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Defining a successful commercial asteroid mining program ☆

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ABSTRACT

This paper summarizes a commercial Asteroid Mining Architecture synthesized by the Senior Space Design Class at the University of Washington in Winter/Spring Quarters of 2013. The main author was the instructor for that class. These results use design-to-cost development methods and focused infrastructure advancements to identify and characterize a workable space industrialization architecture including space transportation elements, asteroid exploration and mining equipment, and the earth orbit infrastructure needed to make it all work. Cost analysis predicts that for an initial investment in time and money equivalent to that for the US North Slope Oil Field, the yearly world supply of Platinum Group Metals could be increased by 50%, roughly 1500 t of LOX/LH2 propellant/year would be available in LEO, and very low cost solar panels could be assembled at GEO using asteroidal materials. The investment also would have a discounted net present value return on investment of 22% over twenty years.

1. Introduction

Continued growth in world's Gross Domestic Product (GDP) depends on continued growth in affordable energy and technology development. Both are endangered by depletion of fossil fuels and the so-called technology metals used in fuel cells, advanced batteries, computer chips, flat screens, electric motors, and photovoltaic cells. The world will never completely run out of these metals, but the best ores are gone, and the cost continues to rise as the mining costs for poorer and poorer ores rises[1–3].

Currently fossil fuels account for 81% of the world's primary energy. We need affordable renewable sources of energy, but non-hydroelectric renewables provided only 2% of the world's energy consumption in 2010. The problem is cost and risk. Renewable energy cannot compete head to head with fossil fuels because many of the key technologies are either too expensive or unproven. They are too expensive because they rely on critical metals that are in short supply.

Our technology development is endangered for the same problem, i.e. the rising cost of key rare earth elements in near future. Computer chips and flat screens need trace amounts of various scarce elements and reserves of these elements are in such short supply that costs have been doubling every year. Many of the critical metals required were deposited on the Earth's crust by meteor impacts after the crust cooled, so the supply is limited. These elements are primarily: gold, cobalt, iron, manganese, molybdenum, nickel, osmium, palladium, platinum, rhenium, rhodium, ruthenium, and tungsten. Logic says that at some time in the future, space resources will

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become competitive with ground-based resources as non-renewable earth resources are depleted. The purpose of our study is to project how soon that might happen

To do that, we designed a space transportation architecture specifically aimed at putting mining equipment on selected near earth asteroids for the lowest Life Cycle Cost (LCC) possible. The major elements we analyzed were: the ETO system (both reusable and low cost expendable), the LEO Space Operations Center (SOC), where payloads are collected and redistributed, the earth-to-asteroids transportation system (both high-thrust and low-thrust two-way systems were considered), the asteroid payloads (mining equipment and habitats), and finally the mining product return element (a variety of robot re-entry capsules were analyzed). We are basing costs on the results of previous NASA-funded studies [4–8] and some commercially developed cost estimating tools [9]. Planetary Resources is a local company and they helped us with business insight and technical data.

The planning horizon is 25 years starting in about 2015, so the asteroid mines and habitats will be fully operational by 2040. The goals of this project were to trade major transportation elements to minimize both nonrecurring and recurring costs, i.e., LCC, and show that the full-up architecture can deliver critical metals to world manufacturers cheaper than the same metals produced from the depleted ores available on earth in 2040. The scenario we used assumed that the hypothetical World Space Council has agreed to provide ownership of individual asteroids and guaranteed loans to an industrial consortium to build and operate the transportation system and asteroid mining operation. Our goal was to reach a discounted ROI above 20%, so the hypothetical project could gain financing.

The initial robotic prospector spacecraft preliminary design and the conceptual architecture design and cost estimation was completed Winter Quarter and then detailed designs were generated for selected architectural elements. Our goal was to get close to a Preliminary Design Review (PDR) on three or four of the architectural elements by June 2013. The project used commercial rules, where possible, with emphasis on risk assessment and risk mitigation. All key technologies were at or near Technology Readiness Level (TRL) of TRL 6, and if a key technology is below TRL 6, then both a demonstration program and a backup technology development program were included in the nonrecurring costs. Likewise, element reliabilities were estimated and redundancies added to insure an acceptable loss rate, and that safety standards were met. The cost of the additional redundancy and the estimated loss rate went into the LCC.

2. Key elements

The overall space architecture is shown in Fig. 1. Elements of the space architecture are launched to Low Earth Orbit (LEO) from a dedicated launch site, retrieved on LEO by an Orbital Transfer Vehicle (OTV), and delivered to a Space Operations Center (SOC) in a high LEO chosen to above 99% of the space debris and also be nuclear safe. The SOC serves several functions. It is simultaneously a zero-gravity research center, a tourist destination, and a waypoint for space tugs departing and returning from deep space. Returning space tugs deliver large quantities of critical metals for earth, water for propellant for outgoing tugs, and other materials for space manufacturing of hardware to support further space industrialization.

After initial conceptual studies it was obvious that nuclear-powered tugs and nuclear surface power plants were essential to any asteroid mining operation. Hence, we contacted Idaho National Labs, who design, build, and test nuclear power plants for a living. We described what we needed and they provided a paper showing design options with costs. Our space tugs are called Reusable Nuclear-Electric Tugs (ReNETs) and are general-purpose cargo haulers utilizing a 3.5 MWe Brayton-cycle, nuclear-electric power plant based on previous NASA-funded studies [10].

These became our ReNET and surface power plant designs. They also pointed out the extended test times required to obtain a reliable, long-lived system, and hence the five years added before go-ahead. The ReNET cycle was based on a scaled up version of the Prometheus Single Loop 200 kWe design with a radiator operating at 400 K. The 3.5 MWe ReNET was sized to haul 150 mT of payload outbound and return with 250 mT of payload. Good average delta velocities for asteroid trips are 6.5 km/s outbound and 5.5 km/s inbound (from the HEO SOC). The ELF thrusters were design to operate on either argon or water and the in situ propellant option is what really saved the business case.

