The 2010 Space Studies Program of the International Space University was convened at the ISU Strasbourg Central Campus, Parc d’Innovation, Illkirch-Graffenstaden, France.

Team ASTRA’s logo depicts an asteroid in the barren void of space, surrounded by a dynamically swooping rendition of the internationally accepted cartographic symbol for a mine. Its suggestive motion is representative of team ASTRA’s immense energy and devotion to making asteroid mining a reality.

While all care has been taken in the preparation of this report, it should not be relied on, and ISU does not take any responsibility for the accuracy of its content.

The Executive Summary and the Final report may be found on the ISU web site at http://www.isunet.edu in the “ISU Publications/Student Reports” section. Paper copies of the Executive Summary and the Final Report may also be requested, while supplies last, from:

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ABSTRACT

Consumption of the finite resources of Earth continues to increase, and this modern phenomenon places a significant stress on the global economy, the ecosystem, and the future of societies on Earth. One proposal to address this scarcity is to exploit resources from near-Earth objects (NEOs), such as asteroids. Over 7,000 known NEOs have been classified according to their orbital properties (JPL, 2010). It is believed that a substantial fraction of these NEOs contain platinum group metals, which are highly prized in the current market, and occur in greater relative abundance than on Earth. For instance, the asteroid 3554 Amun contains over an estimated USD 6 trillion worth of these metals (Lewis, 1997). Iron, nickel, cobalt, methane, water, ammonia and other useful materials are present in many asteroids. Conversion of some of these materials into fuel can assist with the extraction and return of precious metals.

The objective of the ASTRA project is to identify the challenges associated with commercial asteroid mining and to identify possible solutions. This report addresses several aspects of commercial asteroid mining, including physical sciences, engineering, law, business, and life sciences. The team developed several preliminary mission architectures, followed by a trade-off study used to identify the preferred option. The results of the trade-off study directly shape the outcome of the ASTRA project, a roadmap detailing the activities necessary for successful implementation of the selected architecture. Finally, the report concludes with a summary of key recommendations for continued development to ensure the realization of Team ASTRA’s vision. This includes a recommendation for a robotic precursor mission to gather information about the asteroid in order to develop the technology readiness levels needed for full-scale mining operations.
The 2010 International Space University (ISU) Space Studies Program (SSP) took place during July and August at the ISU’s central campus in Strasbourg, France. The SSP brought together graduate students and space professionals from all over the world and immersed them in an intensive nine-week, interdisciplinary, intercultural, and international curriculum of lectures, workshops, site visits, and research.

A key component of every SSP is the Team Project in which the students undertake a space project on a topic of international relevance. In 2010, three different Team Projects were carried out. This report contains the findings of one of them: Asteroid mining Technologies Roadmap and Applications (ASTRA), a project that examines the feasibility of future commercial exploitation of the resources of near-Earth objects (NEOs) and determines a roadmap to achieve this.

Executed by a team of forty-four students from twenty countries, ASTRA was supported by space experts from around the world, both inside and outside the ISU community.

The objectives of the project were to:

- Provide students with experience in interdisciplinary and international teamwork, while fostering skills in effective management of time and resources.
- Encourage students to identify, share, and develop existing and novel ideas related to the exploitation of NEOs.
- Provide recommendations for future international planning and execution of space programs and space activities that will lead to the practical exploitation of NEOs.

The team assessed current knowledge of near-Earth objects, identified scientific, technical, legal and economic challenges to their commercial exploitation and potential solutions to these challenges, defined possible architectures and performed a trade-off study on these, before creating a roadmap that was then used to generate recommendations for future activities. Throughout the execution of the project, the team demonstrated professionalism, discipline, and maturity. We, the project faculty and teaching associate, are pleased to commend both the team and its report to you.

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This report, *ASteroid mining Technologies Roadmap and Applications (ASTRA)* is the product of a team project produced by the students from the International Space University Space Studies Program (ISU SSP) 2010, held from 28 June through 27 August 2010 at Strasbourg in France.

The ASTRA report is about asteroid mining. There is a reasonable certainty that a number of near-Earth objects contain valuable ore in concentrations far exceeding those found on Earth. Access to these resources could benefit society in a number of ways, such as solving the future scarcity of critical resources and boosting the world economy.

The primary goal of this project is the development of a roadmap leading to the realization of a commercial asteroid mining venture. Starting with the identification of the various challenges that are foreseen to realize asteroid mining, solutions and recommendations shall lead to numerous mission architectures. A trade-off study identifies a single architecture for the development of our final roadmap. We expect that this roadmap, using its holistic approach, will serve as a comprehensive guide to those seeking to make asteroid mining a reality for the benefit of humankind.

During nine weeks, our project team has carried out intensive work. Team ASTRA, consisting of forty-four students from twenty countries, has a variety of educational backgrounds, experiences, talents and interests. Challenges that arose from teamwork, cultural differences, different languages or time constraints have been overcome. More importantly, this report truly represents our team effort, since advantage has been taken from all the different contributions, views and approaches coming from all our team members. The ASTRA report is the result of our teamwork and we believe that this report meets our goal described above.

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<td>AAS</td>
<td>American Astronautical Society</td>
</tr>
<tr>
<td>AERCam</td>
<td>Autonomous Extravehicular Robotic Camera</td>
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<tr>
<td>AIAA</td>
<td>American Institute of Aeronautics and Astronautics</td>
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<td>ARCSSTE-E</td>
<td>African Regional Centre for Space Science and Technology Education in English</td>
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<td>ASTRA</td>
<td>Asteroid mining Technology Roadmap and Applications</td>
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<tr>
<td>AU</td>
<td>Astronomical Unit</td>
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<td>CBC</td>
<td>Canadian Broadcasting Corporation</td>
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<td>CIA</td>
<td>Central Intelligence Agency</td>
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<tr>
<td>DALY</td>
<td>Disability-Adjusted Life-Years</td>
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<td>ΔV</td>
<td>Difference in Velocity</td>
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<td>DNA</td>
<td>Deoxyribonucleic Acid</td>
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<tr>
<td>EBA</td>
<td>Elimination By Aspects</td>
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<td>ECLSS</td>
<td>Environmental Control and Life Support System</td>
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<td>ESA</td>
<td>European Space Agency</td>
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<td>ESMD</td>
<td>Exploration Systems Mission Directorate</td>
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<td>EVA</td>
<td>Extra-Vehicular Activity</td>
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<td>Federal Aviation Administration</td>
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<td>FASEB</td>
<td>Federation of American Societies for Experimental Biology</td>
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<tr>
<td>GCR</td>
<td>Galactic Cosmic Ray</td>
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<td>GDP</td>
<td>Gross Domestic Product</td>
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<td>GEO</td>
<td>Geostationary Earth Orbit</td>
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<td>Headquarters</td>
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<td>HRI</td>
<td>Human-Robot Interaction</td>
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<td>IAA</td>
<td>International Academy of Astronautics</td>
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<td>IAF</td>
<td>International Astronautical Forum</td>
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<td>IAHS</td>
<td>International Association of Hydrological Sciences</td>
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<tr>
<td>i-SAIRAS</td>
<td>International Symposium on Artificial Intelligence, Robotics and Automation in Space</td>
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<td>ISRU</td>
<td>In-Situ Resource Utilization</td>
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<td>International Space University</td>
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<td>Lincoln near-Earth Asteroid Research</td>
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<td>Lowell Observatory near-Earth Object Search</td>
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<td>LSS</td>
<td>Life Support System</td>
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<td>NEA</td>
<td>near-Earth Asteroid</td>
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<td>NPV</td>
<td>Net Present Value</td>
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<td>NRC</td>
<td>National Research Council</td>
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<td>NSLS</td>
<td>National Synchrotron Light Source</td>
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<td>NASA Solar Electric Propulsion Technology Application Readiness</td>
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<td>OPEC</td>
<td>Organization of the Petroleum Exporting Countries</td>
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<td>OST</td>
<td>Outer Space Treaty</td>
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<td>PGM</td>
<td>Platinum-Group Metals</td>
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<td>Project Management</td>
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<td>Private-Public Partnership</td>
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<td>Rare Earth Elements</td>
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<td>Return On Investment</td>
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<td>Seasonal Affective Disorder</td>
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<td>SAE</td>
<td>Society of Automotive Engineers</td>
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<td>SMART</td>
<td>Simple Multi-Attribute Rating Technique</td>
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<td>SPE</td>
<td>Solar Particle Event</td>
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<td>Shuttle Remote Manipulator System</td>
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<td>Space Studies Program</td>
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<td>Strengths, Weaknesses, Opportunities and Threats</td>
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<td>United Nations Office for Outer Space Affairs</td>
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<tr>
<td>W</td>
<td>Wide-Field Infra-red Survey Explorer</td>
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<tr>
<td>Y</td>
<td>Years Lost to Disability</td>
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<td>YLL</td>
<td>Years of Life Lost</td>
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1 INTRODUCTION

As humans deplete the Earth of its resources, it becomes increasingly apparent that many of our activities are damaging to both the environment and humankind. Our expanding consumption within Earth’s finite biosphere poses a threat to the global economy, the ecosystem, and the societies of Earth. Large-scale operations like strip-mining pose a threat to the environment that might be higher than establishing a mining infrastructure in space. Alternative sources of rare metals are needed both to address growing demand and to maintain an increasingly green public’s support of the aerospace industry.

One proposal to address this scarcity is to import material to Earth from near-Earth objects (NEOs) such as asteroids (Globus, 2010). There are thousands of near-Earth asteroids (NEAs) (JPL, 2010). Current literature estimates suggest asteroids as a source of trillions of dollars worth of precious metals and minerals. The establishment of a space-bound mining program would generate new industry and potentially massive profits, and stimulate innovation. The technology used to mine these asteroids may one day be adapted to facilitate deflection of earthbound potentially hazardous objects for to generate the materials necessary for the construction of human settlements in space.

Naturally, a project of this scale encompasses a variety of spheres: science, engineering, commerce, and law to name a few. Team ASTRA’s goal in undertaking this report is twofold: (i) to assess the feasibility of developing an asteroid mining infrastructure and (ii) to formulate possible architectures for such an endeavor in the context of a roadmap. Our hope is that this report, as a first iteration survey of the complex challenges and issues inherent in the task, and its recommendations will help inform future architects of asteroid mining programs.

1.1 Mission Statement

The mission statement for Team ASTRA is:

To develop a roadmap for the commercial mining of near-Earth asteroids, using an interdisciplinary approach to contribute to humankind.

1.2 Motivation for Asteroid Mining

The primary motivations for asteroid mining are to commercialize a new and profitable space industry, to meet an existing demand for more resources on Earth, and to help preserve the Earth’s environment by seeking resources from extraterrestrial sources. Secondary motivations are to expand human capabilities in space and to develop space-based mining technologies that may possibly be adapted for deflection of hazardous NEOs in the future.

1.3 Purpose and Scope

This project is an investigation of issues related to asteroid mining that culminates in the
development of a roadmap aiming to guide the development of near-Earth resource exploitation. This study examines the interdisciplinary aspects of such an endeavor, including the fields of science, medicine, engineering, law, business, and social impact as they pertain to the overarching goal of establishing a mining infrastructure in space. Included in this investigation are the identification of preferred candidate asteroids, development of preliminary mission concepts, and trade-off study considering mining large or small asteroids and human or robotic missions. The team also addressed legal implications, economic viability, and potential role of humans in an asteroid mining mission and developed a business plan.

Topics not addressed include detailed mission design, spacecraft system and subsystem design, deflection of hazardous asteroids, formal costing, and legal implications of space debris from asteroid mining activities. Due to the lack of current knowledge of NEOs it is not helpful to pick a specific candidate for mining. Instead, identification of candidate asteroid types relies on the assessment of typical orbits and composition. As a result, the findings of the roadmap developed here are more general in nature, and not limited to one specific asteroid.

1.4 Stakeholders

Within the context of this report, we must consider two distinct phases of commercial asteroid mining when identifying the stakeholders of the project. The first phase is the development of the mission concepts, which are outlined in this report by Team ASTRA of ISU SSP10. The second phase is the actual implementation of the commercial asteroid mining entity. The stakeholders of each phase of the project are presented in Table 1-1.

<table>
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<tr>
<th>Table 1-1: Commercial asteroid mining stakeholders</th>
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<td><strong>ISU SSP10 Customers</strong></td>
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1.5 Methodology

To perform this study, Team ASTRA adopted the following methodology:

1. Identification of the challenges presented by asteroid mining
2. Identification of the possible solutions answering the previous challenges
3. Definition of possible architecture options
4. Interdisciplinary trade-off of the options and selection of the primary architecture
5. Development of the interdisciplinary architecture
6. Development of an interdisciplinary roadmap to asteroid mining

Repeated use of the methodology described above, allowed us to iterate the study outcomes.
2 SCIENTIFIC BACKGROUND

Near-Earth objects are objects in orbits with perihelion distance of less than 1.3 Astronomical Units (AU). Near-Earth asteroids is the name for NEOs that are asteroids. There are 7085 such asteroids as of July 2010. Unfortunately, there is a significant gap in the knowledge about the specifics of their orbital parameters and their compositions. The characterization of only a handful is possible according to size, shape and mineralogy (JPL, 2010).

There are, estimates of the number of NEAs. These come from past studies that indicate a power-law relationship between quantity of asteroids and their size (Stokes et al. 2003). Figure 2-1 displays this relationship, and we can observe that while the number of existing asteroids greater than 1 km diameter is uncertain, estimates indicate there to be around 1000. (NRC, 2010). Studies of small objects entering and burning up in the atmosphere help further reduce the uncertainties in the relationship. Using these estimates, we can expect that there are approximately 100,000 asteroids greater than 140 meters in diameter. By 2020, NASA must detect 90 % of the potentially dangerous NEAs larger than 140 meters (George E. Brown Jr. Near-Earth Object Survey Act, 2005).

Mineralogical composition is also a useful trait for classifying asteroids. Classification involves analyzing light reflected from the surface of a given asteroid, and comparing it to known standards (Gaffey, 2002). The three main categories are C-type (containing carbon, hydrated minerals and organic chemicals), S-type (containing metal and high levels of distinguishable minerals), and M-type (containing mostly metals). The majority of asteroids are C-type (75%), while seventeen percent of asteroids are S-type, and the remaining eight percent are mostly M-type with some small proportion of rare asteroid types (Nelson et al., 1993; Shoemaker et al., 1979; Tholen, 1989). It is uncertain whether NEAs follow the same distribution.
There are attempts to identify and classify NEOs. However, these attempts are focusing on localizing potentially hazardous objects, which are NEOs whose orbits bring them within 0.05 AU (7.5 million km) of the Earth (NRC, 2010). A number of programs and offices oversee this effort. It is vital to identify significant programs in space agencies, universities, and military institutions that have already produced relevant data. Examples are (NRC, 2010):

- Near-Earth Asteroid Tracking (NEAT), NASA and Jet Propulsion Laboratory
- Catalina Sky Survey, University of Arizona
- Siding Spring Survey, Siding Spring Observatory, Australia
- Lincoln near-Earth Asteroid Research (LINEAR), United States Air Force, NASA, and MIT’s Lincoln Laboratory
- Lowell Observatory near-Earth-Object Search (LONEOS) funded by NASA

The detection of NEOs is complicated as many are dark and thus hard to see using Earth-based observations in the visible spectrum. The solution is to use infrared telescopes. However, the atmosphere is opaque in the infrared frequencies, which means that such telescopes must be space-based. Another problem is that many NEAs have orbits that are contained either partially or fully within the orbit of the Earth. As such, they are extremely difficult to see from the Earth against the glare of the Sun. Currently, no dedicated space-based NEO detection spacecraft exist, although both Germany and Canada are working on this. (Johnson, 2010; NRC, 2010)

Robotic missions have visited a small number of asteroids. In 1991, NASA’s Galileo mission visited 951 Gaspra and 243 Ida, asteroids on the inner edge of the main belt (NASA, 2010a). Although both S-type, these asteroids have completely different composition. The NEAR Shoemaker mission performed fly-bys of 253 Mathilde (main belt, C-type) and landed on the NEO 433 Eros in 2001 (NASA, 2010b). ESA’s Rosetta spacecraft flew by asteroid 2867 Steins in September 2008 (Lakdawalla, 2010), and Lutetia in July 2010 (ESA, 2010). The only sample-return mission attempted to date is Hayabusa (JAXA, 2010), which landed on asteroid Itokawa in 2005 and returned to Earth in 2010. At present, it is unclear whether Hayabusa retrieved any valid samples. These missions provided relatively precise surface maps, as well as density and composition estimates. The results did not always agree with expectations and highlight the enormous amount of work remaining to obtain an accurate database of all NEAs.

Nevertheless, it is possible to analyze the statistics of the known asteroids. Figure 2-2, compiled by ASTRA from the JPL Small Bodies Database of near-Earth asteroids, shows the distribution of NEAs in highly eccentric and inclined orbits. A potential mission to an asteroid requires that asteroid to be in a low-inclination orbit. For example, for an asteroid to be accessible with a 5 km/s ΔV, that asteroid will be limited to a maximum orbital inclination of 9.62 degrees (Johnson, 2010). About half the known asteroids have orbital inclinations less than 10 degrees (JPL, 2010).

If all asteroids follow the same distribution as large ones, it becomes possible to derive information about the total NEA population. One of the fundamental works in this regard is Bottke et al. (2002), who created probability distributions of destinations of asteroids and correlated this with known observations. They deduced that around twenty percent of NEOs come within 0.05 AU of the Earth (that is they are potentially hazardous objects).
From the perspective of asteroid mining, it is interesting to analyze the JPL database and look at the distribution of currently known asteroids. By simulating the orbits of all the 3300 low-inclination known NEAs based on statistics obtained from the JPL database, it is possible to track their distance from the Earth as a function of time. Hence, one can deduce the percentage of time over the next 30 years in which at least one asteroid is within any given distance. If we also limit ourselves to a 0.02 AU wide, and 0.1 AU radius disk around the Earth in a geocentric rotating frame, we can create a map showing the probability distribution of at least one known NEA being at any region in near-Earth space as shown in Figure 2-3. This distribution corresponds also to the percentage of time over the next 30 years that that region of space contains at least one NEA. We based these calculations on the Ephemeris information in the JPL database. Although for any individual orbit, ephemeris predictions of orbits are not particularly accurate, the overall statistics will still be representative. In the figure, the dark circle represents the orbit of the Moon and the scale indicates the probability (in percent) of at least one NEA being in the region of space.
Figure 2-3: Distribution of low-inclination NEAs in near-Earth space.

Assuming that the 10 million asteroids larger than 10 meters follow the same distribution as the known ones then there will always be at least one suitable asteroid within a region that is reachable with existing technology. The ΔV requirements and travel time will be comparable to going to the Moon (Johnson 2010, O'Leary 1983).

The assumption that the total distribution of asteroids follows that of the observed distribution is defendable when based upon the extremely limited knowledge that exists; however, it is not necessarily accurate. Studies indicate that while large NEOs generally stay within the inner parts of the solar system, many smaller Earth-impacting asteroids come from the central asteroid belt (Morbidelli and Gladman, 1998). In addition, smaller objects are more likely to have their orbits perturbed by non-gravitational effects (examples: Rubincam, 2000; Walsh et al., 2008).

While reasonable orbital characteristics of the NEA population larger than 1 km exist, we know little about the millions of smaller asteroids and their compositions. Further studying and understanding of the asteroid population is a crucial step for a commercial mining entity (Recommendation I). For this reason, this report does not choose example asteroids. Instead, based on the above information, it can be stated that many asteroids are likely to accessible with a reasonable ΔV and within a reasonable time. Consequently, this report will instead identify the required characteristics of asteroids that would be suitable candidates for a mining entity.
3 CHALLENGES

The path leading to a successful commercial asteroid mining venture requires addressing many complex interdisciplinary challenges, which are divided into disciplinary sections concerning physical sciences, human factors, societal issues, engineering, law, politics, and business.

3.1 Science

The information available today on the properties of asteroids is very limited and often based on assumptions. Answers to open scientific questions are needed before asteroid mining can take place. These questions concern the characterization of the chemical, physical and orbital properties of asteroids, detailed below.

3.1.1 Composition

It is fundamental to future mining for us to determine asteroid composition, both qualitatively and quantitatively, the asteroid composition. We can determine physical features such as mass and bulk density to assist with the analysis of composition (Kowal, 1996). Using existing data from remote observations of asteroids, we can infer the mineralogical composition of similar classes. Errors associated with remote observation include incorrect reduction and characterization, potential modification of the observed spectrum caused by surface weathering, and instrument artifacts, affecting final reflectance spectra (Binzel, 2002). The foregoing errors create a challenge to obtaining reliable data on asteroid composition.

3.1.2 Spin and Solidity

We must examine the fragility of asteroids and their ability to withstand mining procedures. We must determine on a case-by-case basis whether an individual asteroid is a solid rock with sufficient material strength or a rubble-pile of components held together by gravity. Studies show that the forces concomitant with a rotational period of less than two hours would be sufficient to tear apart a non-solid asteroid structure larger than 150 meters, and that such a high spin rate has never been observed for large asteroids (Harris 1996). No known asteroid larger than 200 meters across rotates faster than once every 2.2 hours. In fact, only objects smaller than 100 meters have higher spin rates, and these are believed to be monolithic (Asphaug, 2000). Determining the solidity, spin axis and spin rate are crucial challenges to asteroid mining.

