From Research to Resource
Piloting Near-Earth Asteroids Through the Valley of Death

by

Dylan Cohen

B.A., Physics; B.A., Public Policy
University of Chicago, 2014

Submitted to the MIT Institute of Data, Systems, and Society and the Department of
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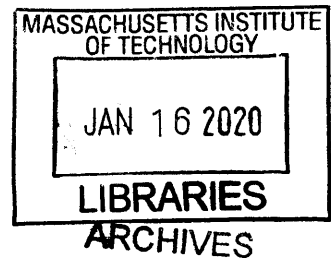the Degrees

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Abstract

Can the resources of near-Earth asteroids be profitably mined? Near-Earth asteroids (NEAs) contain water, which can serve as a fuel in space, and platinum group metals, which are valuable on Earth. The presence of these resources has prompted high valuations of the near-Earth asteroid population, but it is not immediately apparent if those valuations are accurate or if they can be realized. This thesis developed the Valley of Death model to frame the challenges opposing the development of an asteroid mining industry. This model poses the two following questions. What is the cash flow of a water/platinum group metal asteroid mining industry? How can the Valley of Death be crossed to realize that cash flow?

The first question was answered in the affirmative for water with a Monte Carlo simulation of the near-Earth asteroid population under resource content, price, and accessibility constraints. To assess the cash flow of platinum group metals a basis of comparison was developed between large platinum-rich near-Earth asteroids and terrestrial mines. This comparison demonstrated that, while the high valuation of the asteroids is accurate, the technical challenges of mining, refining, and transporting platinum render it unlikely to have a positive cash flow without dramatic technological advances that provide no immediate benefits. To answer the second question, the twin concepts of uncertainty reduction and technological advancement, resting on a foundation of progress incentivization, were developed. Uncertainty reduction consists of clarifying the legal status of asteroid mining and identifying the precise content and location of near-Earth asteroid resources. Technological advancement is needed to mine water at scale and to accurately assess the costs of mining platinum group metals. Incentivizing both tasks, possibly with prize competitions, will enable the industry to traverse the Valley of Death. This thesis concludes by discussing edge cases in asteroid mining which provide avenues for future research.

Thesis Supervisor: Richard Binzel
Title: Professor of Planetary Sciences and Margaret MacVicar Faculty Fellow

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Thank you as well to Dr. Frank Field, Barb DeLaBarre, and Ed Ballo. You are the beating heart of the Technology and Policy Program, and you have created a truly unique and wonderful learning environment. TPP builds a strong foundation for inquiry at oblique angles to traditional scholarship, and I believe that that is an eternally relevant skillset. Thanks to this program I feel well-armed in facing the troubled waters of an uncertain future, and I can offer no higher praise than that.

Finally, a very sincere thank you to my family, the TPP cohort, and everyone else who has been kind enough during these last three years to let me rant to them about asteroids.

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1   Introduction

Asteroid mining has been a staple of science fiction ever since the idea was first conceived 121 years ago (Serviss, 1898). In recent years, breathless pop-science articles have heralded the arrival of an age of trillionaires whose wealth flows from an endless stream of asteroid resources. Despite this burgeoning interest, there have been relatively few efforts to fully evaluate asteroid mining as an industry. The research that has occurred has been narrowly focused. Planetary scientists studied asteroid compositions and resource content (Elvis, 2014), legal scholars studied asteroid mining law (Reed, 2018), and businesses considered market opportunities (Edwards, 2017), but none presented a comprehensive view of this potential field. This thesis aims to remedy that absence by applying planetary science conclusions to the legal and economic circumstances of the field to produce a guide to the feasibility of an asteroid mining market.

To begin with, the term "asteroid" refers to any small rocky body orbiting the sun. The relatively small size of these objects makes them difficult to detect compared to other celestial bodies, and for that reason asteroids are a relatively recent field of study. The first and largest asteroid, Ceres, was discovered in 1801(Cunningham et al., 2011). Only ten asteroids had been discovered by the 1850s and less than 500 had been found by 1900. The asteroids discovered were, for the most part, from the asteroid belt, a region of space between Mars and Jupiter which holds a significant fraction of the Solar System's asteroid population, particularly those large enough to be easily found (European Space Agency, 2019). Asteroids in that belt have orbits around the sun with large enough radii that they will never come near Earth.

