DECISION POINTS

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ABSTRACT

Exploitation of extraterrestrial mineral resources will follow practices in terrestrial mineral exploitation. In the various steps in exploration many decision points must be met and passed to undertake the next step toward development of the possible resource into a mine. For a resource to become a mine it must be able to show a profit. The decision points that follow must be met and passed successfully before going on to the next step along the road to discovery and development of a mineral deposit into a mine.

INTRODUCTION

At the present time, everything in LEO has the value of gold at $379.00/oz or $10,000.00/kg. If present published estimates are correct, this will decline in the future to about $37.90/oz or $1,000.00/kg by about the year 2010. The sooner water can be supplied to LEO from sources in space, the higher the selling price that can be obtained. One hundred tonnes of water ice at LEO in the year 2000 will have a value of roughly $1,000,000,000.00, and roughly $100,000,000.00 in the year 2010. The markets will be Mir, the Space Station and possibly a proposed orbiting hotel proposed by Japan for a tourist industry in this time frame. Propellant for raising satellites from LEO to GEO (Geosynchronous Earth Orbit) and for manned and unmanned missions to other NEOs is probably the largest potential market.

Water, the source and sustainer of life on Earth, is a very rare commodity in our solar system, while ice is plentiful. Sixty percent of the terrestrial fresh water is tied up as ice at the poles and in alpine glaciers. Our understanding of the role and behavior of ices (water, carbon dioxide, carbon monoxide, nitrogen, methane ices, etc.) will be of fundamental importance as humans move out from Earth.[D]

The large bulk of mass placed in orbit is low-technology materials, mainly propellant. These might be obtained from the Moon, nearby asteroids or Phobos and Deimos. From LEO, the outbound delta-V to some asteroids is as little as 4.5 km//sec (compared with 6 km/sec to land on the Moon). The real killer for the Moon is the fuel needed for the 3 km/sec take off delta-V. For some asteroids the return to LEO would only require 0.06 km/sec.[L1]

Availability of propellants on nearby bodies in space is of crucial importance.[L1]

Space is the driest of deserts! In a desert, no resource is of any value unless there is water, first for life support, and then to process the resource. With water everything is possible. Without water nothing is possible. Water is used for life support, propellants, chemical and mineralogical processing. We are mostly water.

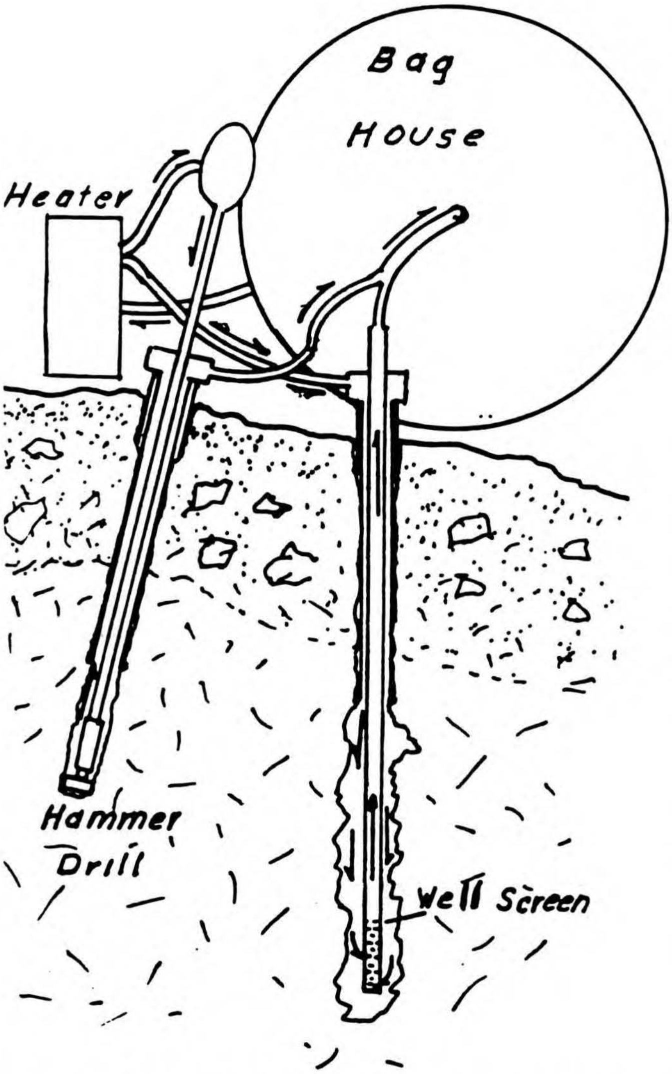

Figure 2. Drill rig proposed in "Exploitation of Space Oases" in 1995.[K]