3.1.3 Collisions and Detection

The vast distances in space provide a very low rate of collision between asteroids. There is currently a strong effort led by NASA to detect and map 90 percent of all asteroids larger than 140 meters, whose orbits pass within 0.05 AU of the Earth orbit before 2020 (NASA, 2007). However, there is still a population of around one billion smaller asteroids for which there are no data (Globus, 2010). This presents the challenge of detection methods for small asteroids, as well as avoidance techniques if these smaller asteroids are a threat to mining missions.
3.1.4 Chemical and Physical Aspects of Processing in Microgravity

Terrestrial mineral processing involves a number of physical and chemical processes, which transform resources for use in our global community. The extracted ore (typically a metallic oxide, sulphide, or silicate) is processed to produce the metal of interest as well as a range of waste products. Many of the processes in common use rely on gravity. Physical and chemical processing of ore commences after extraction. The first step is comminution, which reduces particle size using crushing and grinding equipment. Screening the resultant mineral and gangue mixture takes advantage of density variation between components and allows separation of the desired size of material. The next stage of processing, concentration, is the process of separating the desired mineral from waste material or gangue, and uses a variety of physical techniques. These include gravity concentration, magnetic and electrostatic separation and froth flotation. De-watering is frequently required following physical separation procedures. The product can then be further refined using hydrometallurgical, electrometallurgical, and pyrometallurgical techniques, which further refine or purify a material.

How microgravity will affect these processes is unknown. However, the mineralogy of the asteroid will dictate which processing method is used, possibly requiring the input of water, energy, gasses, organic chemicals or catalysts. Adapting these techniques to microgravity will be a challenge.

3.2 Human Factors

3.2.1 Space Environment Considerations

There are physiological, psychological, and cognitive challenges to humans working in space (Clément, 2003). This necessitates countermeasures to mitigate the effects; previous missions so far have used exercise, pharmacological solutions, crew selection and training, and environmental design to counteract these problems. The space environment also exposes humans and equipment to a variety of harmful radiant sources, including Galactic Cosmic Rays (GCRs), ionizing radiation, and solar particle events. We require improved shielding materials for spacecraft hull and EVA equipment, as well as pharmacological interventions, to reduce exposure and mitigate its effects. By extrapolating from data collected from lunar missions and fly-by studies of asteroids, we expect to find fine particulate dust on the surface of the asteroid. This dust could pose health hazards to humans due to inhalation and abrasion. Dust saturation leading to hardware problems such as mechanical failure of joints and moving parts, and detrimental effects to thermal radiators and solar arrays if they become saturated with dust is a significant concern. A mission could use externally mounted “suitports” in place of airlocks in order to minimize the amount of dust entering the capsule. We must design mechanical articulators to exclude foreign matter, as well as a method to periodically clear the thermal radiators.

3.2.2 Supporting Human Life

Long duration missions have particular risks associated with psychological stress, isolation, confinement, and crew dynamics. Crew selection, training, in-flight counseling, communication with family, media and entertainment, mentally stimulating activities, and meditation can help to minimize these risks. We must optimize the design, construction, and allocation of space for
activities to maximize worker productivity, minimize psychological distress and monotony, and to facilitate the ease of work. We should use a comprehensive environmental design incorporating lighting (at particular wavelengths for simulated sunlight), ergonomic design of work consoles and stations, sinuous architecture, privacy for crewmembers, possibly plant selection, and a dual-use meditation chamber. We also need life support subsystems to manage the atmosphere, water, waste, food, and safety-monitoring systems required for a human mission. Many technologies already exist for an integrated ECLSS. We must perform a trade-off study to select the specific technologies to use. Using humans for an asteroid mining mission introduces the risk of injury and loss of human life; we must take appropriate safety measures. We should make available a first aid kit, pharmacy, basic surgical suite, and vital monitoring system. We must also explore emergency crew return protocols and vehicles. Conflict between crewmembers may arise from differences based on gender, culture, group dynamics, and power structure. We must implement a code of conduct for crewmembers, agreed upon by all participants.

3.2.3  Human vs. Robot

During the mission, mining equipment may need periodic maintenance and repair, as well as unexpected troubleshooting. We can use humans, robots, or a hybrid use of both to repair the equipment as needed. Robots are desirable for planned repetitive tasks, whereas humans offer enhanced dexterity and adaptability. However, placing human workers in space exposes them to health hazards many magnitudes greater than those experienced on Earth, resulting in an increased risk of cancer and infertility. We must consider the degree to which it is appropriate, or ethical, to subject humans to this environment. Fully informed consent is necessary and we must explore acceptable levels of risk for very long duration missions.

3.3  Societal Issues

Support from policymakers, influential public figures, and society as a whole is a key prerequisite for successful space ventures. Active promotional outreach needs to ensure that people perceive that asteroid mining is not only potentially feasible, but also that it offers an opportunity rather than pose a threat. Particular challenges are the distribution of mining wealth between countries and communities, the possible role shift of astronauts towards becoming asteroid mining personnel, and considerations in the domains of ethics, environment and health. Ideally, the overall effects in these domains should be demonstrated as positive in order to extend the rationale for asteroid mining beyond that of simple economic profit.

3.4  Engineering

When describing any potential new activity in space, it is common to encounter a technique or procedure that we have not yet successfully used in space. This presents an engineering challenge. There are a large number of these associated with asteroid mining, and they are difficult ones since they involve conducting industrial activity in space on an unprecedented scale. The major asteroid mining engineering challenges are: transportation, surface operations, risks, safety, and explorer missions. The subsections below discuss these engineering concerns.
3.4.1 Transportation Systems

Transportation systems design for asteroid mining poses many challenges. The major difference between asteroid mining and traditional mission profiles is that the mass returned to Earth will be appreciably larger than the mass launched. The spacecraft and mining equipment designs need to accommodate the proposed duration of the mission. For a small asteroid returning to Earth-orbit, the propulsion methods for accelerating an entire asteroid must be assessed.

Transportation of payloads to the surface of the Earth will occur in several stages. The mechanism for delivering resources to a stable storage orbit must not perturb the orbits of satellites in Low Earth Orbit (LEO) or Geostationary Earth Orbit (GEO). We need to design thermal shielding for reentry of high-mass payloads.

3.4.2 Surface Operations

Surface operations encompass the physical procedures required for landing on and processing a given candidate asteroid. In some cases, the selected asteroid will be spinning rapidly, presenting an array of challenges. It may be necessary to reduce the angular momentum of an asteroid prior to landing. It may be advantageous, however, to exploit the angular momentum, using centrifugal force for mining operations or payload return. The spacecraft will need to be secured to the asteroid artificially, since it is unlikely that the low mass of an asteroid will provide adequate gravity to retain it. Ore extraction will require advanced technology to cope with a low-gravity, zero-pressure environment with highly variable temperatures. Ore processing could be accomplished using known physical and chemical processes with minimizing energy requirements as a prime concern. The transfer of raw materials to the processing facility necessitates a robust system design. We must design a processing plant for the separation and treatment of valuable elemental constituents. We must examine provision of equipment, robots or people, materials and energy for this facility. Potential robotic failures pose a continuous threat to mission success. In-situ resources could be exploited depending on the chemical composition of the asteroid. Another challenge is designing and implementing a reliable, sustained power supply for mining equipment and other necessary support systems. Communication delays between surface operations and managers on Earth will necessitate highly autonomous surface operations technology.

3.4.3 Explorer Missions

Explorer missions will be necessary to obtain detailed composition data of the asteroids to enable candidate selection, and to develop technology and experience necessary for profitable asteroid mining. Recent precursors of missions of this type include NEAR and Hayabusa (JAXA, 2010), which returned valuable data about asteroid surface composition and physical properties. Phobos-Grunt (a Russian sample return mission to Phobos, planned for launch in 2011) and potential follow-on missions to NEOs can provide a great wealth of composition information, as well as ‘ground truth’ for existing remote sensing data. The challenge posed by this type of mission is the successful attainment of sufficient data and samples.

3.4.4 Risks and Safety

The risk of failure in potential mining systems should be assessed and mitigated. In the case of human involvement, measures should be taken to protect workers from potentially dangerous
exposure to microgravity, radiation, floating debris and hazards posed by mining equipment. Planetary protection should be the highest priority when returning an asteroid or payload to the Earth’s surface. These considerations present engineering challenges including the design of necessary shielding, debris detection, and reliable repair mechanisms for space-based machinery.

3.5 Legal Issues

There are legal challenges to consider when undertaking asteroid mining activities. The intention of current space law is to prevent space from becoming a contested region and to ensure that activities in space are for the benefit of humankind. It is important that asteroid mining activities are consistent with the principles established in current space law. This section investigates the challenges that the current legal framework provides for asteroid mining carried out in outer space in four areas. These are the legislation and jurisdiction challenges affecting asteroid mining, non-appropriation, liability and responsibility issues, and the distribution of resources.

3.5.1 Legislation and Jurisdiction

Current legislation governing activities in outer space do not explicitly consider asteroid mining. There are several challenges present within existing space treaties and international law. First, the Treaty on the Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies (Outer Space Treaty or OST) states that any activity in space must be to the benefit of humankind (Art. I OST, 1967). This presents a challenge because of the wide interpretability of this statement (Lee, 2009). The International Telecommunication Union (ITU) allocates orbits, such as geostationary orbits, to divide the various radio frequency bands that are available amongst the users. Here, a market is created that allows private exploitation of a limited resource in space. Adopting a similar framework to asteroid mining is an important challenge. We must examine current space law to ascertain applicability to asteroid mining. This includes the United Nations Convention on the Law of the Sea (United Nations, 1982) and the Antarctic Treaty (Antarctic Treaty, 1961), as well as applicable national legislation of space-faring nations who regulate space activities on a national level. It is important to define the jurisdiction for the activities associated with asteroid mining for the attribution of responsibility and liability, as discussed in Section 3.5.3 below. Considerations in this area include identifying the launching State, responsibility for changing the asteroid’s orbital configuration, and jurisdictional issues relating to activities of humans in outer space.

3.5.2 Appropriation

There is debate on whether or not the existing legal basis prohibits the extraction of material from an asteroid and selling it to customers (Kerrest, 2004). Art. II of the OST states that celestial bodies are not subject to national appropriation by claim of sovereignty. For those States that are signatories to the OST, activities of private entities conducted in outer space are subject to supervision by the State (Art. VI OST). Consequently, each State is obliged to supervise and exert control over its non-governmental entities to ensure compliance with international law. This control then presumes that any claim of appropriation by an entity may transfer to the State. This contravenes the OST. It is not permissible for a State to gain an advantage by purchasing mined ore from one of their private entities, although commercial transactions will eventually lead to benefits because of corporate and personal taxes paid to that State. Equivalently, the private entity may have an advantage by selling only to specific States.
However, both scenarios contravene Article IX of the OST which states that “States Parties to the Treaty should carry on activities [...] with due regard to the corresponding interests of all other States Parties to the Treaty” (Trimble, 1984).

Current international law does not guarantee the right to conduct mining activities on near-Earth objects (NEOs). Article I of the OST states that outer space shall be free for exploration and use by all States. This, however, may not preclude mining activities. Moreover, Art. 6, paragraph 2 of the 1979 Agreement Governing the Activities of States on the Moon and Other Celestial Bodies (Moon Agreement, 1984) stipulates that it is acceptable to remove samples under the auspices of scientific investigations but does not take into consideration the commercial extraction of resources. We foresee that this could prevent other entities from exploring, using or mining a NEO, when one entity starts mining the asteroid.

### 3.5.3 Responsibility and Liability

Another legal challenge associated with asteroid mining is how to determine liability when a celestial body with an altered trajectory causes damage on Earth or to a spacecraft. The 1972 Convention on International Liability for Damage Caused by Space Objects (Liability Convention or LC) and the 1976 Convention on the Registration of Objects Launched into Outer Space (Registration Convention or RC) are taken into consideration to identify the legal challenges in regards to responsibility and liability. Issues arising are the status of asteroids with altered orbits under the LC and the liability of a State if an asteroid de-orbits and causes damage.

A mining operation run by a private entity could be associated with more than one State. In this case, it is unclear which State would be liable for the asteroid or asteroidal material. With present international space law, it is unclear how to manage these issues (Lee, 2009). In the event of a human mission, it will be a challenge to address the mitigation of liability for astronaut activities. To determine liability, it is necessary to establish methods to assess the risks associated with sending humans on a mission to mine an asteroid. Consideration of liability for contaminating the Earth with material mined from asteroids is also necessary. Currently, it is unclear which nation or governing body would be liable for this damage (Foster, 1972).

### 3.5.4 Distribution of Resources

Under existing space law, distribution of mined resources is quite impractical, since space is the province of humankind. Moreover, appropriation has no foundation in law (Verschoor and Kopal, 2008). As there are inconsistencies between the Moon Agreement and the OST, there are now two competing regimes for the exploitation of mineral resources from celestial bodies in effect under international law (Lee, 2009). The legal regime and international governance regulating the distribution of resources acquired in outer space therefore needs to be clarified.

Besides inconsistencies such as the definition of common heritage, the indeterminate international governance regime and the absence of certainty over a legal framework for celestial bodies make interpretation of the law difficult. This may prevent commercialization and thereby the distribution of resources or compensation (Menter, 1979). Depending on the type of venture (governmental, multinational, private or private-public), the distribution of resources is more than a practical challenge. Participating actors may have to distribute proceeds to non-participating actors, because without compensation it is highly unlikely that the non-participating actors would support a prospective agreement. Definition of frameworks for
compensation should be done prior to asteroid mining activities. The United Nations (UN) may become an appropriate regulating authority for these purposes. However, we believe that the UN will decline involvement in matters beyond the scope of its principle goals. Another controversial concept in the existing body of space law is the principle of “common heritage of mankind” in Art. I of the OST. We must determine if asteroid mining can indeed be conducted for the common heritage of humankind.

3.6 Business

Developing a financially feasible business model for an asteroid mining entity poses a number of discrete but interrelated business challenges. The choice of the mined raw material is a cornerstone in the economic viability assessment. Based on a study of present and future markets, we must investigate various raw materials in terms of their economic return. We must realize the economic return without flooding the market and thus deflating the market price. We can assess different mission architectures in terms of how well they balance the competing challenges of maximizing the quantity of material mined while avoiding a positive supply shock market that destroys market prices.

Another significant challenge to address is the total cost of the mission. We classify significant costs into four primary categories: pre-launch, launch, post-launch, and insurance costs. The research, development, and production of the project will be the most significant contributor to pre-launch costs. These are heavily dependent on the complexity of the mission (for example, human versus robotic missions, in-situ mining versus returning the asteroids to Earth for mining). Total mass, which consists of spacecraft, mining equipment, and possibly crew, drives launch costs. Total mass and mission architecture determine the type of launcher to be used and the number of launches that will be required. Post-launch costs must take into consideration ground and in-orbit operations, as well as the mass of material to be returned. It is likely that we will require different types of insurance throughout the various phases of the venture to manage operational and market risks.

It is important to identify temporal considerations, such as time-to-market and time to break-even, and the financial feasibility of the various asteroid mining mission architectures. These timing considerations are critical as they inform both capital requirements and liquidity, two of the most significant challenges faced by new business ventures. Timing challenges are particularly difficult for asteroid mining, given that the timing of cash flows is largely dependent on the mission timeline. Mission timelines for this type of cutting-edge space activity are prone to frequent delays and schedule changes. Delays can occur at any phase of the mission, including research and development, launch, mission execution, and material distribution.

3.7 Challenges Conclusion

In the preceding sections, we have identified challenges and itemized them by their relevant discipline. The purpose of these challenges is to focus the development of mission architectures that will lead to technically feasible, commercially viable asteroid mining. In the following sections, we will outline possible solutions to these challenges, and integrate them into an interdisciplinary roadmap.
4 HUMAN FACTORS ANALYSIS

Recent advancements in the aerospace and medical fields have made the establishment of a permanent human presence in space more tangible than ever. While adding humans to an asteroid mining mission is a risky, costly, and laborious process, human involvement offers a number of important advantages. Those characteristics that make us uniquely human - flexibility, adaptability, creativity - translate into problem-solving, decision-making, and troubleshooting capabilities. These traits have the potential to dramatically improve the performance and success of a mission. While research and development in the robotic approximation of these characteristics is underway, comparable success has yet to be achieved. For example, complex maintenance and repair of mining equipment or facilities may be better suited to the unparalleled dexterity afforded by a human hand, avoiding the loss of millions of dollars in otherwise unsalvageable assets. However, the true value of human spaceflight lies not only in money. While financial impact is certainly a cornerstone consideration for a commercial venture and is often the dominant metric and motivator in Western (if not all) societies, a human mining mission would also have the added benefit of fulfilling a societal craving: that of our need to explore and to expand our society beyond the limits of Earth. More simply than that, a human presence in so strange a place as space inspires us, and subsequent generations, to achieve even greater technological and scientific heights. To draw upon a simple analogy, cultural institutions like the Eiffel tower, opera houses, or theatres may not be financially utilitarian, but they continue to exist because they help us to fulfill a greater cultural need (Codignola and Schrogl, 2009). While human missions are more costly, they provide valuable benefits in the areas of cultural inspiration and increased mission performance. In addition to the potential role of humans in long-term space flight, this section discusses the ethical, social and medical aspects of such missions.

4.1 Potential Role of Humans

What is it that specifically sets humans apart from robots? First, robots are much faster at processing information than humans (Carroll, 2009). In addition, while lacking the gold-standard dexterity of humans, they can be fitted with semi-dexterous manipulators designed to accomplish specific tasks (Akin et al., 2007). The drawback of incorporating humans in spaceflight missions lies in added complexity and cost. The spacecraft and launch vehicle must meet much higher reliability and safety requirements when human lives are involved. In addition, human missions require an Environmental Control and Life Support System (ECLSS) to provide conditions necessary for survival in space. A hybrid mission of human-robot cooperation presents an interesting alternative, using the best aspects of these two options. Many researchers and astronauts advocate this collaboration as the ideal mission architecture, resources permitting (Jacobs et al., 2007; Carroll, 2009). An asteroid mining mission would ideally use in-situ human tele-operation of robots for minimal time delay, plan for human-robot collaboration in facility maintenance, and encourage troubleshooting in tandem.
4.2 Ethical Aspects of Sending Humans

The space environment subjects human workers to health hazards many magnitudes greater than those experienced on Earth (Clément, 2005). For instance, galactic cosmic rays and ionizing radiation result in an increased risk of cancer, infertility, and potentially loss of years of life. Prolonged exposure to microgravity causes muscle atrophy, loss of bone mineral density, cognitive distortions, and more. If it were possible to send robots on such a mission, why should humans be subjected to this environment? To what degree can we consciously expose humans to such conditions? While the practical thresholds for acceptable doses of radiation will be further discussed in Section 4.4.6, we will consider here whether or not it is right to send people into space for an asteroid mining mission, and what conditions must be met before we should do so.

To evaluate the risk to humans in space, we must consider objective measurements of environmental conditions, their effect on crew’s health, the pre-flight health of crewmembers, the expected losses to their health, and the nature of the tasks required in the mission. Informed consent is imperative, but not always sufficient. Future missions require a comprehensive study of these factors. Additionally, potential crewmembers should be made aware of all findings to ensure they have a clear appreciation of the risks, hazards, and implications of agreeing to participate in an asteroid mining mission. While it is often difficult to assign numerical values to lost health, metrics such as years of life lost (YLL) and years lost to disability (YLD) must be factored into a model calculating disability-adjusted life years (DALYs: one DALY equals one year of full health lost). Only then can compensation of individuals on the mission be fair and in proportion to the risk and personal sacrifice (Browning, 2004).

Another vital question raised in the context of asteroid mining is that of planetary protection. One scientific hypothesis for the origin of life on Earth is that it began when microbes hitchhiking on a meteorite collided with the planet (O'Leary, 2008). It is conceivable that backward contamination – that is, bringing microbes from asteroids back to Earth – could occur when bringing ore back from an asteroid mining mission (Crosby, 2009). These microorganisms, to which we have had no evolutionary exposure, might pose a threat to our immunities or to those of other organisms on Earth, thereby threatening populations, ecosystems and the integrity of the biosphere. Caution must be exercised, for example, through irradiation and chemical sterilization, to ensure that no extraterrestrial organisms are imported back to Earth (Recommendation IX).

4.3 Social Aspects of Sending Humans

Wherever humans travel, we export with us our societal and cultural paradigms. Social hierarchies, career cultures, gender and national cultures are but a few examples of social constructs that affect the social dynamic of the crew in an asteroid mining mission (Kanas and Manzey, 2008). Differences in these traits, group dynamics, power structure and so forth, may give rise to interpersonal conflict in an isolated, long-duration setting. This would reduce crew productivity and performance at best, and at worst could jeopardize mission success. To minimize these issues and to aid the crew in productive cohabitation, a code of conduct for crewmembers is necessary. Ideally, this code should address daily living, professional conduct, safety, privacy, and harassment. It should also reference current legal practices dealing with
conflict and criminal behavior in space. Sexual congress between crewmembers will be discouraged in light of the social stress such relations can place upon the crew, such as conflict and/or pregnancy. However, with multiple missions and the “fishbowl effect” of the spacecraft, such an eventuality may occur, and medical and psychiatric support must be available.

Proper crew selection will be essential. Additionally, the crew should receive pre-flight training in recognizing and dealing with common psychosocial phenomena experienced in such isolated environments. Communication techniques, conflict resolution skills and intercultural proficiency and sensitivity must be addressed (Kozarenko and Holland, 2003). Candidates should be selected based on select-in criteria (such as leadership experience and temperament) to endure the significant psychological stress, isolation, confinement, and crew dynamics inherent in such a mission (Clement, 2005). Ideally, crewmembers would score high in conflict resolution skills, with ground-based counseling available for incidents in-flight that cannot be resolved internally. Isolation of the crew from society and family will be especially pronounced in long duration missions. Frequent correspondence will help maintain crewmembers’ feeling of connectedness. A variety of pre-recorded media and entertainment, mentally stimulating activities, meditation and exercise programs will be carefully coordinated to minimize these risks.

