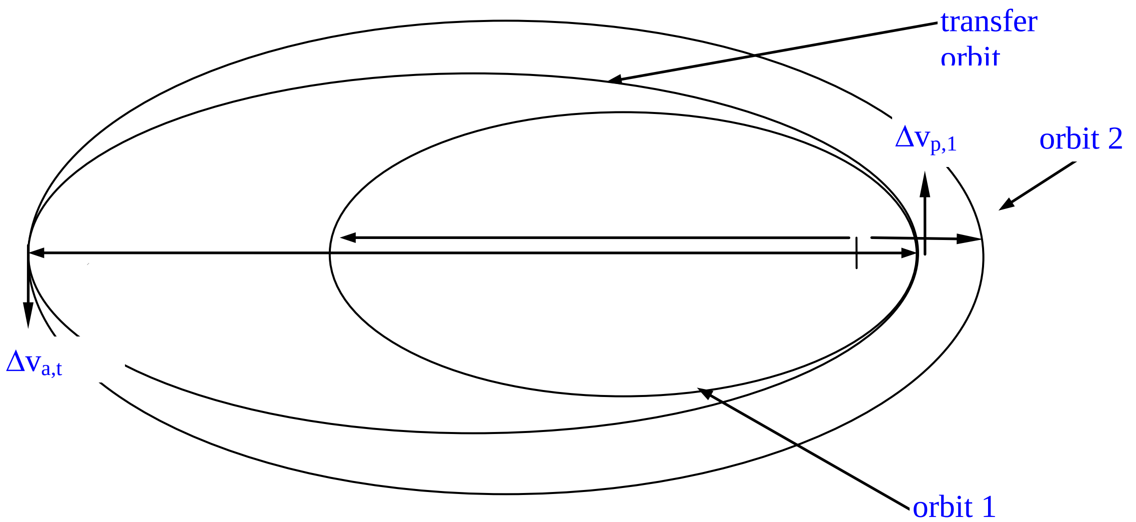


Figure 4.3 Hohmann Transfer Orbit

Delta-v's for Elliptical Orbit Transfers

The formulae below are taken from Thomson (1986) pp70-71:

The velocity at periapse of orbit 1 is:

$$v_{p,1} = \sqrt{\frac{\mu(1+e_1)}{r_{p,1}}} \qquad \text{where } \mu = G \,.\, m_s \qquad \text{eqn (1)}$$

The transfer orbit must satisfy:

$$v_{p,t} = \sqrt{\frac{\mu}{r_{p,1}}\left[\frac{2\left(r_{a,2}/r_{p,1}\right)}{1+\left(r_{a,2}/r_{p,1}\right)}\right]} \qquad \text{eqn (2)}$$

First (periapse) impulse is: $\Delta v_{p,t} = v_{p,t} - v_{p,1}$ eqn (3)

At apoapsis, the transfer ellipse velocity is found from the Conservation of Momentum:

$$v_{a,t} = r_{p,1} \,.\, v_{p,t} \,/\, r_{a,2} = \sqrt{\frac{\mu}{r_{a,2}}\left[\frac{2}{1+\left(r_{a,2}/r_{p,1}\right)}\right]} \qquad \text{eqn (4)}$$

- the required velocity at this point, to enter orbit 2, is $v_{a,2}$:

$$v_{a,2} = \sqrt{\frac{\mu(1-e_2)}{r_{a,2}}} \qquad \text{eqn (5)}$$

Thus, second impulse is $\Delta v_{a,t} = v_{a,2} - v_{a,t}$; eqn (6)

The total Δv for the Hohmann transfer is:

$$\Delta v_{total} = \Delta v_{p,t} + \Delta v_{a,t} \qquad \text{eqn (7)}$$

$$\Delta v_{p,t} = \sqrt{\frac{\mu}{r_{p,1}}\left[\frac{2\left(r_{a,2}/r_{p,1}\right)}{1+\left(r_{a,2}/r_{p,1}\right)}\right]} - \sqrt{\frac{\mu(1-e_1)}{r_{p,1}}} \qquad \text{eqn (8)}$$

$$\Delta v_{a,t} = \sqrt{\frac{\mu}{r_{a,2}}(1-e_2)} - \sqrt{\frac{\mu}{r_{a,2}}\left[\frac{2}{1+\left(r_{a,2}/r_{p,1}\right)}\right]} \qquad \text{eqn (9)}$$

Note also, $e = \frac{Q-q}{Q+q}$ and $Q = \frac{q(1+e)}{(1-e)}$

The Δv for orbital plane inclination change is, at its simplest, when i is small and the inclination change is made at 1AU, at Earth circular velocity:

$$\Delta v \quad = \quad 0.5 \text{ km/s} \times i \text{ (degrees)} \qquad \text{eqn (10)}$$

There is a relationship between the hyperbolic departure velocity of a departing spacecraft (its velocity relative to the Earth at a point outside Earth's gravity well: v_∞) and the required velocity of departure from LEO ($v_{\text{burnout, LEO}}$). It is:

$(v_{\text{burnout, LEO}})^2 = v_\infty^2 + (v_{\text{esc, LEO}})^2$ or in words,

(LEO departure velocity)^2 = (escape velocity at LEO)^2 + (velocity at ∞)^2 eqn (11)

This comes directly from the Conservation of Energy.

The above formulae are used in calculations of Δv requirements for the examples in Chapter 9.

Chapter 5: Mission Plans and Trajectories

This Chapter considers the alternative out-and-return trajectories to different target bodies, taking into account allowable stay times for resource extraction. Five "mission types" are identified.

5.1 Hohmann missions and timing considerations

From consideration of the orbital locations of targets discussed in Chapter 3, we can see that there will be a variety of mission and trajectory types. 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, it may be aphelion-centred or perihelion-centred.

For low-e targets: **can be** continuous thrusting return;
can be 'long' mining season (> 90 degrees of orbital arc);
can be repeating (but synodic period may be long).

For high-e targets: **must be** impulsive transfer (< 20 degrees of orbital arc);
must be short mining season;
must be aphelion or perihelion mining season;
must be "one-off".

Timing Scenarios

The synodic period of a body, with respect to the Earth, is the time that elapses between similar configurations (e.g., conjunctions; oppositions).

$$(\text{synodic period})^{-1} = +/- (\text{period of body})^{-1} -/+ (\text{period of Earth})^{-1}$$

Thus an Arjuna with a period of 15 months would have a synodic period of 60 months (5 years).

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).

This implies longer project timelines than indicated simply by use of transfer orbit period, T, because of the necessity for phasing orbits. In turn, these longer timelines impact negatively on Net Present Value.

On the other hand, they allow for a longer mining season and hence allow less demanding specifications on mining equipment and on solar collector/furnace.

However, if we contemplate a thrusting time/thrusting arc which extends through more than approx 15° of anomaly or (say) 50 to 100 days immediately post- aphelion for an Apollo, Amor, or Comet, then the departure from impulsive, Hohmann, ballistic conditions is large, and the Δv requirements increase, generally by up to 1.5 times.

In the worst case, with continuous-thrusting spiral trajectories, calculations have shown Δv to be twice that for Hohmann transfers.

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.

5.2 Alternative Mission Types

From a review of the orbital geometries we can see that there are various scenarios available:

5.2.1 ‘Apollo-Type’: Apollo or high-e Amor asteroids

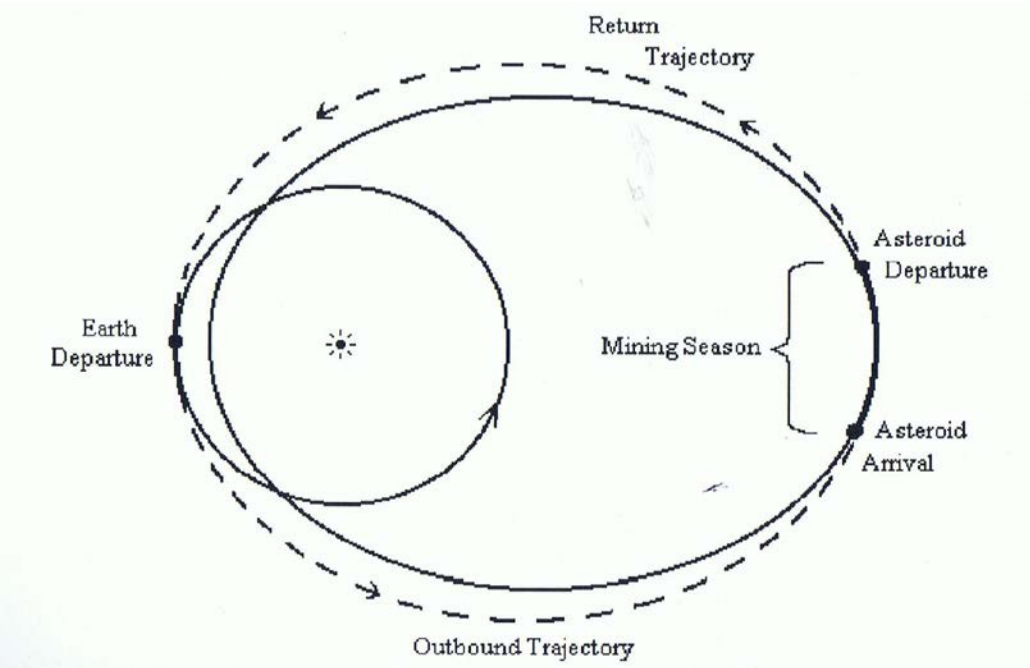


Figure 5.1 “Apollo-Type” Mission

Objects with “high” eccentricity, low-i 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; Δv for return must be achieved in a small fraction of T.

This trajectory applies to a target body which is in an elliptical orbit, a >> 1 AU, i.e., an Apollo, Amor or short-period comet; and assumes Hohmann transfer with rendezvous near but before aphelion for minimum Δv_{out} ; a “short” aphelion-centred mining season, (approx 3 month mining stay); and a post-aphelion departure for Earth-return, with approx 3 month thrusting, for minimum Δv_{return}.

Such a mission encounters the problem of long project duration, which is undesireable as regards NPV. In addition, it does not allow good use of the time: only a small arc centred on aphelion is available for mining, and only a limited arc is available post-aphelion for boost into return trajectory. There is also a need to destroy a relatively large return (hyperbolic) arrival delta v. 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.

The use of Hohmann ellipse transfer out and back, and "short" aphelion-centred mining season, implies that mission duration must approximate the period T of transfer orbit which itself must approximate an integer no. of years (because the Earth has to be there when the payload gets back!).

Note therefore with regard to synodic period that either one adopts a low-thrust spiral trajectory approach or adopts a selection rule: that earth-body transfer orbits must be of period = integer no. of years (±10-15%).

To minimise delta-v (deep space), the object's orbit should be "Earth-grazing", i.e., q = 1.0 AU.

So, $T_{\text{transfer orbit}}$ = 2 years implies a semi-major axis = 1.587 AU, and thus, with q = 1.0 AU, Q must be 2.174 AU. This gives aphelion at the inner edge of the Main Belt.

For $T_{\text{transfer orbit}}$ = 3 yrs, a = 2.08 AU, and for q = 1.0 AU, Q = 3.16 AU.
This aphelion is at the outer edge of the Main Belt.

5.2.2 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 (see orbital periods for short period comets in Kuck's list).

Dormant comets may be desireable 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 Δv requirement for return, which translates into a requirement for much higher propellant usage on return transfer, and hence a larger "mining" requirement. Note also the imposition of very short mining season.

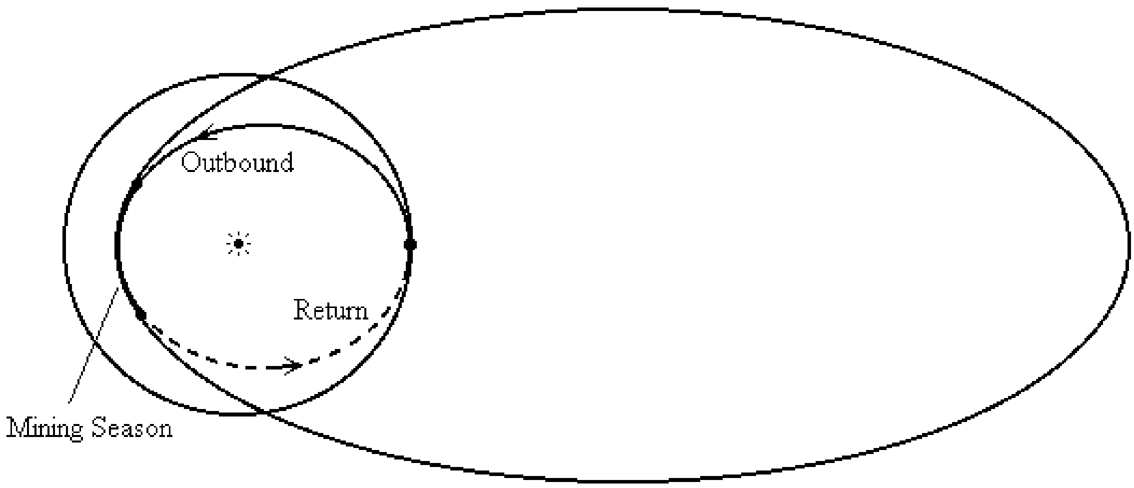


Figure 5.2 "Comet-Type" Mission

5.2.3 'Aten-Type': High-e Atens:

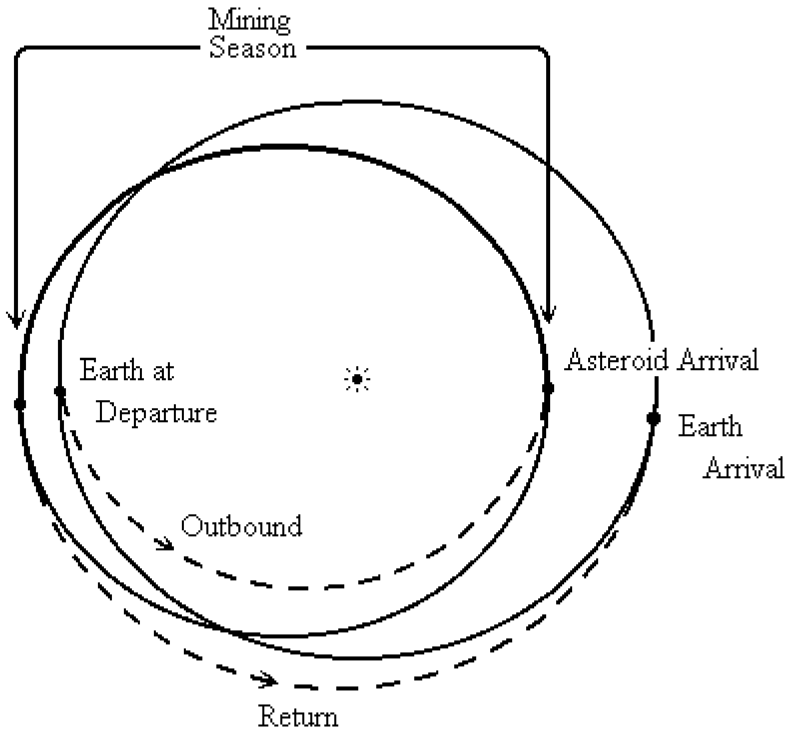


Figure 5.3 "Aten-Type" Mission

This mission type assumes a Hohmann transfer to rendezvous with the target asteroid at its perihelion; and near-aphelion departure after T/2 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).

This mission profile assumes a target body a < 1; elliptical orbit (an Aten); and a mining season commencing at perihelion, and running until aphelion. Note that phasing to achieve Earth rendezvous on return forces off-optimum transfer orbits anyway, thus one might contemplate an aphelion arrival (requiring high Δv_{ds} to rendezvous) and a perihelion departure for low return Δv requirement.

This implies another "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.

This "selection rule" can be shown by inspection to be equivalent to a requirement that the semi-major axis of the target asteroid be close to 1 AU; this mission profile can also target Apollo asteroids with semi-major axes close to 1 AU.

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. (see Chapter 9)

If one were to abandon Hohmann missions, either for "Apollo-type" or for "Aten-type" missions, on the basis that the time constraints on mining season and on thrust times (which must be short c.f. the transfer semi-orbit), are too severe, then one needs to look for orbits that appear to match closely to low-thrust, spiral-out, spiral-in pattern, ie, low eccentricity.

5.2.4 **Arjunas and low-e Amors ('Arjuna-Type'):**

The "Arjunas", and some Amors, have very nearly circular orbits. There are also probably some as yet undiscovered asteroids, in a class as yet unnamed, whose aphelia are < 1.0 AU, and are of low eccentricity.

Such close, low eccentricity, low i NEAs, may be favourable for spiral, non-Hohmann returns; a characteristic of these trajectories is the 'softness' of the launch window for return; effectively there are little or no time constraints; one is free to set solar collector size to minimize processing time plus return transit time. However, because of the long synodic period, "those objects with semimajor axis approaching 1 AU exhibit increasingly longer gaps between direct ballistic opportunities, owing to the low relative motion between themselves and the Earth" (Niehoff, 1978).

Low-ellipticity targets, both outside Earth orbit (Amors) and overlapping Earth orbit (Arjunas) give much less concern about phasing and mining season duration. This is because much more of the orbit arc for can be used both mining and thrusting. The return transfer orbit may approximate continuous - thrust spiral; and multiple-return missions are more feasible provided total mission time remains short enough for NPV considerations.

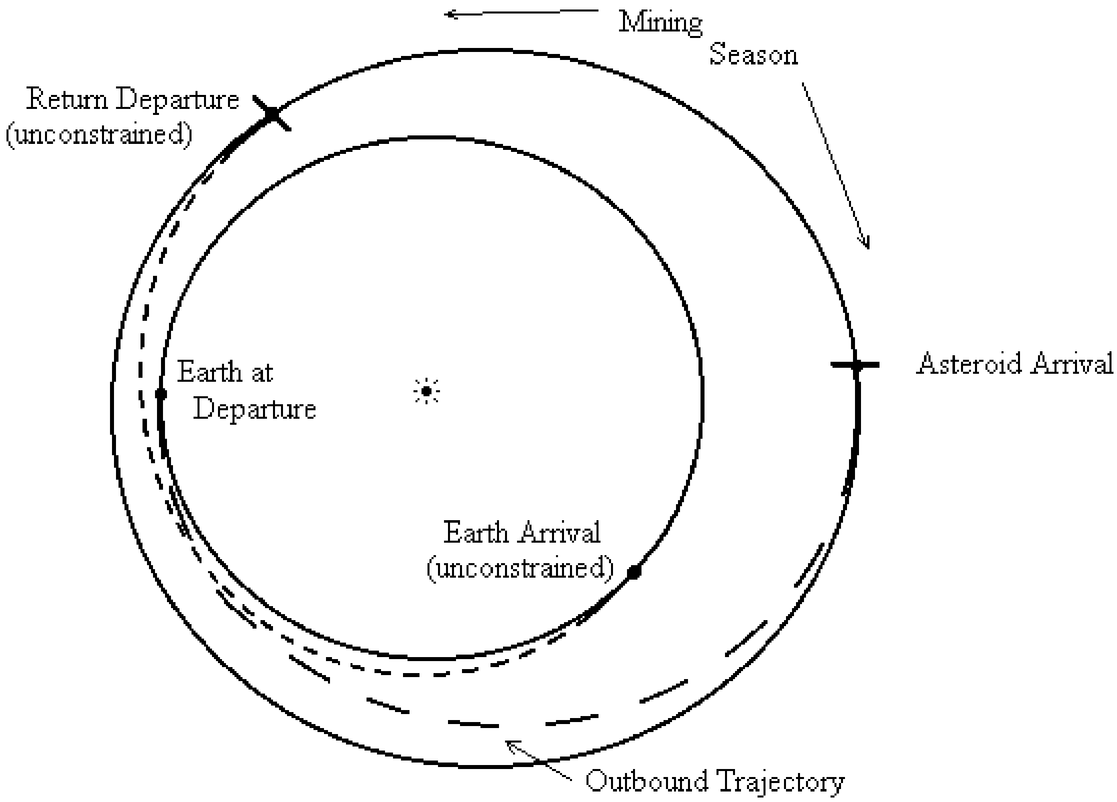


Figure 5.4 "Arjuna-Type" Mission

For low eccentricity targets with low eccentricity transfer orbits (eg Arjunas, but also some Apollos and Atens and Amors), Hohmann transfer is not essential; the major concern may be Δv for inclination change.

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 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) by lunar flyby.

5.2.5 High-inclination, low eccentricity targets:

The overriding characteristic of these missions is the need for high thrust during passage through the nodes. With low eccentricity targets, phasing with regard to perihelion / aphelion is not an issue, but inclination change can 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 may be important.

In this case, the timing and duration of the out and return trajectories will be determined primarily by the location of the ascending and descending nodes, rather than the location of the aphelion or perihelion, as in cases 1 and 2 (i.e. launch when Earth is at AN/DN). All configurations seem to suggest ≤180° return thrusting, centred on a node; and ≤180° mining season, centred on a node; and 90° to 180° outbound trajectory.