To date, there are two NEOs that should have water ice at depth. One is comet Wilson-Harrington (1979 VA) with perihelion near the Earth's orbit. Rendezvous at perihelion will require a ΔVp = 11.4 km/sec or rendezvous at aphelion with a ΔVa = 6.8 km/sec in a 4.3 year orbit. At aphelion it is 4.3 AU from the sun and receives 1/16 the energy it would receive at perihelion. The high ΔV needed and the long time from launch to return eliminate Wilson-Harrington from consideration as an early source of water.

Deimos (the outer moon of Mars) is the other NEO that should have water ice at depth. It is accessible every two years.[L1] A comparison of NEOs and their ΔVs in km/sec follows.

	ΔV LEO to	Trip Time days	ΔV to LEO	Trip Time days
Lunar Base	6.2	3	3.2	3
Deimos	5.6	270	1.8	270
1982 XB	5.3	220	0.22	470
1982 HR	5.3	180	0.26	320
1980 AA	5.3	690	0.36	450
Anteros	5.27	390	0.39	290
Mars	4.8	270	5.7	270
1982 DB	4.5	210	0.06	480

ΔV for Transfers from LEO.[L1] The minimum velocity change (ΔV, in kilometers per second) and trip time in days required to reach each of these destinations to and from LEO is displayed for comparison. About 76,000 other asteroids larger than 100 meters are more accessible than the Moon. Phobos and Deimos, although not as easily reached as the best asteroids, are still more accessible than the Moon.[L1] Deimos is accessible every 26 months between launch opportunities.

Phobos has not been considered at this time because of the severe cracking due to the Stickney crater event. To drill for ices under these conditions would entail too great a risk of encountering cracks and loss of circulation of drilling fluid and any product.

Pre-Exploration: The first thing before money is spent on exploration is to eliminate as many questionable targets as possible. The first cut is to eliminate bodies with inclinations greater than 15°.
Next, eliminate those with long

periods, in this case those with periods greater than three years. Next, figure the periods of transfer orbits both at perihelion and at aphelion along with the combination of half periods. These should be some integer multiple of the Earth's period of one year.

Of the NEOs reported in 1996, fifteen objects survive the above cuts. There are 11 Apollos, 1996 AJ_1, 1996 AW_1, 1996 BG_1, 1996 BT, 1996 FG_3, 1996 FT_1, 1996 GF_{17}, 1996 MO, 1996 TD_9, 1996 TY_{11} and 1996 VB_3; one Arjuna, 1996 XB_{27}, and three Amors, 1996 AS_1, 1996 FO_3 and 1996 GT. The Amors are assigned a lower priority than the Apollos and Arjuna because of their longer periods and less intensive solar illumination. Because of their high solar illumination at perihelion, 1996 BT at 0.20 AU and 1996 AJ_1 at 0.29 AU, get very hot and 1996 TY_{11} gets hot at 0.57 AU. The closer to the sun the body travels, the more energy is available for drilling and processing as well as for propulsion. The other Apollos and the Arjuna all are warmer at perihelion than the Amors. About half of the Apollos selected have orbits with shorter periods than the Amors. Thus a table of priorities can be developed for further steps in the investigation.

Exploration: A choice of objects to investigate must be made. Resources are never available to investigate all possible targets. First, which objects offer the best possibilities of containing economically recoverable quantities of water ice.

Size: Objects less than 100 meters in diameter are unlikely to contain enough water ice to be worth exploiting. This eliminates some of the very small objects detected by Spacewatch. This eliminates bodies such as 1991 BA with a diameter of 8 meters, 1991 VG at 14 m, 1993 BD_3 with a diameter of about 20 meters,[C] 1993 KA_2 at 7 m,[S] 1994 GL at 80 m,[S] 1994 XM_1 at 10 m,[S] and some 30 other bodies of less than 50 meters diameter.[R]

Orbits: Any NEOs (Near-Earth Objects) to be considered must have proper synodic or phasing constraints on launch and return arrival times to be considered as targets. Launch opportunities are separated by long periods of time, making them one opportunity targets. This eliminates most as early opportunity targets.