The term built environment describes the design, construction, management and use of man-made surroundings and how they impact the human activities within them. (Knight and Ruddock, 2008). An interdisciplinary approach to spacecraft design incorporates architectural, engineering, ergonomic and psychological inputs for the built environment to create a space that optimizes worker productivity and minimizes psychological distress and monotony. For example, special lamps mimicking the sun’s rays at particular wavelengths of light, used in the treatment of seasonal affective disorder (SAD), have shown efficacy in improving mood, productivity, and in helping to recreate diurnal cycles aboard spacecraft (Clement, 2005). Ergonomic design of work consoles has the two-fold purpose of making work easier and maintaining musculoskeletal health. Sinuous ergonomic architecture, often depicted in science-fiction films, presents a marriage of form and function, creating a healthy work and living space that is pleasurable to live in. In addition, such architecture should facilitate privacy that is integral to maintaining appropriate personal boundaries and positive crew dynamics. A dual-use space that functions secondarily as a meditation chamber with audio and light capabilities would promote crew mental health and peace of mind. Finally, spacecraft decor could include cheerful colors and changing imagery of Earth’s landscapes, thus minimizing Earth-longing.

4.4 Medical Aspects of Sending Humans

4.4.1 Microgravity

To maintain the advantages of using humans and to ensure productivity, consideration must be given to sustaining crewmember health. Of all the challenges to human life in space, none impacts so wide a number of systems as microgravity. Weightlessness poses physiological challenges to cardiovascular, musculoskeletal, endocrine, immunological and neuro-cognitive systems. Developing specific countermeasures is necessary to minimize harmful side effects. While life sciences research is beginning to elucidate a general framework of trends and understanding, it is important to note that only one human, Valeri Polyakov, has exceeded one year in continuous spaceflight (New Mexico Museum of Space History, 2010). Consequently, it is difficult to extrapolate data for use in models of longer missions.
4.4.2 Cardiovascular

One of the first bodily changes to occur in microgravity is a shift of fluids from the lower extremities to the head. This phenomenon also results in decreased plasma volume and down-regulation of red blood cell production, a phenomenon referred to as physiological anemia (Clément, 2005). Countermeasures include the use of pressure garments and lower body negative pressure devices during flight, and fluid loading just prior to Earth re-entry. In addition, significant cardiac deconditioning occurs in microgravity and would likely be detrimental over a long-duration mission. Current exercise regimens aboard the ISS are typically two one-hour sessions of exercise per day, approximately five hours of moderate intensity aerobic exercise per week with the remaining time committed to resistance exercises (Trappe et al., 2009).

4.4.3 Musculoskeletal

Muscle atrophy and bone loss in microgravity are major obstacles for long-duration spaceflight. In microgravity, muscles lose mass, volume, and strength. Specifically, muscle mass decreases by 10-20% during short-duration missions and losses of up to 50% are projected for long-duration missions without additional countermeasures. Current approaches to counteract this include dietary supplements, a variety of exercises (treadmill for aerobic power, cycle ergometer for aerobic capacity, resistive elastics for muscle strength and retention of bone minerals), and the Russian-developed “penguin” suit for continual axial loading of the legs (Clément, 2005).

Microgravity also affects bone structure. Bone remodeling and mineral deposition is proportional to the forces placed on the bone according to Wolff’s Law (Wolff, 1986). No longer supporting its own weight against the force of gravity, the body begins to excrete what it perceives as excess calcium from the body. This calcium, however, is what provides the bones with their strength and structure. Astronauts in space experience bone loss at a rate of approximately 1-2 percent per month. The normal rate of bone loss in persons over the age of 45 is about 0.5 percent per year. Some space-faring individuals have experienced bone loss at a much higher rate, returning to Earth with a 20 percent bone loss after just a six-month mission. In addition, astronauts continue to experience bone loss for several months after the mission. Bone loss at a rate of 1-2 percent per month in space places astronauts at a much greater risk of bone fracture and injury. This is especially dangerous if an astronaut were to break a bone during flight, perhaps due to the physical exertion of an EVA. Moreover, excessive amounts of calcium mineral leaving the bones could lead to kidney problems in long-duration missions. Recommended countermeasures for bone loss include therapy, nutrition, exercise, and pharmacological measures such as alendronate and vitamin D (Clément, 2003). Research into additional countermeasures is recommended for this area if a long-duration asteroid mission is to be undertaken.

4.4.4 Endocrine

Endocrine subsystems, especially those regulating bone and muscle remodeling, undergo changes in microgravity similar to those that are part of the natural aging process (Strollo, 2000; Biolo et al., 2003). In contrast, these changes are reversed within months of return to Earth. When considering human involvement in asteroid mining missions, further study of the biological effects of prolonged changes in hormonal cycles and levels is required. Russian researchers examining male rats in microgravity demonstrated that reduced loading of their
musculoskeletal systems in microgravity reduced serum testosterone levels and those of other growth hormones (Kaplanskii et al., 2003). In addition, tests conducted on female mice have revealed perturbations of the estrous cycles and significant decreases in estradiol levels after only eight days in microgravity (Harm et al., 2001). Reduction in sex hormone production is an important factor contributing to the inhibition of growth and to the eventual atrophy of muscles mentioned above.

4.4.5 Immunological

The human immune system is an overwhelmingly complex orchestration of cells, signals and other elements further complicated by the multifactorial impacts of the space environment. Harmful radiation, microgravity, and the relative lack of microbial diversity onboard the spacecraft provide a challenge to the immune system unlike any encountered in our history. As demonstrated by Sonnenfeld et al. in 2002, there are significant decreases in cell-mediated immune responses, including leukocyte proliferation and cytokine production, after exposure to microgravity, resulting in “immune compromization”. Cosmonauts’ T-cell counts decreased during 75-185 days of space flight (Konstantinova, 1991; Legenkov and Kozinets, 1996).

Other factors contributing to these changes in immunity include stress, neuroendocrine factors, sleep disruption, and nutrition (Sonnenfeld et al., 2003). These findings are corroborated by data from analogous ground-based bed-rest studies of humans and experimental animals (Sonnenfeld, 2005). These decreases in immunity are especially worrisome in light of studies conducted by Juergensmeyer et al. in 1999, demonstrating an increased rate of bacterial resistance to antibiotics in microgravity. Given that bacteria multiply and mutate at a much greater rate in microgravity, we must explore the possibility of the evolution of a virulent superbug impervious to the available antibiotic arsenal in the context of possible long-duration asteroid mining.

4.4.6 Radiation

The space environment beyond the Earth’s magnetosphere exposes humans and equipment to a variety of harmful radiation, including galactic cosmic rays (GCRs), ionizing radiation, and solar particle events (SPEs). Radiation exposure is a serious issue for asteroid missions, raising concerns about cancer, infertility, and other such issues. Current practices include several approaches to reducing the effects of this exposure. Pharmacological countermeasures are comprised of two main groups: antioxidants that nullify the effects of harmful free radicals generated by ionizing radiation, and radioprotective drugs. Examples of these drugs include WR-33278 that binds DNA, and Lazaroid that protects neurons. These bolster inherent defenses or strengthen points particularly susceptible to radiation in the cellular machinery (Clément, 2005). Multiple types of shielding are key to protection. SPEs may last from hours to days, but require mere centimeters of shielding, while GCRs are constant, requiring several meters of shielding to achieve complete blockage. The methods of shielding are diverse. For instance, storm shelters provide transient respite from SPEs aboard spacecraft. Also, for protection against GCRs, magnetic shielding, currently still in development, is a potential solution (Clément, 2005). Current research is exploring other novel modes of radiation protection. For example, some researchers have focused on developing techniques for shielding selected subpopulations of bone marrow cells with the ultimate effect of increasing one’s lethal radiation threshold.
Crew selection is also important. Older persons can sustain greater exposure to radiation than their younger colleagues can. That is to say, older people have increased carrier-dose equivalents. The average cell cycle of older persons is slower in a variety of tissues, which makes them less susceptible to radiation effects on cellular division (Bird, 2010). The NASA-defined acceptable limits of exposure aboard the ISS measure 10 times the allowable yearly dose of a nuclear power plant worker (Clément, 2005). In projections for lunar colonies, predictions state that crewmembers would exceed this dose within 4–7 months (Cucinotta, 2010). All current designs for human missions to asteroids using current technologies exceed this limit, rendering such endeavors infeasible at present.

4.4.7 Asteroidal Dust

Lunar dust, also referred to as regolith, is characterized by its fine particulate nature, jagged edges and greater chemical reactivity relative to terrestrial analogs. Thus, it is also more abrasive. These properties render regolith a considerable threat to crewmembers’ pulmonary, nervous and cardiovascular systems. Asteroidal dust covering mechanical surfaces might also greatly reduce the efficiency of thermal radiators and solar arrays. Admittedly, little is known about the surface of asteroids, but the moon serves as a close analog of an airless celestial body. It is reasonable to assume a high probability of encountering dust on an asteroid, which may have similar qualities and pose similar threats to the astronauts and equipment.

More data concerning the characterization of asteroid surfaces is required. For instance, it is unknown if smaller asteroids retain regolith due to their low gravitational fields. For example, current research suggests that most, if not all, regolith is transferred from smaller asteroids to larger ones in the event of a collision (Matson et al., 1977). One proposed solution to avoid regolith import into the living areas of the spacecraft is the use of suitports. An alternative to the airlock, the suitport acts as a docking station where EVA suits are attached and sealed externally (NASA, 2010c). To perform an EVA, crewmembers must first enter the suit from inside the rover or habitat volume, close and seal the space suit and the rover’s hatch, and then unseal and separate the suit from the rover. Further solutions may include improvements in mechanical articulation design to minimize areas where dust may become lodged, and improvement to the positioning of radiators and solar arrays on spacecrafts and spacecraft joints to minimize the need for frequent dust removal.

4.5 Human Factor Analysis Conclusion

The prospect of adding humans to an asteroid mining mission affords enhanced performance, adaptability, and decision-making capabilities. These traits are especially valuable when dealing in the high costs of space related activities. We can further enhance these skills. The partnership of humans and robots suggests greater potential than either mode alone, allowing for greater possibilities in productivity, precision, and performance. Future research focusing on this collaboration will be integral to enabling missions of this stature (Recommendation X). While shorter duration missions are feasible with current technology, improvement in countermeasures should be made in order to undertake long-duration spaceflight (Recommendation XI). The trade-off study incorporates these considerations when comparing human and robotic missions.
5 SOCIETAL ISSUES

Asteroid mining, once it becomes a reality, will have a profound impact on society at large. Historically, the discovery of new sources of wealth has brought severe social changes, affecting society in multiple ways. With recognition that priorities and values have shifted over time, we know it is important to understand how this new source of wealth will change society. History is rife with examples of the introduction of new wealth and the effect to society has not always been positive. For example, the discovery of the New World led to slavery and war. Also, beginning in the Middle Ages and continuing until the last century, the discovery of oil as a new energy source revolutionized the world (Karl, 2007). What were the side effects that this brought to the face of history? One piece of the picture is the abuse of human rights, oppression, monopolies, lobbying, and dangerously increased power concentrated on a few people (Trujillo, 1996). On the other hand, progress also brings prosperity, new opportunity, and chance for positive change. The question to address, particularly when exploration has monetary incentive as one of its primary objectives, is if this darker face of humanity must be present to achieve our aspirations for asteroid mining.

This section focuses on the social challenges resulting from asteroid mining, ranging from changes in social classes, to the impact on developing countries, to ethical, environmental and health issues. Public support of asteroid mining, achieved through a robust outreach program, is also critical to its success.

5.1 Changing Social Classes

Traditionally, the working class has carried out physical labor such as mining, while spaceflight has been the domain of academically trained astronauts. The choice of title and type of training for asteroid miners requires careful consideration, since it carries potential to re-shape the scope of occupational social status at both extremes. There can be a decrease in prestige associated with human space flight. Conversely, the social position of mining workers could be elevated. Predictions are difficult at this stage, but it is clear that these are important policy considerations. Therefore, we must consider and prepare for the socio-economic implications of human laborers in space.

5.2 Employment and Developing Countries

Platinum is an extremely rare metal in Earth’s surface, having an average concentration of three parts per trillion (Cohen, 2007). The primary producer of platinum is the Republic of South Africa, who serviced over 80% of the market in 2005 (George, 2007). Corporations such as Anglo American PLC, the largest private sector employer in South Africa, mine its platinum. It is likely that many workers would be left unemployed, should terrestrial platinum be undercut in the global market. This would exacerbate the existing situation of 24% unemployment (CIA, 2010). However, the overall economic impact would be minor, since the production of platinum accounts for approximately 2% of South Africa’s Gross Domestic Product (GDP); South Africa also exports numerous other natural resources.
Developing countries are frequently lagging behind in exploration ventures. In terrestrial mining, private companies from industrialized countries are the major players, and in some African countries, the only players (MiningReview.com, 2010). It is clear that the exploitation of resources in space has potential to leave behind the developing world while elevating the wealth and technology of only those nations rich enough to participate. To ensure that the space environment is used to the benefit of all humankind, it is necessary to avoid inequalities. An obvious step towards realizing this goal is cooperation, transparency, and technology transfer between major space-faring nations and the developing world. In an asteroid mining venture, it is important for developing nations to understand how they would benefit directly from participation. A positive step is investment in geology, mining and engineering faculties of universities in Africa. This will develop local capacity for involvement of Africa in the future asteroid mining industry. The United Nations Office for Outer Space Affairs (UNOOSA) has set up regional centers for space science and technology education for indigenous capacity building in developing regions. These centers currently run programs in remote sensing, satellite communications, satellite meteorology, and basic space science (ARCSSTE-E, 2007). These centers could further improve their curriculum by introducing courses covering asteroid mining.

5.3 Ethical, Environmental and Health Considerations

The mining industry produces negative environmental consequences. Platinum salts, when inhaled, cause severe respiratory dysfunction for mine workers, and extraction of alluvial deposits of platinum can cause water pollution (Pepys, 1972). Safety precautions are available for these issues, but are not frequently employed. The sale of platinum, however, also has positive environmental consequences. In 2006, for example, 54% of all platinum sold was employed in control devices for automobile emissions, such as catalytic converters (George, 2006). The environmental benefits of platinum production, therefore, are far greater than the costs. Asteroid mining, being a possible means of decreasing the price of platinum, can enhance the efficiency of devices that now employ an inefficient mixture of platinum group (and other) metals. (NSLS, 2010). Platinum is also integral to the construction of hydrogen fuel cells, which can be of great benefit to the environment by enabling the use of hydrogen as a substitute for carbonaceous fuels (Vielstich, 2003). The environmental risks imposed by asteroid mining are less than those imposed by terrestrial mining, and are much more likely to be regulated by governments due to the high profile and international nature of asteroid mining activities.

Occupational health and safety of miners on Earth is discussed in studies such as the one performed by R.S. Roberts in 1989 (Roberts, 1989). This study details the associated risk of respiratory and kidney cancer for the mining of nickel. The use of mercury for processing metals during the mining procedure is associated with cardiovascular disease (Boffetta, 2001). The ethics of exposing humans to unknown chemical mixtures in asteroids and possible microbiological organisms requires examination, and a human risk assessment is essential.

5.4 Outreach and Convincing Policy Makers

Public outreach is an important method of providing information to both the general public and stakeholders. Outreach is required to promote understanding of the venture, and to encourage social and financial investment. There are two ways to provide the information to the public,
indirect outreach through the media and direct outreach. When considering indirect outreach through the media, the Internet is the most effective tool for any generation; however, there are some differences among generations and the medium they prefer. As age increases, TV, radio, newspaper and magazine become the more effective medium (Figure 5-1). Conversely, a younger demographic has tendencies towards using Internet as the preferred medium (Forrester Research Inc, 2009). Moreover, educating the younger generation is also very effective.

![Media consumption – hours per week](Forrester Research Inc., 2009)

In terms of direct outreach, providing information in person, planning and operating events, and delivering pamphlets are effective means. The advantage of direct outreach is that there is less opportunity to misunderstand information. When approaching potential stakeholders, direct outreach is more efficient. Cost-effectiveness is an important consideration. For example, TV advertisement is very effective, but also expensive. International collaboration between agencies, universities, and industry could provide the necessary framework for the dissemination of information. Awareness across all these areas is key to obtaining the required support of policy makers. It is necessary to develop an effective communication plan to identify the audience, choose an appropriate means of dissemination, and deliver the message.

### 5.5 Societal Issues Conclusion

The immediate societal impact of asteroid mining is the adjustment of the worldwide market of raw materials. The availability of asteroid raw materials will change the landscape of the traditional mining industry. Communities or countries dependant on mining may lose part of their economic basis, or be forced to adopt more efficient operations. Still, asteroid mining as a profitable space venture will result in a developmental boost. New opportunities will arise, ideally leading to increased quality of life. Since a favorable opinion is a key factor to success, these profound changes need to be accompanied and facilitated by public outreach. In this frame, team ASTRA recommends initiation of a public outreach program to gain public support, so that policymakers shall be proponents of asteroid mining (Recommendation V). In addition, in order to insure the support of nations currently relying on mining, stakeholders should inform them on the benefits they would gain from asteroid mining (Recommendation VI).
6 MISSION CONCEPTS

Asteroid mining, being a new proposal for the space industry, requires a more detailed characterization of the NEAs in terms of their sizes, orbits, and compositions. It also requires the development and demonstration of new technologies for the realization of these concepts. The concepts defined in this section will assist in the development of mission architectures and the interdisciplinary roadmap.

6.1 Remote Sensing

We recognize that many asteroids have never been observed. Since NEAs emit radiation mostly in the infrared band, an all-sky survey by an orbiting satellite in this band presents itself as a useful tool for NEA discovery. The Wide-Field Infrared Survey Explorer (WISE), is a useful model for Earth-orbiting platforms for asteroid discovery, but has been limited to detection of Main Belt asteroids larger than three kilometer, with a projected ten month lifetime (NASA, 2010e). Search for asteroids was not the primary priority of the WISE mission, and suffered as a result. This is unfortunately typical of NEA searches as well. Follow-on missions that address this problem include the NEO Survey Observatory (Reitsema, 2009). The NEO Survey Observatory is proposed to rest in a Venus-trailing orbit and observe a broader swath of the solar system than can be observed from Earth. Three such spacecraft, properly placed in heliocentric orbits separated by 120 degrees, would be able to observe the entire near-Earth orbital region simultaneously. In addition, NASA has proposed enhancements to the WISE data pipeline to facilitate more accurate and comprehensive data collection with respect to NEAs (NASA 2010d). Missions of this type will solve some of the science challenges mentioned earlier; those having to do with asteroid characterization in terms of size and orbital parameters.

6.2 Fly-by

A fly-by can perform stability tests (distinguishing between loosely bound agglomerate asteroids and monoliths) and penetrometry, the study of subsurface composition by examining penetrator impact (Craig, 2010). We can use fly-by missions to characterize favorable asteroids and test new technologies for asteroid grappling after they have outlived their scientific utility. NEAR-Shoemaker (NASA, 2010b) touched down on the surface of 433 Eros, so it is feasible to use such an end-of-life maneuver to test asteroid tethering techniques. In so doing, fly-by missions will not only satisfy scientific challenges, but develop technologies useful to asteroid mining.

6.3 Sample Return

A comprehensive program of asteroid remote sensing and fly-bys will produce an immense quantity of scientific data and a limited study of engineering principles for application during asteroid activities. The next logical step in augmenting our knowledge of asteroid composition, especially the composition of sub-regolith materials, is the return of a large sample from an asteroid. Existing precursor missions include Hayabusa, the first of its kind (JAXA, 2010). Proposed missions include Phobos-Grunt, a Russian sample return mission to the martian
moon Phobos. While these missions have been oriented mostly toward scientific goals, we will alter future missions will to include demonstration of technologies. One proposed solution to the challenge of remaining attached to an asteroid for a long duration is to attach a spacecraft or tether to the surface of an M- or S- type asteroid using a magnet. We can test magnetic attachment of this type in future sample return missions. It is also possible to augment future missions to include demonstration of volatile extraction or carbonyl processing on a small scale. It will also be possible to test much simpler systems, such as a mechanism for returning samples inside otherwise empty fuel tanks. We can also use these technologies to increase mission duration. If, for example, we were able to produce fuel or coolant through volatile extraction that is in excess of the initial mission budget, we could increase the overlap between fulfillment of scientific objectives and accomplishment of engineering goals.

6.4 Launching a Spacecraft

We could employ a single launch or multiple launches for the mission. If we design the asteroid mining spacecraft appropriately so that the dimensions are suitable for a single launch, assembly in LEO would not be necessary. However if a heavier vehicle is needed for transporting all of the necessary equipment, multiple launches would be required. In the latter case, we would need to assemble multiple parts of the spacecraft in LEO either by humans or robotically. Then we could transfer the assembled vehicle to the asteroid. Another possibility would be to launch several vehicles separately to the vicinity of the asteroid where they would dock at several access points in order to perform surface operations such as the installation of thrusters or the mining itself.

6.5 Approaching the Asteroid

After transferring spacecraft to asteroid vicinity, it is imperative that the spacecraft enters the same orbit as the asteroid. We refer to this maneuver as a rendezvous. Subsequently, if the asteroid is small enough relative to the spacecraft, we attach it to the vehicle and we transport it to a desired location such as LEO. A discussion of penetrometry techniques as well as the Philae Lander has been documented (Paton, 2006). Another option would be to land on an asteroid and install thrusters at several locations of asteroid surface as an alternative propulsion method. For large asteroids, that we cannot transport whole, landing the entire spacecraft is the only considered option.

6.6 Surface Operations

Once we return the small asteroid to a location in Earth vicinity, we deliver the necessary crew and equipment from Earth to its surface for the purpose of mining operations. The requirements of this type of crewed mission have been assessed (Korsmeyer, 2008). In the case of a large asteroid, mining would have to be performed in-situ utilizing only the equipment that has brought as part of initial mission.
6.7 Processing and Transfer of Asteroid Material

For a small asteroid, there is the potential to bring the extracted material to the Earth’s surface for processing. For a large asteroid, at least partial processing would need to be performed in-situ for the minimization of return-payload mass. Technology employed for the transfer of asteroid material to the Earth would depend on the mass and composition of returned payloads. We can return an entire small asteroid, large pieces of it, or a payload of partially processed ore.