A key feature of ReNET is that it was designed to operate effectively on either argon or water (argon for initial missions departing Earth and water for future missions using asteroid supplied propellant). Another key feature is the Carbonaceous Asteroid Miner and Processor (CAMPr) that is transported to the target asteroid by ReNET where it mines both metallic and carbonaceous ores and separates out the critical metals and organics for further processing into PGMs, water, and other products use back at earth. A fission reactor Brayton-Cycle power plant almost identical to the ReNET power plant powers the CAMPrs. It also furnishes 3.5 MWe of bus bar power.

The schedule identified with the proposed architecture is shown in Fig. 2. Phase 1 is the development phase, lasting about five years, and is when the asteroid prospector spacecraft are developed and tested, and long lead items such as the nuclear power plant are prototyped and tested. Phase 2 lasts two years, and is when the prospectors are launched to the various NEAs and the earth orbit infrastructure is launched and tested.

If the prospectors find rich ore deposits on accessible NEAs during Phase 2, then the program go-ahead is given, and the major elements start final development. This includes the ReNET and the CAMPr, and if all out mining is indicated, the SSTO also. Depending of the scale of the operation selected, the CAMPrs are launched for three years, or up to eight years, and then the architecture switches to transporting to earth the metals and water harvested at the existing mines. Because of orbital mechanics some NEAs can only be visited periodically, so scheduling visits is a complicated process.

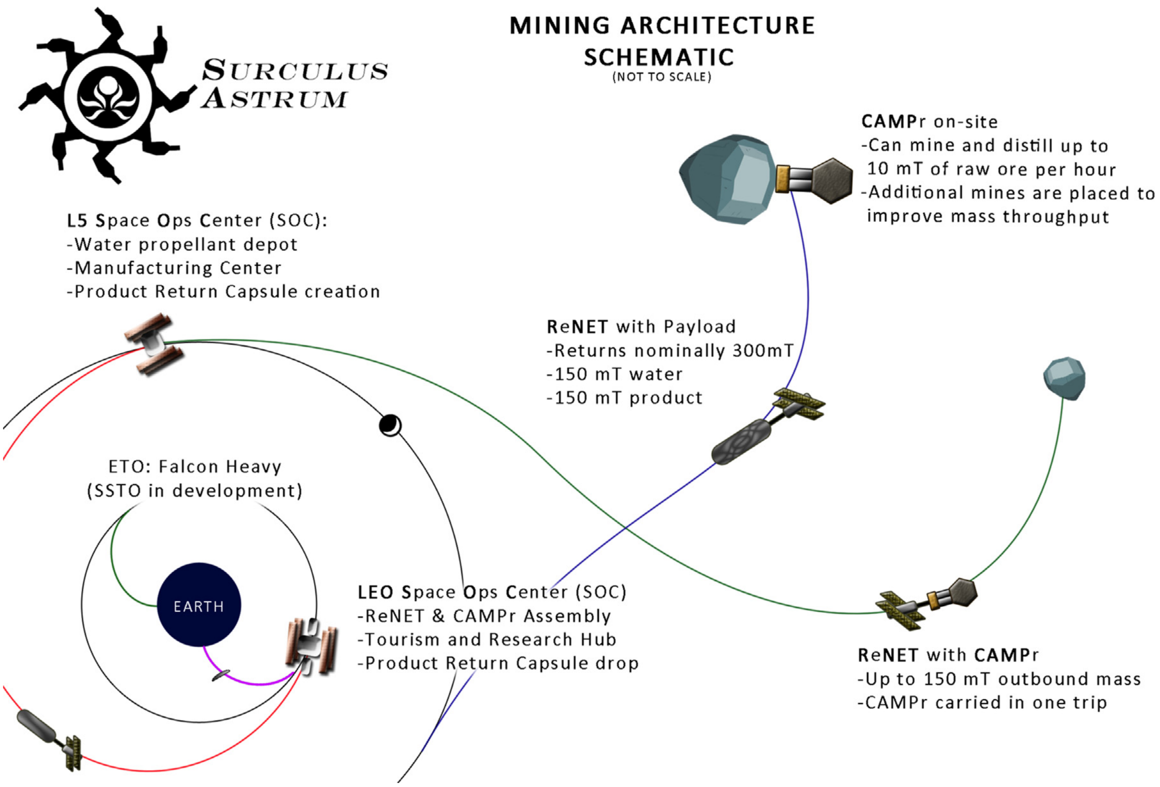

Fig. 1. Flowchart of celestial's overall mission architecture. Processing of multiple NEO's is supported in the design, maximizing profit for development.

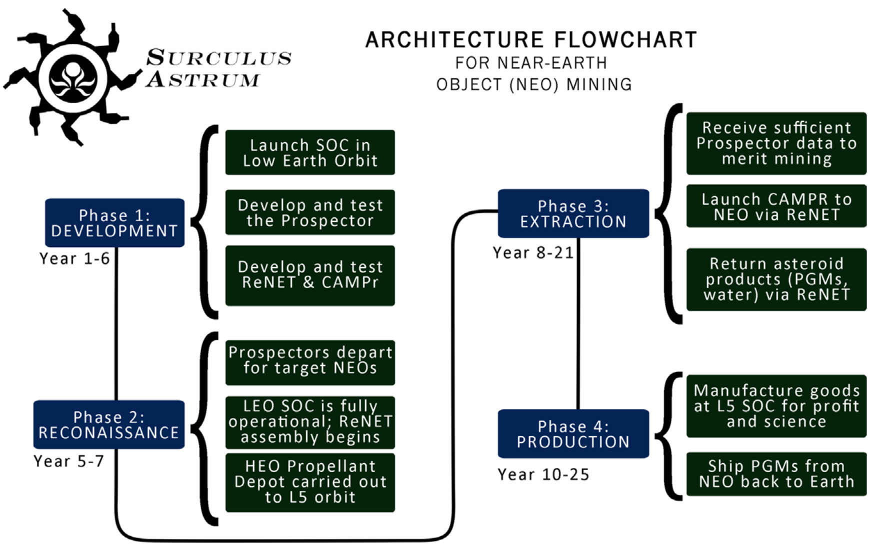

Fig. 2. Mining architecture flowchart.