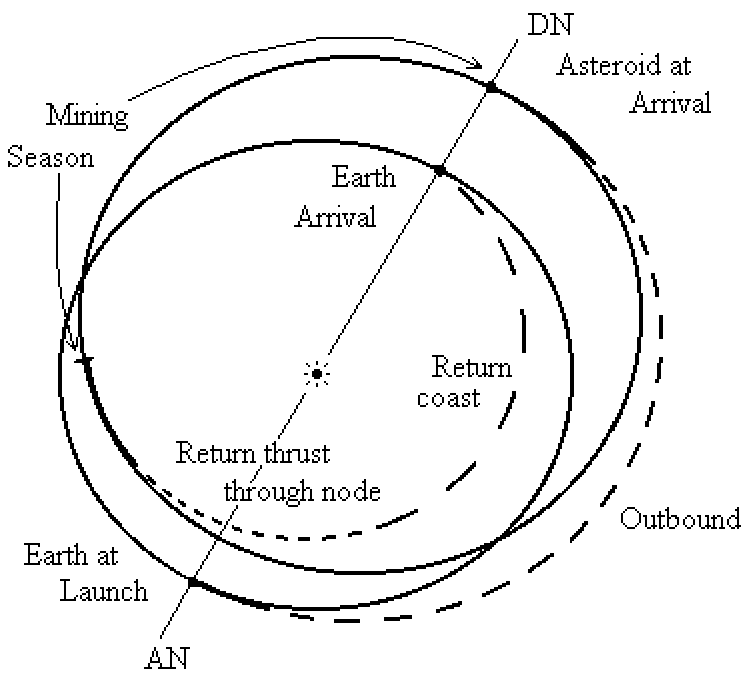


Figure 5.5 "High-i, Low-e" Missions

Note that perihelion missions in 5.2.2, 5.2.3, and 5.2.4 above may keep the target close enough to Earth to enable teleoperation rather than require machine autonomy. This may very well impact on probability of success.

Note also that perihelion missions are shorter duration, and enjoy the advantage of better solar insolation. Both impact positively on NPV. But short mining season implies high mass throughput requirement, as does the higher propellant production requirement due to higher Δv characteristic of the transfer orbit.

5.3 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:

(i) rely on propulsive braking, using some of the Asteroid-derived propellant; this is simplest, but undesirable, as it reduces that which is available for sale. It is also most efficient in propellant use if done in an impulsive, high thrust manoeuvre, a system demand not otherwise addressed.

(ii) rely on aerobraking, using an Earth-fabricated, LEO-fabricated, or asteroid-fabricated aerobrake. May be metallic or refractory silicate. The question is, how to fabricate an aerobrake on an asteroid, by remote means, using insitu resources?

(iii) use of a conducting tether for electromagnetic braking has been considered, but it does not give anywhere near enough retardation, either when considered as a passive conductor cutting the Earth's magnetic field (taken to average 0.1 gauss over an interception distance of 12,000 km), or with an actively driven current of any reasonable size.

(iv) use lunar flyby to remove hyperbolic Δv. This will naturally insert the returning craft into HEEO (Highly Elliptical Earth Orbit)! Navigation requirements 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. Note that gravitational capture exerts no stress on the payload package. However there is a tight constraint on the return "capture window". O'Leary quotes max 1.5 km/sec for single lunar flyby. (O'Leary, 1982). A maximum $V_{hyperbolic}$ of 1.5 km/s 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 whose orbits are nearly tangent to Earth's orbit, and with aphelia less than 1.25 AU or perihelia more than 0.83 AU.

i.e., $q > 0.83$ AU, $a > 0.9$ AU; and $Q \sim 1$ AU
or $Q < 1.25$ AU, $a < 1.25$ AU; and $q \sim 1$ AU.

Future detailed trajectory design will need to use mathematical and analytical tools described in Yen, 1984, ('mission opportunity maps'), and optimizer programs such as Science Applications International Corp's Trajectory Optimizer program (available from SAIC, Schaumberg., Illinois).

5.4 Arguments against Multiple Trip Scenarios:

The NPV calculations in Chapter 7 & 8 have been performed assuming a single return. Repeated returns to the target asteroid have not been considered in this work, because

(i) the high required IRR means that receipts following the first one are heavily discounted;
(ii) 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;
(iii) it is assumed that the operator will want to recover the remote miner and refurbish and upgrade it;
(iv) it is assumed that lessons learned after the first mission will dictate modifications to both the equipment and the mission planning.

Chapter 9 gives fully worked examples for each of these mission types.

5.5 Conclusions:

(i) there are several mission types that can be identified, each with implications for length of mining season and total mission duration;

(ii) Earth-return hyperbolic velocity is a major mission Δv demand;

(iii) synodic considerations suggest that "multiple return" missions to a permanently-emplaced mining facility are not competitive.

We also note:

(i) Phasing requirements inhibit "multiple return" missions; and

(ii) Non-Hohmann transfer is ok for low-e; Hohmann transfer with aphelion (or perihelion) mining season is best for high-e targets

Chapter 6 : Engineering Choices - Mining and Processing

6.1 Considerations in Space Mining

The definition of "ore" depends on what can be recovered to sell or barter for profit. It is that which can be sold upon return to earth, eg Platinum Group Metals; or (the object of this thesis) that which can be sold for delivery into some orbit in space; or that which is not valuable to others, but which is valuable to the operator, as import replacement, or for process enablement.

6.1.1 Mining in Near-Zero-Gravity conditions

In order to perform mining operations on an asteroid or comet, one has to dock the mining equipment with it and "make secure". How? Note that gravity on a 10 km diam rock is about 1 milli-g; on a 1 km rock, gravity is about 0.1 milli-g (i.e., $0.1 cm/s^2$). So there's no weight to provide stability. Also note that average rotation period is about 5 hours.

Anchoring is easy with rigid, competent, strongly bonded matrices - you can 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. This may need very wide area anchoring, over an extended footprint, up to and including the approach of totally surrounding the target asteroid - wrapping it in plastic, so to speak.

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 (for screw-plate technology, for anchoring in low gravity, see Kloski (1995)).
- weld tie-downs into massive clasts of metal, ice, or solid silicate rock
- use large area fluked anchors

- burrow completely into the regolith, somehow (e.g., using contra-rotating screws)

6.1.2 Possible Extraction and Collection Methods

Hard rock mining on the Moon can easily be extrapolated from Earth experience, but mining on asteroids will, because of the low gravity, require positive anchoring of the drill, pick, or cutting head, so as to generate adequate force against the rock, ice, or metal.

The reaction forces created by such operations as drilling or scraping may require to be spread over a very wide “footprint”, if the regolith strength is low, and because of the milli-g gravity.

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.

Containment will be important, because escape velocity for small asteroids may be of the order of 20 cm/s.

Frozen volatiles may be cut or melted at low temperature. Solid metal must be cut or melted at high temperature, or reacted at a lower one, eg. using vapour-metallurgical techniques of the Mond process, as have been proposed by Lewis and Nozette (1983) and Lewis, Jones, and Farrand (1988).

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.

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.

In any operation, the mining machinery must be anchored to the asteroid surface, and the released material efficiently recovered.

6.1.2.1 Surface mining

Regolith mining on the Moon would, by analogy with sand and gravel pit operations on the Earth, use Front End Loaders and trucks, or Load-Haul-Dumps. Small quantities may be reclaimed by use of scraper/winch systems. Gertsch (1984) has proposed the classical three-drum slusher/scraper for lunar operations, because of its simplicity and low mass. None of this however appears to be applicable to asteroids, where the overriding considerations appear to be (i) very low strength regolith; (ii) zero gravity..

Note that 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 a screw conveyor or an enclosed drag chain conveyor, or uses a cactus or clamshell grab and gives positive displacement. An enclosed flail will also disaggregate and crush.

6.1.2.2 Underground extraction

There may be good reasons to use underground mining techniques, both on the Moon and when mining on asteroids:

(i) easier to generate reaction forces for cutting, drilling, or dragging (i.e., more "normal" technology)

(ii) the surface layer may be depleted in the desired material (e.g., volatiles at depth supposed to reside within Phobos or Deimos; or volatiles 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.

Underground mining on the Moon would probably use roadheader-type technology, with subsequent shotcreting to seal the excavated heading and enable it to contain an atmosphere.

Virtually all underground mining technologies could be used, but one should be chosen which uses minimum consumables, or none at all. One also should be chosen which does not require a large normal reaction force, and which has minimum impact on ground which is suspected to be weak and friable. (Even in milli-g, failures of ground will be inconvenient).

Note that the underground mining techniques are the only ones relevant for mining "massive" competent material, material which is not regolith. Hence they are the only techniques for use with regolith-free bodies, and in the case of needing to respond to an Earth-impact threat, they are necessary for placement of sub-surface nuclear explosives, desireable for best coupling of momentum from blast ejecta to the body.

6.1.2.3 In-situ extraction

A particular case of underground extraction is, as noted by Sharp, Miller, and Gertsch (1993), and Kuck (1995), fluid extraction through drillholes. 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 of uranium orebodies, and in solution extraction of salt deposits.

Kuck (1995) has listed the following benefits and risks of in-situ extraction:

benefits:

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

risks:

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

This is simple technology, but may be threatened by loss of circulating fluid, into excessively permeable material or voids or fissures. Hence there must be provision for make-up fluid, preferably from the material being mined, or the ability to seal the volume from within which the material is being extracted. In certain circumstances, e.g. use of steam in a permafrost deposit, this sealing may occur naturally.

Mining is assumed to achieve 10% by processed mass recovery of volatiles from predominantly phyllosilicate and carbonaceous matrix regolith, <u>or</u> close to 100% recovery of water by drilling to extract primordial ice from an extinct comet core..

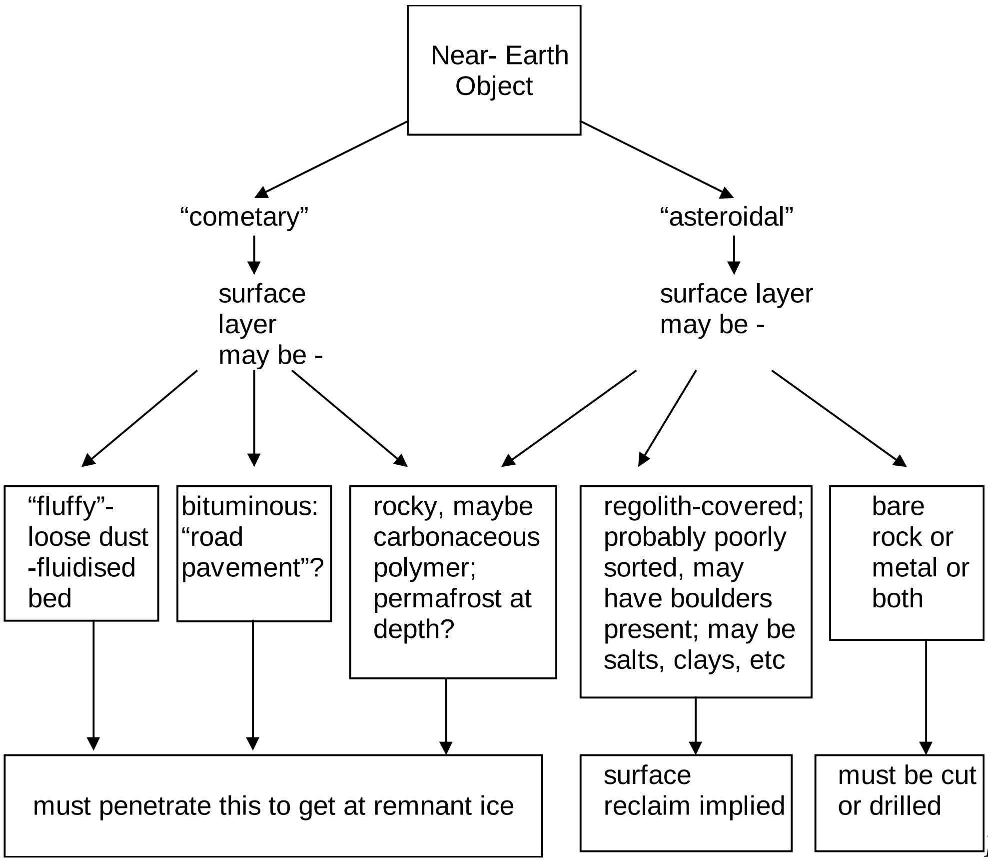


Figure 6.1 Mining Engineering Choices and Constraints

6.2 Metallurgical Processing / Beneficiation.

These processes will depend on the material which has been collected, and the product(s) being extracted. Table 6.1, drawn partially from Burbine & Binzel (1994), brings together the concepts presented below.

6.2.1 Comminution:

Most metallurgical separation processes commence with crushing and grinding so as to liberate the wanted particles or at least to obtain access to free surfaces of fine particles of the desired mineral. This is not true however in the cases of eg mineral sands processing, where the particles are already freed and the task is merely one of separation; or extraction of salt, sulphur, uranium or gypsum using surface or insitu dissolution methods. Liberation of individual valuable grains from matrix material may in some situations be quite easy as, depending on the details, it may be possible to sort directly from the regolith eg using a magnet for NiFe grains (Lewis proposes a magnetic rake), or remove as a liquid or vapour (eg various ices, or metal carbonyl as in the Mond process).

If the desired material is all in the big lumps, then crushing is not needed, in order to obtain recovery; simply identify and separate. This may be the case with, for example, lumps of ice in cometary bodies, or alternatively, lumps of silicates for rejection; and in the case of lumps of metal in the regoliths of rocky bodies.

In this case, mining and beneficiation of material from a loose, coarse, heterogeneous regolith may most simply be done by “manual sorting” using a dextrous 3 or 4-fingered robot manipulator for selective collection of lumps of a signature matching that retained by the robot and defined by a discriminating expert system.

Note alternatively, that the valuable resource may be in the “fines”, and there may be “enough” fines available in the regolith to dispense with crushing and grinding, requiring merely sorting, e.g. by sieve or cyclone, to separate and collect the desired feedstock.

If the material being handled is regolith and if the desired fraction is in the fines, then the process may require little or no comminution, or only very gentle disaggregation, followed by size separation.

In this case, adequate liberation of volatiles, especially, might not require grinding; in which case, this operation should obviously be deleted!

However, assuming that it *is* necessary to crush and grind, note that particle separation is then desireable to provide one stream of material of enhanced grade for further treatment, and another stream (tailings) for rejection.

6.2.2 Separation

Separation of fine particles can be by any of the following:

- electrostatic field, e.g. high voltage plate separators;
- magnetic field, e.g. cross-belt magnets;
- density differences e.g. air- or hydro- cyclone;
- vaporization / condensation
- sublimation / deposition, e.g. the Mond process)
- sizing / sieving

6.2.3 Processing: influence of the desired product type -

(a) Metal

- if present as loose grains - electrostatic or magnetic separation is needed
- if present as macroscopic lumps in a silicate matrix - crushing then sieving
- if present as interconnected dendrites with minor silicate - carbonyl separation
- if present as continuous mass - cut off big slabs (?)

(b) Volatiles

- if present with minor silicate (‘dirty iceberg’ - melt or cut off slabs

- if minor component (icy mudball - permafrost) - drill into, vaporize and distill
- if present only in chemical combination (eg, water of hydration, ammonium or carbonate compounds), then severe heating required (e.g., to 800 K)

(c) Hydrocarbons

- if present with major silicates, then heat and distill.

Vapour phase processes will imply:

heating and volatilization, probably with a carrier or reactant gas
collection of gas, vapours, and entrained solids
separation of entrained solids
condensation of vapours collectively or sequentially
recovery of gas, reheating and re-injection

6.2.4 Processing - influence of plant feedstock:

- is it mixed aqueous and organic liquids, e.g., from drill hole mining of extinct comet? - in this case, oil-water separator technology is needed: see the oil industry for useful technology.

- is it mixed liquids as above, with gases and vapours, i.e., emulsion or foam? - again see the oil industry.

- is it various sizes of solid particles (coarse to fine, soft to hard, siliceous or metallic, reactive or not) in gases; then the experience and techniques of the dry process metallurgist are called for- see the mineral sands people.

- is it solids, liquids, and gases? - then one will need to heat, separate by cyclone, and treat separately. Filter screens can be expected to blind. Perhaps review material handling in food industry.

Table 6.1 **Product - Process Options**

Bell Superclass	Type (Tholen)	Inferred Mineralogy	Meteorite Analogues	Resources	Metallurgical Properties	Processing Options
Primitive	D	clay, organics	none	volatiles	?? very friable	crush, heat, and separate. CI, CM CR all give >10 % w/w as H_2O, CO_2, CO, CH_4, other hydrocarbons
	P	clay, organics	none	volatiles	?? very friable	
	C	clay, organics	CI, CM (C1,C2)	volatiles	high proportion of matrix / kerogen	
	K	olivine, pyroxene, carbon	CV, CO (C2, C3)	nil?	-------	
Metamorphic	T	?	none	?	-------	-------
	B, G, F	clay, opaques	altered CC's (CR?)	? volatiles	cemented, hard phyllosilicates and limestone ?some metal	crush and heat to ≈ 800 C; separate volatiles and metal
	Q	olivine,pyroxene, NiFe (grey)	OC's (- H, L, LL)	NiFe PGMs?		crush and separate using electrostatic or magnetic methods (how to handle bulk metal?) *or* carbonyl process
Igneous	S	olivine, pyroxene, NiFe (red)	S IV could be OCs; pallasites?	NiFe?	hard, finegrained	
	M	NiFe	irons	NiFe		
	E	enstatite	enstatite achondrites (aubrites)	---	-------	------
	A	olivine	brachinites	---	-------	-------
	V	plagioclase, olivine, pyroxene	basaltic achondrites	---	-------	-------
	R	olivine, pyroxene	olivine-rich achondrites	---	-------	-------
	(M?)		enstatite chondrites	NiFe	hard	crush and electrostatic separation

6.3 Feasible Products and Processing Methods

According to Lewis (1993), the prime targets should be the asteroids which are analogues of the carbonaceous chondrites, initially for their volatiles, for the following reasons:

(i) they are apparently plentiful in number
(ii) they contain H_2O, CO_2, CO, CH_4, NH_3, etc..
(iii) they contain metal (albeit mainly in oxidized form; but readily reduced)
(iv) the metal phase should contain high grade PGMs

This implies earthmoving or burrowing into regolith; heating to extract water and other volatiles; perhaps further heating to reduce metal oxides to metal and produce CO_2 ; extraction of metal by, e.g., electrostatic or magnetic means, or by carbonyl volatilization.

Note that this is going to require quite a bit of solar heating; it is energy intensive. Thus the question arises, what is the status of lightweight solar mirror technology?

The same solar mirror can drive the solar thermal rocket for material return, provided the power requirements are similar.

A different approach is taken by Kuck (1995) who recommended targeting the dormant comets, because it is only with them that it is unequivocally clear that one can obtain water; and he claims that the greater required mass of mining and processing equipment for extracting volatiles from the asteroids militates against their early viability. The down-side of Kuck's proposal is that almost all of the probable targets for his scenario are in orbits which are much less accessible, energetically speaking, than the potential targets that Lewis can propose.

Zuppero is also supportive of comet mining, but has specifically recommended as his target 1979VA Wilson-Harrington, and has proposed a nuclear thermal rocket using recovered water as the propellant (Zuppero, Whitman, & Sykes, 1993; Zuppero, 1996).

Meinel & Parks (1985) forego In -Situ Propellant Production. But this can only be supported by limiting target choice to the most energetically accessible asteroids, and by severe restriction on returned mass, and by assuming market is in high earth orbit, i.e. GEO or HEEO.

Kargel has proposed mining the ordinary chondrite analogue asteroids for the PGMs.(Kargel, 1994). However, precious metals are likely only to be a small byproduct in any near-term project, and only become viable as a primary product on its own at a scale that implies very large impact on the earth's supply of Platinum, and a very large in-space mining operation.

The details of the beneficiation process to be chosen obviously depends on the material being recovered. If it is fines from which it is hoped to extract Fe-Ni metal sand plus volatiles, then one might consider the following conceptual flowsheet (adapted from O'Leary, 1982).

Conceptual flowsheet, from O'Leary:

1. material collection, for example, by scraper or screw conveyor;
2. pressurization, to ~ 0.01 atmosphere, to enable pneumatic handling;
3. comminution, to ~ 0.2mm, to release NiFe fines and volatiles;
4. sizing, for example, by dry cyclone, for effective separation;
5. magnetic separation, by cross-belt magnets to collect metal grains, magnetite, and ilmenite;
6. heating, using solar furnace, to ~ 500C to extract vapours and gases;
7. separation of gases and remaining solids, by cyclone;
8. condensation of gases and vapours in cold traps (shaded vessels);
9. recirculation of permanent gases for pneumatic handling.

6.4 Equipment Considerations

Here are addressed some aspects of likely equipment mass and power requirements.

6.4.1 Grinding and crushing

Assuming that the material does need comminution, there are several possible equipment choices.

Energy requirements are estimated using the Bond Work Index; this is basically an indication of ore hardness. It is defined as the specific work (in kilowatt hours per tonne) required to reduce particles from infinite size to 100 microns. Average Work Index for industrial feedstocks appears to be 10 to 15 kW-hr/tonne.

It is worth noting that about 99% of energy input into crushing and grinding goes into heat, with only 1% going into the energy of formation of new surfaces.

One can readily visualise a conical gyratory “grizzly” with external annular conical screens for scalping oversize and delivering fines for further separation. Note that screens must be non-blinding and capable of being cleared by reverse flow cleaning.

Roll crushers have low energy requirement, of order of 0.5 kW/tonne.hr., and give a low production of fines.

Fluid energy mills: An example is the “micronizer”, which gives a very fine grind, and 1 metre diam model handles 2 tonnes /hr. (SME Mineral Processing Handbook).

Hammer mills are used as coal pulverizers; hot gas can be used to dry the coal during pulverizing, from 8% moisture to 1% moisture.

6.4.2 Materials Handling

1. Solutions here are not altogether obvious, given:
   (i) the process takes place in zero-g;
   (ii) the material(s) are ill-defined and likely to be extremely poorly sorted in particle size, and chemically heterogeneous, and possibly mutually reactive when heated.

2. Low pressure pneumatic transport was suggested by O'Leary, referenced above. As in the case of Kuck's Frasch-process-style extraction, it is important to know whether you can supply or generate make-up fluid to replace losses due to leakage, reaction, etc.