6.8 Technology Development and Testing

The development of technology for this mission requires extensive progress in the field of robotics. There are several ways to meet the challenges of developing systems for autonomous mining, material collection, and processing in the hostile environment of space. Firstly, for the mining system technology development, the physical composition of the asteroid will determine some of the constraints for the systems design. The physical components of the mining equipment require specific material properties to successfully mine while maintaining long-term durability for the mission. Collection of the ore as well as protection of the machinery from floating debris and dust is a prime consideration.

The chemical processes used as part of the mining system should be reliable and safe. The functionality of this equipment and the consistency of physical and chemical reactions should be tested in a microgravity environment. Performing experiments using a series of microgravity flights could validate asteroid mining technologies. Numerical modeling and ground based experimental testing can aid in the development of optimal equipment-design. We can perform iterative testing to effectively develop and improve these designs until they are ready for use in the space environment itself. The final stage of testing for the technology is a test mission to a small asteroid or possibly even the Moon. At these locations, we can perform tests on a small scale in order to validate the robustness and reliability of certain equipment. We can also demonstrate techniques such as drilling, tunneling, strip-mining and excavating. This kind of mission will be the ultimate test in verifying the functional capabilities of the developed technologies and their design.

6.9 Mission Concepts Conclusion

We must consider the main concepts outlined in this section for the feasible design of an asteroid mining mission. Since each mission stage needs to address a specific challenge, the design of architectures should adopt techniques based on the mission concepts identified. The existing initiatives for NEO exploration from space and scientific agencies around the world provide a robust platform for the study of asteroid mining engineering solutions as well as the collection of scientific data necessary to perform such activities in the future. We can assess the engineering requirements of these concepts based on the current and predicted technology-readiness-levels. We must quantitatively assess the feasibility of returning a small asteroid to the vicinity of the Earth using current technology. Even if this does eventually become technically feasible, the safety issue of how to ensure that the asteroid does not hit the Earth would remain. In the next section, we will establish a set of architectures based on these mission concepts.
7 LIST OF ARCHITECTURES

To complement the trade-off process, a set of architectures are required to assess the economic viability of various combinations of the mission concepts. After extensive consideration of the engineering challenges presented, the mission concepts were established. Based on these mission concepts we defined a set of suitable architectures. The discussions also took into account potential technological capabilities. Each architecture constitutes the various mission stages including the launch, choice of asteroid size, transport options, use of humans and robots, mining technology, and resource exportation.

7.1 Explorer Mission Architectures

Before discussion of the framework for the mining mission, we must define several architectures for the explorer missions. These missions aim to acquire scientific data on candidate asteroids. Each explorer mission architecture has an increasing number of data acquisition steps in which the costs of these steps correlate with the level of accurate scientific data obtained, the minimization of risk and the potential return on investment of the mining operations. Below we describe three of these explorer missions:

Architecture E1: This architecture begins with the examination of the NASA Jet Propulsion Laboratory database, analysis of meteorites, review of previous missions and analysis of Earth analogs. The next step is an Earth-based remote sensing mission and a subsequent space-based remote sensing mission. Their objective is to obtain detailed data on the topography and physical properties of asteroids.

Architecture E2: This architecture is identical to E1 with the additional stage of further fly-by missions for a number of asteroids.

Architecture E3: This architecture is identical to E2 with the additional element of sample return missions and potential human missions for scientific analysis of asteroids.

7.2 Concept Map

The process of creating the mining mission architectures begins with the production of a logical concept map. We created two of these maps: for small and large asteroids. We produced each concept map by analyzing previously identified interdisciplinary challenges and identifying the associated mission stages. As an example, we present the concept map for small asteroid mining.

By tracing any path through the concept map Figure 7-1, we can define a specific architecture based on the set of stages for mission design. While we have not defined every single sequence, the most prominent ones have been set apart for consideration in the list below.
7.3 Potential Sequences

From the above framework, we separated out each possible path into a defined single-line sequence diagram. The result is eleven separate architectures; logically separating into five based on the possibility of mining a large asteroid and six based on the possibility of mining a small asteroid. Below, we have listed descriptive summaries for each of the eleven sequences. We have also included examples of the diagrammatic representations for several of these.
7.3.1 **Small Asteroid Architectures**

**Architecture S1:** This architecture involves a single launch vehicle. Astronauts set-up thrusters on the asteroid and send it back to LEO. The human crew then returns to Earth and the whole asteroid transfers to the Earth’s surface. The mission ends with transporting any re-usable technologies and equipment to a new asteroid.

![Architecture S1 diagram](image)

**Figure 7-2: Architecture S1**

**Architecture S2:** This architecture begins with a single launch vehicle to the asteroid. After robotically attaching to the asteroid, the spacecraft returns it to LEO. Next step is to launch machinery and human crew to the asteroid in LEO and transfer mined resources to Earth. Finally, we should transfer re-usable equipment to next asteroid.

**Architecture S3:** This architecture requires multiple launch vehicles to send various components for the assembly of a spacecraft in LEO. The spacecraft subsequently travels to the asteroid. Astronauts set-up thrusters on the asteroid surface and return to Earth. The thrusters propel an asteroid and place it in LEO. Additional crew launched to its surface performs mining using additional equipment bought from Earth. Afterwards re-usable equipment travels to new asteroid to repeat the process.

**Architecture S4:** This architecture requires multiple launches. Each spacecraft arrives at separate locations on the selected asteroid. Then, robotically installed thrusters return the asteroid to LEO. Machinery and crew launched to the asteroid return to Earth along with extracted resources after the mining process is complete.

**Architecture S5:** This architecture requires multiple launch vehicles to send various components for the assembly of a spacecraft in LEO. The spacecraft travels to asteroid, attaches to it, and brings it back to LEO. Machinery and crew launched to the asteroid return to Earth along with extracted resources after the mining process is complete.
Architectures S5: This unmanned architecture requires multiple launch vehicles to bring spacecraft components for assembly in LEO. The integrated spacecraft travels to an asteroid. The thrusters attach to the asteroid to return it to LEO for ease of access with further operations conducted from Earth. We transport the whole asteroid to the Earth's surface where we perform the mining and processing operations.

7.3.2 Large Asteroid Architectures

Architecture L1: This architecture requires multiple launch vehicles for robotic assembly in Earth vicinity. The crewed vehicles launch into LEO and transfer to the asteroid to set-up mining equipment before returning to Earth. Robotic mining takes place in-situ. There is robotic transfer of the mined material to Earth vicinity where processing takes place before delivery to Earth.

Architecture L2: In this architecture, multiple vehicles launch to LEO and human-crew assembly of the spacecraft takes place in orbit. The spacecraft travels to the asteroid. After setting up mining equipment on the asteroid, the crew returns to Earth and autonomous robotic mining and processing takes place in-situ. Delivery of extracted materials to Earth ensues.
Architecture L3: This unmanned architecture requires robotic assembly of multiple vehicles launched to LEO. The assembled spacecraft travels to the asteroid. The setup of mining equipment, the mining itself, and the processing of the mined materials is all performed robotically. The delivery of extracted materials to Earth follows.

![Image](image_url)

**Figure 7-5: Architecture L3**

Architecture L4: The main characteristic of this architecture is that it requires heavy-lift equipment. The crew set-up the mining equipment as well as perform the mining itself. The processing of mined materials takes place *in-situ*. The materials and crew return to Earth.

Architecture L5: This architecture is identical to Architecture L3. The only difference is the use of explorer missions as precursors to the main mission.

### 7.4 Study of Small Asteroid Return

The feasibility of transferring a small asteroid into Earth vicinity depends on the required type of propulsion, propellant mass, and time of transfer. The team assumes an idealized hypothetical small asteroid in a circular orbit around the Sun, with an orbit radius of 1.0443 AU, sharing an orbital plane with the Earth. We select this radius to be in the region of high asteroid density, according to Figure 2-3. We calculated an approximate asteroid mass of 500,000,000 kg, which corresponds to the lower limit of detectable bodies using current technology. Change in velocity is a common parameter used in trajectory design, and we refer to this as $\Delta V$. The following calculations present the transfer $\Delta V$ and propulsion requirements for an example asteroid.

#### 7.4.1 Hohmann transfer of small asteroid to Earth vicinity

A low-energy Hohmann transfer between the circular asteroid orbit and the Earth orbit requires two thrust maneuvers. The first thrust maneuver injects the asteroid into a transfer ellipse towards Earth; the second thrust maneuver is required to inject the asteroid into Earth orbit. For the assumed asteroid, an overall $\Delta V$ requirement of 3.39 km/s for both thrust maneuvers is calculated (0.24 km/s for the first thrust maneuver and 3.16 km/s for the second thrust maneuver). The $\Delta V$ requirements are independent of asteroid mass. The transfer time equates to approximately 6 months.
Taking the low $\Delta V$ requirement of 0.24 km/s for the first thrust maneuver as an example, the team estimates the fuel required to achieve this acceleration for the example asteroid. We assume that an engine similar to the Space Shuttle main engine has a specific impulse of 450 s and a thrust of 2,500,000 N (Pratt & Whitney, 2010). Using the rocket equation and the relation between specific impulse, mass flow rate, and thrust, we find that the required fuel mass is approximately 28,000 tons and the engine burn time is 14 h. Since this fuel requirement is not feasible, and it only considers the first thrust maneuver, we need to investigate different options. In particular, we can consider long term, low-thrust options, potentially with high specific impulse for their economical use of fuel.

### 7.4.2 Low-thrust transfer of small asteroid to Earth vicinity

We characterize a low thrust transfer by continuous acceleration, at a relatively low rate. Using the Edelbaum approach, a relation between continuous thrust and transfers time is obtained (Gaylor, 2002). We have illustrated the results found for the example asteroid in Figure 2-3. Current technology, such as the NSTAR low thrust engine, can provide approximately 0.05 – 0.1 N of thrust (Boeing, 2010b). To achieve economical transfer times (one to several years), continuous thrust in the kN domain is required, see Figure 7-6. This would require on the order of 50,000 NSTAR ion engines.

![Figure 7-6: Transfer times of several years and the required continuous thrust](image)

From this small case study, it is clear that we will need to achieve significant technological advances in order to consider the option of transporting a small asteroid to the vicinity of the Earth. If much smaller asteroids can be detected then low thrust transfers may be suitable.

### 7.5 Architecture Conclusion

By creating a framework and defining the individual architecture sequences, the trade-off team will be able to move forward with the analysis of each architecture to select the single most viable option. We complement this with the performance of a detailed technical analysis on the feasibility of returning a small asteroid. We designed these architectures to be at a conceptual level, allowing broad discussions on the potential viability of each option. The technology readiness level (TRL) is a prime parameter for consideration by the trade-off team. In addition to these criteria, we also assess the explorer missions based on the required investment and of the minimization of risk.
8 TRADE-OFF STUDY

This section presents the trade-off study to select an asteroid mining architecture by analyzing a proposed set of candidate architectures. The first section lists several methods and identifies the most suitable for this trade-off study. The second section provides a summary of the results of the first-level trade-off study leading to preferred architecture options for mining large and small asteroids respectively, and a second-level trade-off study between these two options, which leads to the proposed baseline architecture.

8.1 Trade-Off Process

The trade-off study is a process to choose the optimal architecture option out of alternative architectures. The trade-off study steps are: Define the problem, establish a trade-off method, select alternative solutions, determine the key characteristics of each alternative, evaluate the alternatives and finally choose the optimal solution. The architecture options were distinct in the way that a comparison between mining a large asteroid and multiple small asteroids was possible. Determining what is optimal is defined as the global optimum in view of the aspects of cost, risk, performance, and schedule. The architecture must also meet the requirements of the stakeholders of the project, (see Section 1). The trade-off study process began with identifying existing methods and selecting a suitable method.

8.1.1 Review of Trade-Off Study Methods

The axioms of a trade-off study (INCOSE 2000, Dennis et al. 2004) form the basis of the trade-off study process. Edwards (1971) introduced the Simple Multi-Attribute Rating Technique (SMART). SMART is a systematic method that scores and assigns weights to the attributes of decision alternatives to provide the optimum solution. This technique is simple, transparent, speedy, and robust but not suitable for complicated decisions. Unlike many black-box methods for decision-making, SMART provides a clear understanding of the nature of the problem (Dennis et al. 2004). The stages of the SMART method are:

- Identify the decision maker(s)
- Identify the alternatives
- Identify the attributes relevant to the different alternatives
- Assign scores to measure the performance of each alternative
- Determine the weight of each attribute
- Take a weighted average of the values assigned to that alternative, make a provisional decision
- Perform a sensitivity analysis

Other reviewed methods include the Elimination By Aspects (EBA) method (Tversky 1972), the Theory of Innovative Problem Solving (TRIZ) (International Council on Systems Engineering, 2000; Dennis et al. 2004), and the NASA System (NASA 1995).

A SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis is an important method in a trade-off study for asteroid mining and can simplify the complex problem of asteroid mining for
the main architecture options, such as:

- Human versus robotic missions
- Asteroid return versus in-situ mining
- Use of mined material in space versus use on Earth
- Carrying fuel for return versus in-situ fuel generation for return flight
- High-thrust, short-duration propulsion versus low-thrust, long-duration propulsion

The SWOT analysis is based on internal and external factors. Internal factors are those such as performance, cost, period, and risk, whereas external factors are those such as safety, security, and market prospect.

### 8.1.2 Trade-Off Study Method for Asteroid Mining

The best way to make an effective trade-off study is to evaluate the most detailed parts of the architecture and to break down a low-level attribute list for each alternative. Moreover, the evaluation process should be timely, appropriate for the needed decision, set-up properly, robust and complete (Dennis et al., 2004: ASME International 2010).

Based on the studied methods, the team decided to execute the trade-off study utilizing a customized SMART method, which would be suitable to the level of detail of the architecture options. A SWOT analysis supported the trade-off study to decide between human and robotic missions.

### 8.2 Trade-Off Study for Asteroid Mining

The team used the architectures developed in the conceptual phase and divided the trade-off study into three phases:

1. SWOT analysis of robots versus humans
2. First-level trade-off study
3. Second-level trade-off study

The first-level study considered three architectures for asteroid identification and characterization, six architectures for small asteroid mining and five architectures for large asteroid mining. The second-level trade-off study examines the trade-off between the two preferred options from the first-level trade-off study for mining a large and multiple small asteroids.

#### 8.2.1 SWOT Analysis - Robots versus Humans

In the scope of this team project, we conducted a SWOT analysis for robots versus humans in the context of asteroid mining. Table 8-1 summarizes the results. The team concluded that a human-only mission to mine asteroids is not preferred because of the huge complexity, risks and costs involved. A fully autonomous robotic mission or a hybrid approach requires further study.
## 8.2.2 First-Level Trade-Off Study

### Trade-off study on architectures of asteroid identification and characterization

The objective of asteroid identification and characterization is to gather sufficient scientific information and characterization of identified NEO asteroids for mining in a cost effective way to ensure minimum time to market. Cost, scientific information, and safety factors emerged as the major attributes. We analyzed three architectures (E1, E2 and E3), described in the previous section. Table 8-2 shows the distinguished features of these architectures. From these features, we deduced a scoring table (see Table 8-3). The key point is that the addition of human missions in architecture E3 increases the cost and risk, but may not provide a proportional increase in the information acquired. The total score is best for Architecture E2 because it is an optimum combination of the features. We recommend that architecture E2 be augmented by sample return missions, because of their comparatively low cost and great potential.

<table>
<thead>
<tr>
<th></th>
<th>Robot</th>
<th>Human</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Strengths</strong></td>
<td>Lower cost and lower risk</td>
<td>Better decision making in unexpected situation</td>
</tr>
<tr>
<td></td>
<td>More endurance/durability in space environment</td>
<td>Better flexibility and dexterity over robot</td>
</tr>
<tr>
<td></td>
<td>Better technology maturity → short to mid-term feasibility</td>
<td>High adaptability, can learn from the process and can recover from certain failures → higher rate of success</td>
</tr>
<tr>
<td><strong>Weaknesses</strong></td>
<td>Lower flexibility, capability limited by original design</td>
<td>Need complex life support system</td>
</tr>
<tr>
<td></td>
<td>Lower dexterity</td>
<td>Low technology maturity</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Limited physical endurance, shorter mission duration</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Increased risk and cost to the whole mission</td>
</tr>
<tr>
<td><strong>Opportunities</strong></td>
<td>Mass production of robotic mining equipment → scalable</td>
<td>Symbol for human conquer of space (better social influence)</td>
</tr>
<tr>
<td></td>
<td>Technology applicable to other purposes (automated space colony construction, in space rescue &amp; repair…)</td>
<td>Potential leading to a new space tourism market</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Potential scientific progress / discovery</td>
</tr>
<tr>
<td><strong>Threats</strong></td>
<td>Failure of a component may affect the whole mission</td>
<td>Risk of human life loss</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Social and ethical issues</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Legal issues (new legal framework needed)</td>
</tr>
<tr>
<td><strong>Suit to</strong></td>
<td>All asteroid orbits, sizes, scientific survey, simple mining and all periods of planning</td>
<td>‘near-Earth asteroids’, more complex mining and mid to long-term planning</td>
</tr>
</tbody>
</table>

### Table 8-1: SWOT analysis of robots versus humans

<table>
<thead>
<tr>
<th></th>
<th>Robot</th>
<th>Human</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Strengths</strong></td>
<td>Lower cost and lower risk</td>
<td>Better decision making in unexpected situation</td>
</tr>
<tr>
<td></td>
<td>More endurance/durability in space environment</td>
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</tr>
<tr>
<td></td>
<td>Better technology maturity → short to mid-term feasibility</td>
<td>High adaptability, can learn from the process and can recover from certain failures → higher rate of success</td>
</tr>
<tr>
<td><strong>Weaknesses</strong></td>
<td>Lower flexibility, capability limited by original design</td>
<td>Need complex life support system</td>
</tr>
<tr>
<td></td>
<td>Lower dexterity</td>
<td>Low technology maturity</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Limited physical endurance, shorter mission duration</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Increased risk and cost to the whole mission</td>
</tr>
<tr>
<td><strong>Opportunities</strong></td>
<td>Mass production of robotic mining equipment → scalable</td>
<td>Symbol for human conquer of space (better social influence)</td>
</tr>
<tr>
<td></td>
<td>Technology applicable to other purposes (automated space colony construction, in space rescue &amp; repair…)</td>
<td>Potential leading to a new space tourism market</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Potential scientific progress / discovery</td>
</tr>
<tr>
<td><strong>Threats</strong></td>
<td>Failure of a component may affect the whole mission</td>
<td>Risk of human life loss</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Social and ethical issues</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Legal issues (new legal framework needed)</td>
</tr>
<tr>
<td><strong>Suit to</strong></td>
<td>All asteroid orbits, sizes, scientific survey, simple mining and all periods of planning</td>
<td>‘near-Earth asteroids’, more complex mining and mid to long-term planning</td>
</tr>
</tbody>
</table>
Table 8-2: Characteristics of architecture options for asteroid characterization

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>E1</th>
<th>E2</th>
<th>E3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Examine Available Data</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Earth-Based RS</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Space-Based RS</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Fly-by</td>
<td></td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Sample Return</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Human Missions</td>
<td></td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>

Table 8-3: Scoring of architectures for asteroid characterization

<table>
<thead>
<tr>
<th></th>
<th>Weights</th>
<th>E1</th>
<th>E2</th>
<th>E3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost Effectiveness</td>
<td>1</td>
<td>10</td>
<td>8</td>
<td>0</td>
</tr>
<tr>
<td>Scientific Information</td>
<td>1</td>
<td>0</td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td>Human Safety</td>
<td>1</td>
<td>10</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>Time-to-Market</td>
<td>1</td>
<td>10</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td><strong>Total score</strong></td>
<td><strong>30</strong></td>
<td><strong>36</strong></td>
<td><strong>10</strong></td>
<td><strong>10</strong></td>
</tr>
</tbody>
</table>

Attributes and scoring system for trade-off study for mining of asteroids

The cost efficiency of asteroid mining is of prime importance, and we therefore treat it as a global criterion for evaluation. Architectures should focus on the use of technologies that have high Technology-Readiness-Level (TRL) and avoid dependence on critical technologies. Consequently, the team used the following criteria during the first-level trade-off study:

- Efficiency: Resource efficiency of architecture related to cost for an identical return
- Robustness: Ability to adapt to different procedures, circumstances and parameters
- TRL of asteroid transportation systems: feasibility of landing on and attaching thrusters to an asteroid is less compared to attaching the vehicle to an asteroid
- TRL of entry systems: Entry of mined resources (less quantity) is most desirable compared to bringing a whole asteroid
- Human risk factor: Mission risk associated with the inclusion of human spaceflight in terms of potential harm to life
- Safety of Earth: Mining in space is safer than bringing asteroids to Earth
- Seamless operation: Risk related to the number of launches, stages and phases
- Cost effectiveness: Cost effectiveness as related to robotic or human missions
- Debris: The potential to create a debris hazard on Earth or in Earth orbit
- Autonomy: The ability of an architecture to operate independently from human input

The team assigned relative weights to the attributes, in the interval between zero and one. The weighting characteristics reflected the overall requirements of rendering asteroid mining profitable, cost efficient and technically feasible. The team scored architectures in a relative way in the interval between zero and ten; for each attribute, the most favorable architecture received a score of ten while the least favorable architecture received a score of zero. The team ranked each remaining architecture relative to these two values.
Trade-Off Study for Mining of Small Asteroids

We considered six small asteroid architectures from Section 7 for the trade-off study for mining small asteroids. The features of these six architectures used for scoring are in Table 8-4.