2.1. *Asteroid prospectors*

The asteroid prospectors were small, only 200 kg, so they could be launched as shared payloads for a discount. The plan was to launch several on available GTO launches and then wait in orbit until the launch window opens for the asteroid of interest. The design in based on the 1999 Lunar Prospector with updates in avionics, power, and propulsion. Avionics were from modern cubesats, power was advanced (i.e. stirling cycle) RTGs using Cerium144 instead of the way more expensive Pu238, and the propulsion was Electrodeless Lorentz Force (ELF) thrusters developed by Professors in our department and in life testing under USAF contracts. The start of life power out of the ARTGs was 4 kWe, enough for trips to the NEAs of interest. Trajectories were simulated using the NASA-developed Copernicus Program. Fifteen

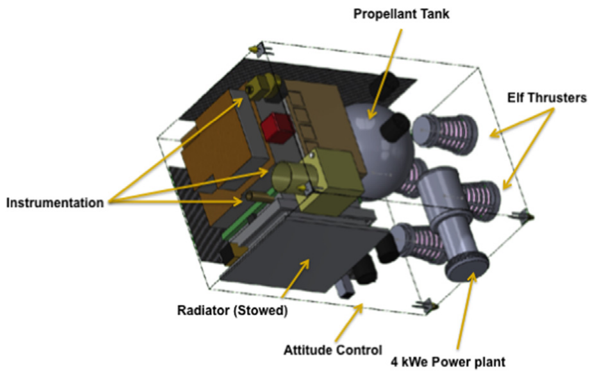

Fig. 3. Asteroid prospector.

prospectors were launched over a three year period (Fig. 14 is wrong on scheduling). A cutaway picture is shown in Fig. 3. Each prospector carries a Gamma Ray Spectrometer (to locate and measure the amount of hydrogen and iron atoms present), a Laser Interferometry Detection and Ranging (LIDAR) to create three-dimensional model of the NEA surface (to identify landing/mining sites), and a laser communications system to transmit the data back to a telescope at the L5 SOC. The prospector remains in orbit around the NEA after prospecting to serve as a relay for the CAMPrs as they move around on the NEAs surface.

2.2. Earth to orbit launch systems

Three different Earth to Orbit (ETO) Launch Systems were investigated. They were: Falcon Heavy, Partially Reusable Falcon Heavy, and/or a new Single Stage to Orbit (SSTO). Life Cycle Cost of the transportation system over the development and operations cycle is a major architecture discriminator, and Fig. 4 compares the LCC of each of the ETO options. As can be seen, the Partially Reusable Falcon Heavy has the lowest LCC if only 12 mines are developed (50 launches/year delivers approximately 5 mines per year), but if a major mining effort is desired (e.g. 37 mines deployed over eight years), then developing the SSTO pays for itself and provides major cost savings.

The SSTO proposed has numerous features to improve its economics. First, it uses existing SSME and AJ-26 rocket engines to minimize Design, Development, Test, & Evaluation (DDT&E) costs. Since, the SSME uses LOX/Hydrogen propellant and the AJ-26 LOX/RP-1 propellant it is obvious that our SSTO is a tri-propellant design, as shown in Fig. 5, and that reduces the propellant volume, and hence the SSTO empty weight, and development and unit costs. I managed to acquire a number of launch vehicle design tools during my long career and the students used them to good effect. The US would have an SSTO system operating right now, if NASA had chosen either the McDonnell Douglas or Rockwell Boeing X-33 designs instead of the Lockheed Martin design, which was flawed from the start. The SSTO shown has reasonable margins and has a very good chance of operating as advertised. The only new technology required is the inflatable heat shield (IRVE), and that is currently in test at NASA LaRC.

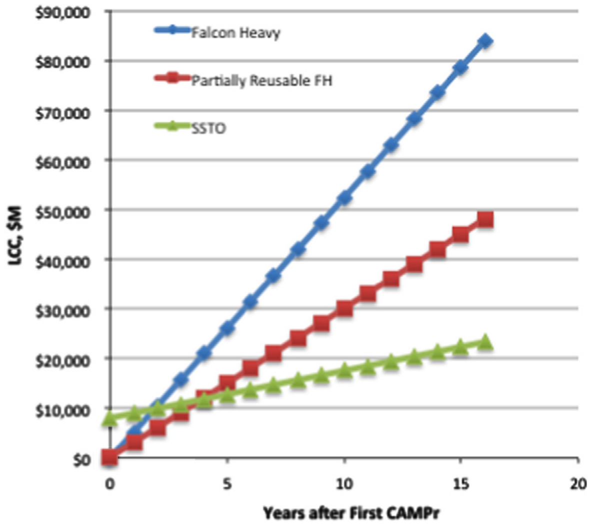

Fig. 4. Launch system LCC comparison.

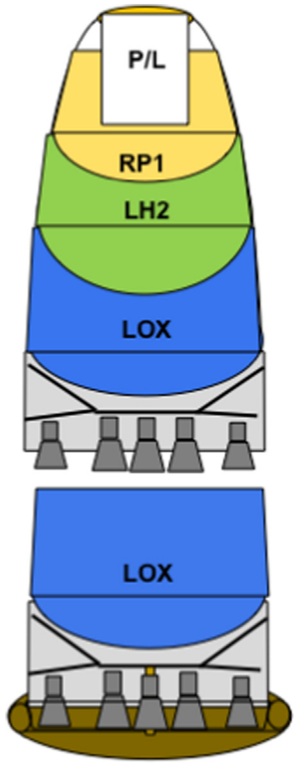

Fig. 5. SSTO architecture.

The operating costs for the SSTO are about $9.5 M per flight based of 50 launches per year. That includes propellants, consumables, insurance, technical support, and range costs (we have our own launch site on the southern tip of big island of Hawaii).

The five SSMEs and the 12 AJ-26s burn from liftoff to about Mach 4.5 where the AJ-26s shut down and the SSMEs extend their nozzles. Two of the SSMEs shut down about 415s into the 492s ascent burn to keep acceleration under 4 gravities.