Again as in the case of Kuck's process, if one were mining for volatiles, you would certainly expect to be able to generate adequate make-up gases such as CO, CH_4, N_2, CO_2, HCN, NO_2, etc. There are various advantages with pneumatic handling: good heat transfer properties; minimise reliance on mechanical equipment; easy release, entrainment and capture of mined volatiles, by use of a cold trap (which as pointed out by O'Leary, can be as simple as a shaded storage container).

Note that the extraction "head" must be gas tight else material will be lost; a "guard ring" approach to design is needed.

3. Steam ejectors can be used as gas pumps or pressurizers:
   - they can achieve compression ratios of up to 10:1;
   - they can handle gas with entrained dust or condensate;
   - they have no moving parts, hence no maintenance requirement.
   (see Perry's Chemical Engineer's Handbook, McGraw Hill).

4. Pneumatic conveyors "can be used for free-flowing materials of almost any particle size up to approx 6mm at rates over 10 tonnes per hour. Typical pressure loss is about 0.5 atmosphere." At 20 t/hr., transporting 0.5 gm/cc suspension, 150 mm

diam pipe is needed. (see Society of Mining Engineers Mineral Processing Handbook, 1985).

5. Screw conveyors for material handling: should work effectively in zero-gravity. They are very robust, accept coarse material, and for material of bulk density close to 1 gm/cc, the power requirement is approx 1kW per 10 tonnes/hr tranported through 10 metres of conveyor flight.

6 Rotary feeder /star wheel feeder can hold off 1 atmosphere pressure.

6.4.3 Heat Processing

Both "Kuck Process" and Carbonaceous Chondrite Devolatilization rely on heating for product recovery; here the power requirement for the minimum-scale project concept is discussed.

6.4.3.1 Melting Ice

Assume it is planned to extract (via Frasch process for example) 5000 tonnes of H_2O ice from an extinct comet core, within a period of 6 months. This throughput implies a processing rate of ~ 250 grams/second.

Heat = Mass × Specific Heat of Fusion

Power required is = $2.5 \times 10^{2} \times 4.2 \times 80$ joules/sec = 80 kW;

If the water needs to be volatilized, then the power required becomes ≅ 800kW.

Since solar insolation at 1AU is 1 kW/m^2, the required mirror size is then either 80m^2, or 800m^2.

6.4.3.2 De-volatilizing carbonaceous chondrites

Assume that it is planned to ‘cook out’ approx 10% of the mass of a CI or CM chondrite (and /or reduce another 10% of the mass (FeO to Fe) if CR chondrite). Note that it is necessary to heat to approx 800C in order to extract H_2O from talc and other phyllosilicates (Ganguly & Saxena, 1989). The temperature required to extract H_2O from gypsum is (depending on the rate of heating) 500 to 600C.

No quantitative data exists for volatiles release as a function of temperature and heating rate, for meteoritic materials, and there is very little information on the effect of heating rate even for simulants, such as gypsum, epsomite, calcite, dolomite, clays, oilshale, and combinations of these materials. **Extraction of volatiles has not been studied at all from the point of view of yield determination, experimentally**.

There is however some information available, as an aside, collected during stepwise heating experiments done for the purpose of identifying hydrocarbon species in Allende, Murchison, and Murray meteorite samples; and from experiments done for the purpose of looking at isotopic ratios of hydrogen, oxygen, and nitrogen; but it is incomplete and it was not performed to address the question of volatiles yield vs temperature vs time for various carbonaceous chondrite types.

The stepwise heating experiments done by Levy, Studier et al, Kerridge, Robert and Epstein, Villieras et al, and others, all tend to indicate that up to 10% H_2O, and possibly up to 5% CO_2, may be released. These are however, underestimates, because in most of the above cases, volatiles that were released at temperatures below 150C or below 200C were not reported, or were not accounted for, were treated as nuisance material, and pumped to waste, or collected on KOH and discarded. Ganguly & Saxena (1989) have done calculations which suggest up to 30% by weight of the carbonaceous chondrite material could be released on heating, but this has not yet been tested.

Experimental results (Levy, 1973; Kerridge, 1985) and theoretical calculations (Ganguly & Saxena, 1989) both suggest that the release reqires that the chondritic material be heated to quite high temperatures (variously 400, 600, 800 or 1000C).

CR chondrites have significant calcite / dolomite ; we know therefore that they may be heated to extract CO_2 .

Autoreduction of FeO with Carbon will depend on the mineral grains being in close contact and at high temperature. There is indication of autoreduction occurring in some chromatograms of Levy et al, at 600C. It also appears to be occurring in the pyrolysis experiments of Robert & Epstein, 1982.

However, in neither these nor other possible cases was it commented on, because it was not what the experimenters were interested in: they were not looking for a resource-extraction process.

As a result, Lewis and Hutson's assertion that "up to 40% by weight is extractable volatiles" is as yet untested by experiment, although clearly plausible, based on abundances and on the circumstantial evidence from the above heating experiments. Ganguly has experimentally shown a 3% water release from talc on its thermal decompositon to enstatite and quartz.. He has also indicated good theoretical reasons to expect similar yields from thermal decomposition of other phyllosilicates.

So, a reasonable assessment of the literature reviewed is that if one wishes to extract water and carbon dioxide from CI, CM, or CR material then one has to heat it to (probably) about 600 to 800C. If it is desired to obtain CO_2 by autoreduction of intimately mixed FeO and C matrix in CI, CM material, then it must be heated to approx 800C.

Assume for a process restricted to volatiles production, i.e., no metal production, a temperature requirement of 500C, and a volatiles recovery of 10% of the feed mass.

What is the heat capacity of common solids?

$CaCO_3$	80 J/mole.K	M.W. = 100	hence	0.8 J/gm.K
$CuSO_4$	100	160		0.6
SiO_2	50	50		0.83

- so 1 J/gm.K appears appropriate; note that water is 4.2 J/gm.K.

At 12 tonnes / hour (3 kg/s) feed rate (to give 5000 tonnes of water after 6 months at 10% recovery), and ΔT of 400C, the implied power requirement is 1.5 MW, in the absence of heat reclaim / recuperator / heat exchanger. Note that this is only about twice the power requirement for volatilization of ice at the rate giving same volatiles production rate.

6.4.3.3 Further heating and processing considerations

What particle sizes do we need for liberation of H_2O, CO_2, etc., on heating? -and what energy is required to grind to this size, if indeed grinding is required?

What heat energy is required to heat this sized fraction to say 600C? -and what heat reclaim can be obtained?

It seems intuitive that release will be aided by reducing the particle size. However, Ganguly suggested that the dehydration reaction is adversely affected by too small a particle size, because that inhibits nucleation of the new species; however, he expects this to occur only at sub-micron sizes. This being the case, Ganguly would suggest that the production rate would be found to increase with reducing particle size, down to this small diameter, then reduce as size decreases below the optimum for nucleation, the optimum being perhaps at a micron or so.

However, a paper on Brucite decomposition indicated best size for speed of reaction to be at 150 microns; my own rough experiments on dehydration of gypsum showed little effect of particle size. Thus there may not be any need for fine grinding at all, with particles up to even 500 microns or so potentially processable with no great loss of yield.

It is likely that some of the engineering rules of thumb regarding sizing, throughput, mass, and heat transfer relating to fluidised bed reactors and pneumatic dryers may be applicable. For example, Fluidised Bed Reactors:

- provide extremely good heat transfer performance;
- are well understood if operating in the dilute phase flow regime; this holds if mass of particles is less than 5 times the mass of the fluid ($m_p < 5\ m_f$).
- Particle diameter should generally be between 60 micron and 2 mm; i.e., not necessity for fine grind.($60\mu m<d_p<2mm$).
- Gas cyclones can be used to return oversize particles to the FBR, or to separate and dump.
- gas cyclones can be used to preheat the charge and / or to cool the tails.

Pneumatic conveying dryers "are suited to free-flowing powders and granular, crystalline, or fibrous solids" (Perry's Chemical Engineers' Handbook). They may also be set up to grind the feed at the same time.

Note retention time of particles in hot zone is very short - a few seconds only).

Volumetric heat transfer is in order of 2000 J/m ^{3} K. Thus, if ~1 MW is required, this implies heating / grinding chamber needs to be about 1m ^{3} in volume. (This can be reduced by heating of shell to add radiant heat input).

Typical products handled in pneumatic conveyor-dryers are (Perry's, p20-54):

material	initial moisture	final %	rate (kg/sec)
coal (1 cm)	11.5 %	1.5	1200
kaolin	10	0.5	120
clay (ball)	25	0.5	60
gypsum	25	5.0	50
silica gel	50	10.0	80

6.4.4 Masses and throughputs of mining and processing equipment

Materials collection: A Figure of Merit for mass throughput of mining and processing equipment is ‘f’, kg feed per day per kg of equipment. Examples are:

Front End Loader: at 1 bucket per minute with a bucket load of 5 tonnes and machine mass of 10 tonnes, f = 720 kg/day per kg equipment

Scraper/winch: at 600 tonnes per day, with winch plus scraper mass of 0.2 tonnes,
f = 3000 kg/day per kg

Grinding/separation: depends on type: fluid energy mills probably mass approx 50 kg, unmodified; and appear to require about 10 kW for 500 kg/hr throughput; so f = 250

Impactors/hammermills: mills massing 100 to 200 kgs give 2 to 5 tonnes per hour, hence f = 500. Coal pulverizers are generally hammermills and the feed is often direct -heated with hot gas to dry coal from 8% moisture to 1%.

Generalising and extrapolating from the above, f (daily throughput/mass of equipment) may be approx = 200; hence to mine and process chondrite material at 300 tonnes per day should require approx 1.5 tonnes of equipment.

This will give (according to the assumptions) 30 tonnes volatiles / day, and therefore a payload plus propellant cargo after 180 days of 5000 tonnes.

6.5 Process Flowsheet Concepts

What:		How:
1.	collection	by augers or scoop arms
2.	discard lumps	by dimensions of collector or by annular 'grizzly'
3.	pressurize and fluidize soil	rotary valve or screw feeder; gas ejector
4.	grind and heat	fluid mill or impactor / hammer mill
5.	separate gases from solids	dry cyclone or baghouse
6.	heat recovery & depressurize solids	some sort of gas expansion engine
7.	discard solids	some sort of slinger / ballistic ejector
8.	condense product vapours	adiabatic (heat engine) expansion into storage bag
9.	store as ices	radiative cooling of storage bag
10.	repressurize carrier gases	mechanical compressor driven by 6 or reheat 8; and solar collector heat exchanger

See Fig 6.2 over page.

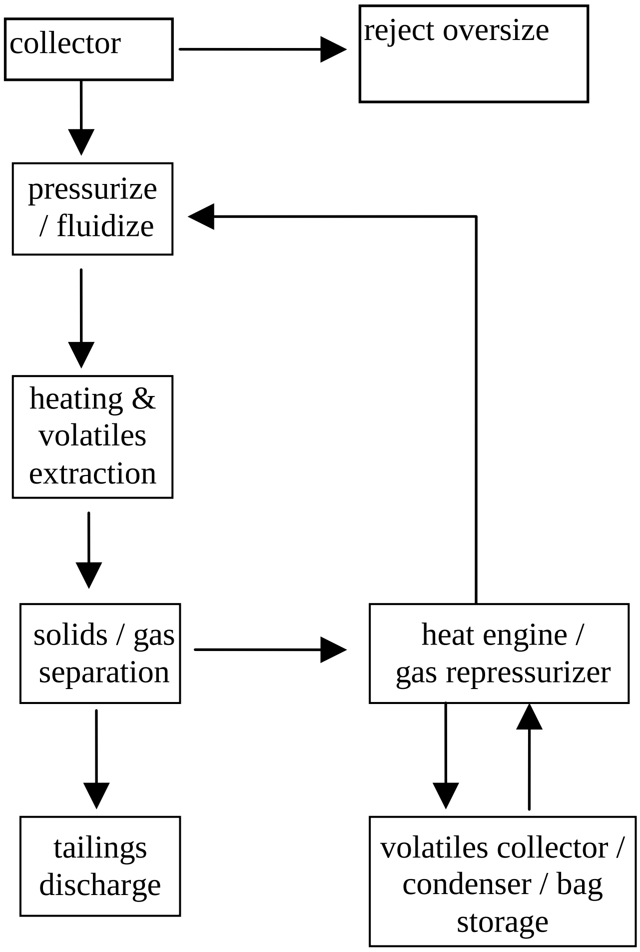


Figure 6.2 Conceptual Process Flowsheet for volatiles extraction from Carbonaceous Chondrite-type Asteroidal Regolith

Notes on Flowsheet

This flowsheet is intended to extract volatiles (primarily water) from carbonaceous chondrite and hydrated silicate materials, found loose in asteroidal regolith.

Pressurization is necessary to enable gas-pneumatic handling of the solids, and for efficient heat transfer.

Rotary valves can hold off 1 Atm (100 kPa). Screw conveyors are also capable of supporting substantial backpressure.

Grinding and heating duty should be integrated and simultaneous, because both require adequate residence time and fluid bed conditions are good for heat transfer.

Grind size should be kept as coarse as possible. to reduce grinding work requirement and to ease solid - gas separation, and/or to minimize blinding of filter cloth (say 50% passing 200 micron or coarser).

Temperature needs to be raised to approx 600 C to ensure dehydration.

Gases must be cooled to (if possible) -50 C to ensure volatiles are condensed; this should be partly by expansion through a heat engine; similarly, initial reheat after condensation of volatiles should be by mechanical compression, rather than heat exchanger; recompression being necessary for reuse as carrier gas, and heat exchangers being massive items.

Other issues:

It is necessary to address the mass of the heat engine and compressor, or steam ejector, or diffusion pump, for recirculation of the heat transport and grains-transport gases. It is also necessary to address the mass of the cyclone or filter upstream of or internal to the volatiles collection and condensation bag.

In the case of the in-situ drilling and melting scenario, the compressor requirement is (say) 0.5 kg/sec of gas at (say) 4 atmospheres (400kPa), and this implies about 2 kW power requirement. Such a pump might mass 10 or 20 kilograms.

In the case of the mining and processing of regolith, there is a larger power requirement, mainly because of the order of magnitude greater throughput required, so in this case, the heat engine/compressor will mass (say) 100 to 200 kg.

6.6 Kuck Process Option.

If one can be sure that the body to be mined is a comet core with remnant deep or shallow ices (under a non-volatile insulating layer that may be fluffy or rocky, or bituminous) then one might consider to choose Kuck's modified Frasch process for combined mining/processing. (see Figure 6.3 below).

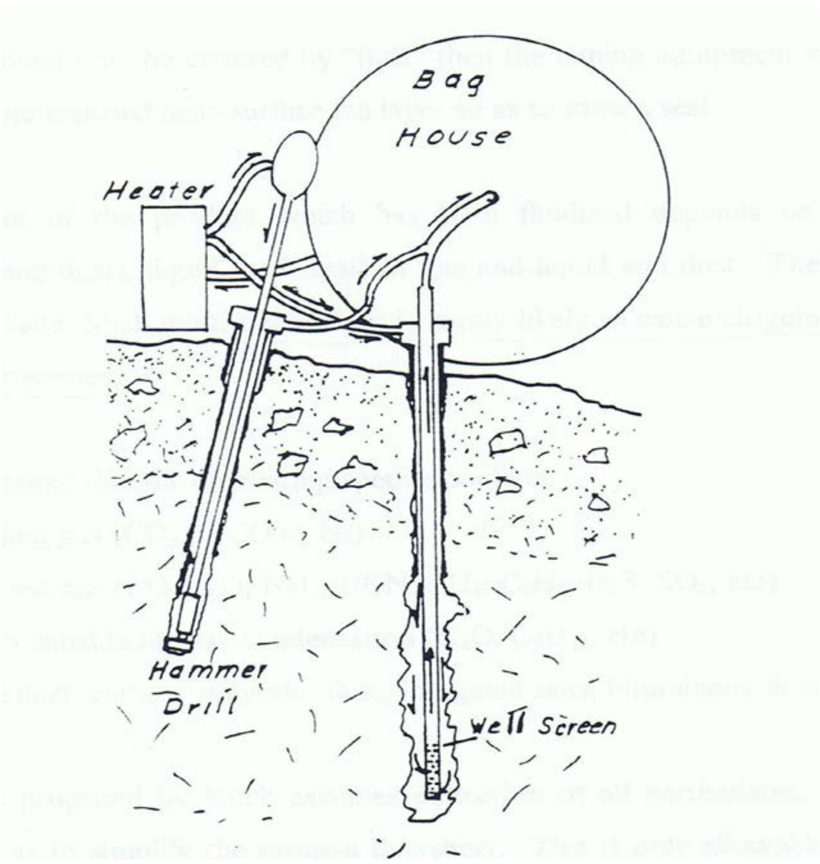


Figure 6.3 Drilling to recover volatiles from comet core (from Kuck,1995)

Note that we can only surmise as to the nature of the lag deposit or detrital cover layer. Lewis suggests that it may be as uncompacted and strengthless as fluff.

Kuck's process requires at least enough competence or strength in the surface layers to anchor the drill to, and to cement the wellcasing to. A poorly sorted rocky armour of 3 to 5 metres thickness with bituminous / tarry infilling would be appropriate for this approach. Sandvik use the 'Tubex' method to drill into sanitary landfills and permafrost ground, and this could be adapted for the duty envisaged (Kuck, pers.comm. 1996).

Lewis's picture of a fluffy covering would be totally unsuited to a Kuck-process extraction rig, inasmuch as the drill rig relies on the strength of the surface non-volatile layer to provide reaction forces and anchoring forces, and to provide a gas-tight seal within which the volatiles can be fluidised.

Should the comet core be covered by "fluff" then the mining equipment will have to cut or melt into the exposed near-surface ice layer so as to form a seal.

The treatment of the product which has been fluidized depends on whether it is gas/vapour (and dust), liquid (and dust) or gas and liquid and dust. There may also be contaminant salts. Such multi-phase flow is highly likely to cause clogging in all but the simplest of processes.

It should be noted that the circulating species could be :

mobilising gas (CO_2 or CO or N_2)
volatilized gas (CO_2, CO, NH_3, HCN, CH_4, C_2H_6, H_2S, SO_2, etc)
vapours capable of easy condensation (H_2O, C_6H_{14}, etc)
silicate dust, carbon 'polymer' dust, inorganic salts, bituminous fines.

The process proposed by Kuck assumes collection of all particulates, along with the volatiles, so as to simplify the process flowsheet. This is only allowable if you believe that solids will be but a small proportion of the total collected mass.

Otherwise, very simple separation of the dust is the first essential process step, and must occur at a temperature above the condensation point of the most easily condensed, highest condensing, vapours.

Simple cyclone gas cleaners are readily adaptable to zero-g. So are baghouses, but blinding must be considered to be a major problem.

Various gas cleaning and condensation steps may be necessary, with the permanent gases being re-compressed, reheated, and re-injected for further volatiles recovery.

<u>Items to be addressed in engineering a design for the Kuck process are:</u>

- what total volatiles payload should one aim for? (a figure of 1000 tonnes delivered into LEO is suggested elsewhere in this thesis)

- what heat input is needed to melt (or melt and volatilize) the required mass of payload and propellant?

- what hot gas flowrate would be desireable to do this? - and at what pressure?

- what solar collector size is therefore required?

- what radiator capacity is needed, to condense volatiles and dump heat engine waste heat?

- what is the estimated total mass of plant?

Note: if we do not volatilize, but merely melt, the desired material, then a gas-cleaning step would tend to reject product. Thus, a “melt only” Kuck process is restricted to a scenario in which (i) the total mass proportion of dust is low; and (ii) the presence of dust does not threaten the propulsion system.

Considerations of market capacity and minimum mass return for financial viability indicate that the required production of volatiles is in the order of 5000 tonnes in 6 months. This gives a required extraction rate of about 1.2 tonne per hour.

If it is assumed the product mass is 100% water, and apply latent heats of fusion and vaporization, we find the required heating power is about 1 MW, to melt and vaporize this quantity. Note that this is only half or less of the energy input required in extraction of volatiles from carbonaceous chondrite -type asteroidal regolith processing.

If there is no need to vaporize the recovered liquid, then the heat input power requirement is lower again, by a further factor of ten. This is the minimum heat power requirement under the simplest version of the “Kuck process”.

It is noteworthy that the power needed for the solar thermal rocket is about 750 kW for long period thrusting (say 6 months).

Thus it appears that the same solar collector of approximately 1 MW will meet the requirements for both processing and propulsion, in the case of the Kuck volatilization process (and is nearly adequate also for the carbonaceous chondrite devolatilization process, too).

What mass throughput and energy requirements do the various process equipment items have?

As noted elsewhere, this requirement may be relaxed if orbit phasing constraints allow a longer stay time, and therefore longer mining season. Another way of buying more time, and hence permitting a lower equipment mass, is to choose a higher energy outbound trajectory which “gets you there earlier” albeit at higher outbound Δv cost.

If the operation consists of drilling and extraction using a hot-gas lixiviant (Kuck’s process) then the total drilling and extraction equipment mass could be under 1 tonne.

6.7 Mass budget and system integration considerations

Assume a single launch, with no on-orbit assembly. The mass which can be launched outbound to a Near Earth Asteroid is then assumed to be 5 tonnes, this being the maximum payload of a Russian Proton rocket for injection into a Mars or Venus transfer orbit: these missions have Δv's of approx 5 km/sec, similar to the mission being envisaged.

The quoted best power to mass ratio of solar photovoltaic arrays is now somewhat below 10 kg/kW. Thus a 200 kW array will mass 2,000kg. An inflatable solar collector will have a much lower mass than this. The recent Shuttle-launched INSTEP inflatable dish collector had areal density of 0.4kg/m^2 and diameter of 14 metres. (Hence an area of 160 m^2, mass of 64 kg, and potential thermal power output of 200 kW.)

Navigation, surveillance, remote analysis, sample analysis, etc., may require 50 kg.