**Table 8-4: Characteristics of architecture options for mining of small asteroids**

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>S5</th>
<th>S6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multiple launches to asteroid</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single launch to asteroid</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Multiple launches and assembly in LEO</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transportation to asteroid</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Landing and setting up thrusters</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Attaching to asteroid</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transport asteroid to LEO</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Launch additional crew</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mining at LEO</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Mining at Earth</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Humans to asteroid</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Humans to LEO</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Robotic</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The team selected Architecture S5 and the features are multiple launches and assembly in LEO, transportation of an asteroid to LEO, human mining at LEO and delivering the resources to Earth. See Table 8-5 for an overview of the scoring.

**Table 8-5: Scoring of architecture options for mining of small asteroids**

<table>
<thead>
<tr>
<th>Attributes</th>
<th>Weights</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>S5</th>
<th>S6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency</td>
<td>1.0</td>
<td>0</td>
<td>5</td>
<td>0</td>
<td>5</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Robustness</td>
<td>1.0</td>
<td>7</td>
<td>0</td>
<td>7</td>
<td>10</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>TRL Asteroid transportation system</td>
<td>0.3</td>
<td>0</td>
<td>10</td>
<td>0</td>
<td>0</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>TRL Entry system</td>
<td>1.0</td>
<td>5</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>Human risk factor</td>
<td>1.0</td>
<td>0</td>
<td>8</td>
<td>0</td>
<td>8</td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td>Safety of Earth</td>
<td>1.0</td>
<td>0</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>Seamless operation</td>
<td>1.0</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>0</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Cost effectiveness</td>
<td>1.0</td>
<td>0</td>
<td>5</td>
<td>0</td>
<td>5</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Debris</td>
<td>0.2</td>
<td>10</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>Autonomy</td>
<td>1.0</td>
<td>5</td>
<td>0</td>
<td>5</td>
<td>5</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>24</strong></td>
<td><strong>37</strong></td>
<td><strong>37</strong></td>
<td><strong>53</strong></td>
<td><strong>66</strong></td>
<td><strong>55</strong></td>
<td></td>
</tr>
</tbody>
</table>

**Mining of large asteroids**

The team adopted the criteria from the small asteroid mission architecture trade-off study and applied them with the required adjustments to the large asteroid mission architectures. Similarly, we kept the relative weighting of the criteria. Table 8-6 summarizes the scoring.
A trade-off study among the five large asteroid mission architectures (L1 – L5) leads to the conclusion that a fully robotic mission (L3) is most favorable in terms of cost, risks to human beings, autonomy, and seamless operation. The next most favorable mission architecture is likewise fully robotic (L5).

### 8.2.3 Second Level Trade-Off Study: Large versus Small Asteroid Mission Architectures

The team conducted a second-level trade-off study, comparing the selected large asteroid mission architecture (L3) to the selected small asteroid mission architecture (S5). We used the result of this process as an input for the generation of the asteroid mining roadmap. Four business attributes, two legal attributes and one attribute relating asteroid mining to society complement the technical attributes in the second-level trade-off study.

#### Second level trade-off study attributes

The legal attributes are appropriation of resources and human versus robot considerations. Mining is more acceptable from a legal perspective on a large asteroid, without the involvement of humans. The economic trade-off attributes are the initial investment, time-to-market, resource rate of return and risk of investment. Favorable conditions are low initial investment, short time-to-market, high resource rate of return, and low risk of investment. Public visibility and interest ranks the proposed mission architectures in terms of their appeal to society.

#### Long-term large asteroid missions and short-term large asteroid missions

The team determined that the ranking of large asteroid mission architectures crucially depends on mission duration. The large asteroid mission architecture L3 receives better scores under the assumption that a short-term visit to the asteroid is possible. If only a long-term visit is possible (corresponding to revisit times that are not economically feasible), the verdict on L3 is unfavorable.

Table 8-7 below shows the trade-off study between S5 and L3, assuming that a short-term visit to a large asteroid is feasible and the same scenario, assuming that the visit to the large asteroid would be long-term, leading to a very long time-to-market.
### Table 8-7: Comparison of long term and short term mission for large and small asteroids

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Weights</th>
<th>Short term</th>
<th>Long term</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>S5</td>
<td>L3</td>
</tr>
<tr>
<td>Initial investment</td>
<td>1.0</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>Time to market</td>
<td>1.0</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>Robustness</td>
<td>0.5</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>Seamlessness</td>
<td>0.9</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>Maintainability</td>
<td>0.5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Autonomy</td>
<td>0.3</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>Resource rate of return</td>
<td>0.9</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>Risk of investment</td>
<td>0.7</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>Human safety</td>
<td>1.0</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>TRL</td>
<td>1.0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Sustainability</td>
<td>0.9</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>Appropriation of resources</td>
<td>0.7</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>Legal aspects of human versus robotic missions</td>
<td>0.4</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>Public visibility and interest</td>
<td>0.7</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>Probability of finding an appropriate asteroid</td>
<td>1.0</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td><strong>Total Score</strong></td>
<td></td>
<td>43</td>
<td>57</td>
</tr>
</tbody>
</table>

#### 8.3 Proposed Baseline Architecture

Following the trade-off study, the team proposes the following choice of architectures for asteroid mining:

- If a large asteroid that allows for a short-term visit can be identified, the large asteroid mission architecture L3 is recommended
- Only if no large asteroid for a short-term visit can be identified, a small asteroid propelled into Earth vicinity is recommended (architecture S5)

The selected asteroid mining architecture L3 comprises a spacecraft assembly in LEO followed by a transfer to the asteroid with mining and processing of raw materials *in-situ* and robotically.

#### 8.4 Trade-Off Study Conclusion

The trade-off study team developed new scoring tools to decide which architecture would be suitable for the ASTRA project’s goals and requirements. We performed a two-level trade-off study. The first-level trade-off study consists of three comparisons: the better option for the characterization of asteroids, the better architecture from the small asteroid group and the better architecture from the large asteroid group. The second-level trade-off study consists of a comparison between the best architecture of the small asteroid group with that of the large asteroid group. The study leads to the proposal of an architecture that includes mining a large asteroid *in-situ*, assuming a suitable candidate asteroid is identifiable. New data in the future may change this conclusion but the trade-off study method would still be applicable.
9 LEGAL AND POLICY ISSUES

In this section, we determine legal issues concerning asteroid mining by investigating international existing legislation. The legal community recognizes the need to modify or generate the existing international legal regime before we can exploit the resources of celestial bodies. Conversely, a large group of private entities considers such an international legal regime to be unnecessary, because they see this as an increase of cost, delay and prevention of these activities. These entities see the uncertainty as a possibility for large profits; they believe that if they dare to use this general uncertainty, they would be rewarded (Tronchetti, 2009).

The goal of this section is not to define a new legal regime or body. Many scholars, such as Lee (2009), Tronchetti (2009) and Schmitt (1994) have proposed this in detail. The latter already suggested the Interlune InterMars Initiative in 1997, addressing the use and acquisition of lunar resources by the private sector, while recognizing the ‘common heritage of mankind’ and realizing fair distribution of exploited helium-3 resources (Schmitt 1994). Instead, this section will assess the current legal framework pertaining to the challenges described in Section 3.5. Specifically, this section will identify loopholes to legitimize asteroid mining activities. For the remaining challenges lacking substantiation in law, we propose a way forward towards the development of new legislation allowing a commercial asteroid venture. The following four subsections address legislation and jurisdiction, appropriation, responsibility and liability, and distribution.

9.1 Legislation and Jurisdiction

The need exists to determine applicable legislation for the mining of asteroids conducted in outer space. If the asteroids are mined in outer space, the States who are parties to the Outer Space Treaty (OST, 1967) would be bound by its provisions and as lex generalis, general law. It is supplemented by further treaties and principles of international space law (among others Liability Convention, Registration Convention, Moon Agreement) which are lex specialis, a law that governs a more specific subject matter.

The OST presents a challenge because of its wide interpretability. For example, it states that any activity in space must be conducted in a way that is for the benefit and in the interest of all countries, irrespective of their degree of economic or scientific development and shall be the ‘province of all mankind’ (Art. I OST). Asteroid mining would have to be conducted in this way. One interpretation that would enable asteroid mining argues that most commercial space activities (such as telecommunications and remote sensing) benefit in a general sense. Since the interpretation of this principle of Art. I OST, is very subjective, one State may consider what is beneficial to them differently compared from another State. Therefore, each State would define on its own what is beneficial for them (Gorove, 1982). Based on these arguments, this principle of the OST would represent a moral obligation rather than a specific duty (Lee, 2009). Consequently, the mining of asteroids would not be hindered by this principle.

Other commercial space activities such as telecommunication follow this same interpretation and are adaptable to asteroid mining. The current legislation that exists through the International Telecommunication Union (ITU), allocates space resources such as valuable Earth
orbits (ITU, 2007). We propose to use this law by analogy and apply it to the concept of asteroid mining, but these rights, granted by the ITU, cannot be seen as appropriation rights as such (Hertzfeld, 2010). Hence, no solution is evident to adopt a similar framework for asteroid mining by analogy.

Defining the jurisdiction for the activities associated with asteroid mining is important. Under Art. VIII of the OST “a State Party to the Treaty on whose registry an object launched into outer space is carried shall retain jurisdiction and control over such object, and over any personnel thereof, while in outer space or on a celestial body”. In regards to the registration of space objects, there is a need to determine the Launching State to attribute the country that is responsible and/or liable for asteroid mining projects. In case of only one State launching a space object, this law will not create any difficulties. However, when more than one State launches, the States involved have to select amongst themselves, which State has to register the space object. That State would accordingly exercise quasi-territorial jurisdiction and control over the space object (Lee, 2009). According to the approach of the United States of America, only objects that are owned by the U.S. government or private entities will be registered, regardless of where they are launched (Hodgkins, 1992). We suggest following this approach in regards to asteroid mining if more than one State is planning a mission. The reason for this being that the owner of the payload would want the continual jurisdiction and legal control of it, rather than the other Launching States.

It is increasingly difficult for the international legal framework to specify liability and jurisdiction for the activities of different types of entities in space. A possible solution is to compel many commercial entities and their governments to prescribe, clarify and limit their liabilities towards each other through means of private contracts. The States should regulate this individually by implementing laws requiring this in the States’ national laws.

### 9.2 Appropriation

Establishing the legality of asteroid mining to ensure that an entity can extract and sell resources is an important milestone. The uncertain legal framework surrounding asteroid mining is an impediment to asteroid mining (Tronchetti, 2009). Section 3.5.2 covered the challenges of appropriation with regard to asteroid mining. This section discusses these challenges, describes the legality of asteroid mining based on current legislation, and proposes addressing further challenges by investigating the legislation described in the United Nations Convention on the Law of the Sea (UNCLOS, 1982). Such analysis can lead to creation of new legislation to unambiguously legitimize the use of resources in outer space for the benefit of humankind.

In Section 3.5, an examination of the OST revealed a challenge with regard to the appropriation of resources obtained from asteroids. Recalling the prohibition against national appropriation, in conjunction with the State’s obligation to supervise commercial entities, prevents a commercial entity from appropriating an asteroid for mining. The OST clearly indicates that space is free to use and explore by all States. Without further specifying the meaning of ‘use’, a relatively broad meaning is implied. The effect of this interpretation is to allow ‘using’ space for any purpose on condition that it does not directly violate all other relevant binding rules of law. Given the intent for the use of space, it is worthwhile to examine the issue of appropriation, as stated in the OST, to find a loophole for the legitimate appropriation of resources.
Despite the prohibition to national appropriation described in Art. II of the OST, its applicability to a public entity is firmly established in space law (Tennen, 2003). As discussed in Section 3.4.2, the applicability of Article II of the OST, in conjunction with Article VI, prevents an entity from exercising appropriation rights on the moon and other celestial bodies. Is it possible, then, for an entity to conduct mining activities on an asteroid without an implication of appropriation? To answer this question, a distinction between the asteroid and the resources removed from them is necessary. In 2009, Tronchetti distinguished the property rights of immovable and movable objects in outer space. He states that the concept of property rights does not necessarily extend to materials removed from the surface of a celestial body. This position is supported by a large number of scholars (Tronchetti, 2009). If this interpretation becomes widely accepted, a spacecraft can land on an asteroid without claiming appropriation. Thus, other entities are free to explore and use this asteroid. However, once material is removed from the asteroid the entity is entitled to use this resource for its own purposes, including sale to others. Unfortunately, when a State does not concretely benefit from the mining activities of another State, it is unlikely to provide support for this interpretation of the law. Therefore, new legislation is necessary to legitimize asteroid mining activities.

The inspiration for the underlying principles of the OST came in part from the law of the sea. The United Nations Convention on the Law of the Sea (UNCLOS), signed by 160 nations in 1982, has many common elements with the Outer Space Treaty (OST). While UNCLOS is not applicable in space, it does provide a methodology to share a common resource. We think that adopting elements of UNCLOS into a new legislation to regulate asteroid mining is the most straightforward way to address the issue of non-appropriation. In 2010, Brittingham suggests that adapting UNCLOS into a new space treaty will not be challenging. Table 9-1 below shows the primary similarities between the treaties that are relevant for the purpose of asteroid mining activities.

<table>
<thead>
<tr>
<th>Treaty</th>
<th>Citation</th>
<th>Article</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Peaceful Purposes</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OST</td>
<td>The Moon and other celestial bodies shall be used by all States Parties to the Treaty exclusively for peaceful purposes</td>
<td>IV</td>
</tr>
<tr>
<td>UNCLOS</td>
<td>The high seas shall be reserved for peaceful purposes</td>
<td>88</td>
</tr>
<tr>
<td><strong>Sovereignty</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OST</td>
<td>Outer space, including the Moon and other celestial bodies, is not subject to national appropriation by claim of sovereignty, by means of use or occupation, or by any other means</td>
<td>II</td>
</tr>
<tr>
<td>UNCLOS</td>
<td>No State may validly purport to subject any part of the high seas to its sovereignty</td>
<td>89</td>
</tr>
<tr>
<td><strong>Render Assistance</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OST</td>
<td>States Parties to the Treaty shall regard astronauts as envoys of mankind in outer space and shall render to them all possible assistance in the event of accident, distress, or emergency landing on the territory of another State Party or on the high seas</td>
<td>V</td>
</tr>
<tr>
<td>UNCLOS</td>
<td>To render assistance to any person found at sea in danger of being lost</td>
<td>98 (1a)</td>
</tr>
</tbody>
</table>
While UNCLOS does contain provisions for the exploitation of resources obtained at sea, the OST does not. The convention defines resources as meaning minerals and defines the “area” as “the seabed and ocean floor and subsoil thereof, beyond the limits of national jurisdiction” (UNCLOS, 1982); and the authority as the International Seabed Authority. Article 137-2 of the UNCLOS claims the following: “All rights in the resources of the Area are vested in mankind as a whole, on whose behalf the Authority shall act” (UNCLOS, 1982). This Article provides a means for the appropriation of mineral resources by a private entity under the jurisdiction of an authority. The absence of a parallel statement in the OST leads to the question: were rights to appropriate resources in outer space purposefully omitted from the OST for specific reasons or was it omitted because the technology to perform these activities did not exist at the time? At any rate, similarities between UNCLOS and the OST can establish a starting point for the new legislation making appropriation of mining/mineral rights in outer space possible. The UNCLOS’ wide acceptance (160 States) provides confidence that the State Parties to the OST will easily accept this new legislation.

We recommend drafting new legislation, however, it is time consuming and it will possibly not be ready in time. This could prove advantageous to a private entity hoping to participate in asteroid mining activities. Although legislation allowing asteroid mining activities provides investors with more certainty in obtaining a return on their investment, it might constrain their activities. These constraints could include existing legislation discussed previously such as ‘benefit to mankind’ and ‘corresponding interests of other States’ (OST, Art II, IX). Consequently, conducting asteroid mining activities prior to new legislation may serve to legitimize this activity by becoming customary law. A popular example of customary law is during Yuri Gagarin’s flight in-orbit. When no State objected to this activity, it became legally acceptable for a human to orbit over another country, thus establishing a distinction between sovereign airspace and space.

9.3 Liability and Responsibility

There are several liability issues in the area of asteroid mining. First, this study will address liability and responsibility associated with damages that may occur when moving a small asteroid to the vicinity of the Earth. Launching States are internationally liable for damage to another State Party to the OST, whether this damage occurs on the Earth, in air space, or in outer space (Art. VII OST, 1967 and Art. II and III LC, 1972). The LC and RC provide the definition of a Launching State, holding the State responsible for actions of its citizens (Art. I LC, 1972 and Art. I RC, 1976). Further, under the current law, the State is not only liable for damages caused by actions of governmental and non-governmental, but also for national private companies (Art. II and III LC, 1972).

Since commercial asteroid mining will involve private companies, appropriate international or national laws for liability and responsibility are of importance. Art. VI OST says that States have to take international responsibility for national space activities conducted by both public and private entities (Art. 5-7 International Law Commission’s Draft Articles on State Responsibility). Furthermore, according to the principle of restitution in integrum, a State is liable to pay reparations to the victim State if any damage or harm is caused. The State that inflicted the damage should restore the victim State as much as possible to their position before the damage occurred. These regulations do not pertain to asteroid mining in particular. In this regard, the space-faring nations that have national laws set in place, have determined the amount of insurance required
for space missions. This framework details how much each party (insurance keeper, State, company) should pay for damages. A recommendation is to extend these laws to include asteroid mining.

International space law is general and does not specifically regulate any activity where the orbital trajectory of an asteroid is changed. From basic physics, moving an asteroid from its orbit to the vicinity of the Earth will require the application of a force to alter the trajectory. We propose that the State that moves an asteroid is liable and responsible for it.

Moreover, human missions are an alternative to robotic missions when mining asteroids. However, they are more complex from a liability and responsibility point of view. The asteroid miners that will work in outer space are less likely to receive the same training in advance of the mission as astronauts do and would therefore not qualify as such in a legal sense. The legal framework has not been a problem in the past for the activities of astronauts, due to the small number of astronauts and the limited scope of their activities. With a human commercial mining operation in space, the number of people impacted will increase. Instead of a new legal framework, national labor laws following from jurisdiction of the mining State could regulate States’ liability and responsibility of the asteroid miners and others involved in the mission. This would likely work in the short term, when an industry standard is established. To ensure mitigation of liability and responsibility for activities in space, a national framework must be established to appropriately compensate workers with due regard to the mission risks. Since the architecture chosen at the completion of the trade-off study merely involved humans in space for activities already covered by existing legislation, further discussion will not ensue.

Lastly, the liability and responsibility issues associated with contamination are considered. The issue arises that “returning humans or soil and rock samples from Mars might contaminate species on Earth, although scientists regard the possibility as extremely remote” (Clément, 2003). In other words, mining processes could produce harmful byproducts. In transporting asteroid resources back to Earth, damages could occur. States should avoid “adverse changes in the environment of the Earth resulting from the introduction of extraterrestrial matter” (Art. IX, OST). To mitigate the liability issues associated with contamination, we recommend establishing a framework to ensure that States test the materials in space to confirm their composition, that the material is appropriately isolated during the return to Earth, and that States have appropriate insurance when needed.

### 9.4 Distribution

Since the existing space law differs in its wording, uncertainty exists on how to distribute mining resources. The Outer Space Treaty describes that space activities are the ‘province of mankind’ while the Moon Agreement uses ‘common heritage of mankind’. It is unclear whether these comments have the same implication regarding fair distribution (Brittingham, 2010). The varying interpretations of these two treaties must be resolved to establish a distribution model. ‘Common heritage’ and ‘mankind’ could be perceived as a fusion of the terms equitable access for all (here mining companies), and some equitable benefits for all (Porras, 2006).

State Parties have the right to collect and remove samples of substances, that is minerals from the Moon, as long as they provide access to all samples for scientific purposes (Art. 6, Para. 2, Moon Agreement, 1979). However it is often stated by legal experts, that the Moon Agreement...
is not perfect (Hertzfeld, 2010), and “the Moon Agreement may be considered a failure” (Tronchetti, 2009), since only a low number of countries ratified it. Thus, only few countries are bound to follow its provisions. We believe that not only the scientific community should have benefits, but that commercial mining companies should also benefit from asteroid mining.

The OST states that the use of outer space is carried out for the benefit and interest of all countries. The Moon Agreement provides special consideration for developing countries, and for countries that have contributed either directly or indirectly to the exploration of the Moon. The interpretation of the Outer Space Treaty by developed countries is that bringing resources to the world market with a fair market price provides benefits realized more indirectly rather than directly for all humankind (UN Res. 51/122, 1996). Conversely, developing countries, specifically those that are unable to take advantage of space and that are without space capabilities, interpret common heritage and the province of all as a regime for equal distribution that has no bearing on effort or contribution (Brittingham, 2010). An agreement needs to be created that acknowledges all participants’ views, balances fundamental principles, is widely accepted by the States and generates profit. If no agreement can be accomplished, creating a unilateral political statement could also provide a solution. The acceptance by States of the existing space law principles have, over the last decades, lead to an increase of space activities and major benefits for all. It is important to keep these fundamental principles regarding future exploitation of recourses from celestial bodies (Tronchetti, 2009).

An international regime is required to define equitable sharing by all States. Before an international regime is established, and mining becomes feasible, the exact method to distribute resources in an equal way cannot be determined in detail (Verschoor and Kopal, 2008). States want the opportunity to obtain all the details concerning their resources and it would be desirable to have an agreement with a win-win-situation for both developing and developed States. However, to be able to utilize recourses from celestial bodies, i.e. from asteroids, we need financial and technological capabilities, and only space-faring nations and private entities possess those capabilities (Tronchetti, 2009).

Granting access to samples and resources for scientific research provides a fair opportunity for other States to participate. Furthermore, these entities could provide a financial compensation to non-participating States. For example, a regulating body could guarantee equitable distribution and opportunity, by charging a tax or fee to the mining entity, and diverting the proceeds to an international fund to distribute to the appropriate States. This could make it feasible for private entities to begin asteroid mining ventures without concern for equitable distribution.