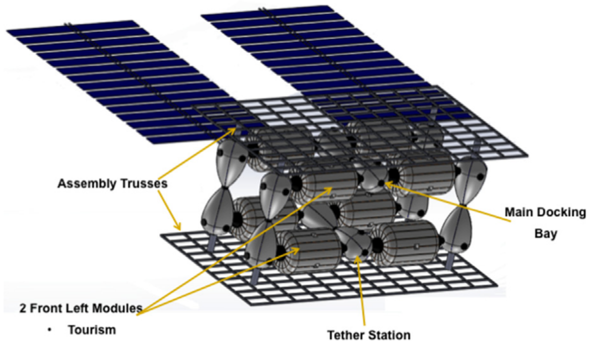

Fig. 6. LEO SOC configuration.

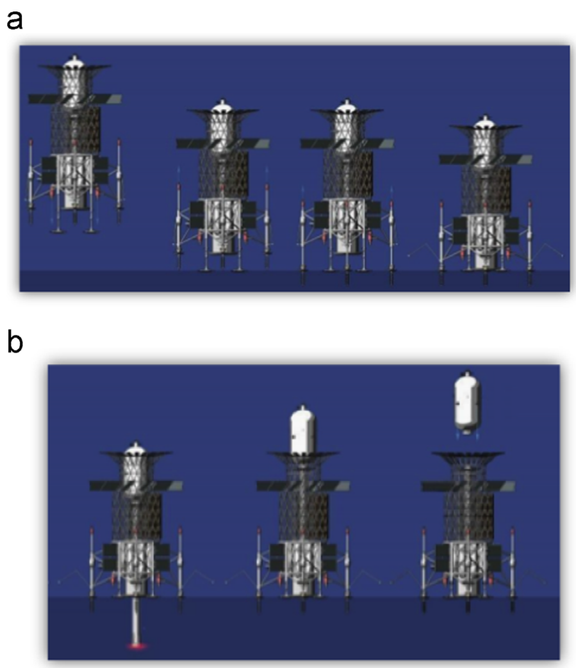

Fig. 7. (a) Miner module operations – setup and (b) miner module harvest and transport.

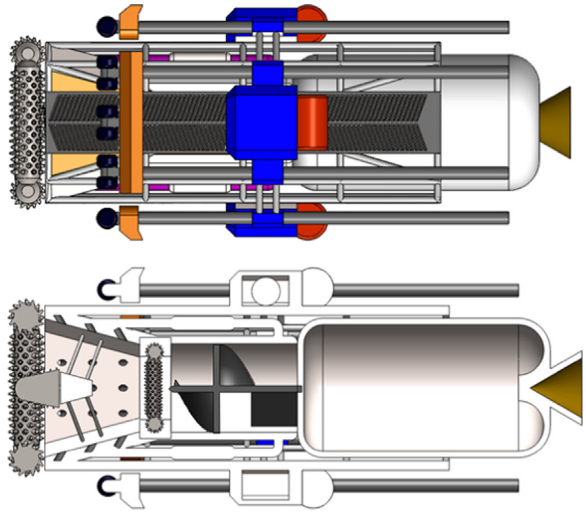

Fig. 8. Boring head for M-Type asteroid.

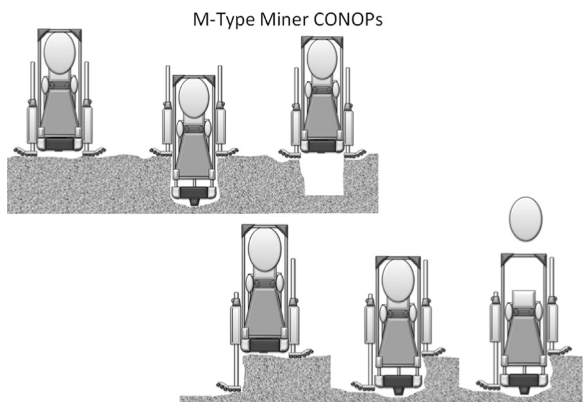

Fig. 9. M-Type Miner COJNOPs (side view).

The SSTO has a Gross Liftoff Weight (GLOW) of 3,931,000 lbm (1783 mT), a payload of 72,750 lbm (33 mT), and an empty weight of 288,000 lbm (130.6 mT). It is a Vertical Take Off, Vertical Landing (VTVL) configuration built almost entirely of advanced composites with a deployable, inflated base re-entry shield (see Fig. 4) made from flexible TPS materials similar to those used on IRVE [11]. This approach allows for both low cost and the extremely low dry weight.

2.3. Space operations centers

There will be two or three Space Operations Centers, one at 1000–1300 km altitude and one at high altitude (e.g. L5). There might also be an optional SOC at GEO if the market for space manufactured GEOSAT Platforms takes off. The LEO SOC is where outbound payloads are assembled and picked up by outbound ReNETs (hence the high altitude) to insure a nuclear safe orbit. This orbit is also above 99% of the space debris, simplifying operations. The SOC is both a storage and transfer station for payloads trans-shipped outbound, and a cash cow to generate profits prior to product return from the asteroids. I was a principal in the 1992 Commercial Space Transportation Study (CSTS) [12] where the six major Aerospace Companies in the US joined forces to do an in depth look at what space markets would open if the cost of launch to orbit was reduced from the then current \$5000 /lb to as low as \$200 /lb using a fully reusable launch system at high flight rates.

We interviewed hundreds of businesses and discovered a huge pent-up demand for zero-gee research space where proprietary techniques could be explored and utilized. This demand has never been satisfied because the ISS discourages proprietary research. Our SOC was designed to meet this demand and guarantee low launch costs by the high flight rates associated with mining. Bigelow is currently advertising a zero-gee work space for \$25 M for 60 days, and will probably get it. We were costing experiment lockers with support staff on orbit for \$100,000/month.