The materials storage bag has to hold 4,000 tonnes at a density of say 0.2 tonnes/cubic metre. This will require a volume of 25,000 cu.m., and hence a surface area of (say) 6,000 sq.m.; if the areal density of storage bag material is 0.25 kg/sq.m., then the bag mass is 1600kg. (eg., “Monarflex” reinforced polyethylene tarpaulin material, strength 7.3 kN/m). Ordinary industrial “Bulker Bags” have areal density of ≈ 0.5 kg/m^2.

Structure, anchor mechanism, sunshield, etc., can be estimated at perhaps 300 kg..

This leaves for deep-space propulsion, and for reclaim and separation equipment, a mass budget of possibly 3000 kg, to make up to a total mass of 5000kg, which is the mass budget of the Proton rocket, into various NEA transfer orbits; in fact however there is some "slack" in the system: Δv demand on the Proton can be reduced substantially by lunar flyby on the outbound trip which can give a free 1 km/s boost, and hence allow heavier load.

Before any further detailed consideration of materials reclaim and processing systems and their probable mass, it should be noted that there are two approaches that can be taken:
(i) the material can be processed and separated, and tailings discarded, at the asteroid prior to departure for return to Earth; or
(ii) the raw material can be loaded undifferentiated, then processed during the return flight to produce the required propellant.

The latter choice suggests a larger return departure mass, a lower mass throughput requirement on the processing plant, but demands a certainty that the required propellant is in fact recoverable from the amount of material collected; the latter also contains some mass-saving and time-saving process integration possibilities. Because of the fact that volatiles yield will be unknown until processing takes place, approach (i) has been adopted throughout this thesis.

6.8 Telepresence, telerobotics, and autonomous mining robots

The remote miner will need a high level of autonomy because it will be several to many light-minutes away from active human control: real-time remote control will simply not be responsive enough. The miner will have to be imbued with at least a level of intelligence that looks after housekeeping tasks, and makes the system go into a safe shutdown in event of anything unexpected. Preferably it should contain a level of intelligence capable of accepting, then unfolding, expanding, and interpreting, then implementing, high-level instructions.(see Pidgeon et al., JBIS 45, pp87-92)

Reviews of Artificial Intelligence literature suggest that there are two alternative approaches to developing “empirical” AI for autonomous vehicles: one is to “train” a neural net to experimentally attain the required goal; the other is to develop a rule based expert system and then implement it using fuzzy logic.

Telepresence and teleoperation have other problems apart from time-of-flight signal delay: they also require very wide bandwidth, high data rate communications links between the machine and the operator. Nevertheless, mines in Sweden and in Canada operate multiple drilling jumbos (Kiruna, Sweden) and trucks and load-haul-dumps (Inco, Sudbury; Cameco, Eagle Point, Canada) from remote locations. A Robbins raise drill was used at the Hilton mine, near Mt. Isa, Queensland, Australia, to bore an internal vent shaft, and was operated totally by remote control from a Robbins control room in Seattle, Washington, USA, using the public telephone system. Apparently, remote controlled / automated LHDs have also been trialled at Isa/Hilton. Autonomous and teleoperated mining technology is developing rapidly.

There is very rapid development occurring in the field of artificial intelligence, and further review of this area is beyond the scope of this thesis.

6.9 Conclusions:

Conceptual flowsheet development and equipment sizing can be done; initial study suggests that equipment for extraction of 5000 tonnes of volatiles from 10 times that mass of asteroidal regolith in 6 months can be designed to meet a notional processing equipment mass budget of under 5 tonnes.

Extraction of volatiles from an extinct comet core icy matrix may under the same demands require as little as 2 tonnes of processing equipment.

Chapter 7: Engineering choices: Propulsion and Power

7.1 Considerations in propulsion system choice

The basic parameters which are used to describe the performance capability of rocket engines are exhaust velocity, V_e, which is self-explanatory, and reported in kilometres per second, or specific impulse, I_{sp}. Specific impulse is generally expressed in seconds, and represents *the number of seconds for which one kilogram of propellant can provide one kilogram force of thrust*. (This description of the meaning of specific impulse is not correct in a pedantic sense, and the correct measure is *Newton-seconds of impulse per kilogram of propellant*, which gives a number ten times larger than the number in seconds, because one kilogram force is approx ten Newtons; nevertheless, seconds continues to be used as the unit for Specific Impulse.) Obviously, the higher I_{sp} is, the more efficient is the propellant useage, and the less is required to achieve any given Δv. I_{sp} in seconds is numerically equal to exhaust velocity V_e in km/sec multiplied by 100.

As discussed earlier, it is usual to characterize the energy demand of a space mission by the velocity change, Δv, required to accomplish it.

The "Rocket Equation" is a rewrite of Newton's Second Law of Motion, and relates velocity change Δv, exhaust velocity V_e, mass of rocket at departure M_o, and mass of propellant M_p:

$$\Delta v = V_e \ln (M_o/(M_o-M_p))$$

Thus a high final velocity is achieved by a high propellant mass fraction, and/or by a high exhaust velocity.

The choices available depend on whether the velocity change must be delivered rapidly, i.e. high acceleration required, or whether it can be delivered slowly over a long period. If the former then a high thrust rocket motor is needed, and the choices are limited to chemical rockets or nuclear thermal rockets. Even then, the mass that would be able to be returned to LEO would be limited, dependent on the rocket thrust and burn time available, and the minimum required acceleration. If low acceleration, non impulsive propulsion is allowable, then more possibilities exist.

7.1.1 Impulsive (high thrust) systems

Chemical rockets may either burn propellants that have been carried up from the earth's surface or propellants that have been produced from the mined resource.

Space-storable chemical rockets to date have almost invariably used as propellants, monomethyl hydrazine and nitrogen tetroxide; this combination is readily storable for years, and has an I_{sp} of 270 to 300 seconds. Alternatively, solid rockets having an I_{sp} of 250 sec. have been used.

The formula that determines the I_{sp} of a thermally generated jet is

$$V_e = 270\ (T/MW)^{0.5} \quad ; \quad \text{and,} \quad V_e = 10 \times I_{sp} \quad (m/s)$$

where T is temperature of exhaust gases in degrees Kelvin, and MW is their average molecular weight.

However, because the whole point of asteroid mining is to deliver large amounts of mass to LEO at less cost than launching it from Earth, the use of Earth-sourced fuels is not helpful. If the resource contains easily recoverable volatiles then it is possible that oxygen and fuel can be chemically extracted, stored, and then burned, rapidly, to provide high thrust and acceleration. The thrust levels possible might be very large, e.g. equal to the Space Shuttle Main Engines, which give 2,000,000 Newtons each, in vacuum. Storage of LOX and LH_2, however would require cryogenic refrigeration and insulation, a major mass burden.

Nuclear rockets were being actively developed 20 years ago (the NERVA project). The concept was to pump hydrogen through the core of a nuclear reactor to heat it to exhaust as reaction fluid.

A full scale operating nuclear rocket was constructed and ran, and achieved an I_{sp} of 800 seconds, and nearly attained flight readiness before funding was withdrawn (Dewar, 1994). Nuclear rockets are now perceived by many to present unacceptable risk of release either of fission products from possible rupture of fuel rods during operation within the atmosphere, or of fuel, which would be highly enriched uranium or plutonium, in the case of a crash or of the necessity to destroy the vehicle during ascent into orbit for range safety reasons. Thus it is likely that nuclear rockets will only be accepted if they are launched 'cold' and are started from "nuclear - safe" orbit, generally taken to be several hundred kilometres altitude. However, the concept has been fully engineered, with major recent technology recovery by Grumman focussing on particle bed reactors (R Haslett, 1993). The advantage of the nuclear thermal rocket is that the energy source - high enriched uranium - is of very high energy density, and the reactor can use any non coking volatile material as its coolant/working fluid/propellant.

There are other nuclear rocket concepts, which are potentially very powerful, capable of very large impulses (mass times velocity): Project Orion, which proposed propulsion by rapid repeated nuclear explosions behind a pusher plate; and Zubrin's "Nuclear Salt Water Rocket" (Zubrin, 1991), which proposes fissioning and expulsion as superheated vapour of an aqueous solution of enriched uranium salt. Another nuclear pulse - driven concept is the Medusa, described in Solem (1993). The exhaust in these cases would be highly radioactive, so the rocket could not be used anywhere except in space, for orbit transfers, but they would provide truly staggering performance, and make science-fiction-like missions easy! (I_{sp} of 10,000 sec and thrust of many kilonewtons...)

Speculative, but approaching technical feasibility, are fusion power and propulsion systems, using either magnetic or inertial electrostatic confinement (e.g. Shultz, 1994).

7.1.2 Non impulsive (low thrust) systems

Low thrust systems are incapable of lift off from a planetary surface, because of their poor thrust to mass ratio, but may still be able to provide large Δv performance, because of very long thrusting times. The acceleration provided by low thrust systems is necessarily very small, but its continued application over many days or weeks can still give a large Δv.

Non impulsive propulsion systems generally use an inert propulsion mass (reaction mass) and an external (generally electrical but possibly solar) power supply. Examples are:

- Resistojet: Nitrogen gas expelled after heating by electrical resistors; reject due to very poor specific impulse: I_{sp} =170 sec. Electrically boosted monopropellant hydrazine, $I_{sp} \approx 600$ sec, depending on exhaust temperature.

- Ion rocket: Mercury, Argon or Xenon ions accelerated by electrostatic repulsion; excellent specific impulse: I_{sp} =2000 to 6000 sec; technology is well advanced, but thrust levels are very low: 0.1 to 0.3 Newton. (Fearn, 1982; Rudolph & King, 1984)

- Arcjet: Ammonia gas heated by electric arc; models have been run for several weeks continuously, at tens of kilowatts power levels and several Newtons thrust levels; specific impulse is about twice that of chemical rockets, i.e., 600 to 800 sec, and they can potentially use any gas as propellant; technology well advanced. (Nakanishi, 1985; Deininger & Vondra, 1991)

- Mass driver: Electromechanical accelerator; this propulsion method would provide thrust by ejecting at high velocity any waste solids, e.g. silicate "tailings" from prior or concurrent materials processing; thrust can be quite high; technology was under development for a few years only at a couple of institutions, MIT and Princeton. (O'Neill & Snow, 1979; Kolm et al, 1979)

The electrical power requirements of the above propulsion methods range from 5 to 10 kW/N for the low I_{sp} Mass Driver technology, to intermediate power requirements for the arcjet, up to 20 to 50 kW/N for Ion rocket technology.

- Solar thermal rocket; this method would use solar heat to pressurise and expel any volatile material; technology immature. I_{sp} could be anywhere from 200 to 800 or more seconds, depending on the working fluid's temperature and molecular weight (Shoji, 1985). See also "Inflatable Concentrators for Solar Propulsion and Dynamic Space Power", Grossman and Williams, 1990. (reports the work done at L'Garde Inc, Tustin, Calif).

- Solar sails: these obtain their reaction force from the reflection of sunlight, thus use no mass at all, and require no power supply, however the thrust is very low.

- Combustion of electrolytically produced fuel: as a possibility, hydrogen and oxygen could be derived from asteroidal water ice, using solar or nuclear generated electricity, and burned in a low thrust long running engine.

7.2 Considerations of Power Sources

Most of these propulsion methods require a supply of electrical power. A power source is also needed for the mining and processing operations. This can be from solar photovoltaic panels, a solar concentrator mirror driving a heat engine and thence an electrical generator, or from a nuclear reactor or radioisotope generator. Speculatively, fusion power should also be considered, both as a power source and applied directly for thrust.(refs).

The largest near term space electrical power systems are Photovoltaic (PV) or solar thermodynamic and in the range 50 to 100 kW, but there is no technical reason to limit their growth.

Comparison between PV and solar thermal power must note the following:

- thermal energy is required for volatiles recovery and for Mond process.

- solar thermal rocket technology has been developed (by Shoji et al) to the point where it is a reasonable option
- the thermal power requirements for processing and for propulsion for the examples considered in this thesis, are similar enough to suggest the use of the same collector for both purposes, giving major mass savings
- ultra lightweight inflatable solar collectors have been developed by L'Garde Inc., who quote 150 kg for 25 m diameter dish.
- PV technology has also been getting lighter but suffers the disadvantage of at best 20% conversion efficiency.
- electrical energy has the advantages that it is needed, anyhow, for electronics and electromechanical purposes.

New lightweight solar arrays using amorphous silica on flexible substrates are quoted to have power to weight ratio above 100 W/kg (Stuart & Gleave, 1990). L'Garde quote 150 W/kg for >1 kW inflatable support arrays.

The SP-100 nuclear reactor has a power to mass ratio of 25W/kg (Kelley, Boain & Yen).

From the above considerations, the following Propulsion - Power Matrix can be drawn:

Table 7.1 Propulsion - Power Options

		Propulsion		
		steam rocket (1)	arc jet or microwave (2)	mass driver (3)
Power	solar thermal (A)	yes	no	no
	solar photovoltaic (B)	no	possible, but must compete with (1A)	yes
	nuclear (C)	yes	disadvantaged c.f. (1C) because of need for radiator	better than (3B) as it is not disadvantaged by reduced solar constant at aphelion

Given that "bootstrapping" - i.e., the use of in-situ derived propellants for return propulsion - is the major project enabler, the propulsion system choices reduce to the following options:

(i) mass driver powered by PV or nuclear reactor and using regolith silicate;

(ii) arcjet powered by PV or nuclear reactor and using any volatile (preferably steam because of its availability);

(iii) thermal rocket using any volatile (preferably steam) and powered by solar or nuclear heat.

System choices (2B) and (2C) above require demonstration that arcjets can work acceptably with steam. System choice 1A is that proposed by J S Lewis, and followed most fully in this thesis; system choice 1C is the preferred option of Zuppero et al, in their discussions of comet mining, and in particular, the exploitation of 1979 Wilson-Harrington. System choice 3C was the preferred option of O'Leary and of O'Neill in their writings of the early 1980's and late 1970's.

A notable advantage of the mass driver is that it can use the residue from the volatiles and metals extraction process; thus reducing the total mass to be mined; and that the processing can take place during the course of the return trajectory; thus reducing overall mission time and improving financial feasibility.

Simplicity and light weight suggest use of arcjet with nuclear power, or a solar thermal steam rocket. The photovoltaic powered arcjet is also possible, but is disadvantaged by its higher mass / power ratio; although the PV array pointing requirement is much less stringent than is the pointing requirement for a solar concentrator. The arcjet also has in its favour a much higher probable specific impulse, I_{sp}.

7.3 Conclusions:

The "best" system choices for power and propulsion are interrelated, and depend also on the desired product and processing options and requirements. The simplest near-term choice is solar thermal power and propulsion, using water ice as reaction mass.

Chapter 8: Project Selection Criteria

8.1 Economic Analyses

There have been various papers addressing the economics of mining the asteroids and mining the moons of Mars; (e.g., Leonard, Blacic & Vaniman, 1987; Cordell & Wagner, 1986).

Several papers discuss "Figures of Merit" for assessment of missions and use mass payback ratio (MPBR) as a "Figure of Merit" for comparison of alternative asteroid mining missions (e.g., Lewis, 1993; Lewis, 1991; Meinel & Parks, 1985).

8.1.1 Findings from the Literature

Several papers note the important fact that *time-cost-of-money* puts an upper limit on the allowable project cycle time, and that time from capital committment 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!! However, Collins (pers. comm., 1996), points out that the Japanese time-cost-of-money allows a much lower venture capital I.R.R.)

Some other observations from these and other 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? Here the important concept of Figure of Merit has been evolved to enable a quick quantitative evaluation of the overall mission impact of various candidate technologies." - (Lewis, Ramohalli, & Triffet, 1990 - this author's italics).

Leonard, Blacic, and Vaniman used the US National Commission on Space report, "Pioneering the Space Frontier" to define their minimum market size and rate of development. Assumed <u>volatiles</u>, ie water, to be the essential product. They noted that time-cost-of-money requires the project developer to minimize startup capital; also the equipment must arrive on ‘minesite’ ready-to-start with no delay (this implies minimization of on-site infrastructure construction requirement). They assumed 200 tonnes of mining equipment, nuclear power, manned, ion rocket technology. They suggested “Phobos manufacturing capability may develop before manufacturing on the Moon.”

They concluded: “Using propellent (for nuclear-ion rocket propulsion) lifted from Earth, the breakeven point (for feasibility) is at an Earth-to-leo launch cost (not below) between $500 and $1000 per kilogram for volatiles from the Moons of Mars to be profitable. If propellent for the ion thruster can be derived from extraterrestrial resources, the breakeven point moves much closer to the very optimistic figure of $200 per kilogram Earth launch cost.”

Lewis (1991a) provided several “mission architectures” for delivery of water from Near-Earth asteroids to HEEO, and calculated MPBR for these missions, for single and multiple return trips.

Ramohalli, Kirsch and Priess have shown that ‘Figures of Merit’ may be useful for purposes of inital screening of a myriad of concepts. They looked particularly at Mars Sample Return missions, and used FOM approach to assess competitiveness of ISPP concepts. FOM considers specific impulse, mass ratio, reliability, inverse risk, repairability, ease of autonomous controls, scalability and adaptability. They gave several possible definitions of FOM;

1 mass payload/mass launch
2 standard cost/total lifecycle cost of the mission
3 mass sample returned to leo/mass craft launched from leo
4 total useful mass/mass at launch
5 any of above, modified by factors for reliability, repairability and inverse risk.

Using Lotus 1-2-3 spreadsheet they experimented to find optimum FOMs given multiple independent variables. They noted that the high Isp of LH_2-LOX is not in itself a good enough reason to choose this propellant over other alternatives.

In “An Investment Analysis Model for Space Mining Ventures” (1991), Knut Oxnevad found that:

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

(ii) *Traditional MPBR “does not take into account development costs, difference in value between mass launched and mass returned, nor does it take into account the time-cost of money.”* Oxnevad went on to point out that *rigorous economic comparative analyses should emphasise NPV rather than MPBR.*

Oxnevad also discussed the “International Asteroid Mission”, a study project carried out by students of the International Space University in 1990. This plan assumed a manned mission, and was based on sale of mass to a Low Lunar Orbit space station site. Oxnevard, as a member of the study group, suggested 20-25% nominal discount rate (used for comparable high risk terrestrial projects), and calculated its NPV as negative $60 billion! Clearly, high capital cost, high discount rate, and long payback time all contributed to this ‘show-stopper’ finding.

Cutler & Hughes, 1985, made similar points:

(i) “high MPBR is not particularly important. Low initial capital is important.... Optimizing selected physical parameters such as delta-v or Isp does not in general lead to most economical system.”

(ii) “A *general economic methodology to evaluate schemes for extraterrestial resource utilization is needed. At the moment no standardized 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.”

There is discussion as to whether comet mining, in particular, would be better done via aphelion mining, with the concomitant burdens of long project time, impacting on NPV; low solar flux, impacting on power supply; and long signal time-of-flight delay, impacting on ease of teleoperation; or perihelion mining, with the problem of very large delta-v for out and return flights, impacting on available throw-weight outbound; and on proportion of payload that must be expended as propellant on return trip; and very short mining season duration, impacting on the total mass that can be mined and processed in the time available. These choices demand *economic*, as well as technical, analysis.

To summarize, 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 chapter addresses these requirements.*

8.1.2 Simple financial feasibility example

Any mission plan must meet constraints based on required rate of return, mission cycle time (which would itself depend on the orbital synodic period for return visits to the target), the mass that can be launched as a remote/autonomous miner to the target, and the propulsion choice and Δv for the return journey. And of course, the value per kilogram of returned product.

Let us assume that a project is envisaged to return 1,000 tonnes of useful material to Low Earth Orbit, and that it is worth, in orbit, $200 per kilogram. (Note that present freight cost to LEO is approx $10,000 per kilogram). Thus the value of returned product is $200 million. Let us also assume that the reaction mass can be extracted from the mined material, and that it will be used in a low thrust long operating propulsion system, either an arcjet using the permanent gases or the volatiles, or an electromagnetic mass driver using silicate fines, or a solar thermal rocket using recovered volatiles. Mission time is determined by trajectory scenario and available power. Long flight time impacts on project financial viability, so duration of transfer trajectories out and back, available power for processing, and the power requirements of the propulsion system become critical considerations.

Total outbound and return flight time depends on the details of the scenario, but should be restricted to 3 or so years. Net Present Value (NPV) of $200 million at 3 years in the future at 20% interest rate is about $115 million, thus setting the upper limit for the project budget.

The rest of this Chapter is intended to derive more rigorously a generic approach to performing a Feasibility Study for a hypothetical asteroid mining project.

