Acta Astronautica 108 (2015) 106–118

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro

Defining a successful commercial asteroid mining program ☆

Dana G. Andrews *, K.D. Bonner, A.W. Butterworth, H.R. Calvert, B.R.H. Dagang, K.J. Dimond, L.G. Eckenroth, J.M. Erickson, B.A. Gilbertson, N.R. Gompertz, O.J. Igbinosun, T.J. Ip, B.H. Khan, S.L. Marquez, N.M. Neilson, C.O. Parker, E.H. Ransom, B.W. Reeve, T.L. Robinson, M. Rogers, P.M. Schuh, C.J. Tom, S.E. Wall, N. Watanabe, C.J. Yoo

University of Washington, USA

ARTICLE INFO

Article history:
Received 14 November 2013
Received in revised form
11 October 2014
Accepted 27 October 2014
Available online 12 December 2014

Keywords:
Asteroid Mining
Development of Space Resources
Space Operations Center
Single Stage to Orbit

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

☆ This paper was presented during the 64th IAC in Beijing.

* Corresponding author.
E-mail address: andrews8@uw.edu (D.G. Andrews).
URL: http://www.aa.washington.edu (D.G. Andrews).

http://dx.doi.org/10.1016/j.actaastro.2014.10.034

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.