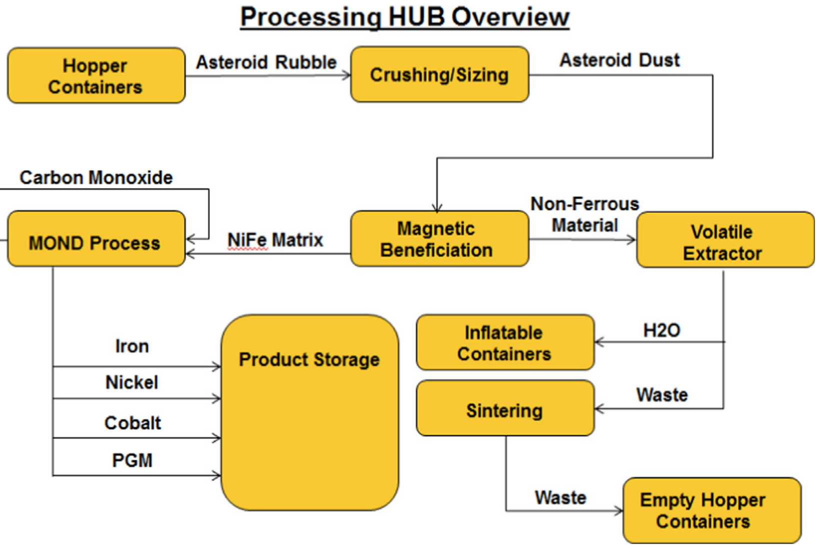

Fig. 10. CAMPr ore processing steps.

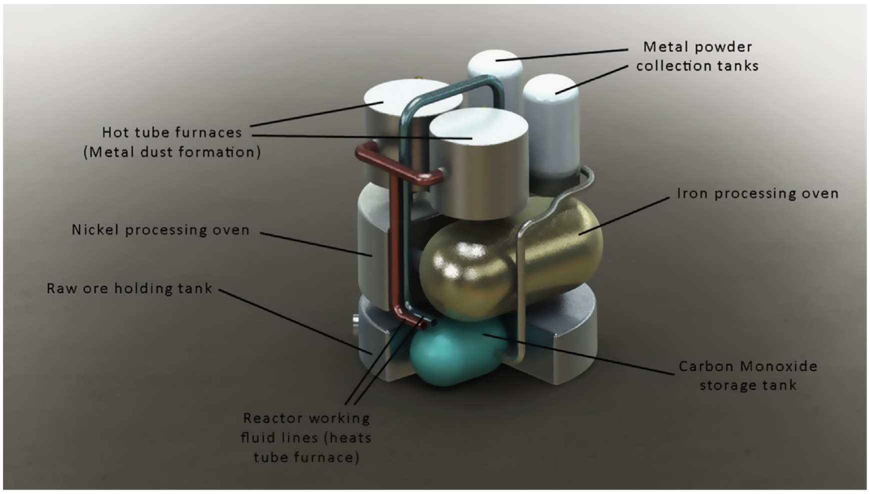

Fig. 11. Metal carbonyl reactor.

The SOC would hold about 48 racks, each with 8 lockers. Assuming a 20% vacancy rate, that is \$360 M per year. We assumed the tourist businesses would rent facility space from us, plus pay us for the launch, at a rate of \$4 M per person for a two week stay. Assuming an average of 16 persons on orbit, that's another \$1.66B per year. The SOC nominally operates in a 17 deg 1000 km orbit, but could go as high as 1300 km, which is at the lower limit of the inner belt during some solar conditions. The higher altitude was used for calculating launch performance.

The power for each SOC was 480 kWe. We looked at a Skyhook tether to increase the launch system efficiency, but a tether sized to haul 40 mT was too heavy to be economical. The tether was excellent if a smaller launch vehicle (10 mT payload) was chosen or a dedicated launch system for people was chosen. The SSTO drops off its payloads at 350 km where they are picked up by a reusable Orbital Maneuvering Vehicle (OMV), that is based at and refueled at the SOC. The OMV design has been completed many times and all components are TRL 5 or 6.

This SOC is also where saleable products are delivered for transport to earth, or for on-orbit propellant delivery. The high altitude SOC receives payloads from the outbound ReNETs cycling between the low altitude and high altitude SOCs, plus cargo from the deep space ReNETs cycling between the high altitude SOC and the NEAs. A typical ReNET arriving from a NEA is carrying 180 mT of water, 10 mT of PGMs, and 10 mT of other metals in powered form for manufacturing. Eighty of the 180 mT of water is kept at the high SOC for the return leg to the NEA and the other 100 mT is distributed between the SOCs for sale as propellants. If an SSTO is not in the program, water can be priced at \$1500 /kg and be competitive with earth-launched water. If the SSTO is available, the

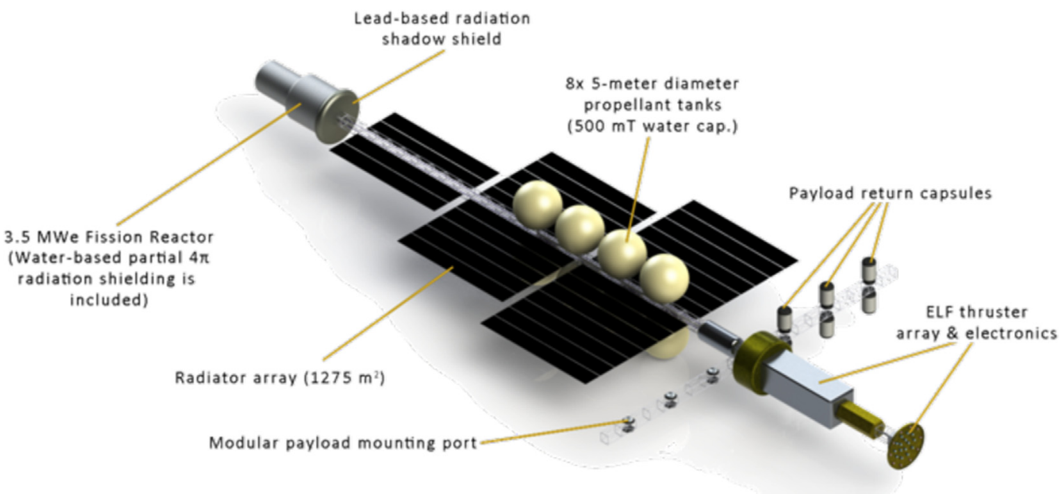

Fig. 12. ReNET tug configuration.