8.2 Technical and economic interrelations - the "Spider Diagram"

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

The following linkages are apparent:

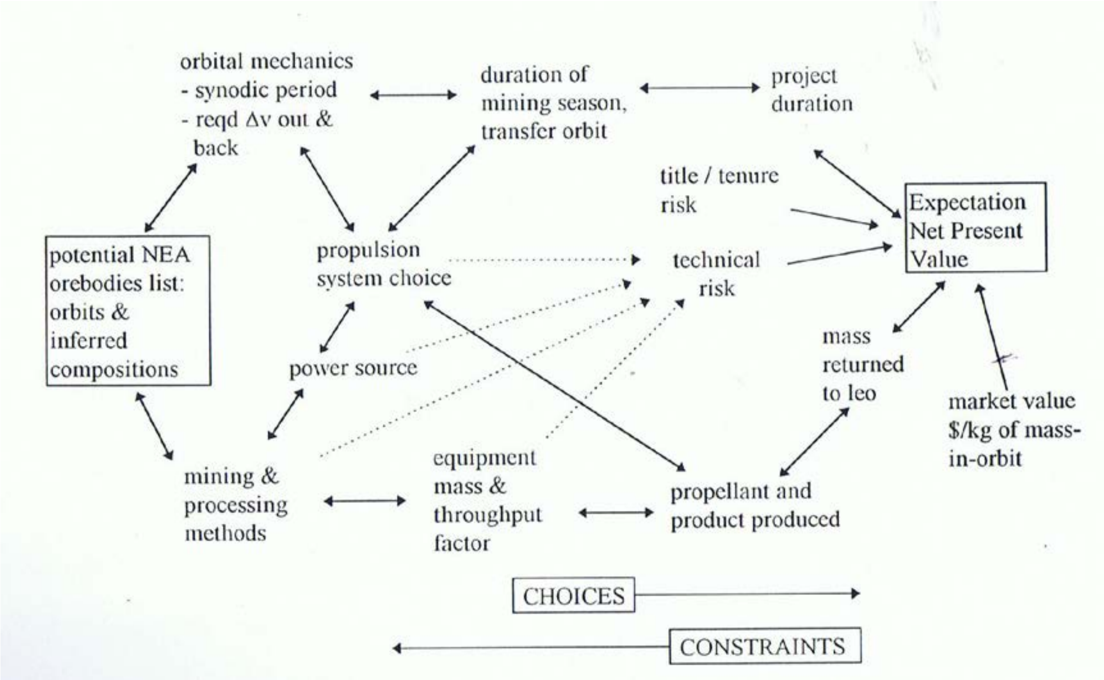


Figure 8.1 Project Feasibility "Spider Diagram"

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 considered in Appendix 1.

8.3 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 6 or more years as unattractive and not worth investing in. *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 more heavily discounted it must be, in the NPV calculation.

The following rules generally apply:

- capital - minimize
- time before income stream - minimize
- requirement for technical innovations - minimize
- revenue - maximize
- multiple products - desireable
- sensitivity to market fluctuations - minimize
- multiple potential customers - maximize
- large market – desireable

It is important to try to find a way 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, LH_2 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 **rewrite the formula for Net Present Value in terms of astrodynamic and the Rocket Equation variables.**

8.3.1 Breakeven Analysis

Breakeven occurs when fixed plus variable costs equate to revenue. In space mining missions, it seems likely that the great majority of costs will be fixed costs, namely, equipment development and acquisition, launch and control. These are in the nature of sunk costs and are not proportional to output. The implication of this for asteroid mining is that once the initial payload is returned and sold, very large reductions in the price of product can be sustained, limited only by the need for reinvestment capital.

8.3.2 Sensitivity Analysis

The Sensitivity Analysis needs to calculate for each of a range of interest rates and debt/equity fractions, the return obtained for a given delivered payload mass after various mission times, for different value-in-orbit figures.

Table 8.1 Sensitivity Table:

Mass returned to LEO: (say) 1000 tonnes.

Value in LEO: (say) $200/kg, therefore $200 million.

NPV is:

Cost of Capital	Project Mission Time (yrs)				
	2	2.5	3	3.5	4
15 %	150	140	130	122	115
20 %	140	127	116	105	96
25 %	128	114	100	91	82

For the same mass returned and a value in LEO of $500/kg, i.e. $500 million, the NPV will be:

Cost of Capital	Project Mission Time (yrs)				
	2	2.5	3	3.5	4
15 %	380	350	330	305	285
20 %	350	317	290	264	240
25 %	320	286	256	230	205

The Sensitivity Analysis is intended to answer the questions:

- what happens if costs to LEO drop to (say) $500/kg? (or $200/kg, vide P Collins)
- what if lunar LOX, LH_2 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?

8.3.3 Reliability / Probability Analysis

An appropriate 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 $(NPV)_w = NPV_1 \times p_1 + NPV_2 \times p_2 + NPV_3 \times p_3 + ...$

where probabilities $p_1, p_2, p_3, ...$ etc add to = 1.

8.3.4 Net Present Value Derivation &Calculation Process

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

$PV = R \times (1+i)^{-n}$ where i is the interest rate paid for risky investment capital.

Table 8.2 shows PV's for space-sourced mass (at 25% pa and $500/kg value of mass in orbit).

Table 8.2 Present Value versus Time to Payment

Time (yrs)		0	1	2	3	4	5	6
		$million						
tonnes returned	500	250	200	160	127	102	82	65
	1000	500	400	320	255	205	165	130
	1500	750	600	480	381	307	248	195
	2000	1000	800	640	510	410	330	260
	2500	1250	1000	800	638	512	412	325

$NPV = \Sigma_{i=1..n} R_i .(1+i)^{-n} - C$ (C is invested Capital)

NPV in the comet or asteroid mining case depends on:

<u>cost</u> to launch and conduct the mission

<u>mass</u> returned and what you can sell it for

<u>time</u> it takes to accomplish

Outbound mass consists of

final stage propellant to give reqd ($v_\infty + \Delta v_{DS}$)

mining and processing equipment

solar collector

payload bag

return propulsion system

Whilst outbound Δv is not critical, except within the constraints of the launcher capability, return Δv must be minimized; and duration of mining season should be maximized, consistent with minimizing total mission time and maximizing mass returned.

The implications for asteroidal or cometary resource return projects are that missions taking longer than (say) three years would 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, the formula for NPV can be expanded as follows:

For a single payback receipt, $NPV = R(1+i)^{-n} - C$

(i) n = time from capital-raising to launch + $T_{transfer\ orbit}$ + time from Earth-capture to sale

(ii) $T_{transfer\ orbit}$ = (semi-major axis, "a")$^{3/2}$ (years)

(iii) Receipt, R = \$/kg value of mass in orbit × mass of volatiles returned for sale;

- note that \$/kg launch cost sets upper limit on what the resources enterprise can charge for mass in orbit.

(iv) $M_{returned} = M_{produced} \times e^{-\Delta v / v_e}$

- from the Rocket Equation, which says $\Delta v = v_e \times \ln (M_{start} / M_{finish})$.
- (this neglects equipment mass, small compared with the returned payload)

(v) $M_{produced} = M_{mined} \times$ % recovered volatiles

(vi) $M_{mined} = M_{mpe} \times$ throughput factor "f" $\times\ t_{mining\ stay}$; M_{mpe} is the mass of the mining and processing equipment; and "f" is kg/day handled per kilogram of equipment, and is considered likely to be approx 200, based on discussion in Chapter 6.

(vii) $v_e = 270\ (T/MW)^{0.5}$ metres/second, where T is in Kelvin and MW is molecular weight of the exhaust gases. (Note that you divide the exhaust velocity by 10 to get I_{sp} in seconds.)

(viii) $\Delta v_{return} = \sqrt{\Delta v_{ecliptic-transfer}{}^2 + \Delta v_{inclin-change}{}^2}$ --if the line of nodes is coincident with the line of apsides

(ix) $\Delta v_{incl} = (0.5 \times i\ (degrees))$ km/s

(x) Mass launched = $M_{mpe} + M_{outbound\ fuel} + M_{power\ source} + M_{payload\ bag} + M_{instr\ \&\ control}$
(= mass of mining and processing equipt + mass of power supply + mass of cargo container + mass of instrumentation and controls)

(xi) C = capital costs + running costs until product return
= $((M_{mpe} + M_{ps} + M_{i\&c}) \times$ (\$/kg purchase cost + \$/kg "airfreight" to orbit) + (annual budget) × n yrs)

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

$= \$/kg_{orbit} \times M_{returned} (1+i)^{-(a\ 3/2)} - C$

$= \$/kg_{orbit} \times M_{prod} \times e^{-\Delta v/v_e} \times (1+i)^{-(a\ 3/2)} - ((M_{mpe} + M_{ps} + M_{i\&c}) \times \$/kg +$ annual budget $\times$ n)

(xii) Note that $M_{prod} = (M_{mpe} \times f \times t) \times$ % recovered volatiles;
then (finally):

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

Note for interest that Mass Payback Ratio is given by
$MPBR = (M_{mpe} \times f \times t \times \%recov \times e^{-\Delta v/ve})/(M_{mpe} + M_{ps} + M_{i+c})$

Note that the formulae for Δv are given in Chapter 4.

For an Aten-type mission, the duration of mining stay will equal half of the period of the asteroid; and flight time will be roughly the sum of the three orbital half-periods, namely the outbound transfer orbit, the target asteroid half-period mining season, and the payload return transfer orbit half-period. The requirement to rendezvous with the earth makes this close to 1.5 years. Thus for Atens and Apollos of low ellipticity, mining season is extended, and T is in all cases about 1.5 years. Atens are thus in principle better NPV targets, even for same delta-v requirements.

Process for determining NPV

This applies to mining missions with short stay times centred around aphelion or perihelion, with Hohmann transfers out and back; 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; and that capture into earth orbit is via lunar flyby to remove hyperbolic velocity. The Δv 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 Δv (return) from target body using Hohmann transfer calc or otherwise.
3. adjust for Δv reqd for inclination change (i in degrees):
4. from I_{sp}, 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 check mass returned.
7. calculate elapsed time from period of transfer orbit.
8. insert all variables into formulae above, and calculate NPV.

Expectation Value of NPV: Strictly, NPV should be discounted to take into account the less-than-unity chance of success:

Exp NPV = $p_1 \times NPV_1 + p_2 \times NPV_2 + p_3 \times NPV_3 +$,
where p_1 = fractional probability of outcome i ; e.g., if probability of total success is 80% and probability of total failure is 20%, then Exp.NPV will be:

Exp.NPV = 0.8 × NPV + 0.2 × (-C)

So finally, **Expectation NPV =**

$p_{success} \times$ [\$/kg product in orbit $\times M_{mpe} \times f \times t \times$ % recov $\times \; e^{-\Delta v / v_e} \; \times \; (1+i)^{-a^{3/2}}$

- ($M_{launched\ miner}$ × \$/kg 'airfreight' + ($M_{mpe} + M_{ps} + M_{i+c} + M_{cont} + M_{prop}$) \$/kg mfg + annual budget × ($a^{3/2}$ + T))] ,

where T is the total pre-launch project preparation time plus the post-return time to finalise sales.

Then finally one needs to insert formulae for Δv_{return}, V_e .

8.4 Conclusion

This process of calculation can be performed for other mission scenarios as described and discussed in Chapter 5. Examples are developed in Chapter 9.

Chapter 9: Project Example Calculations

In all of the following cases we assume that the desired product for return is water; that the reclaim is to be done by a remote/autonomous miner; that the requirement for simplicity demands that the project rely on a single launch; that the mass budget is restricted to 5 tonnes; and that a solar thermal rocket propulsion system has been chosen, with an operating temperature of 2400K, a conservative figure for a Rhenium nozzle, giving an I_{sp} of 310 seconds.

Other realistic alternative scenarios could be developed, e.g. assuming PV power and arcjet propulsion, but these have not been pursued here, because the intent of this chapter is merely to demonstrate some of the trade-offs which are uncovered.

9.1 Example #1: 1989ML ("Apollo-Type") mission

We wish to deliver 1000 tonnes of volatiles to earth orbit from 1989ML, an Amor. (Assuming volatiles are indeed obtainable from this body, via dehydration of clays, etc..).

We will assume an arbitrary 60 day stay time (or mining season) on the body, centred around its aphelion, and near-Hohmann-ellipse transfer orbits out and back..

1. Let us calculate the outbound Δv to depart LEO on heliocentric transfer to 1989ML, and return departure Δv required to place the payload in an earth-return trajectory.

1989ML has these orbital parameters:

Perihelion q	Aphelion Q	Eccentricity e	Inclination i	Semi-major axis a	Period T
1.099 AU	1.445 AU	0.1365	4.38 degrees	1.272 AU	1.435 yr

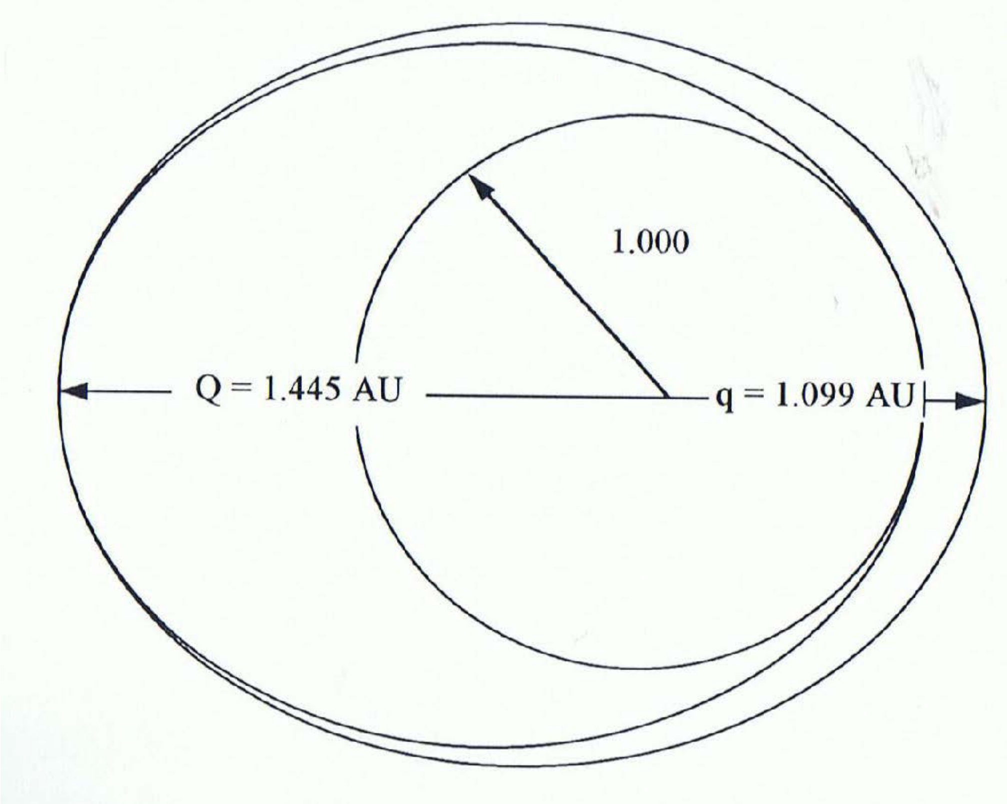


Figure 9.1 "Apollo-type" mission

The outbound velocity requirements $\Delta v_{\text{outbound, hyperbolic}}$ and $\Delta v_{\text{departure, leo}}$ will now be calculated:

The velocity required by a spacecraft at the perihelion of the transfer orbit shown in Fig 9.1 above, is

$v_{\text{perihelion, transfer}} = \sqrt{\frac{\mu}{1.00}\left[\frac{2(1.445/1)}{1+(1.445/1)}\right]}$ from eq (2) of 4.4.1;

$\mu_{\text{sun}} = 1.33 \times 10^{20}\ m^3/s^2$; 1 AU = 1.5×10^{11} m

so $v_{p,t} = \sqrt{\frac{1.33\times 10^{20}}{1.5\times 10^{11}}\left[\frac{2.890}{2.445}\right]}$

= 32.37 km/sec

Since the circular orbital velocity of the earth is v_{earth} = 29.8 km/sec,

the difference, $v_{outbound, hyperbolic}$ = 2.57 km/sec..

The question then becomes, 'what is the required Δv in LEO to give Earth-escape plus sufficient excess energy to provide this hyperbolic velocity?'

$\Delta v_{departure, leo}$ = ?

$v_{burnout}^2 = v_{\infty}^2 + v_{esc}^2$ (from Conservation of Energy, and eqn (11), 4.4.1)

$= 2.57^2 + 11.2^2$

$\therefore v_{bo} = 11.49$ km/sec

Since orbital velocity in LEO is 8.0 km/s, $\underline{\Delta v_{departure,leo}}$ = 11.49 - 8.0 = $\underline{3.49 \text{ km/sec}}$

Note that deep-space rendezvous Δv is small, and is in fact identical to return departure Δv calculated in the next section, and is 0.62 km/sec.

Now we will calculate the return requirement:

$\Delta v_{return} = v_{aphelion, ML} - v_{aphelion, transfer\ orbit}$ (ref eqn (6): the Δv to change from transfer orbit to outer orbit at aphelion is identical (but in opposite direction) to the Δv required to change from the outer orbit to the transfer orbit, at aphelion.)

$$v_{Q,ML} = \sqrt{\frac{\mu(1-e_{ML})}{Q_{ML}}}$$ (from eqn (5), section 4.4.1)

$$= \sqrt{\frac{1.33\times10^{20}(1-0.136)}{1.445\times1.5\times10^{11}}}$$

= 23.025 km/sec

$v_{Q,\,transf} = \sqrt{\dfrac{\mu(1-e_{tr})}{Q,tr}}$ (from eqn (5), again)

$$\left[e_{tr} = \frac{Q-q}{Q+q} = \frac{1.445-1}{1.445+1} = 0.182 \right]$$

$v_{Q,tr} = \sqrt{\dfrac{1.33\times10^{20}}{1.445\times10^{11}}(0.818)}$

= 22.404 km/sec.

$\therefore \Delta v_{\text{return, departure}}$ = 23.025 - 22.404 = 0.621 km/sec (to decrease heliocentric velocity).

Note that there may also be an inclination change required, since i for 1989ML is at 4.38° to the ecliptic.

If the line of nodes of the orbits of Earth and 1989ML is coincident with Q, q for the transfer orbit, then no separate deep-space Δv "burn" for inclination change is required. However if the line of nodes is not coincident with the major axis of the transfer orbit, then an inclination change will be required, so as to rotate the plane of the transfer orbit into the ecliptic. At its simplest, when the line of nodes is 90° away in anomaly from Q, q of transfer orbit, this will require a Δv for plane change at the line of nodes, of magnitude = 0.5 km/sec per degree of inclination change.

Thus at worst, for 1989ML,

$\Delta v_{\text{inclin change}}$ = 2.19 km/sec, for 4.38°.

Note that the plane-change Δv dominates!
(This also applied on the outbound journey, although it was not mentioned above.)

Note that in general, this Δv_{inclin} will not take place at the same time as asteroid departure, i.e., Δv_{return} , but at some later time, and will therefore be additive, i.e.,

$\Delta v_{return, total}$ =2.19 + 0.62 = 2.81 km/sec.

If and only if the departure from 1989ML can be delayed after aphelion long enough to coincide with its passage through the line of nodes, can the inclination change and the transfer orbit "burn" occur together. If that is possible, then

$\Delta v_{return,total} = \sqrt{(0.62^2 + 2.19^2)}$ = 2.28 km/sec. (from Pythagoras).

Thus for 1989ML, taking plane change into account, Δv_{return} = 2.8 km/sec. at worst.

2. Let us assume use of a solar thermal rocket, with exhaust temp. of 2400 K. (This operating temperature requires a Rhenium nozzle).

$v_e = 270\sqrt{\frac{T}{MW}} \cong 3100$ m/s; since $v_e = 10 \times I_{sp}$, I_{sp} = 310 seconds.

From the Rocket Equation, $\Delta v = v_e \times \ln\left[\frac{M_{start}}{M_{finish}}\right]$, we get alternatively:

$M_{start} = M_{finish} \times e^{\Delta v/v_e}$; for v_e = 3.1 and Δv = 2.8 km/sec, respectively,

$e^{\Delta v/v_e}$ = 2.47 for the above Δv_{return} .

So M_{start} = 1000 × 2.47 = 2470 tonnes at departure from asteroid.

Thus the volatile mass used as propellant is 1470 tonnes.

3. What energy is required to produce 2500 tonnes of water in (say) 60 days, assuming 1989ML is a carbonaceous chondrite - type asteroid, and that volatiles recovery is 10% of treated mass?

The implied regolith processing rate is 18 tonnes/hr. or 432 t/day, implying for equipt f =200 an equipt mass of 2.2 tonnes.

The heating power needed to raise the temperature of this mass from 0°C to 600°C, given specific heat of regolith of ≅ 1 J/gm.K, is 3 Megawatts (without use of heat exchanger).

With heat recovery from tailings prior to discarding them, we might reduce heat input requirement to (say) 1 MW. This should be preferably via a heat engine rather than a heat exchanger, because of the massive nature of heat exchangers, and the necessity in any case for a supply of mechanical energy.