9.5 **Legal and Policy Conclusion**

The current legal framework provides some legitimacy for asteroid mining. In the past, commercial entities have had success in legitimizing their operations by loosely applying the of ‘benefit to humankind’. This is supported by the opinions of a number of scholars who believe that removed resources are amenable to property rights (Tronchetti, 2009). Nevertheless, examination of loopholes in international space law has identified some difficulties in finding a solid legal basis for asteroid mining, demonstrating an urgent need for a new international regime or an amendment of the current one. Such a regime would regulate the extraction and distribution of resources obtained in outer space. This legal regime should have support from most countries, especially space-faring nations, and should apprise nations and private entities of
the profitability of asteroid mining. Entities should be able to trade resources on the free market while the legal regime ensures that asteroid mining activities benefit humankind.

The new or amended legal regime should protect and secure activities like asteroid mining as suggested by many scholars. Brittingham states, ‘the UNCLOS, especially after its Realpolitik redrafting, gives us an effective framework towards drafting a new Outer Space Treaty’ (Brittingham, 2010). A legal regime regulating mining activities in outer space must bear in mind the fundamental principles that have guaranteed the safe development of space activities over the past 50 years. Industrial countries have not signed the Moon Agreement because of the financial and practical implications of the ‘common benefit to mankind’ doctrine. New or amended legislation should consider these issues to enable a wide acceptance of these laws.

A lack of economic incentives for the participants of mining activities is a major reason for the United States’ rejection of the regulatory framework of the UNCLOS (Tronchetti, 2009). Asteroid mining regulations should encompass the interests of all nations, regardless of their level of participation. As is accomplished in the UNCLOS, regulations should provide incentives to non-participating States and a real possibility for return of investments for the participating States and their entities.

In theory, it would be best to establish and implement this new legislation before entities actually begin mining asteroids. Realistically, it would take a long time to create and practice legislation that would find wide acceptance. In reality, we believe that entities will most likely embark on asteroid mining without clear legal regulations in place for these activities.

If States involved in asteroid mining were to regulate their actions on an intergovernmental basis, their actions could possibly generate customary law over time. It is probable that States will protest the mining activities of other States in space. Non-space-faring nations may fear that their exclusion will prevent them from profiting from these activities in the future. Team ASTRA recommends that the governments of space-faring nations issue official governmental statements, considering concerns of the States that are not yet able to use space for commercial purposes. Team ASTRA further recommends that such an official governmental statement should define how collected resources are to be distributed between nations using a parameter. In this way, likelihood of protest is minimized. Issuing an official governmental statement takes less time, money and effort than amending existing international space law. Additionally, a governmental statement will not only have political force, it will also reduce the concerns of non-space-faring States (Recommendation IV).
10 BUSINESS ANALYSIS

The prospect of sending a spacecraft with mining equipment to an asteroid, and returning with vast quantities of valuable ore or precious metals, has been one of the most anticipated space enterprises for decades. The commercial rationale is straightforward: resources on Earth grow scarcer and more expensive over time as consumption of the finite stockpile continues. A commercial asteroid mining venture seeks to take advantage of increasing mineral prices, and the decreasing costs of space activities, to profitably address mineral market demand.

As previously stated in Section 2, little is known about the precise mineralogical composition of asteroids. Based on meteorite sample data and current prices, we estimate that a small 500 meter diameter asteroid could contain upwards of USD 16 billion worth of Platinum Group Metals (PGM) (Nelson et al., 1993). These revenues are particularly attractive if the metals can be reliably returned to Earth in a cost-effective manner. Determining financial viability, however, is not just an assessment of whether expected revenues will exceed mission costs.

In evaluating any business venture, the issue of opportunity costs must be addressed. Asteroid mining presents a particularly interesting, yet straightforward, opportunity cost question. What is the marginal rate of return of investment dollars for terrestrial mining compared against asteroid mining? In other words, if one was to invest the R&D and operational funds required for asteroid mining in terrestrial mining ventures instead, which would provide a greater return? This question will be addressed later in the section, but until asteroid mining can provide a greater return, it is not economically feasible as investors will not contribute capital for inferior returns.

In addition to the commercial motivation for private entities to pursue asteroid mining, there are other compelling rationales, including economic justifications, for nation-states to pursue these extraterrestrial resources. One can imagine scenarios in which governments would seek to increase their access to natural resources for the purposes of driving domestic economic growth, bolstering domestic industry, building economic independence, or developing national/global security technologies, affordably or profitably.

For example, the People’s Republic of China currently produces 93 percent of the world’s rare Earth elements (REE), such as dysprosium and terbium, which are critical for certain “green” technologies and military applications (Bradsher, 2009). These elements are becoming increasingly rare as green technologies take off. Believing that NEOs are a potential source of REE, a national government or group of governments could be motivated to pursue asteroid mining in order to obtain green energy independence, or foster self-sufficient green energy industries. Given the significant capital requirements for asteroid mining ventures, these motivations are relevant as governments could serve as a potential source of capital. This is discussed later in the section.

In evaluating any truly new business venture, the question is often asked, why has this not been done before? In the case of asteroid mining, whose concept has prevailed for decades, this is a particularly salient question. As discussed in Section 3, there are a number of extremely difficult technical and commercial challenges to asteroid mining. With respect to business, no venture has yet been started to pursue asteroid mining for two reasons. The capital to finance such an
endeavor has not been raised because of the risk profile and long time to return on investment. This section seeks to address these and other critical issues and present some possible solutions. Additionally, a considerable group of legal experts argues that the exploitation of resources on asteroids, the Moon, and other celestial bodies has not yet begun, due to limitations of the Outer Space Treaty, as discussed in the previous section (Tronchetti, 2009).

10.1 Market Analysis and Opportunity

10.1.1 Defining the Opportunity

In simplest terms, asteroid mining is a financially viable business venture if the minerals returned and sold on Earth can generate revenues that exceed the total costs of the business. Although this determination is critical to informing whether asteroid mining can exist as a for-profit concern, it does not answer the question of whether or not investors would be motivated to pursue such an endeavor. To do so, we must also look at the opportunity costs of asteroid mining.

A Net Present Value (NPV) analysis is the most traditional means in the business world of determining the value of a particular venture or investment. NPV analyses account for opportunity costs by selecting the most appropriate cost of capital. If the NPV is positive after discounting future cash flows by the cost of capital (which is, in reality, an opportunity cost calculation), then investors should be motivated to proceed with the business. We should not limit ourselves, however, to looking at opportunity costs through the NPV lens. (In fact, our modeling of the potential profitability of asteroid mining is driven by real options analyses, and an NPV analysis that is modified to suit mining operations is discussed in detail later.) Given the obvious analog of terrestrial mining, the opportunity cost question is immediately apparent; would investing the capital required for asteroid mining provide better returns if spent on terrestrial mineral exploration?

Figure 10-1 seeks to address this question by combining expected resource prices and costs into a marginal return on investment (ROI) over time and comparing this ROI across asteroid and terrestrial mining. There are two underlying, widely held assumptions underpinning this relationship. The first is that, over time, terrestrial supply of resources will decline as scarcity increases with consumption. With this increasing scarcity, the cost of discovering and mining a given mass of mineral increases. Second, as the space industry evolves and technology advances, the cost to execute space asteroid mining missions declines. It is important to note that there is no single industry curve, but a separate curve for each mineral, in which there could be both terrestrial and asteroid mining. These two trends converge at some point in time (T), where asteroid mining becomes a better use of investment dollars than mining on Earth. To determine where the present lies on the time axis requires precise mission costing that is beyond the scope of this project. This can be narrowed by using available data and illustrative assumptions. This is shown in Figure 10-1.
10.1.2 Sizing the Opportunity

The first key market-defining question is which asteroid minerals should be mined. Although available data is limited, it is generally accepted that asteroids can contain large quantities of nickel-iron ore, and lesser quantities of precious metals, rock, water, and other minerals (Nelson et al., 1993). The financial and mission implications for mining iron versus precious metals are significant and play a major role in both mission architecture and the financial valuation of an asteroid mining venture.

Each case presents its own set of trade-offs. Iron is plentiful on asteroids, reasonably easy to mine, and produced in such great quantities on Earth that the risk of flooding the terrestrial market is low. Iron ore currently sells at approximately USD 148 per metric ton (Steel Index, 2010). As mass is a dominant cost driver for space activities, the marginal returns on iron are relatively low and immense quantities would need to be returned to recoup investment and mission costs. Conversely, precious metals, namely Platinum Group Metals (PGM), are present on asteroids in smaller quantities, are more difficult to mine, and are produced on Earth in lower volumes that could present market-flooding risks. PGMs sell at much higher prices than ore: up to USD 289,357 per kilogram. Initial data suggests PGMs are present on asteroids in greater quantities than on the Earth’s crust (Abundant Planet, 2009). Due to their dramatically higher price per mass ratios, the marginal returns for mining PGM are significantly higher assuming sufficient quantities are present on the target asteroid. The wide variability in the value of a particular asteroid is a primary driver of the need for a characterization mission as outlined in the architecture. Table 10-1 illustrates the prevalence, mass, value trade-off of mining PGMs versus iron using return sample data from Itokawa as basis for S-class asteroid composition.
One of the key variables in forecasting future revenues from asteroid mining is the dynamic nature of the mineral market, especially in the long-term. Although iron ore reserves seem almost endless, some scholars suggest that if consumption continues to increase at the conservative rate of 2% a year, iron ore deposits could be fully depleted within 64 years (Brown, 2006).

In addition to traditional metal markets, there is an opportunity to market asteroid minerals as a new discrete class of product. As DeBeers, the South African-based leader of the diamond industry, has driven worldwide demand for diamonds through international marketing campaigns, one could easily imagine the same being done for precious metals returned from Earth.

There is a compelling case for mining water from an asteroid. Water on asteroids can be used for return mission propulsion or as a marketable resource itself for use in orbit. The market rationale for mining water and transporting it to another location in space is that cost of transporting water from Earth to LEO, for example, could be more expensive than transporting it from an asteroid to LEO. Given that significant demand does not currently exist for vast quantities of water in space, we have not explored this aspect of asteroid mining in depth. The prospects of a burgeoning space tourism industry or the future development of space settlements could drive demand for financially feasible alternatives to launching large masses of water from Earth.

**10.1.3 Addressing the Potential Challenge of Flooding the Market**

One of the anticipated problems with a commercial asteroid mining mission is that of creating an oversupply of certain resources in the global market that depress prices and erode potential returns. This risk of market flooding must be balanced against the prospect that resources...
brought back to Earth must pay for the mission and provide returns to investors. The first step is to assess the expected level of risk faced in saturating global markets. To do this, the amount and type of commodities brought back to Earth from a future space-mining venture must be put into perspective with present and forecasted ground-based rates of production. If the probability of flooding global markets is negligible, then the problem is avoided altogether.

How will the production rate of a commercial asteroid mining mission compare with current and projected ground-based production rates? The amount of supply injected into the market depends largely on the mission architecture, specifically the return capacity of the mission. If we assume that minerals from one 500 meter asteroid are returned each year, this would be equivalent to 418,879 metric tons of iron ore for an M-class asteroid (Nelson et al., 1993) or 578 metric tons of PGM (Abundant Planet, 2009). For comparison, the largest oil supertanker ever constructed, the Jahre Viking, has a deadweight tonnage 564,000 metric tons (GlobalSecurity.org, 2006). In contrast, annual world production for 2009 was 1.6 billion metric tons of raw iron ore (UNCTAD, 2010) and 415 tons of PGM (USGS, 2010). Figure 10-2 illustrates the relationship between the quantity of minerals in a single 500 meter asteroid and global production rates in order to assess risk of potential market flooding.

It is highly unlikely that a commercial asteroid mining mission will saturate terrestrial iron markets. We anticipate that an oversupply of platinum and other similarly rare metals could occur. The difficulty arising from the strategic resources returned to Earth are those whose terrestrial markets are most susceptible to becoming saturated. However, there are techniques to moderate the effects of market flooding. Two broad solutions encompass a multitude of methods that mitigate the effects of market flooding: strategic control of supply and spurring of demand.

Historically, Organization of the Petroleum Exporting Countries (OPEC) and DeBeers have succeeded, to varying degrees, in controlling supplies to maintain price stability. For example, in 1889, De Beers negotiated a strategic agreement with the London-based Diamond Syndicate which agreed to purchase a fixed quantity of diamonds at an agreed price, thereby regulating output and maintaining prices (Knowles, 2005). A quota-based sales strategy such as this is one of the simplest envisaged solutions. The precious metals returned from space could be sold ahead of time at a pre-determined fixed price. Market stability is therefore maintained and sales output secured. A simple example of spurring demand is the creation of a new market for “out of this world” jewelry. The novel origin of these resources imparts them with an increased
perceived value. In addition to driving increased revenues through creating new markets for asteroid minerals, it is also likely that the technologies developed to execute the asteroid mining mission, particularly the robotics, will have commercial applications in other industries.

10.1.4 Spin-offs

The concept of spin-offs refers to the transfer of technology resulting from the investment in research and development into different industry sectors. Many aspects of space technology have increased the quality of human life. Spin-offs also serve as a tool to bring the space sector and the general public closer, reinforcing society’s interest in space activities. For a commercial asteroid mining venture, spin-offs are significant as they present an additional source of potential revenue. For over 40 years, the NASA Innovative Partnerships Program has engaged in just this sort of spin-off commercialization by facilitating the transfer of NASA technology to the private sector (NASA, 2010f).

One of the most famous spin-offs is memory foam, also known as temper foam. It was developed under a NASA contract in the 1970s that set out to improve seat cushioning and crash protection for airline pilots and passengers. Memory foam has widespread commercial applications, in addition to the popular mattresses and pillows. Other well-known products that NASA lists as spin-offs include freeze-dried food, firefighting equipment, and Speedo swimsuits. Each of these applications generates multi-million dollar revenue streams annually (NASA, 2010f).

Although not expected to be a core revenue stream, the technology required to mine asteroids would likely have multiple non-asteroid mining or non-space applications with significant commercial value. Some of these technologies might include new autonomous mining and space systems, improved communication systems that address delay times, and possibly new Life Support Systems (LSS) developed to support human mission elements. Many of these developments could have direct application in other industries. Example applications are terrestrial mining, deep-sea robotics, telecommunications, and autonomous robotics for in-orbit satellite servicing.

10.2 Economic Feasibility

10.2.1 Feasibility Model

Currently, without reliable cost estimates or analogs, it is premature to definitively value the proposed asteroid mining project due to all the unknown variables associated with such an early stage of development. Still we can evaluate different parts of the mission architecture and test their economic feasibility. From a business perspective, the mission architecture can be separated into two distinct phases: asteroid surveying and characterization, and launch of the asteroid mining enterprise, and ongoing operations.

The first phase is a critical step in the whole asteroid mining entity, because it provides the necessary information to decide whether to create the entity or not. Were we to skip this first phase and decide to start the company immediately, we risk mining an asteroid that will not have any minerals. Therefore, this initial asteroid surveying phase can be seen as a real, financial ‘option’, as it allows us to have the option to start the company or not.
The Black-Scholes option pricing model enables us to compare the cost of the surveying mission with the estimated value of the option to launch the business. If we find that the value of the option is less than the cost of the mission, it would not be worthwhile to invest in the first phase and it would be better to wait until the value increases. On the other hand, if the value of the option is significantly higher than the cost of the mission, it would be better to immediately invest in the project (Black et al., 1972).

To estimate the value of this mission, the team used the Black-Scholes model, which requires a wide range of variable inputs including the value of the ‘underlying asset’. This underlying asset happens to be the value of the asteroid mining entity. Unfortunately, assigning a number to this value is not a simple task. As a result, the team constructed a real options simulation model to estimate the value of a hypothetical company (an approach similar to that taken in valuing a goldmine). Once these two models were developed, we are able to estimate the value of the surveying mission and test whether it is feasible. Another advantage of using this model is that we can perform a reverse cost analysis to calculate the breakeven investment required (which can also be referred to as the maximum initial investment the entire asteroid mining project can sustain to be profitable). This model will serve as a very useful tool, and although it has many simplifying assumptions, these can be relaxed in the future. We now discuss the main assumptions and limitations of the model.

### 10.2.2 Underlying Assumptions

The biggest assumption that was made for the model is the assumption of infinite minerals on an asteroid. Thus, the limiting factor in the returned mass of valuable cargo is the initial launch mass, and never the amount of such material present on the asteroid. We also assume that the returned mass will be a fixed multiple of the launch mass. This yields an average cost per kilogram of asteroid mass returned. In the long term (which is the validity domain of this model), the assumption of infinite resources does not hamper the validity of this model.

The main drawback of such an approach is that we must then assume that the costs are fixed throughout time; we do not take into account technological development or other ways that costs can change, such as inflation or currency risks. However, to take into account these details, there are far too many variables and unknowns, which would render the model less reliable.

As described earlier, the team used a similar approach to evaluating a gold mine, which takes into account the costs of opening (reopening) and closing the mine over time due to changes in the value of the minerals. Since estimation of costs are not reliable, we assume that these costs
are fixed throughout the life of the project. Furthermore, to simulate the value of minerals, we assume that investors are risk-neutral.

The final assumption we made is that there is no time difference between sending a vehicle into space and receiving the minerals. This is clearly unrealistic; but it simplified the model to a large extent by eliminating the possibility of price fluctuation. This assumption can be relaxed in future versions of the model.

### 10.2.3 Robustness

Setting aside the above assumptions, the model is quite robust to adapt to different mission architectures, and types of asteroids. We can relax our assumption of zero mission duration and set a time lag between the time of launch and the time of return, even though it is difficult to estimate this time lag at this stage.

Another very interesting variable of the model is the mass return ratio (return mass per unit launch mass), in addition to the total cost per year for the operations. The model will automatically calculate the cost per kg of returned mass. This model can be extended for more detailed engineering, by computing the number of launches per year, how much mass can be returned per launch, and a more detailed cost assessment. It is too early to start estimating these figures, which is why a very broad model was used.

Possibly, an asteroid mining entity would not have to pay for the entire characterization mission. Since this mission would garner significant scientific interest, it presents an opportunity for a joint venture or a Public Private Partnership (PPP), so that the costs can be split. The model can easily account for this, the rule is to input only the costs incurred by the entity.

### 10.2.4 Results & Discussion

Running the model with the most optimistic scenarios (low cost of capital, high mass capacity, low costs of operations), the resulting enterprise value was not sufficient to recoup the initial investment. Using reverse costing, the project would not be profitable even if no initial investment was required. As this venture would likely require significant levels of investment for startup and research and development costs, the project is not currently financially viable.

Performing a sensitivity analysis revealed that the most influential value driver is the mass return ratio. Doubling the ratio from one to two increases the value of the enterprise more than tenfold. Table 10-2 below illustrates this changing of variable.

<table>
<thead>
<tr>
<th>Mass Return Ratio</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Enterprise Value</td>
<td>$90,000,000</td>
<td>$1,300,000,000</td>
<td>$5,900,000,000</td>
</tr>
<tr>
<td>Option Value</td>
<td>$1,000</td>
<td>$60,000,000</td>
<td>$1,100,000,000</td>
</tr>
<tr>
<td>Max Investment</td>
<td>$-</td>
<td>$2,500,000,000</td>
<td>$160,000,000,000</td>
</tr>
</tbody>
</table>

Basing the option value on a conservative investment of USD 100 billion, the results suggest that today the prospects for asteroid mining in the short term are not promising. In order to come closer to making asteroid mining a financially viable venture, we strongly recommend that engineering efforts be focused on maximizing the mass return ratio.
10.3 Financing the Venture

10.3.1 Government Funding

In the latter half of the 20th century, advanced technologies have commonly been created or incubated as government projects (e.g., liquid-fueled rocketry, the Internet). After their initial development and success, projects such as these are commercialized. The government is a popular source for raising a large amount of capital, but at the price of a significantly extended period of research and development. For space missions in particular, government-funded projects generally require an extra margin of safety, especially for human missions. Thus, in conjunction with the increased development time comes an elevation in cost to reduce risks to the minimum possible. Moreover, policies will be altered as governments change during this long-term project, inevitably presenting numerous financial obstacles as time goes on.

10.3.2 Private Financing

In the context of commercial asteroid mining, where time to market is an important element, complete reliance on government funding is not ideal. Traditional means of privately financing a business venture will also not be feasible for such a unique scenario. So, as the development of the project progresses, sources of funding will vary depending primarily on the stability of the venture. From a broad perspective, it is preferable to finance asteroid mining through a PPP. The roadmap to fund the establishment of an extraterrestrial mining industry can be segmented into three distinct phases: mission characterization, technological research and development (R&D), and operations.

The early stages will focus on characterizing various aspects of the mission, ranging from asteroids of interest to the environment surrounding the selected candidates. The entity could leverage planned or proposed government-financed scientific missions with similar objectives in order to minimize the costs of the mission. In addition, certain technological developments would likely be applicable to avoidance and deflection of Earth-bound NEO collisions. This presents an opportunity for the venture to pursue government funding for technological R&D under the auspices of global security. Data gathered from characterization surveys can also be supplied to space agencies or the scientific community as an added source of initial income.

The R&D phase will probably be the most expensive stage of the project. Debt financing by borrowing against the value of the asteroid minerals would not be feasible since the collateral would not be physically attainable in the event of mission failure. Without substantial assets or collateral during the initial phase, the best method to initially raise capital with minimum return is incentive-based public investments. Using Google Lunar X-Prize as an example, various technologies like vehicle designs or microgravity mining equipment could be developed by the private sector by offering a lump sum reward and good publicity upon delivery of the product or service. Industrial partnering presents another potentially promising source of capital. Corporations from the mining or oil industry, which have a substantial amount of available capital, share largely the same interests in the exploitation of natural resources. The venture could also sell shares of the entity to public or private investors, including those governments interested in increasing their access to natural resources. The benefits to public investors (that is, governments) lie not just in increasing access to natural resources, but also in the opportunity to stimulate economic growth, support a new job-producing industry, and develop advanced technologies with spin-off applications. As the R&D phase matures, the business plan is
solidified, and risks are reduced, venture capital and private equity financing can then be considered.