Fig. 13. Candidate asteroid orbits.

competitive price drops to $600 /kg. The proposed LEO SOC is shown looking up from Earth in Fig. 6.

2.4. Carbonaceous & metallic asteroid miners

The Carbonaceous Asteroid Mining & PRocessor (CAMPR) is actually a collection of elements that includes three miners with their free flying hoppers, a central processor and storage facility, and a nuclear power plant that is connected to the miners and processor with electric cables. A typical miner module is shown in operation in Fig. 7. The miner module lands on a predetermined site where ore has been detected and anchors itself to the surface using multiple helical anchors. It then lowers a helical boring tool to the surface and uses intense microwaves [13] to break up the frozen ore and transport it up to the hopper storage bin. Once the hopper is full, it flies to the processor and docks using its reaction control system (RCS). The RCS propellant is water and is resupplied by the processor each flight.

The miners shown in Figs. 7, 8 and 9 are first generation automated versions that simply land and drill. If the ore is not satisfactory, or if they run into a large boulder, they simply pick up and move to the next selected spot. The follow-on versions would be controlled by nearby humans and would have many more options for handling new situations. The miners would stay connected by cables to the power plant so their mobility is limited. The hoppers

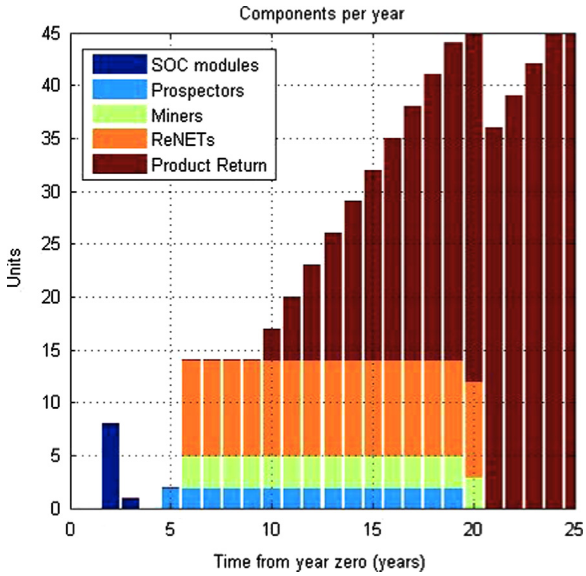

Fig. 14. Limited master build schedule (No SSTOs).

disengage when loaded and hop over to the processor where they dump their ore loads and recharge their propellant tanks.

The miner pictured above is specialised for Carbonaceous Chondrite type asteroids (rich in water but not necessarily metals). If we mine a metallic asteroid (type X & M) we need a multiple blade rotating cutter head instead of a helical boring tool. See Fig. 8.

This type of cutter head is similar to current designs for hard rock borers and can be repositioned to make multiple cuts side by side (i.e. strip mining). The Concept of Operations (CONOPS) for our M-Type Miner is shown in Fig. 9 below.

2.5. CAMPr processing unit

The CAMPr processing unit receives hoppers full of ore, which is usually a mixture of water ice, organics, rock (oxygenated silicon and metals), and native metals in the form of nickel-iron lumps. The major processing steps are shown in Fig. 10 below.

The processor shown in Fig. 10 crushes the ore down into sub-millimeter sized particles and separates the particles according to density and magnetism. The non-magnetic, less dense particles go into the volatiles extractor where they are heated to 700 C to extract the water, CO_2, N_2, CO, organics, etc. A small distillation plant separates the volatiles into inflatable containers brought from earth or storage tanks built on the spot using the carbonyls.

The dense and magnetic particles go into the MOND process, carbonyl reactor where the nickel and iron are gasified and turned into metal powders for future 3_D printing, or pipes, tanks, and heat exchangers using the chemical vapor dissociation (CVD) process. The residue left behind after the nickel and iron are gasified is a combination of cobalt, platinum group metals (PGMs), Rare Earth Elements, (REEs), sulfur, phosphorous, silicons, etc. This

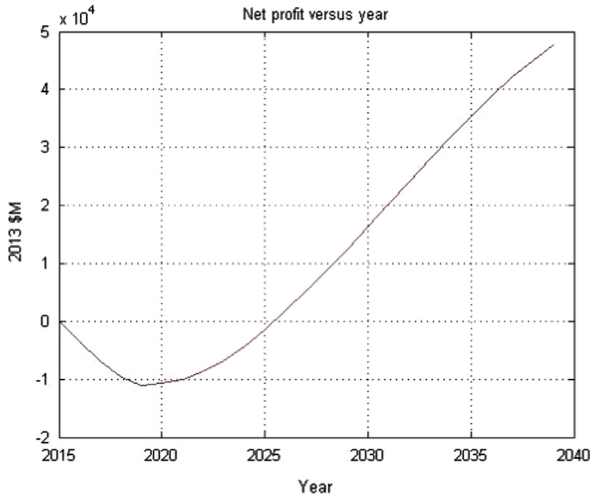

Fig. 15. Net present value contribution by year.

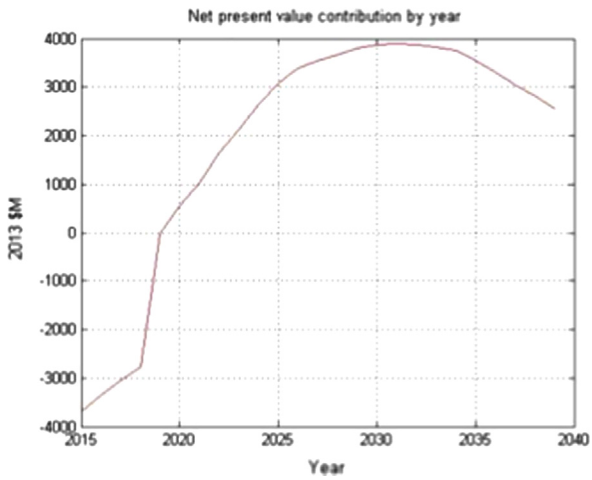

Fig. 16. Cumulative profit/losses for limited option.

reside is again subjected to density and magnetic separation with the magnetic portion, cobalt retained, and the dense portion, PGMs and the heavier REEs, shipped home as product. The lighter residue is retained on site for further future processing. The carbon monoxide required for the carbonyl process is recycled and also available from the volatiles processor. Note that multiple miners were sent to each of the larger asteroids, especially if the prospector had reported multiple deposits of rich ore.