4. Rocket propulsion power and propellant usage:

$$\text{dm/dt} = \frac{power\ \ in}{spec\ \ enthalpy\ \ for\ \ \ ice \rightarrow steam\ \ at\ \ 2400K}$$

$$= \frac{1 \times 10^6\ \ W}{\approx 8000 \times 10^3\ \ J / kg}$$

≅ 0.125 kg/sec

Therefore Thrusting time = $\left(\frac{1500 \times 10^3}{0.125} \right)$ seconds

= 130 days

And the thrust is dm/dt × v_e

= 0.125 × 3100

= 387.5 Newtons

5 Now we can construct a burn time / fuel used / Δv plot for 1989ML, using the Rocket Equation:

thrust time days	propellant used tonnes	d-v attained m/sec	payload remaining tonnes
0	0	0	2500
25	270	354	2230
50	540	754	1960
75	810	1214	1690
100	1080	1753	1420
125	1350	2407	1150
150	1620	3237	880
175	1890	4373	610

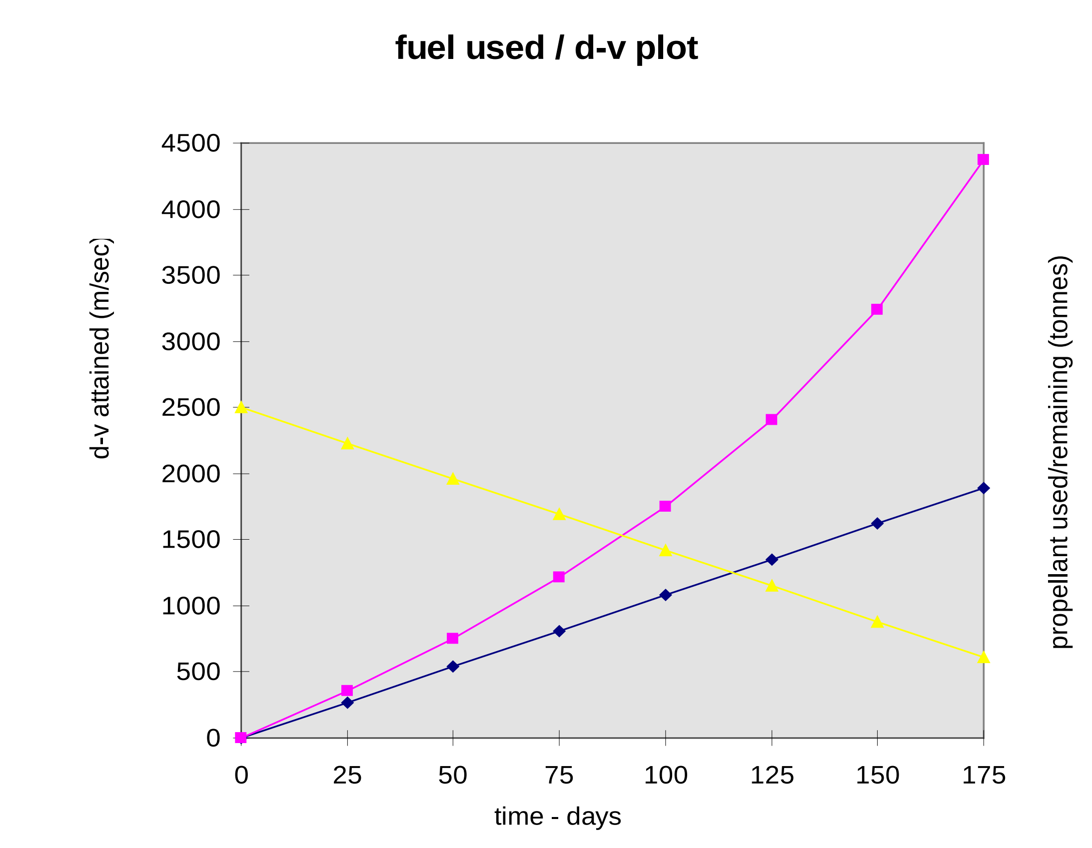


Figure 9.2 Fuel-use vs delta-v graph

NB: Period T of transfer orbit is = (a) $^{3}/_{2}$

= 1.352 years

= 493 days

From this we see that 2.8 km/s is attained in about 135 days of thrusting, with almost exactly 1000 tonnes remaining.

This is assumed to bring the payload into an orbit which is tangent to the earth's, at its perihelion. Capture is assumed to be assisted by lunar gravity flyby, and will be into a highly-elliptical earth orbit (HEEO).

Hyperbolic velocity v_∞ at time of capture will be

v_p,t = 32.37 km/s

v_{earth} = 30 km/s

$\therefore v_\infty$ = 2.37 km/s

Of this, ~ 1.5 km/s can be subtracted in a single lunar flyby (ref O'Leary), leaving a further 0.9 km/s to be removed by propulsive braking, in order to achieve Earth-capture. From the Rocket Equation, this will reduce remaining propellant mass from 1000 to **748 tonnes.** Retro-thrusting would start ~ 25 days pre-arrival.

The final transfer from HEEO to LEO will cost a further Δv of ≅ 2.5 km/s.

This could be accomplished using aerobraking - (but this would imply robotic fabrication of same on the asteroid - another level of complexity) - or could again be achieved propulsively, unfortunately using still more of the diminishing payload:

$$\text{M finish} = \text{M start} \times e^{-\Delta v/ve}$$
$$= 750 \times 0.446$$
$$= 335 \text{ tonnes !!}$$

If we assume sale in HEEO, then 750 tonnes, at (say) \$4000/kg = \$3 × 10^9

Time since drawdown of funds = $T_{transfer}$ plus pre-launch construction and preparation time is taken to be approx 2.5 years; then

$$NPV = \frac{R}{(l+i)^n} - \text{Capital invested}$$

$$= \frac{3\times10^9}{(1+0.3)^{2.5}} - \text{Capital} \qquad \text{(assume 30\% cost of loan money)}$$

$$= \quad \$1500 \times 10^6 \text{ - initial Capital.}$$

Hence initial capital must be less than $1500 million for NPV to be positive, and the project to be feasible.

However for delivery into LEO, where a lower value (of $1000/kg) is assumed to apply, and only 335 tonnes is left over for sale, the sale income is $335 million or an NPV of approx $170 million. This sets the limit on maximum allowable initial capital for the project giving delivery into LEO.

The finding that delivery into high Earth orbit would be about ten times more lucrative is interesting, but in the absence of any likely large-scale market, is quite hypothetical.

9.2 Example #2: 1982DB Nereus ("Apollo-Type") mission

Return of approx 1000 tonnes of volatiles from 1982DB Nereus: assume that approx 10% of the mass of the regolith is readily extracted volatile (H_2O, CO_2 , etc.). Assume an aphelion mining season of 60 days.

1982DB Nereus has the following orbital parameters:

Table 9.1 Nereus orbital parameters

Perihelion q(AU)	Aphelion Q(AU)	eccent e	inclin i(deg)	s.m.a a(AU)	period T(yrs)
0.953	2.025	0.36	1.4	1.489	1.82

We now wish to calculate the Δv required to depart from with sufficient energy to give the required $v_{hyperbolic}$ to enter the transfer orbit to Nereus.

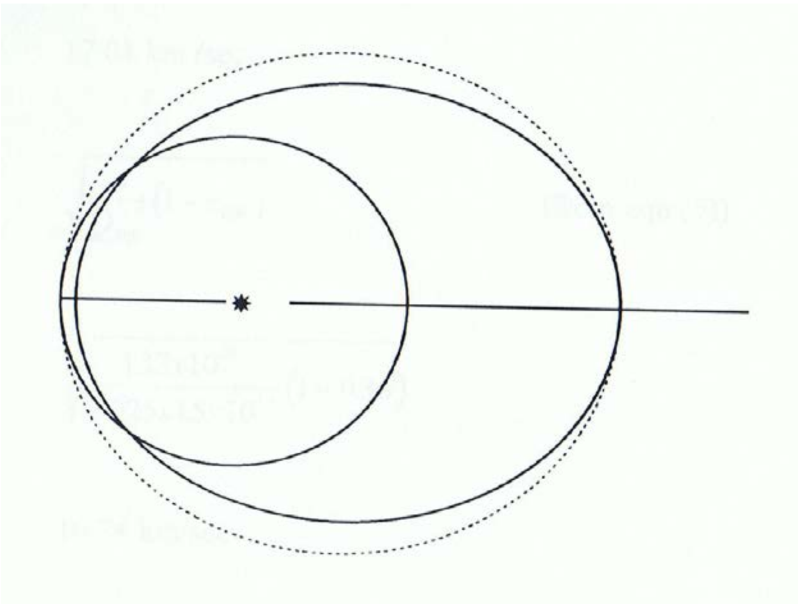


Figure 9.3 "Apollo-type" mission, example #2

$$\mathbf{v}_{\mathbf{p,t}} = \sqrt{\frac{\mu\left(2\left(r_{a2}/r_{p1}\right)\right)}{r_p\left(1+\left(r_{a2}/r_{p1}\right)\right)}}$$

$$= \sqrt{\frac{1.33\times10^{20}}{1.5\times10^{11}}\frac{\left(2\times2.025/1\right)}{\left(3.025\right)}}$$

= 34.45 km/sec

Therefore v $_{hyper}$ = 34.45 - 29.80 = 4.65 km/sec

Δv $_{depart, leo}$ = $\sqrt{\left(11.2\right)^2+\left(4.65\right)^2}-8.0$

= 12.13 - 8.0 = 4.13 km/sec

Deep - Space rendezvous velocity Δv $_{DS}$ must now be calculated:

Δv_{DS} = $\Delta v_{a,\ trans}$ = $v_{a,\ trans} - v_{a,\ DB}$

$v_{a,\ trans}$ = $34.45 \times \frac{1}{2.025}$ from Conservation of Angular Momentum

= 17.01 km /sec

$v_{a,\ DB}$ = $\sqrt{\frac{\mu}{Q_{DB}}\left(1-e_{DB}\right)}$ (from eqn (5))

$$= \sqrt{\frac{1.33x10^{20}}{2.025x1.5x10^{11}}\left(1-0.36\right)}$$

= 16.74 km/sec

So $\underline{\Delta v_{DS}}$ = 17.01 - 16.74 = <u>0.27 km/sec</u>

This is also the Δv required, at aphelion, to inject into an Earth-return transfer orbit.

Return trajectory: Note that Nereus' orbit is inclined 1.43° to Earth's, so there will be a small plane change needed, (unless departure is at the line of nodes!)
So $\Delta v_{inc} = 1.43 \times 0.5 = 0.71$ km/s

The total return Δv is 5.63 km/s (= 0.27 + 4.65 + 0.71). This is because Δv for departure from the asteroid is equal to Δv for rendezvous at arrival; and v_∞ hyperbolic velocity upon arrival will be equal to the departure Δv_{hyper} calculated earlier; 0.71 km/s is the plane-change requirement. Note that the 4.65 km/s delta-v for capture may be reducible by utilising a lunar flyby.

- the rocket equation implies a starting volatiles (propellant) mass of

$$M_{st} = M_f \times e^{\Delta v/ve}$$
$$= 1000 \times 6.15$$
$$= 6150 \text{ tonnes}$$

To collect 6000 tonnes of volatiles, it is assumed that 60,000 tonnes of regolith must be processed. To do this in 60 days implies 1000 tpd

$$\cong 40 \text{ tonnes per hr}$$
$$= 11 \text{ kg/sec}$$

To heat 40 tonnes per hour to (say) 600°C from 0°C will require approx 6 MW.

(Less if Heat Exchanger / Recuperator is used)

If this material requires to be crushed and milled to 500 μm, then
Grinding Power requirement = Bond Work Index × Mass flow rate

Assume Wi = 5 kWhr / tonne;

at 40 tonnes / hr, Grinding Power $= 40 \ \frac{tonnes}{hour} \times 5 \ \frac{kWhr}{tonne}$

$$= 200 \text{ kW}$$

Note that this mechanical power requirement is small compared with the thermal power requirement of 6 MW.

The thrusting time required to achieve any given Δv on the return depends on Heat Power and thus on dm/dt.

For Heat Power to the solar thermal rocket of (say) 3MW, and specific enthalpy of approx 8000×10^3 J/kg to heat water to 2400 K,

$$dm/dt = 0.375 \text{ kg/sec}$$

At 0.375 kg /sec, how long will it take to consume propellant mass of 5000 tonnes (leaving 1000 tonnes of payload)?

$$\text{thrusting time} = \left(\frac{5\times10^6}{0.375}\right) \text{ seconds}$$

$$= 154 \text{ days}$$

Approximately half of the remaining volatiles payload must then be used to drop into low earth orbit, as calculated in the previous example, unless aerobraking or another method of killing excess velocity is used.

The total time from launch for the resource return project is approximately 2.5 years; therefore, as was the case for the previous example, NPV for material delivery into LEO is ($1000/kg × 500,000kg × 0.5) = $250 million, assuming 30% interest rate.

Obviously, anything which reduces the requirement for propulsive Δv for earth return capture, and injection into LEO; and any possibility of a less onerous cost of money, would assist the economics of these missions greatly.

9.3 Example Project # 3: 1989UQ ("Aten-Type") mission

let us consider a mission to an Aten, 1989UQ, again assuming that volatiles can be recovered by thermal processing of regolith material to extract H_2O from clays etc.

1989UQ has the orbital parameters:

Table 9.2 Orbital parameters, 1989UQ

Perihelion q(AU)	Aphelion Q(AU)	eccentricity e	inclination i (deg)	semi-major axis a (AU)
0.67	1.16	0.26	1.28	0.915

Rendezvous can be made either at perihelion or at aphelion.

We will calculate Δv out and Δv return for <u>both</u> cases.

<u>Aphelion rendezvous</u>:

Δv outbound, $v_{hyperbolic}$ = $v_{peri, transfer} - v_{earth}$

[v_{earth} = 30 km/s]

$$v_{perihelion, transfer} = \sqrt{\frac{\mu}{r_{peri}}\left[\frac{2(Q/1)}{1+(Q/1)}\right]}$$

= 30.86 km/s

So $v_{hyperbolic}$ = 0.86 km/s, for aphelion rendezvous

$\Delta v_{departure,\ LEO}$ (i.e., the velocity increment required in LEO to give the necessary hyperbolic velocity to enter the transfer orbit desired) is LEO departure velocity - LEO orbital velocity; LEO departure velocity is that required by Conservation of Energy to give the hyperbolic excess velocity needed for the transfer orbit.

LEO departure velocity, $v_{burn\ out} = \sqrt{11.2^2 + 0.86^2}$

$$= \sqrt{125.44 + 0.74} = 11.23 \text{ km/s}$$

So $\Delta v_{dep,\ leo}$ = 11.23 - 8.0 = 3.23 km/s (for aphelion rendezvous).

Return: $\Delta v_{return,\ aphelion} = \left[v_{aph,UQ} - v_{aph,transferorbit}\right]$

Note that transfer orbit has higher perihelion than 1989UQ, ∴ $v_{aphel,transfer} > v_{aphel,UQ}$.

$$v_{aphel,UQ} = \sqrt{\frac{\mu}{Q_{UQ}}\left(1 - e_{UQ}\right)}$$ from eqn (5) 4.4.1

$$= \sqrt{\frac{1.33 \times 10^{20}}{1.5 \times 10^{11} \times 1.16}\left(1 - 0.26\right)}$$

$$= \sqrt{\frac{1.33 \times 10^{20} \times 0.74}{1.5 \times 10^{11} \times 1.16}}$$

$$= 23.78 \text{ km/s}$$

$$v_{aphel,\ transfer} = \sqrt{\frac{1.33 \times 10^{20}}{1.5 \times 10^{11} \times 1.16}\left(1 - e_{transfer}\right)}$$

$$e_{transfer\ orbit} = \frac{Q - q}{Q + q}$$

$$= \frac{1.16 - 1}{1.16 + 1} = \frac{0.16}{2.16} = 0.074$$

So $v_{aphel,\ transfer}$ = 26.60 km/s

So Δv_{return} = 26.60 - 23.78 = 2.82 km/s

That is, for return from aphelion of 1989UQ, a departure Δv of 2.82 km/s is needed, in order to increase heliocentric velocity in orbit, and intersect Earth orbit.

Perihelion rendezvous: Outbound hyperbolic velocity, $v_\infty = v_e - v_{aphel, transfer orbit}$

$$v_{aphel,transfer} = \sqrt{\frac{\mu}{1.5\times10^{11}}(1-e_{tr})}$$

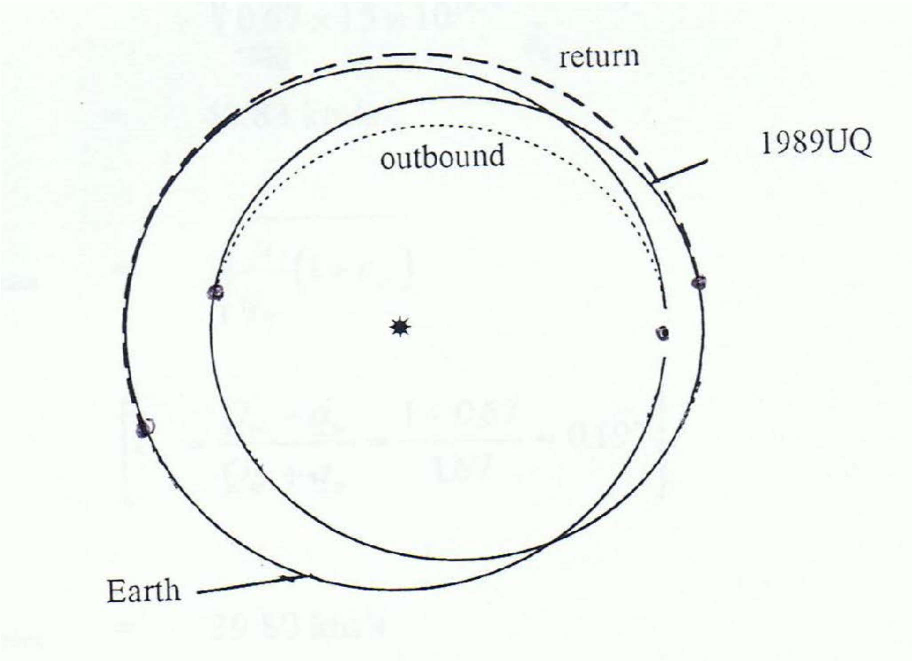


Figure 9.4 "Aten-type" mission (perihelion rendezvous, aphelion return)

$$e_{transfer} = \frac{Qt-qt}{Qt+qt} = \frac{1.0-0.67}{1.0+0.67}$$

$$= \frac{0.33}{1.67} = 0.198$$

$v_{aphel, transfer}$ = 26.67 km/s

Since Earth's circular velocity is 30 km/s, then v_∞ = 3.33 km/s for perihelion rendezvous.

$$\Delta v_{departure, leo} = \sqrt{11.2^2+3.33^2}-8.0$$

$$= \sqrt{125.44 + 11.09} - 8.0$$

= 11.68 km/s - 8.0 km/sec

= 3.68 km/sec

Return: $\Delta v_{return, peri}$: = $v_{peri, UQ}$ - $v_{peri, transfer}$

$$v_{peri, UQ} = \sqrt{\frac{\mu}{q_{UQ}}\left(1 - e_{UQ}\right)}$$

$$= \sqrt{\frac{1.33 \times 10^{20}}{0.67 \times 1.5 \times 10^{11}}\left(1 + 0.26\right)}$$

= 40.83 km/s

$$v_{peri, trans} = \sqrt{\frac{\mu}{q_{tr}}\left(1 + e_{tr}\right)}$$

$$\left[e_{tr} = \frac{Q_{tr} - q_{tr}}{Q_{tr} + q_{tr}} = \frac{1 - 0.67}{1.67} = 0.197 \right]$$

$v_{peri, trans}$ = 39.80 km/s

So Δv_{return} = 1.03 km/s for transfer orbit insertion (braking, to lower aphelion to earth orbit tangent). This is a surprisingly low figure!

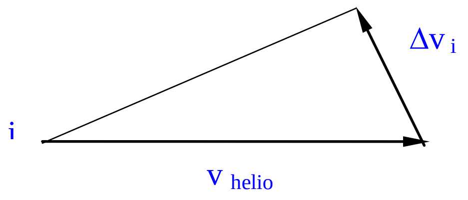
To calculate hyperbolic velocity on arrival at earth orbit, use Conservation of Angular Momentum: $v_{peri, trans} \times q_{tr}$ = $v_{ap, transfer} \times Q_{tr}$

$$v_{aph, trans} = \frac{39.80 \times 0.67}{1.00} = 26.67 \text{ km/sec}$$

So v_{hyp} = 30 - 26.67 = 3.33 km/sec

(in agreement with calculation for $v_{outbound}$)

Δv for inclination change: This depends on where i change occurs, and heliocentric velocity at that point.



tan i = sin i = $\dfrac{\Delta v_i}{v_{heliocentric}}$ ∴ $\Delta v_i = v_{helio} \times \sin i$

for v_{helio} = 30 km/sec,

Δv_{incl} = $(0.52 \times i)$ km/s

So a 1.28° plane change implies Δv_{incl} = 0.665 km/s- if accomplished at 30 km/sec heliocentric velocity.

So Δv for return to earth transfer is 1.03 + 0.67 = 1.7 km/s. Using the 1989ML calculations, we see that this can be achieved in 100 days, with a payload injected into transfer orbit of a little over half of the start mass (i.e., for the 5000 tonne case, 2500 tonnes onto Earth-return trajectory).

Some of this mass will necessarily be used in propulsive braking to attain Earth-capture.

So, for this and other Atens (as noted in Shoemaker and Helin, 1978), there is a choice between perihelion rendezvous and aphelion rendezvous, with a half-period mining stay, then a return trajectory departing at aphelion or perihelion, repectively.

Calling the “Aphelion rendezvous / perihelion-departure return” case Mission 1, and the “Perihelion rendezvous / aphelion-departure return” case Mission 2, the following comparison is found:

Table 9.3 Aten Missions comparison: 1989UQ

	Earth departure $\Delta v_{leo, depart}$	asteroid arrival (aphelion) $\Delta v_{Deep Space}$	asteroid departure (perihelion)	Plane change	Earth arrival (capture only) v_{∞}
Mission 1	3.23	2.82	1.03	0.67	3.33
	Earth departure	asteroid arrival (perihelion)	asteroid departure (aphelion)	Plane change	Earth arrival (capture only)
Mission 2	3.68	1.03	2.82	0.67	0.86

Note the outbound propulsive requirements are easier for Mission 2 (total outbound Δv of 4.71 km/s for Mission 2 versus 6.05 km/s for Mission 1). The return trajectory comparison is interesting: Mission 1 return departure Δv is approx 1 km/s versus approx 2.8 km/s for Mission 2, but the hyperbolic return velocity for Mission 1 is 3.3 km/s versus 0.86 km/s for Mission 2, which is much less demanding in propellant useage, and may well be amenable to lunar flyby capture.

Mission 2 is clearly the less demanding case, having a total return Δv requirement to Earth-capture of 4.35 km/s, versus 5.03 km/s for Mission 1.

NPV will be assisted by the extra time available for mining stay (T/2 = 160 days) which thus reduces the mass required for mining equipment and also reduces the power requirement for its operation.

Additionally of advantage for NPV is the relatively short mission time, which is approximately 17 months from launch.