Following the first successful launch and return mission, potential venture capitalists and private equity investors will have increased confidence in the business. With substantial financial support and physically attainable collateral, debt financing would then be feasible to sustain the routine operations required for commercial asteroid mining. Figure 10-4 below illustrates the timeline of investments required during various phases of the mission.

![Asteroid mining funding roadmap](image)

**Figure 10-4: Asteroid mining funding roadmap**

### 10.3.3 Stakeholder Management

Given such a diverse assortment of investors bearing contrasting interests, it is crucial to establish a thorough and robust strategy to manage stakeholders. Effective stakeholder management begins with understanding the different expectations of each investor throughout each stage of the venture. For example, governments tend to focus more on benefiting the State in a broader context by ensuring employment or economic stability, and less on earning a quick profit. Venture capitalists, on the other hand, are predominantly fixed on gaining a high return on investment in a short period of time. It will require extensive and selective lobbying to persuade investors that their diverse interests will be satisfied by the enterprise. Open, selective, and continual communication with all stakeholders stimulates confidence, and most likely consistent commitment to the business.

An effective way to maintain a healthy relationship with stakeholders is to identify the key stakeholders who have interests in common with the management. Countries have a substantial amount of capital for investment and political power, and at the same time are more willing to accept the long-term return that asteroid mining presents. Nation-states also provide necessary political support for asteroid mining projects, particularly in approval for various stages of the
venture. Industrial partners are an excellent source of income since they have substantial capital and the necessary expertise and long-term commitment that the venture would require. Various industrial sectors would be partners for different portions of the project (e.g., mining equipment, thrusters, surveying spacecraft). To avoid complex stakeholder demands, the project will need to establish governmental and industrial partners as their main source of funding, while the remaining investors would play a relatively minor role.

10.4 Financial risk management and insurance

Every risk incurred by a given venture can be associated with a cost, by means of insurance. Usually, increasing the financial investment in a venture facilitates the mitigation of risks. For example, investing in safety measures may reduce safety risks or taking out insurance may reduce the risk of experiencing financial losses. Financial risks are a special subset of risks, directly associated with markets and the financing of a venture.

Asteroid mining is particularly exposed to financial risks due to the duration of the potential undertaking. The following financial risks can be identified:

- Commodity market risk. Commodity markets trading the mined goods may shift from favorable conditions at the start of a mining mission to unfavorable conditions once the mined goods are returned to Earth. A mining entity itself may flood the market and negatively influence the market conditions.
- Equity risk. Equity available from investors is a function of general economic development and fluctuates on a short timescale.
- Credit risk. Exchange rates, inflation rates and credit rates are equally volatile.
- Regulatory risk. Market regulation is subject to government policy, leading to the potential for rapid change in market conditions.

10.4.1 Financial Risk Management

An asteroid mining venture can reduce commodity market risks by mining materials that have enjoyed continuous demand throughout history (and may therefore be assumed to stay in demand). Minerals with both intrinsic and attributed value (such as platinum, which is used in industry as well as being deemed valuable by virtue of rarity) should be favored over materials with a purely arbitrary value due to their more reliable demand.

Additional risk reduction can be achieved through off-take agreements, which are contractual obligations to buy portions of a producer’s future production (Gerosa, 2009). In practice, a customer with a long-term demand in a specific raw material may commit to advance payments, at a fixed price, for a certain amount of raw material to be mined and delivered in the future. This compensation structure is similar to a stock option or commodity future. This insures both parties against market volatility and supports a mining venture in the investment phase.

Governments with long-term infrastructure or other development projects can serve as customer and partner in this context. Governments, as part of a PPP, may also help minimize equity risk, under the assumption that they are inherently more solvent than private investors, even in times of crisis.
Finally, insurance and risk hedging schemes of various kinds can assist in mitigating mainly equity and credit risks.

### 10.4.2 Insurance

A mining entity might take out insurance against:

- Credit risks
- Equity risks
- Labor market risks
- Loss or malfunction of equipment. The probability and risk is established during the testing phase of the equipment.
- Third-party liability: Death or injury of human beings not involved in asteroid mining (third parties)
- Death or injury of human beings involved in asteroid mining (miners, astronauts)
- Volatility of the rocket fuel market (fuel hedging)

Insurance of space ventures more complex than the launch and operation of telecommunication satellites is still in its infancy; space tourism has only recently triggered the development of dedicated policies (Lloyd’s, 2010). Insurance practices for terrestrial oil and precious metal concerns might partially be applicable to asteroid mining and can be used as a basis for dedicated policies. As the number of asteroid mining companies will never be particularly large, insurance premiums are likely to remain high given the inability of insurance companies to spread their risk across a large group of mining companies.

A mining venture can lobby its government for relaxed third-party liability insurance requirements. Instead of buying external policies, a mining venture can consider self-insurance if the overall capital requirements are low.

In addition to insurance, hedging is another method of risk mitigation. Hedging can protect against unfavorable price fluctuations by allowing investors to buy and sell options called futures contracts. Hedging is often used for guarding against risks that are not insurable, such as price fluctuations and interest rate changes. Asteroid mining is a long-duration mission: there may be significant price changes of the mined resources over the period from time of investment to time to market. Hedging helps suppliers to sell their commodities at an agreed price. If the price falls, they make more profit and are encouraged to supply more. If the price increases, they sell at a loss, but the loss will not be as bad as when they were not hedged. For instances where there is borrowing from the bank, hedging shields the mining entity from paying a higher cost on loan if there is net increase in interest rates. Regardless of the interest rate at the expected time of repayment, the mining entity pays at the agreed interest rate, securing the asteroid mining venture against unexpected fluctuations in interest rates.

### 10.5 Business Analysis Conclusion

To guard against the depletion of minerals on Earth, it will become necessary to exploit resources from outer space. Asteroids contain an abundance of many minerals similar to those found and used on Earth. We conducted a market analysis to determine the existence of a market for returned asteroid resources. We concluded that commercial asteroid mining will
eventually become a reality.

Scarcity and demand are the primary drivers that determine the value of a resource. It is therefore more profitable to return only Earth’s most sought after resources (for example: platinum group metals) (Recommendation IV). The problem associated with returning large quantities of rare materials is the risk of flooding the applicable markets. It is possible to mitigate the effects of market flooding by strategically controlling supply and spurring demand (Recommendation VIII). The sudden availability of an abundance of rare materials can spawn a variety of spin offs, which translates to additional revenue. Niche markets for luxury space materials will open up, as it is human nature to search for new avenues to demonstrate social status. Quota-based sales at fixed prices will help to maintain market stability and to secure output.

Time to market will determine how soon a profit can be made, which determines the ease of attracting funding from investors. Various financing methods were proposed over the period of an asteroid mining venture, from the period of scientific surveys to recurrent mining operations in space. Incentive-based ventures, similar to that of the Google Lunar X-prize competition, will escalate the pace of technology development while stirring up commercial interest for asteroid mining companies and dousing the fears related to the risks involved. Stakeholder management will become crucial given the diversity of investors. With a novel large-scale venture like asteroid mining, the risks and uncertainties involved will present difficulties in obtaining a single insurance policy to cover an entire mission. Hence, a variety of coverage plans were proposed for spacecraft, persons directly involved in asteroid mining, third party liability and other aspects of asteroid mining. Hedging is also necessary for risks due to credit, market and other price fluctuations that come with the long-term nature of the project.

Ultimately, trade-off considerations against terrestrial mining will govern the feasibility of commercial asteroid mining. As it stands, it may be relatively less costly to exploit materials on Earth. As Earth resources become scarce and space technology advances, the relative cost of terrestrial mining will increase and the expenses of space operations will decline. There will come a point in time when the marginal return of asteroid mining supersedes that of the current conventional methods; that is when commercial asteroid mining will become economically feasible.
11 INTERDISCIPLINARY ROADMAP

This section describes and explains the interdisciplinary roadmap for the mission architecture selected in the trade-off study process. A roadmap enables teams to plan and execute a path to achieve its objectives. It establishes a strategy for future actions and incorporates a scheduled plan for the required capabilities and technologies to be in place at the correct times. The development of this roadmap requires consideration of a number of interdisciplinary aspects. It also answers the critical why, what, how, and when questions that define a clear action plan for the achievement of this objective. The team considers science, human factors, societal issues, engineering, legal issues, and business aspects in the roadmap.

11.1 Roadmap Inputs

11.1.1 Science

As previously emphasized, the existing body of knowledge about specific NEOs is extremely limited. Examining available data provides the first step towards identifying candidate asteroids for mining. The set-up of dedicated data analysis centers would continually process the available asteroid data to identify candidates with suitable orbital parameters and sizes. In some cases, the governmental observations may also include information to infer knowledge about the composition. Detailed compositional analysis must form a separate part of the roadmap.

Techniques for remote sensing already exist. Cooperation with organizations who have already established systems for asteroid observation is advantageous. Earth and space based instruments can measure the light curves of an asteroids, a graph of its intensity against time. One method that is not appropriate from the Earth is Light Detection and Ranging (LIDAR). This is similar to radar but uses light. Earth based LIDAR is inappropriate to observe asteroids due to the errors introduced by the atmosphere. This is a good technique for space missions.

Although radar is not suitable for conducting surveys, it is a very effective tool for characterization. A coordination of ground-based optical telescopes could begin to characterize many of these asteroids. To resolve smaller asteroids, optical telescopes require a larger diameter mirror. An improvement in detection speeds and data storage can optimize the process of asteroid characterization. At present, there are no dedicated space-based remote-sensing telescopes to catalogue NEOs; however, infrared space-based telescopes are powerful and efficient enough to achieve NASA’s goals. Advantages of space-based telescopes can include being able to detect asteroids inside the Earth’s orbit, more accurate albedo measurement capability, and the absence of atmospheric interference. Excluding congressional issues, NASA could meet its goal to catalogue 90 percent of hazardous asteroids larger than 140 m in diameter, by 2020. A combination of ground- and space-based telescopes can produce a 90 percent complete survey of potentially hazardous asteroids larger than 50 m in diameter, but not within the next 20 years. Extending the search to include all asteroids larger than 30 m in diameter is not possible using any combination of currently available techniques within the next 20 years (NRC, 2010).

Information about dimension, mass, density, temperature, gravity, and composition must be
determined accurately to design an asteroid mining mission. As such, the activities carried out by NASA will be very useful. In addition, a dedicated space instrument could be developed and employed to produce data specifically relevant to asteroid mining.

Fly-by missions to asteroids are also useful. A number of methods for remotely sensing the surface of an asteroid are currently available. We can forecast that there will be further developments in new and more accurate techniques for assessing the core, structure and the composition of an asteroid. Fly-by missions to visit several candidate asteroids that are in proximity to each other will provide a broad, statistical appreciation of characteristics, which will enable preparation of future mining missions. A good solution is to prepare a fleet of satellites to survey many asteroids to amass a greater quantity of information. Constellations and formation flying satellites may be appropriate for this kind of mission. Constellations use several satellites carrying different instruments each with independent control. Formation flying also uses multiple spacecraft, but with active control to maintain their relative position. Fly-by missions should incorporate landing rovers, using impactors or probes to analyze the surface of the asteroid directly, thereby providing data about the composition of the asteroid. Although fly-by missions can only provide limited information, a rendezvous spacecraft mission can also provide detailed characterization of asteroids (NRC, 2010).

11.1.2 Human Factors

The final mission architecture selected by the trade-off study does not involve human spaceflight. However, in the steps leading up to the first asteroid mission humans feature as part of the technology development path presented in the roadmap. They will be employed for short-duration missions in LEO where they will supervise the testing of the automated robotic assembly technology developed for asteroid mining, and will provide troubleshooting support when needed. This approach assumes that an existing space station will be available for staging such missions, such as the International Space Station, the proposed Chinese Tiangong space station (China Daily, 2010), or a future privatized space station. In this mission architecture there is no specific need to invent and develop new technologies to handle human factors mission aspects, because these will already be available. However, performing even short-duration missions in LEO has detrimental effects on human physiology, and the existing countermeasures are only partially effective. Thus, there will be a general requirement to advance the development of medical countermeasures for human spaceflight.

Apart from human factors, we must also address microbial life and the possibility of bringing space-faring bacteria and contaminants back to Earth. Although the likelihood of such an occurrence is low, the potential risk is great. As such, microbes may present a threat to which humanity and other terrestrial species have no pre-existing immunity. There is evidence suggesting that microbial life can indeed survive in the harshness of space. For example, astronauts during the Apollo 12 mission found evidence of *Streptococcus mitis* on a piece of the Surveyor 3, an unmanned probe sent to the moon 2.5 years earlier. The bacteria had survived 31 months of radiation, harsh temperatures, no water, and no atmosphere. Scientists have made similar discoveries related to the tenacity of microbial life on Earth. In a New Mexico cavern, located 600 meters below the surface, spores of Bacillus bacteria in a state of suspended animation were present in samples of crystal salts. Revival and growth of these spores in a laboratory was possible after lying dormant for 250 million years (Clément, 2003). One theory of the origin of life on Earth postulates that microbe-carrying meteorites seeded Earth during collisions, (O’Leary, 2008). The Outer Space Treaty also addresses the issue of possible
contamination from celestial bodies. Nations should take precautions to avoid homebound contamination that may result in harmful changes to Earth's ecosystem (Clément 2003). To protect against possible contamination of Earth upon return of ore samples and equipment from an asteroid mining mission, it is necessary to develop appropriate methods and tools for sterilization of materials before return to Earth, possibly through irradiation or chemical means.

11.1.3 Social Considerations

From a social point of view, the team hopes that this project will have all the political, social, and academic support possible. Therefore, the modification of public opinion in favor of asteroid mining is crucial, and public outreach must be a high priority in the early stages. By direct and indirect means, making use of press and new technologies, and advertising the goal to bring affordable resources to everyone's attention, we can produce a positive response to the concept. As a part of our scientific discoveries, we can establish collaborations with individuals from academia, form alliances, and strengthen cooperation. This ongoing action can create favorable relationships with the public and convince policymakers to support this project.

11.1.4 Engineering

There are several critical aspects of an asteroid mining mission, which require engineering solutions. The team considers the following aspects in the roadmap development: propulsion systems, assembly of components, transfer from LEO to an asteroid, docking and landing on an asteroid, mining and processing the resources, return from the asteroid, and transport of the materials to Earth.

Propulsion Systems

Robotic mining of large asteroids in-situ and the return of resources to Earth requires the delivery of heavy equipment to Earth orbit. We can consider the following options for the delivery of heavy payloads to orbit:

- Launch the assembled mining system with a heavy lift or super heavy lift launcher
- Transfer mining subsystems to orbit with currently available rockets by multiple launches and assemble them in-orbit

Depending on the mass of the mining system, the first option may require the development of new launchers, which would have financial and schedule implications. The second option is more viable because operational launch vehicles are employable. Possible launchers are:

- Ariane V with payload capability of 20 metric tons to LEO (Arianespace, 2010)
- Delta IV with payload capacity of 23 metric tons to LEO (Boeing, 2010a)
- Falcon 9 Heavy with payload capability of 32 metric tons to LEO (SpaceX, 2010)

Assembly of Components

There are robotic technologies currently available for ground-based self-assembling systems, which form a foundation for this development. Developing new technologies is required to make robotic systems self-sufficient and able to perform complex assembly operations with
launch vehicles and payloads. Proving this technology via ground-based tests is the first step.

After launching components of the spacecraft into Earth vicinity, assembly of the components is required. This is technologically achievable as demonstrated by the assembly of the International Space Station (ISS). The current technologies require human operations such as controlling robotic arms, manipulating payloads in space and EVA. A large number of seamless assemblies are required to allow for quick access to the asteroid. The roadmap for the development of such a complex technology involves many milestones to be completed in a given timeframe.

For an assembly in LEO, a larger platform like ISS is required. In the initial stages of development, humans should supervise robotic assembly operations until the process is reliable. Demonstration of all ground-tested robotic technologies will occur in space. All necessary testing and corrections will happen in this phase. After analyzing the test results, technologies should be sufficiently capable for completely autonomous assembly.

Next, the robotic systems should perform the assembly operations independently. If there is a problem during this phase, the human crew can rectify issues through a rescue mission. This stage is important to provide confidence in fully autonomous robot systems.

The following stage is autonomous integration in LEO. There will be autonomous integration of components from multiple launches. The team suggests multiple launches into LEO, to support single or multiple asteroid mining missions. For example, one launch could contain sufficient mining equipment for many missions. At this stage, we can integrate different components like docking systems, mining systems, ISRU, and fuel generation systems. The process is complex and we expect sophisticated robots to perform the integration. Once we achieve this, a fully autonomous robotic precursor mission can follow.

**Transfer from LEO to the asteroid**

For transfer of the system from LEO to the asteroid, it is possible to employ several different rocket propulsion systems, such as chemical, nuclear, or electrical, for the acceleration or deceleration of vehicles in space. The main parameters used to compare the performance of propulsion systems are thrust and specific impulse. The propulsion system methods considered to transfer from LEO to the asteroid are chemical and electrical propulsion. Both types of engine accelerate the spacecraft by means of thrust but there are fundamental differences between them. The chemical engines provide high thrust enabling fast transfers but they provide low specific impulse. In contrast, the electrical engines provide a high specific impulse but they have low thrust and result in a slow transfer.

To select the type of engine and propellant for an asteroid mining mission, one must consider a number of interdisciplinary aspects. For the current scenario, time constraints for returning resources to Earth limit the choice to chemical engines.

**Docking to asteroids**

One of the critical challenges of asteroid mining is landing on an asteroid. Studying this complex technique can result in the realization of a rendezvous and docking (RVD) system based on classical spacecraft dynamics and control. We must consider specific landing challenges. These
include the selection of a safe landing site dependent on the spinning and tumbling of the asteroid, avoiding potentially hazardous gases and debris released from the asteroid, and considering the influence of the microgravity on the trajectory of the spacecraft. Landing on an asteroid requires a platform that can rapidly secure itself upon touchdown due to the low gravity conditions. Therefore, a good landing system is one that can anchor the spacecraft to the asteroid by means of spear guns and cables.

Given that the selection of a suitable landing site is an essential part of the mission, developing advanced imaging and characterization technologies is of necessity. Soft landing and anchoring to the asteroid’s surface are required for carrying out mining. Potential methods for anchoring include single penetration or penetration using several pyrotechnic harpoons with or without reel cables (Basso, 2006). For ferromagnetic asteroids, magnetic attachment is an option. Table 11-1 shows the requirements and technology for docking.

### Table 11-1: Requirements and technology for docking

<table>
<thead>
<tr>
<th>Requirements</th>
<th>Technologies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precise control and guidance</td>
<td>RVD systems using technology from improved ISS RVD systems</td>
</tr>
<tr>
<td>systems for RVD</td>
<td></td>
</tr>
<tr>
<td>Imaging and characterization</td>
<td>Characterization systems for landing site detection using technologies from</td>
</tr>
<tr>
<td>technologies</td>
<td>improved imaging, pattern recognition, and analysis systems of Mars rovers</td>
</tr>
<tr>
<td></td>
<td>and landers.</td>
</tr>
<tr>
<td>Soft docking / anchoring capability</td>
<td>Anchoring systems involving single penetration, penetration using multiple</td>
</tr>
<tr>
<td></td>
<td>pyrotechnic harpoons with or without reel cables, or magnetic systems.</td>
</tr>
</tbody>
</table>

### Mining and Processing the Resources

The most challenging phase of the mission is the robotic mining and processing of mined material *in-situ*, due to the novel nature of the field and the advanced technical requirements in the area of robotics. We need to consider the challenges of developing systems for autonomous mining, material collection, and processing in the hostile environment of space.

Precursor missions including ground-based experiments, LEO-based techniques, and a test missions to a small asteroid are vital for the success of the mining mission. The first aim of an explorer mission is to gain further knowledge of potential mining in a microgravity environment. To complement this activity, parabolic flights can simulate environment constraints to test equipment. Ground testing using the same tools assisted by robots can assess the technical risks and to determine the dimensions required for the machinery. Numerical simulations and modeling can provide a better prediction of:

- Fluid dynamic behavior by conducting chemical reaction experiments under microgravity conditions
- Behavior of the structure and tolerances on tools
- Constraints on structure dimensions caused by space launch
- Durability of the equipment

Following the first phase, a second preparation phase will consider mining operations in LEO.
It is essential at this stage to test the durability of machinery in extreme conditions and the technical requirements to improve the designs or material if necessary. It is also an opportunity to compare the simulated predictions with the obtained results, to improve the robustness of the simulation tools for future predictions and the mission.

As a last step of preparation, we suggest a test mission to a small asteroid to evaluate all technologies and procedures needed. The objective is to confirm the feasibility of the eventual mining mission, by testing the robotic machinery. This is the final test of reliability and robustness for the technologies developed.

Potential mining techniques include scraping away the asteroid’s surface, drilling, tunneling, strip mining, and excavating. From the mission concepts discussed (Section 6), the most feasible and efficient solution is the chemical concept using iron, nickel, and cobalt. Recent research on M-type asteroids has led to the discovery of asteroids like 216 Kleopatra or 624 Hektor, which are composed of a loose assemblage of metal grains forming an overall dumbbell shape, a narrow neck possibly affected by impact erosion and redistribution of debris (Hartmann, 1978). Metallic powder covers the surfaces of these asteroids, providing an excellent opportunity to collect metal grains with simple robotic machines equipped with magnets.

**Return from the asteroid**

Due to the simplicity, reliability, and high performance of chemical propulsion systems (Wiley, 2003), they are the preferred option for the return mission. They are the fastest way of transportation available with current technology. The main challenge is the capacity to store the potentially toxic propellant during the mission for the return journey to Earth. Collecting and storing the material mined from the asteroid also requires a special tank. The tank shape should consider the associated torques and forces. The bigger the collecting tank, the more drag exerted while reentering the Earth’s atmosphere.