Based on recent crusher installations we settled on a 3 MWe system that crushes 500,000 mT of rock per year. Assuming a C2 type asteroid with about 10% metal content, this yields roughly 50,000 mT of nickel-iron per year and about 50,000 mT per year of water and other volatiles from each mine. The mining portion of the activity has been simplified greatly to enable autonomous operation in this 1st generation architecture. After establishing initial operating capability we would expect a 2nd generation

Table 1
"All-up" architecture business case.

Years after go-ahead	−4	−3	−2	−1	0	1	2	3	4	5	6	7	3	9	10	11	12	13	14	15	16	17	18	19	20	LCC ($M)
NEO architecture/ prospector DDT&E ($M)	40	80	30																							150
Prospectors launched			6	6	3																					15
Prospector recurring cost ($M)			180	180	90																					450
Space business park DDT&E ($M)						50	100	200	120	50																520
Space business park recurring, SM									20	60	100	100	80	60	60	40	40	40	40	40	40	40	40	40	40	900
NEO & business park ELV launch costs ($M)										125	250	125	125	125	125	125										1000
Space business park profits ($M)													14	28	42	48	500	600	1200	1400	1600	1800	2000	2000	2000	13232
SSTO DDT&E ($M) (5 of 15 amortized)						120	300	500	500	300	100															1820
New launch base [Hawaii]						150	600	1000	400	80																2230
Number of SSTO launches												26	50	50	57	56	56	58	61	8	8	8	8	8	8	462
SSTTQs delivered/ year												1	1	l	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0	0	0	5
SSTO recurring costs (ave rest for l5= $580.62M)												574	574	574	144	144	144	144	144	144	144	144	0	0	0	2871.8
SSTO launch costs ($M)												248	477	477	544	534.2	534.2	553.3	582	76.32	76.32	76.32	76.32	76.32	76.32	4407.5
ReNET R&D costs ($M)		50	120	120	30																					320
ReNET DDT&E costs ($M)						50	300	700	1150	700	300	150														3350
ReNET delivered/ year												4	5	5	6	5	5	5	6	0	0	0	0	0	0	41
												4	9	14	20	25	30	35	41	41	41	41	41	41	41	

ReNET inventory on orbit																										
ReNET recurring costs ($M) (TFU= $350M)											1134	1253	1172	1332	1073	1044	1019	1194	0	0	0	0	0	0	9220.7
Space manufactur-ing DOT&E ($M)									100	300	500	300	100												1300
Space manufactur-ing launches									0	0	0	0	0	4	6	6	8	8	8	8	8	8	8	8	80
Space manufact recurring costs ($M) (TFU= $125M)									0	0	0	0	0	225	293.6	273.4	342.7	328	317.1	308.4	301.1	295.2	290	285.4	3260.3
SM modules on orbit														2	5	8	12	16	20	24	28	32	36	40	
Manufacturing profits ($M)														204	510	816	1224	1632	2040	2448	2856	3264	3672	4080	
Mining equipment DDT&E ($M)						80	150	400	1100	600	200														2530
Mining equipment recurring costs ($M) (TFU= $257M)											462.6	956	880.8	835	803.2	778.6	758.8	742	0	0	0	0	0	0	6217.6
Operations cost MY/yr)					5	10	15	20	25	30	60	110	160	210	260	310	360	410	410	410	410	410	410	410	4445
Operations cost ($M)					1.5	3	4.5	6	7.5	9	18	33	48	63	78	93	123	123	123	123	123	L23	123	123	1333.5
Mines delivered into operation											2	5	5	5	5	5	5	5							37
Averaage working mines each year											2	7	l2	17	22	27	32	37	37	37	37	37	37	37	
Water back to LEO SOC (mT)													75	263	450	675		1050	1238	1463	1461	1463	L4tl	1463	11925
PGM product back to Earth (mT/ytar)											0	0	20	70	120	170	220	270	320	370	370	370	370	370	3040
Investment yearly totals, 2010$M	40	130	260	300	120	251.5	783	1555	2196	2443	1659	3512	3798	3457	3328	3091	2906	2966	3153	700	691.4	684.2	534.6	529.3	524.7	41431
Profits yearly, 2010$M						0	0	0	0	0	0	0	14	573	2154	3828	5971	7842	10212	12183	14176	14784	15392	15800	16208	
						−251.5	−783	−1555	-2196	−2443	−1659	−3512	−3784	−2884	−1174	737.4	3065	4876	7059	11482	13484	14099	14857	15270	15688	

Table 1 (*continued*)

Years after go-ahead	−4	−3	−2	−1	0	1	2	3	4	5	6	7	3	9	10	11	12	13	14	15	16	17	18	19	20	LCC ($M)
Net cash flow, 2010$M																										
Cumulative cash flow, 2010$M						−251.5	−1035	−2338	−3751	−4639	−4102	−5171	−7296	−6668	−4058	−437	3802	7940	11935	18541	24967	27583	28956	30127	30953	
NPV ($M)						$14,364																				
20 Year NPV ROI						34.67%																				
20 Year PGM cost, 2010 $/kg						$13,629																				
Nondiscounted 20 year ROI						227%																				
Yearly mine PGM product. (mT)			10																							
ReNET water return/trip (mT)			150																							

CAMPr to include crew quarters and be a more efficient harvester of materials with continuous human direction.

A model of the carbonyl reactor assemble package for launch is shown in Fig. 11.

2.6. *Reusable nuclear electric tug (ReNET)*

Very early in the orbital mechanic simulations of intercept and return trajectories for the more valuable NEAs it became apparent the nuclear electric propulsion was essential. The large Delta Velocities (DVs) meant multi-megawatt power levels were required for reasonable trip times, and large apohelion radii meant solar power plants were extremely inefficient. After a number of sizing trades we settled a 3.5 MWe power plant using a single-string, Brayton-cycle with recuperator. This provides reasonable payload masses and reliability for reasonable development cost and weight. This same power plant powers the CAMPr modules. Power plant failures were included in the economic model.