9.4 Example # 4: Mission to an 'Arjuna', 1991VG.

'Arjunas' are very small (eg diameter = 20 m), have very "Earth-like" orbits, and have very long synodic periods, so either outbound or return trajectory will either be non - Hohmann or will require phasing orbit; Δv's outbound and return are under 1 km/s. 1991VG has the orbital parameters:

Table 9.4 Orbital parameters,1991VG

Perihelion q (AU)	Aphelion Q (AU)	eccentricity e	inclination i (deg)	semi major axis a (QU)
0.975	1.077	0.049	1.45	1.026

Δv to depart Earth to rendezous with 1991VG at its aphelion is:

$$v_{p_t} = \sqrt{\frac{\mu}{q_t}(1+e_t)}$$

$$= \frac{1.077-1}{1.077+1} = \frac{0.077}{2.077} = 0.037$$

$$v_{p_t} = \sqrt{\frac{1.33\times10^{20}}{1.5\times10^{11}\times1}(1+0.037)}$$

$$= 30.32 \text{ km/sec}$$

$$\therefore \Delta v_{\text{outbound}} = 30.32 - 29.80 = \underline{0.52 \text{ km/sec}}$$

$$\Delta v_{\text{departure, leo}} = \sqrt{(11.2)^2 + (0.52)^2} - 8.0$$

$$= \sqrt{125.44 + 0.27} - 8.0$$

$$= 11.21 - 8.0 = 3.21 \text{ km/sec}$$

Δv to depart 1991VG on return, for Earth-transfer-injection from aphelion:

$$\Delta v = v_{at} - v_{aVG}$$

$$v_{at} = \sqrt{\frac{\mu}{Q_{VG}}\left[\frac{2}{1+\left(Q_{VG}\ /1\right)}\right]}$$

$$= \sqrt{\frac{1.33\times10^{20}}{1.077\times1.5\times10^{11}}\left[\frac{2}{1+1.077}\right]}$$

$$= 28.16 \text{ km/sec}$$

$$v_{aVG} = \sqrt{\frac{\mu}{1.077\times1.5\times10^{11}}\left(1-0.049\right)}$$

$$= 27.98 \text{ km/sec}$$

So Δv_{return} = 0.180 km/sec

Obviously, this is a very small velocity change. In addition, we have already calculated that the v_{hyp} on Earth-arrival is ≈ 0.5 km/sec., easily low enough for capture and insertion into HEEO by a lunar flyby manoeuvre.

With these objects, mining season is not constrained by the need to depart near aphelion or perihelion, so mining rate can be quite slow; also total propellant requirement is small. This implies a much smaller equipment mass budget than calculated for the "Apollo-type" cases discussed earlier.

At 0.1 kg/sec, Mining Rate = 8.6 tonnes / day; the formula,
Throughput = 200 × Equipment Mass , gives equipt mass = 50 kg!

The equipment is dwarfed in the Mass Budget by collector bag (still approx 1.0 tonnes).

Total system mass could therefore easily be less than 2.0 tonnes.

Thus, in an engineering sense, the Arjunas will be the most easily accessible bodies; the question which is unanswered is whether there is any loose regolith on their surfaces, amenable to mechanical collection (or indeed whether any of them are "ice bodies").

9.5 Example #5: Wilson-Harrington Volatiles Return

Asteroid 1979VA Wilson-Harrington is now believed to be a dormant comet, because the discovery plate taken in 1949 showed a tail.

Its orbital parameters are:

Table 9.5 Orbital parameters, Wilson-Harrington

Perihelion q (AU)	Aphelion Q (AU)	eccentricity e	inclination i(deg)	semi major axis a (QU)	Period years
0.996	4.286	0.622	2.78	2.641	4.29

What departure Δv is required, in the optimum circumstance, for aphelion rendezvous?

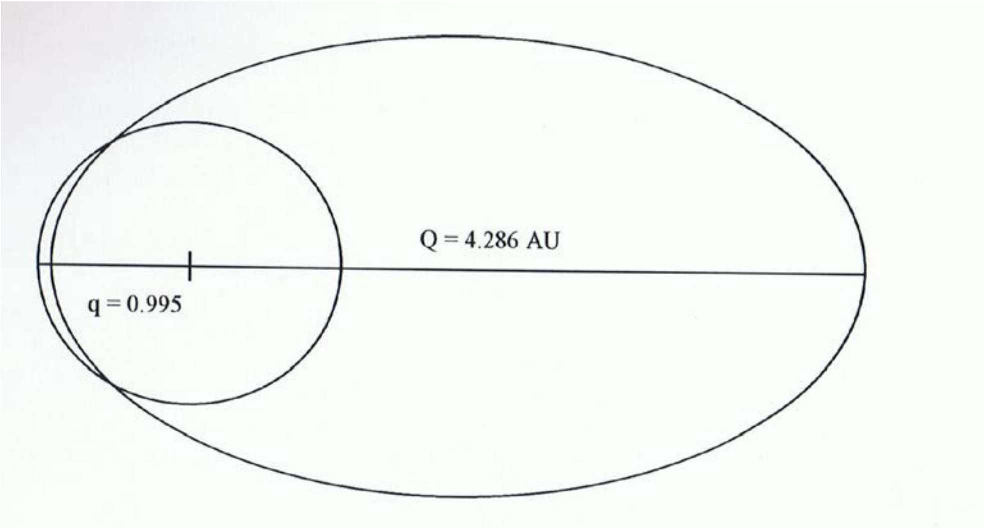


Figure 9.5 Wilson-Harrington orbit

We require to calculate $v_{\text{outbound, hyperbolic}}$ and $\Delta v_{\text{departure, leo}}$.

v_{earth} = 30 km/s

$$v_{\text{perihelion, transfer}} = \sqrt{\frac{GMs}{1.5\times10^{11}}\left[\frac{2(4.286/1)}{1+(4.286/1)}\right]}$$ from eqn (2)

$$= \sqrt{\frac{1.33\times10^{20}}{1.5\times10^{11}}\left[\frac{2\times4/286}{5.286}\right]}$$

= 37.92 km/s

so $v_{out, hyper}$ = 7.92 km/s

$$\Delta v_{depart, leo} = \sqrt{(11.2)^2 + (7.92)^2} - 8.0$$

$$= \sqrt{125.44 + 62.73} - 8.0$$

= 13.72 - 8.0

= 5.7 km/s

The return requirement:

Δv_{return} = $v_{aphelion, transfer}$ - $v_{aphelion, WH}$

$$v_{Q, transfer} = \sqrt{\frac{\mu}{Q_{tr}}\left[\frac{2}{1+(Q_{tr}/r_{earth})}\right]}$$

$$= \sqrt{\frac{1.33\times10^{20}}{4.286\times1.5\times10^{11}}\left[\frac{2}{1+4.286/1}\right]}$$

= 8.847 km/s

$$v_{Q, WH} = \sqrt{\frac{1.33\times10^{20}}{4.286\times1.5\times10^{11}}(1-0.622)}$$

= 8.843 km/s

∴ $\Delta v_{departure, return}$ = 0.004 km/s = 4 metres/second !!!

This departure Δv is TINY! - but the arrival v_∞ at earth orbit is approx 8km/sec!

What about perihelion passage mining?

This is not feasible because, although the Earth-departure Δv will be very small, the deep space rendezvous Δv will be approx 8 km/ s, and the departure Δv from the asteroid will also have to be approx 8 km/s. This assumes departure whilst still near perihelion, and this points to the requirement for a very short mining stay: (30-50 days max).

Therefore we assume an aphelion mining season, and as in the previous cases, assume a requirement for 1000 tonnes returned to Earth orbit, through a total Δv of about 8 km/s.

We need to calculate the total amount of volatiles that is to be collected.
The rocket equation gives

$$M_{start} = M_{finish} \times e^{\Delta v / v_e}$$

with $\Delta v = 8$ km/s, $v_e = 3.1$ km/s, and ; M_{finish} = 1000 tonnes,
then M_{start} = 13,000 tonnes

(This is not a problem in terms of tankage fraction - ref Zuppero, Whitman and Sykes, 1993 - but is a problem in as much as it sets a very demanding throughput requirement on the extraction plant).

If 13,000 tonnes is to be collected in maximum of 50 days, then that is 250 tonnes/day, or approx 3 kg/sec.

Heat energy needed to volatilize 3 kg H_2O per second (from perhaps -50 C) is

$$= [3000 \times 80 + 3000 \times 540 + 3000 \times 150] \text{ cal /sec}$$
$$= (3000 \times 770 \times 4.2) \text{ Watts}$$
$$= 10 \text{ MW}$$

A solar collector to provide 10 MW is outside present technical capability.
To merely melt H_2O, however, would only require - 1.5 MW.

A 1 MW solar collector was envisaged in example #1, processing regolith from 1989ML.

What is required area? Solar insolation at 1 AU =1.3 kW /m^2
So at 4 AU, solar insolation is about one-sixteenth, i.e., 80 W/m^2. Thus 1 MW will require 12500 m^2.

Thus, solar powered resource recovery from Wilson-Harrington appears impractical, with nuclear being the better (and longer-term) option.

9.6 Example #6 : Comet du Toit-Hartley Mission

Orbital parameters are:

Table 9.6 Orbital Parameters, p/DuToit-Hartley

Perihelion q (AU)	Aphelion Q (AU)	eccent e	inclination i (deg)	semi major axis a (QU)
1.201	4.814		2.9	2.99

Let us consider perihelion mining season:

Outbound velocity requirement:

$$v_{Perihelion,transfer} = \sqrt{\frac{1.33\times10^{20}}{1.5\times10^{11}}\left[\frac{2(1.2/1)}{1+(1.2/1)}\right]}$$

$$= 31.10 \text{ km/ sec}$$

so $v_{outbound,\ hyperbolic}$ = 1.10 km/sec

so $\Delta v_{depart,\ leo} = \sqrt{11.2^2 + 1.1^2} - 8.0$

$$= \sqrt{126.65} - 8.0 = 3.25 \text{ km/sec}$$

Deep Space Rendezvous Δv_{DS} is given by

$v_{perihelion,\ DT\text{-}H} - v_{aphelion,\ transfer}$

$$v_{aphelion,\ transfer} = \frac{31.10}{1.201} = 25.895 \text{ km/sec}$$

$v_{peri,\ DT\text{-}H} \quad = \quad \sqrt{\frac{\mu}{q}\left(1+e_{dTH}\right)}$

$= \quad \left[e \quad = \quad \frac{Q-q}{Q-q}\right]$

$= \quad \frac{4.814-1.201}{4.814+1.201} \quad = \quad \frac{3.613}{6.015} \quad = \quad 0.600$

$v_{peri,\ DTH} \quad = \quad 34.28$ km/sec

Hence $\Delta v_{DS} \quad = \quad v_{p,\ dTH} - v_{a,\ transfer}$ = 8.39 km/sec

This Δv is of course also what will be needed to leave du Toit-Hartley on Earth-return trajectory. This Δv_{DS} is actually less demanding than perihelion departure from Wilson-Harrington, because the perihelion is further out.

The Rocket Equation says this implies 15,000 tonnes start mass of volatiles to return 1000 tonnes.

The mass processing requirement is affected by the fact that the solar constant at 1.2 AU is only 0.7 of what it is at 1AU.

NPV will be assisted by the short mission time (essentially 1 year) but negatively impacted by the very demanding mass processing rate and the very high velocity changes required, both out and back.

9.7 Example #7 : p/Howell Mission

Comet Howell has q = 1.406 and Q = 4.882 AU

Due to its higher perihelion, it may be more favourable for a perihelion rendezvous than Wilson-Harrington or p/du Toit-Hartley.

We calculate $v_{outbound}$ as before:

$$v_{perihelion,transfer} = \sqrt{\frac{\mu}{q_t}\left[\frac{2(Q_t / q_t)}{1+(Q_t / q_t)}\right]}$$

$$= \sqrt{\frac{1.33\times 10^{20} \times 2\times 1.406}{1.5\times 10^{11} \times 2.406}}$$

$$= 32.19 \text{ km/s}$$

$$v_{Earth} = 30 \text{ km/s}$$

so $v_{hyperbolic}$ = 2.19 km/sec

and $\Delta v_{depart,\ leo} = \sqrt{125.44 + 4.796} - 8.0$

= 3.41 km/s

Now we calculate Δv_{DS} (Deep Space Rendezvous Δv)

$$v_{aphelion,\ transfer} = \frac{32.19}{1.406} = 22.89 \text{ km/s}$$

$$v_{perihelion,\ Howell} = \sqrt{\frac{\mu}{q_H}(1-e_H)}$$

$$e_{\text{Howell}} = \frac{4.882 - 1.406}{4.882 + 1.406} = \frac{3.476}{6.288} = 0.553$$

$$\text{thus } v_{\text{peri, Howell}} = \sqrt{\frac{1.33 \times 10^{20}}{1.406 \times 1.5 \times 10^{11}}(1.553)}$$

$$= 31.29 \text{ km/s}$$

$$\text{so } \Delta v_{DS} = 31.29 - 22.86 = \underline{8.43 \text{ km/sec}}$$

This will also be the departure Δv at the comet, at its perihelion, for Earth-transfer orbit injection into return trajectory.

9.8 Example #8: Hypothetical Arjuna:

(emphasising near-circular-orbit target, extended mining season,and near-continuous thrusting on return trajectory.)

Let us consider a hypothetical low-e Amor or Arjuna, with orbital parameters:

q = 1.1 AU Q = 1.4 AU e = 0.12 a = 1.25 AU i = 4 degs

$T = (1.25)^{1.5} = 1.4$ yrs.

Assume (say) 4 months outbound ballistic trajectory, with delta-v (deep space) supplied by chemical propulsion (because it has I_{sp} equal to steam rocket and is of adequate thrust). Launch is at ascending or descending node.

Assume (say) 9 months mining season centred about descending or ascending node. Time since launch will at end of mining season be about 13 months, and the asteroid will be some 90 degrees past descending /ascending. node.

Depart asteroid at this point for a 180 deg continuous thrust arc to return to Earth.

Total project duration is then approx 22 months.

All configurations seem to suggest less than or equal to 180 degrees return thrusting arc, centred on a node; and therefore less than or equal to 180 degrees mining season, centred on a node; and 90 to 180 degrees of outbound trajectory.

Note that thrusting duration and mining / processing duration are both now about 200 days; it is sensible to optimise these so as to require the same power input.

Delta-v requirement:

Inclination change requirement will dominate, at 0.5 km/s for each degree. For 4 deg, Δv = 2 km/s. From previously worked examples, ellipticity-matching Δv requirement may be another 1.5 km/s. We will assume 3.5 km/s.

If using long-period thrusting, we need to increase Δv capability of the propulsion system by factor of 1.5 to take into account the inefficiencies of non-instantaneous impulses (e.g. plane change not instantaneous at DN/AN). So a reasonable Δv requirement is 5.25 km/s.

The implied thrust requirement, to return 1000 tonnes of payload through this velocity interval in 200 days, is about 500 Newtons. The propellant useage will be about 5400 tonnes.

The implied mining rate (assuming 10% recovery of volatile from regolith) is 200 tonnes per day (or 8 tonnes per hour) suggesting a mining and processing equipment mass of 1 (one) tonne, from Chapter 6.

9.9 Conclusions: Summary of results of Example Calculations:

Arjunas are extremely accessible.

> All return transfer orbits with aphelia less than 1.25 AU deliver the payload to Earth with hyperbolic velocity less than 1.4 km/s and hence are amenable to capture by lunar flyby.

Atens are open to both perihelion and aphelion rendezvous missions.

Comet resource return missions with aphelion mining phase suffer very long mission times and inadequate solar power. Comet missions with perihelion mining phase need very large velocity changes to rendezvous and depart the object. NPV in these cases depend critically on the mass throughput ratio assumptions that one makes.

Mass-throughput requirements for positive NPV appear to be easily achieveable for the Arjunas and low-eccentricity Apollos and Amors.

The ice-drilling scenario appears very achieveable, provided the target bodies can be successfully identified.

Chapter 10: General Conclusions and Further Work.

10.1 General Findings

The findings of this study are as follows:

1. Some Near-Earth Asteroids offer very promising targets as future orebodies for in-space activities, 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.

   There has been a need expressed in the literature for a general methodology for determining the economics and feasibility of any proposed asteroid or comet mining project. This work addresses that need.

2. Asteroid geology is based on spectroscopic and photometric data for individual bodies, reflecting surface mineralogy and "weathering", and on inferred parallels with meteorites.

   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 characterized 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 Δv to inject into transfer orbit, plus the velocity change needed to rendezvous with the target. These values are complex time-varying functions, and the present thesis did not propose to address this in detail; nevertheless, “global minima” 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 has been 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-e, aphelion mining season (“Apollo-type”)
   - “Aten-type”
   - spiral low thrust (low-e Amor or “Arjuna type”)
   - high inclination, low eccentricity
   - high-e, perihelion mining season (“Comet-type”)

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

   Further work is needed on the mathematics of non-Hohmann (spiral) returns.

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.

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

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 $200/kg or so will be essential for space raw materials resources recovery to be viable 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 pro-forma, or ‘roadmap’ approach to project feasibility determination.

9. Reviews of examples, done on ‘general principles’ basis, give encouragement that cases do indeed exist that would prove economically feasible and make a profit whilst delivering resources to in-orbit purchasers.

10.2 Further Work: Identified Information and Technology Gaps

Tasks which have been identified in this thesis, which can be carried out at low cost, e.g. as Honours and Masters degrees projects, are:

(i) thermogravimetric quantitative studies on volatiles release, using asteroidal analogues (gypsum, clay, calcite, oil shale) and ultimately using carbonaceous chondrite material; to determine yield -temperature-time curves.

(ii) development of specific target and mission alternatives, using Hohmann trajectories, via SAIC's Trajectory Optimizer program.

(iii) Investigate the mathematics of non-Hohmann transfers.

(iv) pursue the spectral characterization of the Arjunas, as the most likely early targets.

(v) pursue neural net and fuzzy logic approaches to 'training' remotely operated machines to operate autonomously.

(vi) commence work on the conceptual mining and processing flowsheets discussed above.

In conclusion, this work provides a rigorous approach for performing Feasibility Studies on asteroid and comet mining ventures, and in addition shows how NPV can be used as a 'design-driver' and reality check in project concept selection and development. This work has identified the information gaps which need to be addressed in order to bring this concept into the realm of the immediately achievable.

Appendix 1 : Legal Regime for Asteroid Mining Tenure

Economic -Political -Legal Setting

Clearly, at some time in the next 20 years or so, there will arise serious moves to commence mining activities in space, almost certainly on the Moon, and perhaps on the moons of Mars, and/or various asteroids.

The rules for governing such activities should be developed now, so as to ensure both encouragement of Humanity's peaceful expansion into Space, and also to ensure a clear contractual statement of mutual rights and responsibilities of the space resources enterprise vis a vis the international community, ie for the mining enterprise, clarity of title.

These rules will almost certainly draw from various aspects of national mining codes, from concepts found in the international law of the sea, and from both formal and customary law applying to such activities as deepsea fishing, research in international waters, and Antarctic research. Also relevant is international law pertaining to offshore oil platforms, and deep sea mining(outside territorial EEZ).

The situation of increasing activities in space, by various, sometimes competing, sometimes co-operating, national, international, and corporate organizations, represents a market for raw and processed materials, and hence peculiar opportunities and risks, for a would-be space resources developer.

Although there is a developing body of "Space Law", there does not exist -yet- a mechanism for purchasing, establishing precedence, or lodging a claim over, an area of, say, the Moon, or over an asteroid. Indeed, at the moment, space is a legal interregnum; a "terra nullius", a land belonging to no-one. How would one protect against appropriation of one's physical assets (i.e., piracy)? Would there be royalties to pay, and if so, to whom? The U.N. treaty on the peaceful uses of outer space needs to be considered together with international customary law deriving from maritime and aviation practices. The international law applying to oil platforms beyond the 12-mile limit, to deep ocean fisheries, to possible future deep ocean mining, and to research bases on Arctic Ocean ice floes, and to Antarctica, would all be relevant.

There are environmental concerns which need to be addressed namely assurance that returning payloads do not impact Earth, or if they do, that they will disintegrate safely at altitude high enough that there will be no harm.

The considerable velocity changes required, and launch window constraints, suggest that physical intervention is virtually impossible, so neither piracy nor physical policing are at all likely..

Management flexibility of private corporations vis-a-vis governmental bodies, together with freedom from governmental budgetary process and policy variations, and less constrained terms of reference, suggest significant competitive advantage for the independent profit-oriented organization.

Legal regime for tenure of mining right.

The following is a review of papers by Jasentuliyana, Harrison Schmitt, Zubrin, and others with a view to indicating the likely final approach to international recognition of asteroid mining. There are parallels with the Law of the Sea, and the recent “Boat Paper” modifying the resources regime of the Law of the Sea is an important signal as to the possible future legal regime.

The initial L.O.S. requirements and proposals regarding deep seabed mining in international waters had been perceived by many in the developed nations (those which had had consortia investigating exploitation of deep seabed resources) and by their mining industry, as inimical to free market commercial enterprises.

The initial rules had been set up explicitly to transfer wealth to developing and underdeveloped countries, in pursuit of the “common heritage of mankind” principle, via a quasi-monopolistic “Enterprise”, the operating arm of the mooted International Seabed Authority, which was to be the regulating agency.

According to Reynolds, 1981, the 1980 draft text of Part XI of the LOS set out "in considerable detail the powers and functions of a supra-national mining authority which was unprecedented in its nature and implications. The mineral resources of the seabed beyond national jurisdiction are seen by the international community, as represented by the UN General Assembly, as the "common heritage of mankind". It is intended that they should be exploited in a way which provides net revenue to be shared principally amongst developing nations as a mechanism of income transfer from "north to south". The original concept whereby an international Enterprise would be the sole exploiter of these resources was abandoned in earlier stages of the LOS conference and superseded by the so-called "parallel system", whereby private or national entities and the Enterprise would share the development of the resources....."