Only those asteroids that are accessible by transfer orbits that have periods that are multiples of the earth's period can be considered. This applies to aphelion and perihelion rendezvous orbits.[S] A third type of orbit is a combination of one half of aphelion rendezvous, perihelion rendezvous and one half of the asteroids period, which would provide a long half period mining season. Any of these should still be limited to total periods that are integer multiples of the Earth's orbit, ie., 1,2,3 and later possibly 4 and 5 years. This further cuts from early consideration many of the objects larger than 100 meters.

Spectroscopy: NEOs that meet the above criteria must have the right composition to be considered as targets. First, this will require obtaining a visible light spectra. If this indicates the right composition, then infrared and ultraviolet spectra may be obtained to further define the composition.

High albedo very bright objects should be eliminated. Carbonaceous bodies all have low albedos. This means that most NEOs that are easily seen are of little interest at this stage of exploration, for they are unlikely to contain ices.

Combined water of hydration in minerals requires temperatures of near 1000°C for recovery, while water ice can be vaporized at temperatures below 0°C in the low pressures available in the vacuum of space. This eliminates many C-class asteroids which contain combined water. Unless the C-type body also contains water ice it is of no immediate interest. This focuses our attention to class P and D bodies which can contain ices without having combined water. Class D bodies are found in space near the orbit of Jupiter at 5 AU. Class P objects are located between the class C and class D objects at about 4 AU. Some class P objects show some water of hydration. Visible light spectra can distinguish the various types of bodies. This is the first actual exploration method to be applied to those bodies selected as possible targets. Spectra should cost about $2,500 each to obtain. Since large telescopes have their time committed to other programs, it will be necessary to schedule spectral observations ahead of time at times when the NEO is most visible.

If the NEO is a type P or D, infra-red and ultraviolet spectra should be obtained to further define the composition.
Again this requires careful scheduling.

Outgassing: For exploring for water ice in a body that has passed the above tests, outgassing would indicate volatiles at depth. outgassing might be detected by duplicating the Russian Phobos II's detection of a shock front cone for Deimos. A magnetometer might be passed through a possible shock front cone formed by the solar wind colliding with any outgasing. A solar sail might be used as the vehicle to carry the magnetometer.

If any outgassing can be detected telescopically, this should be attempted before spending for the magnetometer survey.

If outgassing is detected by one or both of these methods, the NEO should be included in the list of targets for sampling and possible water recovery testing.

Sampling: Two possible approaches for obtaining a sample for analysis are to land a penetrator to recover a sample for return to Earth and/or to send a wildcat miniature production drill to recover water and other volatiles for return to HEEO or LEO.[K] A penetrator might not be able to reach water ice which could be 20 to 100 or more meters below the surface as with Deimos.

If water and volatiles are not found in quantity by the wildcat miniature drill, a decision must be made whether to use the drilling fluid and such volatiles that are obtained for propellant to return to LEO or HEEO with the cuttings as a rock sample or to continue drilling in hope of producing enough volatiles to use as propellant. Propellant is used as drilling fluid and as a heat carrying lixivant to vaporize any interstitial ices. This is essentially a failure mode and salvage operation. If it can return the drill cuttings, they will give information on the composition of the body for the future as well as saleable specimens.

Exploitation: The decision to attempt commercial exploitation of any deposit is dependant on the many decisions made in the above steps having been correct and successful.

Table 2, is a projection of what might take place financially if a company is formed to exploit NEOs and Deimos for water. It proposes developing a robotic drill rig and vehicle for testing recovery of ices from NEOs and Deimos. The first launch is in the year 2000 to a NEO with return of 100 tonnes of ices and drill cuttings to HEEO or LEO. Although a launch date to Deimos occurs in April 1999, it is probably too soon to be ready to launch. Thus the first launch date for Deimos occurs in June 2001 with return late in September 2003. Three vehicles are proposed for this project. The launch costs will be high because of the heavier drill system and the extra propellant/drilling fluid. If everything works out right, the system breaks even in 2003. The value received for sale of product is on a straight line projection from 2000 to 2010. Thus the value received in 2006 is only $4,000/kg as opposed to the value in 2002 of $8,000/kg.

Once propellant is produced in LEO, the drill rig vehicles can be taken to LEO dry. Thus five vehicles can be taken to orbit in one launch. The use of product to fuel the system will save having to lift propellant to orbit. This happens in 2004. This projection uses nine of the original vehicles by 2007 with three vehicles remaining. This projection indicates a profit of nearly $4,400,000,000 by 2007.