The reactor modules are launched prior to activation, and operation never occurs below 1000 km, so there is no chance of radioactive contamination of earth. In our study, all ReNETs were uncrewed, but the reactor was still shadow-shielded for approach to crewed SOCs. A representation of current ReNET configuration is shown in Fig. 12.

3. Summary of results

The principal result of this study is that for reasonable amount of investment and using existing and near-term technologies, it is possible to construct an asteroid mining architecture that significant impacts the world's supply of PGMs and builds infrastructure for industrialization of space. Even more surprising is the fact, that once the mines are established, the enterprise proposed makes a very lucrative profit.

3.1. *Asteroid accessibility*

You cannot mine NEAs unless you can access them relatively often and cheaply. Likewise, it is necessary return the products back to earth relatively often and at reason cost. We used the Copernicus Orbital simulation program to obtain effective trajectories to and from all the NEAs of interest. See Fig. 13.

The design reference mission for the study was asteroid 2007 PA8 because it has: (1) very limited access (high eccentricity of its orbit) and (2) very desirable mining characteristics because of its Taxonomic type of Xc (mixed metallic and carbonaceous). 2007 PA8 is probably the most valuable piece of real estate inside of the main belt. Average trip times to 2007 PA8 are about 1.8 years and ΔVs are about 7 km/s (both from the L5 SOC). Under these conditions, our 3.5 MWe ReNET delivers about 200 mT to and from the asteroid, enough for a reasonable business case. This design reference mission is what sizes the ReNET systems.

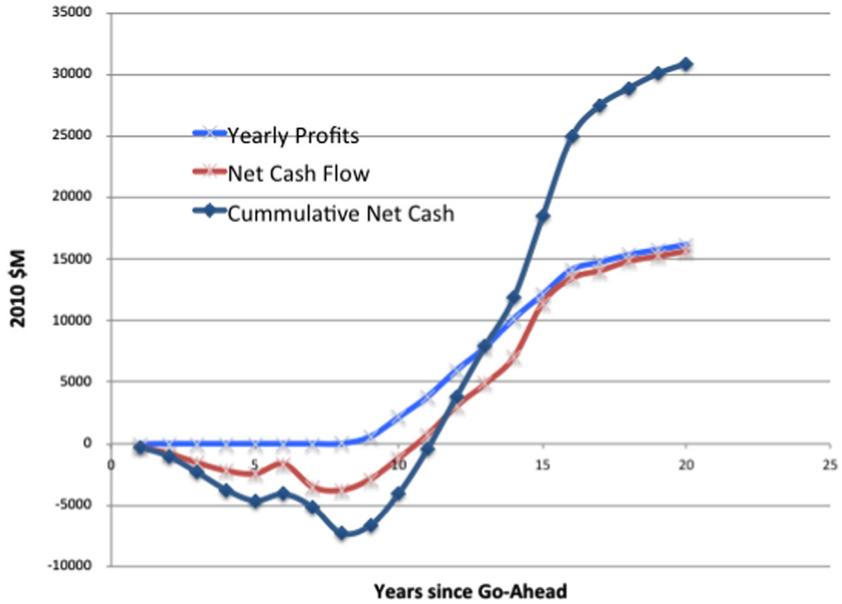

Fig. 17. "All-Up" yearly and cumulative net cash flows.

3.2. Net present value return on investment

The business case assumes that parties involved can claim asteroids under development, and that hypothetical World Development Council guarantees bank loans for development. Hence, if the Net present value return on investment exceeds 20% with a discount rate of 10% banks loans are usually possible.

As discussed earlier, the first five years is technology development and test, plus building and launching prospectors and the SOC components. We realize key elements like nuclear fission power plants are not at TRL 6 right now, but according to our teammates at Idaho National Labs, they could be at TRL 5 in five years if a few tens of million dollars were spent to build and test key elements. We propose to spend the R&D for the power plants and mining equipment, but only start the major developments if the prospector results are positive and indicate minable deposits are present. The master building schedule for the limited cost option (no SSTO development) is shown in Fig. 14. There are a large number of product return capsules shown because they are relatively small, built on-orbit using asteroid nickel and each delivers only about 1200 kg of PGMs. Their cost is only about 1/50 of the value of the product they deliver.

The net present value contribution each year for the mining architecture limited to 12 mines was calculated and is shown in Fig. 15.

The cumulative profit/loss per year for the limited architecture is shown in Fig. 16 and shows how rapidly profit builds once the mines and infrastructure are in place. The NPV starts dropping in later years because of the 10% discount on the cost of money. Out-year profits are worth less in discounted dollars.

3.3. Optimized "All-up Architecture" results

The total expenditures and profits over the life of the proposed "all-up program" (37 mines launched) are tabulated in Table 1. The "all-up program" assumed the Asteroid Mining Company bought five of a production run of 15 SSTOs and used them up over a ten-year period launching and supporting the maximum mining architecture the five could support. It was assumed the other ten SSTOs supporting the rest of the world's space programs.

The maximum architecture the five SSTO's could support turned out to be 41 ReNETs and 37 CAMPrs. The yearly cash flows and cumulative net cash are shown in Fig. 17 below.

3.4. Bootstrapped "All-up Architecture" results

We examined an even more optimistic architecture where we assumed additional manufacturing at the asteroid to not only repair miners and processors, but to actually build up additional mines. With that assumption, we got to a total of 55 mines out at the twenty year point with a net cash flow of $19B per year, and a NPV ROI of 42%.

3.5. Summary

These results show that it is possible to make money mining the asteroids with a well thought out approach, even with limited investment; and that it is probably possible to make outstanding profits, if the well thought out approach is also well financed. A 35% NPV over 20 years, assuming 10% discount rate borders on outstanding given the current interest rates.

Note, that costs were calculated using commercial costing data, which often run 30–40% of NASA costing guidelines.

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