This "parallel system" draft then proposed a series of requirements on prospective operating entities which were perceived to be commercially crippling:

- the Enterprise would be funded by States Parties to set up a minesite
- the Enterprise would freely appropriate its chosen 50% of any Area explored by any prospector or operator
- it would have access to finance from States Parties on interest free or concessional terms
- operating entities would be obligated to make technology available to the Enterprise on "fair and reasonable" terms
- entities would pay royalties to and share net revenues with the Authority

The requirement to cede 50% of every discovery to the Enterprise, together with the demand for technology transfer, and the essentially free funding, caused a rebellion among the then-existing private enterprise consortia. It was also noted, (Reynolds, 1982) that the following could be non-commercial motivations for a State to become active in deep seabed mining:

- for national prestige
- to capture resources lacking within its territorial area
- to access strategic metals
- to pre-empt access to an area by a rival State
- to establish a presence in an area

All of these reasons were seen as threatening the free marketeers, because they were prompts for state subsidization.

This relationship between the Seabed Authority and the Enterprise, and its proposed subsidies and special advantages, were seen by the free market miners as providing such an overwhelming commercial advantage to the Enterprise that they successfully lobbied their home nations to repudiate and refuse to sign the final L.O.S. Treaty, and instead mutually agreed to come to alternative arrangements, including unilateral national legislation, mutually recognised. This group comprised US, UK, Belgium, Italy, and West Germany. Over the dozen years since the L.O.S. Treaty was opened for signature, these and other nations have refrained from signing, and commercialization has failed to eventuate. Some time ago, the Secretary- General of the UN, perceiving that the unacceptability of the resources regime section, Section XI, was stalling international ratification of the Treaty, most of which was regarding such things as navigation, fisheries, the law on piracy, etc., and noting “the prolonged delay in commercial deep seabed mining”, instigated circuit-breaker talks to renew efforts for consensus. These resulted in the “Boat Paper”.

The “Boat Paper”, 1994, is an annex to the L.O.S. (officially the “Draft Resolution and Draft Agreement relating to Implementation of Part XI of the UN Convention on the Law of the Sea”) and modifies Part XI of LOS as follows:

- costs of the International Seabed Authority to be paid by the UN until commercial activities commence, thereafter to be met from assessed contributions by the member states (with restrictions on bureaucracy and budget)
- initially, the role of the Enterprise will be restricted to monitoring
- states no longer obligated to fund a minesite for the Enterprise
- a contractor who has contributed an Area to the Authority shall have after 15 yrs, first right of refusal
- there shall be no compulsory transfer of technology
- approvals of Plans of Work for exploration and for exploitation shall be procedurally clear and open to audit, and shall provide security of tenure under the conditions of the contract
- the Enterprise is constrained to follow commercial principles, and is prohibited from subsidization and dumping

This revised approach has won the acceptance of the US and other key States Parties, and resulted in the signing of the Treaty by the requisite 60 nations and its entry into operation on 16th November 1994 as international law.

The significance of this recent ratification of the LOS is that it is a step towards defining an acceptable regime for international regulation of mining activities in extra-territorial areas. The parties have been forced to take into consideration the commercial realities of requirement for security of tenure over a granted area, and enforceability of contracts, as a right of the operating entity; and the entity's right to proprietary control over its technology and data. The adjustments made in the Boat Paper could probably still be improved on, and the requirement that 50% of explored area, as chosen by the Enterprise, be ceded to the Enterprise, is still widely regarded as confiscatory. However, the LOS is clearly a precedent, albeit an imperfect one, for any regime that would be set up internationally to regulate asteroid mining.

It is possible of course to "go it alone", both in deep seabed mining and in asteroid mining. Regarding LOS, the US had clearly considered this path, going so far as to pass unilateral enabling legislation. But sooner or later, a corporation has to deliver the product to a market, and it would not want to have to worry about an embargo.

Jasentuliyana, the Director of the UN Office for Outer Space Affairs, has taken particular interest in the possible legal regimes and commercial structures for asteroid mining, and lists for comparison (Jasentuliyana, 1990):

- LOS deep seabed mining (position pre-Boat Paper)
- the Convention on the Regulation of Antarctic Mineral Resource Activities
- several successful international space operations activities and organizations, viz Intelsat and Inmarsat, and the international cooperation on the Giotto Mission.

In this review, Jasentuliyana hints that an "Intelsat-like" structure could most easily address the apparent legal impediments of the "common heritage" concept.

Harrison Schmitt proposed a similar Intelsat-like structure for "Interlune", his concept of an international consortium for mining the Moon for Helium-3. (Schmitt, 1992). In the above reference, he notes that Intelsat as a user-based and managed organization has developed because of a coincidence of available technology and obvious international need...and that it was an example of international cooperation not only technically successful but also utilitarian and profitable (returning some 15% p.a. to its investor states).

According to Schmitt, the Interlune concept was specifically designed to address the intents of the Outer Space Treaty and the Moon Agreement, as a monopoly international organization governed by representatives of national, user, and investor parties. However, in conversation, Schmitt now downplays the likelihood of Interlune succeeding in its original form, and suggests “a private initiative may now be more appropriate” (Schmitt, pers. comm, 1995).

Legal Basis of Claims

The various approaches to exploitation of terrestrial ore bodies are worth looking at: by the process of claim, or by application for mining lease, land which is held to be public domain, or belonging to the Crown, or the “res publica”, i.e., “common heritage” property, is made available, on payment of royalties and on acceptance of jurisdiction and perhaps special operating conditions, for exploitation by the claimant / lease-holder / concession-holder. Note however that there are cases of miners rejecting or disputing the claim of the Crown to have jurisdiction, especially when the Crown is perceived to have done nothing to assist in either the development, or the adequate and fair administration of the resource. An Australian example is the Eureka Stockade rebellion of the goldminers of Ballarat, Victoria, in 1854.

Different nations have a variety of approaches to the allocation of mining claims, leases, or tenements, and a variety of approaches to taxation, e.g. by royalty, fees, etc.. Operations can work claims directly as a contractor to the crown or republic, e.g., on a cost-plus basis, or on purely commercial terms as an assigned operator (or concession-holder).

Marks, 1993, reviews the legal precedents available and arrives at a “consensual” model, drawing on the self-regulatory regimes set up by the miners of the Californian goldrush, who were in a legal inter-regnum, being theoretically trespassers on US government lands, but in fact beyond the reach of US effective law. "..The most workable near-term system should probably not be rooted in new and prospective law-making, but in....negotiated rule making created by the miners themselves." These rules, once tested and settled, then subsequently become the basis for formal codification.

"Pending development of an explicit tenure and title system, the better model is one of consensual regulation by the miners themselves..." Marks then lists the basic rules the '49ers' of the Californian goldfields evolved: (i) claim ownership based on priority of possession; and (ii) the right to hold and work the claim based on actual possession and proper marking of boundaries.

In all of the above, the ownership of the land was not deemed to have passed from the state, but only the priority to work the deposit under the rules of the state.

Marks suggests that "priority of possession" in space mining might be derived from "tele-robotic possession", and notes that this concept, i.e., occupation via an active robotic agent, has gained some legal standing in at least one court battle over the rights to recovered sunken treasure.

Marks further notes in passing, "compare the contemplated situation in space: no sovereign effectively able or entitled to exercise jurisdiction or practical control over the miners". This situation may be good because it creates the necessary opportunity to devise a similar miner-to-miner (self-regulatory) system, before "rampant legislating begins".

In "Access to a Res Publica Internationalis: the case of the Geostationary Orbit", Weissner (1986?), in discussing GEO 'slots', a limited resource, describes the Justinian Code of ancient Rome, which is relevant to interpretation of the term "common heritage of mankind". The Justinian Code classified things into *res in patrimonio*, things under exclusive individual control, *res publica*, the common property of the state, e.g., roads, viaducts, ports..., *res communis,* that open to everyone, and *res nullius,* things owned by no-one (and hence subject to appropriation by occupation and use). Weissner identifies the case of GEO slots as equivalent to *res publica* and, in passing, identifies the high seas as *res communis***.** He also considers, and dismisses, the idea of an International Orbit Authority, in analogy with the LOS's International Seabed Authority.

McCandless & Garver (1989) identify "res communis" as identical with the "common heritage of mankind" concept. They also propose, as a regime that would fulfil quite clearly the "common heritage" principles, a Lunar Resources Authority, the purpose of which would be to regulate resources utilization on the Moon.

In contrast, Goldman (1984) reiterates the US treaty negotiators' assertions that "use" of space resources is specifically allowed by the Outer Space Treaty, and that this therefore includes the right to extract resources. This is interpreted to be in conformity with the "common heritage" provisions by virtue of claiming that whilst resources "in place" are the property of humanity at large, resources recovered or reclaimed become the property of the miner, by the allocation of his labour and skills; if this interpretation is to be meaningful, the developer must surrender some freedoms, e.g. (i) accept jurisdiction; (ii) make available some part of the product on fair market terms.

Dunstan, 1987, says: "It is predicted .... (that) the self-interests of space faring nations, as well as the beginning of private uses of outer space, will result in a continued shift from regulation of space activities by international treaty to regulation by private contract and bilateral agreement, but that eventually, international mechanisms for dispute resolution will be required ..."

<u>Possible UN Office of Outer Space Affairs approach:</u>

An approach that the UN Office of Outer Space Affairs could take on the allocation and regulation of rights to recovery of extraterrestrial resources is as follows.

1. It is accepted that the expansion of human activity into outer space is desirable, for reasons of
   (i) humanity's long-term supply of energy and materials for a prosperous and healthy life for all (e.g., energy from Satellite Solar Power Stations or from Helium-3).

(ii) philosophically, the establishment of an open frontier in space replaces the zero-sum game competition over boundaries and resources on Earth.

(iii) humanity's long-term immunity from any planet threatening catastrophe, e.g., comet impact-induced "nuclear winter".

(iv) philosophically, the urge to spread life throughout the solar system, to continue the creative work of God.

These aims will be met when large space cities are developed, such as those described by G. K.O'Neill and earlier by Dandridge Cole.

2. It is generally agreed that the capital for such major activities can only come from commercial entities, which survive by delivering valuable goods or services at an acceptable price to willing corporate or governmental purchasers. The primary reason why commercial enterprises represent the only viable source of capital is because financial disciplines and social responsibilities now preclude governments from major projects.

3. It is now accepted that at least conceptually, there are several "space resource recovery" possibilities:
   - lunar or Uranian Helium-3 for fusion power
   - water ice from permanently shadowed craters at the lunar poles
   - NiFe metal from certain asteroids, with Platinum Group Metals as a byproduct
   - volatiles from certain asteroids and short-period comets
   - water ice from depth below the regoliths of Phobos or Deimos

4. The recovery of such material would provide a "social good" inasmuch as it would leverage and advance humanity's capability to expand into outer space and ultimately colonise it, and thus is to be supported.

5. In order to provide for the encouragement of commercial entities' investment of capital, it is accepted that a mechanism must be put in place by which "rights", "claims", or "leases" over non-terrestrial removable resources can be created, universally recognised, regulated, worked, and traded, with certainty of title.

6. Such a right, claim, lease, or title is taken to represent a contract between the recipient commercial entity intending to recover and use or sell the resource material, and the regulatory agency, acting on behalf of humanity infurtherance of the goals mentioned above in (1), with the sanction of the UN and the agreement of the spacefaring nations, as the only parties capable of intervening.

7. The contract might agree, for example, the following:

- that the regulatory agency will, on the appropriate authority, universally recognised, grant to the entity (with reasonable attached conditions) a right to mine a defined property.

- that such a created right becomes a valuable property in and of itself.

- that materials recovered from such a lease or claim become, upon collection or separation from the regolith or matrix of the body to which the lease applies, the legal property of the operating entity, and as such can be legally bought and sold.

- in return for the grant of these potential commercial benefits, society requires general recognition of the created titles.

- the entity must "work" the lease or claim within a reasonable predetermined timeframe, or forfeit the lease (e.g., detailed astronomical studies to commence within one year, launch of either prospector probe or resource recovery operation within six years).

- the entity must supply information of the following type in support of applications for leases: identity of body, orbital elements, nonbinding letters of intent to purchase products from prospective customers or of intent to supply finance from partners investors or bankers.

- the issue of leases should be on a “first come, first served” basis, so as to avoid “second-guessing” the ability of small applicants to put together the required technical and financial capability, and to avoid the major operators tying up all prospective bodies.
- leases may be “bid for” by entity making an offer of royalty rate, such royalty to be paid by delivery into regulatory agency ownership in earth-orbit of the agreed percentage of product.

- the entity must make some set minimum percentage of its production available on the open market (so as to fulfill the “common good” test).

- the life of the lease should be long enough to encourage permanent occupation, either human or tele-presence, and to enable later sale of a lease over a body which has already proven profitable, and should be renewable on terms favourable to the initial venturer.

- claims for bodies of major dimensions less than (say) 25 km diameter will only be issued to cover the entire body. This is necessary so as to avoid unpoliceable boundary disputes. Claims over larger bodies will be issued to cover areas of maximum extent of (say) 1500 square km..

- the regulator will have responsibility to review the Earth-orbit-capture mechanism proposed and to set minimum safety parameters for control of risk of impact.

- it must be recognised that non-regulated mining can not be readily banned, because physical policing at the resource site will be almost impossible, due to delta-v and synodic phasing considerations (except for the case of the Moon). Thus the regime for regulation must be such that the benefits of compliance must be seen to outweigh the possible advantages of non-compliance, for the venturer.

Appendix 2: Economics of Launcher Systems

The present cost of launch to LEO is approx $10,000 to $15,000 per kilogram (Stuart & Gleave, 1991).

By far the cheapest launcher at the moment is the Russian Proton, quoted to cost $60 million, with a payload into LEO of a little less than 20 tonnes; this is roughly $3000 per kilogram.

The probable launch costs of new small expendable launchers was reviewed by NASA and they found that "dedicated small launcher costs show no signs of dropping below the $5,000,000 per launch threshold considered vital for energetic growth in the small commercial payload market" (quoted in Ad Astra, Jan 1993, p 16). The Orbital Sciences Corp Pegasus launcher costs $30,000/kg.

The only possible viable expendables are those exhibiting extreme simplicity, such as Hudson's "Liberty" (no longer being actively advanced), simple solids or hybrids, which might deliver under $1,000/kg in quantity production, and an upgrade of the Proton.

Many writers have identified that reusable launchers, operated with airline-like maintenance regimes, flight frequencies, and ground support, will be necessary to bring about major cost reduction.

The extent of cost reduction achievable with total reuseability is addressed by Griffin and Claybaugh in JBIS 47 pp119-122 in which they produce a general parametric cost model. See below for details of this model. For a vehicle such as Hotol, at a flight frequency of 20 per year, the model predicts $600/kg. For a less pessimistic flight frequency, of 140 per year, equating roughly to a payload of 1000 tonnes to orbit per year, the cost will obviously be lower.

However, Parkinson, in Spaceflight 32, pp 248-249, and 36 , pp 400-403, looks at total system lifetime cost for Hotol, and reports that the cost including system development is approx $5,000/kg, and that the recurring (operating) cost is approx $1,400/kg, both assuming 20 flights per year and system lifetime of 20 years. This flight frequency however is certainly below that which would represent either full utilization of the vehicle or a breakout into space industrialization, and would appear very pessimistic for a totally reusable vehicle, given that extra flights will spread the development cost thinner.

What is the Demand Elasticity? -i.e., to what extent will the market demand for launch services expand in response to a reduction in “airfreight” charges? We do not know. It may be that mobile phone systems may provide the market to expand from 20 to 40 or more flights per year.

We do have good indications however, that the threshold for space tourism is at about \$500/kg, giving a ticket price to LEO of \$50,000. This has been found in various market surveys, and in addition, the market becomes very large as the price falls below \$50,000 per ticket (P. Collins pers comm).

Launcher Cost Model

A cost model is presented in Griffin and Claybaugh, which can be used to predict lower-bound space launch costs:

Cost Model

Total cost of launch = cost of expended hardware + cost of propellant + cost of launch site operations incl refurbishment

$$C_T = C_H + C_P + C_O$$

cost per kg is c_T $= \dfrac{C_H + C_P + C_O}{M_{PL}}$

$C_H = c_H \, mf \, M_S$ $= c_H \, mf \, R \, M_{PL}$	where mf is mass fraction of vehicle expended and Ms is vehicle structural mass (including avionics), and where $R = \dfrac{M_S}{M_{PL}}$

$C_P = c_P M_P = c_P P M_{PL}$	where $P = \frac{M_P}{M_{PL}}$
$C_O = c_L L R M_{PL}$	where c_L = hourly cost of labour hours per flight per kg dry mass of vehicle

(and $R = \frac{M_S}{M_{PL}}$ (as before))

Thus $c_T = \frac{C_H + C_P + C_O}{M_{PL}}$

now becomes

$c_T = c_H\, mf\, R + c_P P + c_L L R$ where mf is fraction of hardware expended;

$$R = \frac{M_S}{M_{PL}} \quad ; \quad P = \frac{M_P}{M_{PL}} \quad ; \quad L = \text{labour hours/flight/kg}$$

Note that amortization of vehicle fleet can be treated by putting mf < 1 for reusable vehicles, to take into account their replacement.

"it should be noted in passing that a vehicle that can be considered fully reusable in a practical sense ... must be regarded as being expended in fractional increments over its operational lifetime. Also, preservation of a fleet of vehicles must include some accounting for the cost of unreliability and subsequent replacement of a lost vehicle. Those effects can be included within the operations cost category, or by adjusting the expendable fraction, mf"

For expendables, mf = 1; P ranges from ~ 30 (for the Atlas rocket) to 50 for Delta and Titan IV; and R ranges from ~ 2 to ~ 6.

Other data quoted by Griffin and Claybaugh are:

c_H	-	rockets	-	\$20000/kg
		aircraft	-	\$1000 - 2000/kg
c_P	=	\$2/kg for Lox/LH_2 ; \$6/kg for storables		
c_L	=	\$60/hr		

This model was shown to correspond well with the known launch costs of present expendables.

Labour hours for the X-15 program (which was not optimized to minimize labour time requirement), was ~1.6 hours/flight/kg mass. Flight rate was 20/yr; for 20 yrs, with 3 vehicles. (Note: it is unclear whether maintenance cost of B-52 launch planes was taken into account.)

If similar labour efficiency could be attained with a reusable orbiter, the operations cost would be ~ \$600/kg.

The authors then conclude that total cost including propellant has a lower bound of ~ \$300/lb or \$800/kg.

However, if we use their same logic, and put in quoted values for Hotol (from RC Parkinson, Spaceflight, <u>32</u>: 248-249, and <u>36</u>: 400-403), we get:

$$c_T = c_H\, mf\, R + c_P\, P + c_L\, L\, R$$

$$\text{P for Hotol} = \frac{210}{7} = 30$$

$$\text{R for Hotol} = \frac{32}{7} = 4.5$$

$$= \quad \$20\,000 \times 0.001^* \times R + \$2 \times P;$$ **assumes lifetime = 1000 flights*

$$= \quad \$20 \times 4.5 + \$2 \times 30 + 30 \times 4.5$$

= \$285/kg

The hardware cost issue remains unclear here, but will be low, for an assumed lifecycle of 1000 flights, because at a specific hardware cost of \$20 000/kg (the cost of the shuttle), the hardware cost component.

= c_H mf R , is

= \$20 000 $\times$ 0.001 $\times$ R (say 4.5) = \$90/kg

This suggests a probable lower bound total cost of approx \$380/kg.

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Listings of Near Earth Asteroids:

The original thesis used tables imported from "Unusual Objects", a site on the World-Wide Web, address http://cfa-www.harvard.edu/graff/lists/Unusual.html.

It also identified as another major source of asteroid data, SOARD, the Steward Observatory Asteroid Relational Database, at the University of Arizona.

Lists of Near-Earth asteroids which have orbital plane inclinations less than 15 degrees were created from the above sources, these being the NEAs with least plane change Δv cost. The high-accessibility target bodies will be a subset within this group.

Estimates of minimum mission velocity were calculated via spreadsheet, for these listed targets, using the formulae of Shoemaker and Helin.

These listings are not included as they are out of date, but the reader is referred to the web pages found at **neo.jpl.nasa.gov**.

Internet Resources (as of 1998):

European Asteroid Research Node

http://129.247.214.46/

Planetary Data System Small Bodies Node:

http://pdssbn.astro.umd.edu

Planetary Sciences at the NSSDC:

http://nssdc.gsfc.nasa.gov/planetary/planetary_home.html

Lunar & Planetary Institute:

http://cass.jsc.nasa.gov/lpi.html

Asteroid & Comet Impact Hazard:

http://ccf.arc.nasa.gov/sst/

Known Near-Earth Asteroids:

http://ccf.arc.nasa.gov/sst/table_list.html

IAU: Minor Planet Center:

http://cfa-www.harvard.edu/~graff/mpc.html

Icarus Subject Index:

http://astrosun.tn.cornell.edu/Icarus/indices/

Steward Observatory Asteroid Relational Database:

http://dorothy.as.arizona.edu:8008/soard/

Spaceguard Foundation:

http://www.mi.astro.it/SGF/

Ted Bowell's page, Lowell Observatory:

http://www.lowell.edu/users/elgb/Welcome.html

PDS Home Page:

http://pds.jpl.nasa.gov/

Further Thoughts on Target Selection Rules:

1. Davis indicates lowest delta-v generally for targets having:

   $0.05 < e < 0.15$, and

   $0.9AU < a < 1.15AU$

2. For capture via single lunar flyby, we need:

   $q > 0.83AU$ and $a > 0.9AU$; or

   $Q < 1.25AU$ and $a < 1.25AU$

3. For minimal inclination change delta-v, we seek targets with $i < 5$ degrees (say).

4. We look for objects with Line of Apsides close to Ascending/Descending Node.