Robotic: Robotic exploitation of the deposit is more risky than a manned exploitation. It has the advantage of requiring no life support and a smaller less expensive launch vehicle.

The drill proposed in "Exploitation of Space Oases" serves as a test of recovery of any ices at depth as well as possibly returning water ice to HEEO or LEO and about 100 kg of rock drill cuttings. These cuttings can give a sample for testing as well as a commodity for sale to collectors.

The mass of the drill rig, the heaviest part of the system is shown in table 1. The drilling equipment and materials gross less than 200 kg. Thus a total mass of the vehicle, drill and product bag should gross about 600 kg. For the Deimos drills the gross weight should be under one tonne. This leaves 4 tons for propellant/drill fluid for the Deimos systems and 2 tons for the NEO systems.

Larger more robust drilling systems can be designed and sent to bodies that test successfully with the small test drill. Development of the larger drill will depend on a market developing for more water than can be supplied by the test drills.

Manned: This requires the largest capital expense, but it has the capability for large scale exploitation of the resource. This should only be undertaken if robotic test exploitation is successful in recovering and returning a cargo of water ice to HEEO or LEO. The robotic exploitation is essentially a test of whether recoverable water ice is present.

Markets: All commodities lose real value with time. All material in LEO has the value of $10,000/kg or gold at $379/oz at the present, which will probably continue through the year 2000. By the year 2010 the value will probably be somewhere near $1,000/kg or $37.9/oz. By the year 2020, this will probably decline to about $500/kg or less. Thus, early exploitation will take advantage of a high priced market which can finance the development of a mining industry that can support mankind's expansion into space.

Initially, the market will be very small, limited to the small scale operations of Mir and the Space Station. Hopefully, the market will grow so that more robust exploitation efforts can be justified. The drilling rig and recovery system proposed in 1995 by the author should be adequate for a feasibility test.(K)

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S The Spacewatch Report

		Down The Hole Hammer Drill						
						Titanium drill pipe & accessories		
		L	OD	ID	Weight	Number	Weight	Ti
		mm	mm	mm	grams		grams	
Hammer	DTH	210	16		233	3	699	
Under-reamer Guide		78	20		49.4	3	148.2	*
		117	30		67.1	3	201.3	*
Under-reamer		15	27		20	10	200	
		20	37		36.5	10	365	
Casing Shoe		21	24		16	10	160	
		26	35		29	10	290	
Tubing		2000	16	14	425	325	138125	*
Casing		2000	22	20	595	100	59500	*
		2000	32	30	1299	60	77940	*
Collar pipes		1000	43	40	1374	10	13740	*
Total							291368.5	

Table 1. Mass of Drill and equipment for the drill presented in "Exploitation of Space Oases" presented at Princeton May 1995. The total mass is in grams. The drill pipe is titanium for lightness and chemical resistance to corrosion.

Proposed cash flow			12 Initial Vehicles								
	Year		·	1998	1999	2000	2001	2002	2003	2004	2005
Development & Construction							" 3		" 2		
	Drill & Vehicle		"@ 12,508,333				37,525,000		25,016,667		
Launches	"@ $70,000,000										
	Phobos/Deimos		SeaLaunch				210,000,000		140,000,000		
Launches @ $60,000,000			Proton								
General Expense		Estimate		10,000,000	10,000,000	10,000,000	10,000,000	10,000,000	10,000,000	10,000,000	10,000,000
External tank to Mir									10,000,000	10,000,000	
Totals				10,000,000	10,000,000	10,000,000	257,525,000	10,000,000	185,016,667	20,000,000	10,000,000
Interest @ 20%					2,000,000	4,400,000	7,280,000	60,241,000	74,289,000	128,150,333	155,780,400
Grand Total				10,000,000	22,000,000	36,400,000	301,205,000	371,446,000	630,751,667	778,902,000	944,682,400
"Product Sales											
	100 tonnes		Deimos/Phobos		"@ $8,000/kg				800,000,000		
	200 tonnes		Deimos/Phobos		"@ $6,000/kg						1,200,000,000
Total Gross Income Estimate									800,000,000		1,200,000,000
Net profit											
accumulated Net Profit									169,248,333		1,055,317,600

Table 2. Hypothetical cash flow for the project using the drill rig vehicle presented in "Exploitation of Space Oases" at Princeton in 1995. This uses nine of the original twelve drill rig vehicles.