Navigation is another challenge for an asteroid mining mission. We can gain experience from interplanetary missions and the Apollo program to determine what we must improve (Goodman 2009). Inertial navigation calculates positions relative to a known starting point, and it is widely used for the space-based activities. Other more advance techniques that could apply when the spacecraft is at the other side of the Sun when there is no means of contact with Earth is, for example, using Xnav, a system based on X-ray pulsar source navigation and timing (Graven et al, 2008). Other deep space navigation methods can be developed in the meantime and used.

**Transport of Materials to Earth**

The final objective is to deliver the mining products to Earth’s surface. This objective requires development of a specific system capable of frequent reentries. Complete processing of the resources may not occur in-situ, and the return shipment could be a partially processed mixture of ore and minerals. Since multiple cargos are expected, it is ideal to use reusable equipment. The exploitation of current technology is necessary for facilitating the development of a dedicated capsule able to fulfill the project needs. There is already active research on reusable reentry vehicles upon which future research should capitalize (FAA, 2005). The principal research goals should pertain to the reusability and the carrying capability of larger cargos. To manage the delivered minerals to the Earth’s surface, there will be a ground recovery system and team in charge of recovering the cargo and distributing it to the selected destination. The landing site
should be determined according to economic and political criteria.

11.1.5 Legal Issues

It is necessary to address a number of legal challenges before a private entity will undertake an asteroid mining mission. While some issues addressed in Section 9 have a solid legal basis when applied to asteroid mining activities, others require new legislation. This section presents the findings of Section 9 in terms of the roadmap by providing a timeline of activities required to legitimize asteroid mining activities.

The first activity is an investigation into the current legal framework to identify the challenges that apply to asteroid mining. Gaining wide acceptance for legitimate asteroid mining using current space law would be the easiest, most desirable goal. This activity will conclude with the identification of key areas that require new legislation to allow asteroid mining activities. For example, the current legal framework sufficiently covers registration of an asteroid placed into Low Earth Orbit and liability concerns. Conversely, appropriation will be problematic without new legislation clarifying the way ahead.

Following this investigation, the development of new legislation is required. This legislation shall be in place before a private entity invests significantly in an asteroid mining mission. Given the expected complexity of drafting new legislation and the number of state stakeholders, this process could take many years. While other preparatory activities towards a successful asteroid mining mission can occur concurrently, financing may not be forthcoming from a commercial entity based on hopes that new legislation will exist at a future date. Another alternative is that a private entity chooses to conduct asteroid mining prior to completion of the legislative framework. In this instance, the private entity must accept greater risks in the venture to avoid delaying asteroid mining activities. The new legislation will clarify existing space law to allow asteroid mining activities for the benefit of humankind. Specifically, the new legislation will cover the elements of jurisdiction, appropriation, liability, and distribution. A description of these elements follows. In addition, this section makes recommendation for a starting point aimed at minimizing development time of legislation.

Although the availability of asteroids in the near-Earth environment appears plentiful, a process for the allocation of these resources is necessary. This process should be similar to the assignment of frequencies and geostationary orbits established by the International Telecommunications Union (ITU). Such a process will ensure that every state has fair access to resources contained in outer space, thus preventing the contention over access to resources.

Appropriation of mined resources is a significant hurdle to legitimate asteroid mining. Wide support for interpretations of space law legitimizing asteroid mining activities does not exist. Consequently, new legislation is required. The proposed legislation should use the United Nations Convention on the Law of the Sea (UNCLOS) as a base since it is widely accepted (ratification by 160 states) and it contains provisions for the exploitation of mineral resources.

Additionally, we should take into consideration currently existing national space law, such as the U.S. or Australian laws, when creating the new framework. This legislation must ensure that states participating in mining activities, states purchasing mined resources and non-participating states all derive some benefit from asteroid mining activities. Otherwise, there exists no incentive for a state to ratify the new legislation.
Asteroid mining introduces a number of liability issues not covered in current legislation. New legislation must consider the obligations of an entity moving an asteroid to Earth orbit in the event of damage. Current legislation is quite clear when the mining entity is associated with a single state but becomes ambiguous when several states are involved. Moreover, the new legislation must consider participation of humans in asteroid mining activities. An understanding of the conditions affecting the astronaut’s health will help in developing an adequate framework to ensure appropriate compensation. The new legislation will minimize unnecessary litigation and serve to protect the interests of astronauts while in space. Finally, new legislation is required to assess jurisdiction and attribution of fault in the event of contamination of the Earth’s environment due to asteroid mining activities.

Issues stemming from the distribution of resources acquired in outer space in current space law are problematic. Interpretation of current legislation concerning the distribution of mined resources varies between developed and developing states. Consequently, legislation for the distribution of resources acquired in outer space is required. This legislation should produce a win-win-situation for all parties so that distribution legislation does not impede the profitability of asteroid mining while allowing developing states to benefit from the activity.

11.1.6 Business

The business roadmap for ASTRA is significantly different from the other disciplines as it encompasses the economics of the progress of the project. The roadmap consists of two main sections: the decision point and the milestones.

There are two critical decision points during the project. The first occurs before commencing the surveying mission. Prior to this, it is necessary to evaluate the benefits and costs of the mission. To test the feasibility, we must first compare the estimated value and cost of the mission. If this value exceeds the cost, the mission should proceed. Otherwise, we have to wait until the value does exceed the cost.

The second decision point occurs after completion of the surveying mission, when the information necessary to choose which asteroid to mine is available. With this information, analysts have to estimate the value of a hypothetical entity that would mine these asteroids. If this value exceeds the required investment with a large margin, it would be wise to launch the enterprise. Otherwise, it is best to wait until the value reaches this point.

There are four business milestones during the asteroid mining project:

- Media publicity
- Finance of the surveying mission
- Finance of research and development, launch of the company, and public acceptance
- Finance operations and acquire insurance against potential risks

Media publicity is an ongoing attempt to promote activities and progress. This is a preliminary step to gain public acceptance in the future. After confirmation of success of the first decision point, the surveying mission will commence, and we will have to finance it. The business case section of this report describes in detail this process; however, the important point is that a majority of the financing must come from government and incentive-based investments. We want to minimize our personal investment, since this project is of interest to many third parties.
Establishment of the asteroid mining business occurs subsequent to the second decision point. This requires a very heavy investment, thus financing this investment is a major milestone of the project. This investment will require large equity commitments from governments, venture capitalists, and industry partners (Recommendation II). Concurrent to this phase, public acceptance will have to be encouraged by our lobbying efforts.

The final milestone is to finance the operations of the enterprise once the entity is established. This will most likely originate from debt or private equity. Insurance must be arranged for the risks we expect to be encountered.

### 11.2 Risk Assessment

Since the present architecture is an entirely robotically-operated mission, risk to human life is not significant. The dominant uncertainty encountered in the present asteroid mining project is the danger that sub-systems will malfunction resulting in significant negative impacts for the return on investment. To perform risk analysis, the mission is divided into different phases and the risk involved in each phase is highlighted. This is shown below in Table 11-2.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Description</th>
<th>Risk factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Multiple launches to LEO</td>
<td>Failure of single or multiple launches</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Injection to degraded orbits</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Missing of the window for transfer to asteroid due to launch delays</td>
</tr>
<tr>
<td>2</td>
<td>Robotic assembly in LEO</td>
<td>Erroneous electrical or mechanical integration</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Failure of assembly operations</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Component failure</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Damage of equipment during assembly</td>
</tr>
<tr>
<td>3</td>
<td>Transfer to asteroid</td>
<td>Delay in previous phases may result in missing launch window.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Unsuccessful transfer to asteroid due to equipment or propulsion failure</td>
</tr>
<tr>
<td>4</td>
<td>Rendezvous</td>
<td>Failure of sensors</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Failure of thrusters</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Collision with spinning/wobbling asteroid</td>
</tr>
<tr>
<td>5</td>
<td>Landing</td>
<td>Wrong assessment of the landing surface</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Crash landing</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Improper attaching</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Detaching from the asteroid surface after landing</td>
</tr>
<tr>
<td>6</td>
<td>Setting up equipment</td>
<td>Assembly problems</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Robotic malfunction</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Environmental factors like dust, electrostatic effects</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Damage of equipment</td>
</tr>
<tr>
<td>7</td>
<td>Robotic mining</td>
<td>Robotic failure</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Unanticipated nature of the surface</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wrong autonomous decisions</td>
</tr>
<tr>
<td>8</td>
<td>Processing of mined</td>
<td>Microgravity and environmental factors</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Leakages and chemical reactions</td>
</tr>
</tbody>
</table>
### 11.3 Detailed Interdisciplinary Roadmap of Asteroid Mining

Team ASTRA created the interdisciplinary roadmap from the selected architecture and input from all disciplines. Figure 11-1 shows the roadmap commercial asteroid mining.

![Interdisciplinary roadmap](image)

**Figure 11-1: Interdisciplinary roadmap**

#### 11.3.1 2010 to 2016

In the near-term, better composition data for a serious economic feasibility study is needed. Concurrently, social and conventional marketing techniques should generate interest in the

<table>
<thead>
<tr>
<th>Phase</th>
<th>Description</th>
<th>Risk factors</th>
</tr>
</thead>
</table>
| 9     | Return from Asteroid | Failure of transportation system  
Re-contact during take off  
Improper loading of the mined material |
| 10    | Transfer resources to the Earth | Failure of thermal protection system  
Exceeding aerodynamic load limits  
Parachute failure  
Missing the landing zone |
| 11    | Business risks | Wrong evaluation of existing resources |

In addition to the above factors, since the mission is complex, with a large number of mutually interacting phases, human errors, or incompatibility in interfaces may also lead to failures. Finally, catastrophic failures can result in the damaging of orbiting satellites or harm to people and property on Earth, which would result in significant legal and social implications.
The concept of commercial asteroid mining. Demonstration of the following basic capabilities is necessary: heavy-lift launching, robotic assembly of spacecraft, and terrestrial robotic mining and processing. Stakeholders must have realistic legislation proposals ready by this time. Team ASTRA does not recommend crewed missions for actual asteroid mining, but improvements in space environment countermeasures may warrant reconsideration.

### 11.3.2 2016 to 2028

In the twelve-year period following a positive economic feasibility study, major asteroids should be characterized with fly-by missions and space-based remote sensing. Existing capabilities can support demonstration of spacecraft assembly (by humans) in LEO and demonstration of robotic mining systems in a microgravity environment. *In-situ* fuel generation must also be demonstrated. Following these advancements, autonomous assembly and sample return missions can occur. Beyond absolute characterization, such missions would prove asteroid rendezvous techniques, such as harpooning and magnetic attachment (Recommendation VII).

In this period, the majority of funding must come from government and incentive-based investments (such as the Google Lunar X-Prize model) as the ROI of commercial asteroid mining will still be too far away. Significant progress to resolve appropriation issues must occur in this period. In particular, a space analog to UNCLOS’ mineral resource exploitation provisions is necessary. For commercial asteroid mining to be possible, sterile delivery of materials to Earth, academic participation and successful outreach is necessary.

### 11.3.3 2028 to 2040

Positive results of another economic feasibility study are required to move forward. A large database with asteroid orbits and compositions must be available to select a candidate asteroid. Thereafter, a proof of concept mission to demonstrate the sterile return of materials to Earth is necessary. Outreach and political efforts must show positive results with working international legislation that allows for appropriation, delivery and distribution of asteroidal resources. The legislation must also manage liability of commercial asteroid mining companies and countries. A solid business plan must be developed and sold, with financing from governments, venture capitalists and industry partners. Proving the following capabilities in space is necessary: autonomous spacecraft assembly, microgravity asteroid mining and processing, and propulsion systems to return materials to Earth. Only once all requirements above are satisfied can commercial asteroid mining begin.

### 11.4 Interdisciplinary Roadmap Conclusion

This roadmap presents one way of forming a business from an extremely unconventional and futuristic entrepreneurial initiative. The roadmap addresses a series of time-ordered activities that will lead to a commercial mining venture. Consisting of elements from various disciplines, the roadmap effectively addresses numerous challenges indicative of such a complex endeavor.
12 CONCLUSIONS AND RECOMMENDATIONS

There are many challenges that must be overcome before commercial asteroid mining can become a reality, but they are not insurmountable. This section summarizes the conclusions drawn by the ASTRA team, along with recommendations outlined for future work.

To produce an interdisciplinary roadmap, team ASTRA first identified challenges that one needs to address from the following disciplines: science, engineering, life sciences, societal studies, legal and business. The team created mission concepts to solve the science and engineering challenges. We then used these mission concepts to create several possible mission architectures: three common architectures for characterizing asteroids, six for returning small NEAs to the Earth vicinity, and five for mining large NEAs in-situ.

Team ASTRA developed a trade-off study based on the SMART process to compare the architectures. The trade-off study used criteria from all disciplines and was supported by a SWOT analysis. Based on the study, the team recommends the architecture to mine large NEAs robotically, via:

- Explorer missions to characterize asteroids and identify a candidate for mining.
- Robotic assembly of a mining spacecraft in LEO.
- Travel to the asteroid, set-up of mining equipment, mining, and materials processing.
- Return of product to Earth-vicinity.

If one cannot identify a suitable large asteroid, then team ASTRA recommends the use of a propulsion system to move a small NEA to Earth-vicinity for mining with crewed missions.

The team ultimately developed the roadmap, based on the selected architecture, through the review of the challenges posed by all relevant domains. We describe the conclusions of these domains in the subsections below.

12.1 Human Factors

Crewed asteroid mining enhances attributes such as performance and adaptability, but at higher mission cost and risk of life. The trade-off study conducted by Team ASTRA considered several architectures featuring crewed mining missions, which scored less favorably than the robotic architectures. The selected architecture met all requirements at a reduced cost and complexity relative to those involving crewed mining missions, while lessening the negative legal and political impacts. This architecture includes one crewed mission for demonstration of spacecraft assembly in LEO, but the complexity of this mission is similar to the assembly of the ISS.

12.2 Societal Factors

The launch of commercial asteroid mining entities will undoubtedly introduce significant
impacts to society. Its success is largely dependent on garnering both public and legislative support, which necessitates effective outreach to promote the overall concept and demonstrate that the positive achievements outweigh the negative repercussions; although it will reduce employment within the traditional labor-intensive mining industry, it will also provide the opportunity for a technological development boost that will spawn entirely new job sectors. Society will also benefit from new capabilities arising from increased access to previously rare materials. Additionally, it provides the opportunity to promote international cooperation and lessen the global development gap if space-faring nations share these exploited resources, new technologies, and growth opportunities with non-space countries where mining is a significant economic driver.

12.3 Legal Issues

Sovereignty, appropriation and distribution issues as addressed by current international space law do not allow for asteroid mining, as such. Legally speaking, space is considered the ‘common heritage of mankind’, making it difficult to gain acceptance for commercial asteroid mining from international governances. To enable asteroid mining, there is a need for the development of an international regime to construct a new legal framework. In order to be successful, this framework must take into account the needs and desires of all nations, as it would be problematic for any single nation or entity to unilaterally decide to mine asteroids commercially.

The lessons learned from the Antarctica treaty and the UNCLOS treaty demonstrate that clear regulations must benefit all participants and not only those carrying out the mining. The resulting regulations should also provide economic incentives for non-participating States, and those States that stand to lose if terrestrial mining operations are negatively affected. For participating States or entities, a real possibility for return of investments must also be present to make commercial asteroid mining viable.

12.4 Economic Viability

Within the foreseeable future, the team concluded that the mining of high value, low mass products (e.g. platinum group metals) is the only economically feasible option, and that this cannot be self-sustaining until a number of technological advances are made. Fortunately, the utility of platinum group metals as catalysts for a great series of chemical reactions makes them a prized commodity for both private and public stakeholders.

Team ASTRA proposed various financing methods to sustain an asteroid mining venture, with the conclusion that a Public Private Partnership has the highest potential for future feasibility. Valuable scientific data from survey missions provide some of the rationale for some of the public funding. Private incentives similar to the Google Lunar X-Prize can accelerate technological development and commercial interest. As technology matures, risk will decrease and ROI will increase, making venture capital and private equity possible.

Flooding of the market presents a complex problem; we have identified two techniques to mitigate its effects: A quota-based sale strategy to maintain prices and the spurring of demand...
by developing high-end space-derived products.

Even though insurance requirements will be more complex for asteroid exploitation, insurance schemes for terrestrial mining can serve as an initial cost model. Self-insurance may be necessary due to the likely small risk pool for asteroid mining.

It is currently less costly to exploit materials on Earth. As scarcity increases and technology advances, there will come a time when commercial asteroid mining is economically justified.

12.5 Roadmap

Team ASTRA created the interdisciplinary roadmap from the selected architecture and expertise from all areas of this study. It outlines all of the steps that must occur to reach the end goal of commercial asteroid mining in approximately thirty years.

12.5.1 Short Term: 2010 to 2016

Space-based remote sensing is necessary to better characterize asteroids in order to conduct a serious economic feasibility study. To foster interest, asteroid mining stakeholders should use social and conventional marketing techniques and have realistic legislation proposals. In this timeframe, basic required capabilities should be demonstrated, such as the robotic assembly of spacecraft, robotic mining and processing on Earth, and cost effective launch systems.

12.5.2 Medium Term: 2016 to 2028

In the 12-year period following a positive economic feasibility study, we must further characterize major asteroids with fly-by missions and space-based remote sensing. The stakeholders should demonstrate spacecraft assembly in LEO by humans, robotic mining systems in a microgravity environment, and in-situ propellant generation (Recommendation VII). With these capabilities, sample return from large NEOs can occur to prove composition and demonstrate rendezvous techniques. In this period, the majority of funding must come from government and incentive based investments (such as the X-Prize model) as the initial ROI of commercial asteroid mining is too long for private sector investment. Stakeholders must resolve appropriation issues in this period, prove the possibility of sterile delivery of materials to Earth and conduct public outreach.

12.5.3 Long Term: 2028 to 2040

Continuing along the roadmap, the asteroid mining operator must produce positive economic results to attract investment from governments, venture capitalists and industrial partners. The entity must also complete or have access to a database with asteroid orbits and compositions so that candidates for mining can be chosen. The stakeholders must demonstrate more capabilities: return of sterile materials to Earth, autonomous spacecraft assembly in space, microgravity asteroid mining/processing, and propulsion systems with in-situ propellant production. Policymakers must produce international legislation that allows for appropriation, delivery and distribution of asteroidal resources. The legislation must also manage liability of commercial asteroid mining companies and countries.
12.6 Recommendations

ASTRA made considerable progress towards examining the feasibility of asteroid mining. Some areas require further research and development for commercial asteroid mining to become feasible. Recommendations following from the above sections are listed below:

<table>
<thead>
<tr>
<th>Table 12-1: Recommendations</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Recommendation I</strong> - Knowledge of Asteroids: The body of asteroid knowledge, particularly distribution and composition, is limited. Stakeholders should initiate the creation of a database of information from Earth and space telescopes and fly-by missions of asteroids. (Section 2)</td>
</tr>
<tr>
<td><strong>Recommendation II</strong> - Facilitating Development: Governments should provide more support to commercial space ventures (incentives, tax breaks) so that commercial development can start in earnest. (Section 11.1.6)</td>
</tr>
<tr>
<td><strong>Recommendation III</strong> - Economic Feasibility: At present, profitable asteroid mining depends on the return of high value low mass products such as platinum group metals. Stakeholders should study the market for these metals to better forecast future prices. (Section 10.5)</td>
</tr>
<tr>
<td><strong>Recommendation IV</strong> - A New Legal Framework: A new legal framework is needed to foster wide acceptance of legislation, encompass the interests of all nations, and provide incentives to non-participating States. Stakeholders should lobby for the development of this framework. Space-faring nations should issue governmental statements to address concerns of non-space-faring nations regarding distribution of resources. (Section 9.5)</td>
</tr>
<tr>
<td><strong>Recommendation V</strong> - Public Outreach: Outreach programs should focus on gaining public support so that policymakers shall be proponents of asteroid mining. (Section 5.5)</td>
</tr>
<tr>
<td><strong>Recommendation VI</strong> - Policy: Policymakers should consider nations that depend on terrestrial mining to ensure tangible benefits to all humankind. Stakeholders should inform those nations how they can benefit from participating and supporting asteroid mining. (Section 5.5)</td>
</tr>
<tr>
<td><strong>Recommendation VII</strong> - Technological Development: Before asteroid mining is possible, various demonstration missions as well as technology development are required. These include robotic assembly, mining, and processing demonstrations, as well as new launch systems and advanced propulsion technologies development. Therefore, stakeholders should initiate further technology development and preparation of demonstration missions. (Section 11.3.2)</td>
</tr>
<tr>
<td><strong>Recommendation VIII</strong> - Novel Uses for Asteroidal Metals: Asteroid mining entities should spur demand for their products to counteract the effects of market flooding. (Section 10.5)</td>
</tr>
<tr>
<td><strong>Recommendation IX</strong> - Back-Contamination: Adapt planetary protection policies to the return of exploited material to avoid potential microorganism contamination of Earth. (Section 4.2)</td>
</tr>
<tr>
<td><strong>Recommendation X</strong> - Human-Robot Interaction: HRI allows greater flexibility with reduced risk to human life. Development should focus on the control of mining robots to enable complex in-orbit mining operations. (Section 4.5)</td>
</tr>
<tr>
<td><strong>Recommendation XI</strong> - Long-Duration Human Spaceflight: Human participation in asteroid mining missions would provide greater flexibility. Current space environment countermeasures are inadequate to allow such long-duration human spaceflight. Stakeholders should support and initiate necessary advancement of research of these countermeasures. (Section 4.5)</td>
</tr>
</tbody>
</table>

Team ASTRA’s roadmap, conclusions and recommendations are a solid first step in reaching the goal of commercial asteroid mining. In the future, as new technologies emerge and political and economic climates change, the roadmap will require alteration. The architectures definition and trade-off study presented are objective and can be adapted to new inputs.
13 REFERENCES


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