However, beginning in 1898, asteroids that orbit the sun at less than 1.3 AU began to be discovered (International Astronomical Union, 2013). "AU" refers to the astronomical unit, the average distance between the Earth and the Sun. Asteroids in the given range are referred to as Near Earth Asteroids (NEAs) because their orbits are close to and occasionally cross the orbit of the Earth. As of 2019, roughly 20,000 NEAs have been discovered (Chamberlain et al., 2019).

There are three broad taxonomic classes of asteroids: C-type, X-type, and S-type. Carbonaceous, or C-type, NEAs tend to be darker, contain carbon-bearing minerals and volatiles such as water, and represent roughly 20% of the NEA population (Bus et al., 2002; Binzel et al., 2019). X-type NEAs are the category for NEAs that do not fit in the other two classes. They vary widely in

composition, but one subgroup is made up of metallic NEAs, which have high nickel-iron content and the potential for high platinum concentrations as well. The class as a whole is roughly 20% of the NEA population, though the proportion of that that is metallic is unknown (Binzel et al., 2019). Finally, S-type NEAs are "stony" objects comprised primarily of silicates, and S-type NEAs represent 60% of the NEA population (Bus et al., 2002; Binzel et al., 2019). This thesis focuses on the feasibility of mining water from C-type NEAs and mining platinum group metals (PGMs) from metallic X-type NEAs.

Building on this foundational knowledge of the nature of NEAs, it is necessary to clarify what assessments will, and what will not, be included in this thesis. This thesis is an analysis of the feasibility of *profitable* near-Earth asteroid mining. NASA is currently trying to identify ways to use space resources to expand the set of feasible mission architectures, often referred to as in-situ resource utilization (ISRU) (Mahoney, 2017). This is a promising research avenue, and one that does have some bearing on industry level mining, but the profitability restriction means that NASA missions which conduct their own ISRU are not considered NEA mining. Only if another party mines a NEA and sells their product, to NASA or another entity, is it included in the analysis.

Additionally, this thesis is not overly concerned with the technical feasibility of landing on an asteroid and extracting a resource. While it must be touched upon to properly assess the market for the resources, the existence of sample return missions such as OSIRIS-REx demonstrate that it is technologically possible to visit a NEA and return pieces of it to Earth (Arizona Board of Regents, 2019). Instead, the focus is on the price points and scale at which this technology can be developed and operated.

Following this introduction, chapter two begins by developing the "Valley of Death" metaphor as a guide to the pitfalls inherent in the transition of a research driven technological field to an industry centered around the extraction and sale of NEA resources. Chapters three and four consider the prevalence of water and platinum group metals in C-type and X-type NEAs, respectively. This permits the development of an estimate of the value of the resources present in the NEA population, and by so doing enables this thesis to put bounds on the size of a potential NEA mining industry. Demonstrating the presence of value in NEA resources justifies the

further exploration of ways to traverse the Valley of Death. Chapter five explores the current status of international law, national law, and private industry to understand the position from which asteroid mining faces the Valley of Death. Chapter six uses the findings from the previous chapters to develop a guide to crossing the Valley of Death. Finally, chapter seven considers future avenues for research and consolidates the findings from the other chapters into concrete conclusions.

2 The Valley of Death

This chapter has two purposes. First, it explains what the Valley of Death(VoD) is, why it is relevant, and how it will be applied in the remainder of this thesis, all drawn from the disciplines of innovation and technology transfer. Second, this chapter situates the field of asteroid mining in the VoD metaphor as being on the precipice of entering the Valley of Death, motivating the exploration of the valley and its far side which occurs in the rest of the thesis.

2.1 The Creation of the Valley of Death model

VoD as an idiom was first used in a 1989 handbook the Department of Energy made to guide small business inventors to successful commercialization of their technology. In the report, the concept referred to the fact that the development of new technology necessarily contained a period in which money was being spent to develop a market-ready innovation, but no income was being generated (U.S. Department of Energy, 1989). Thus a chart of net value would dip down before, ideally, a market-ready product would be sold and it would rise again, as in the following figure.
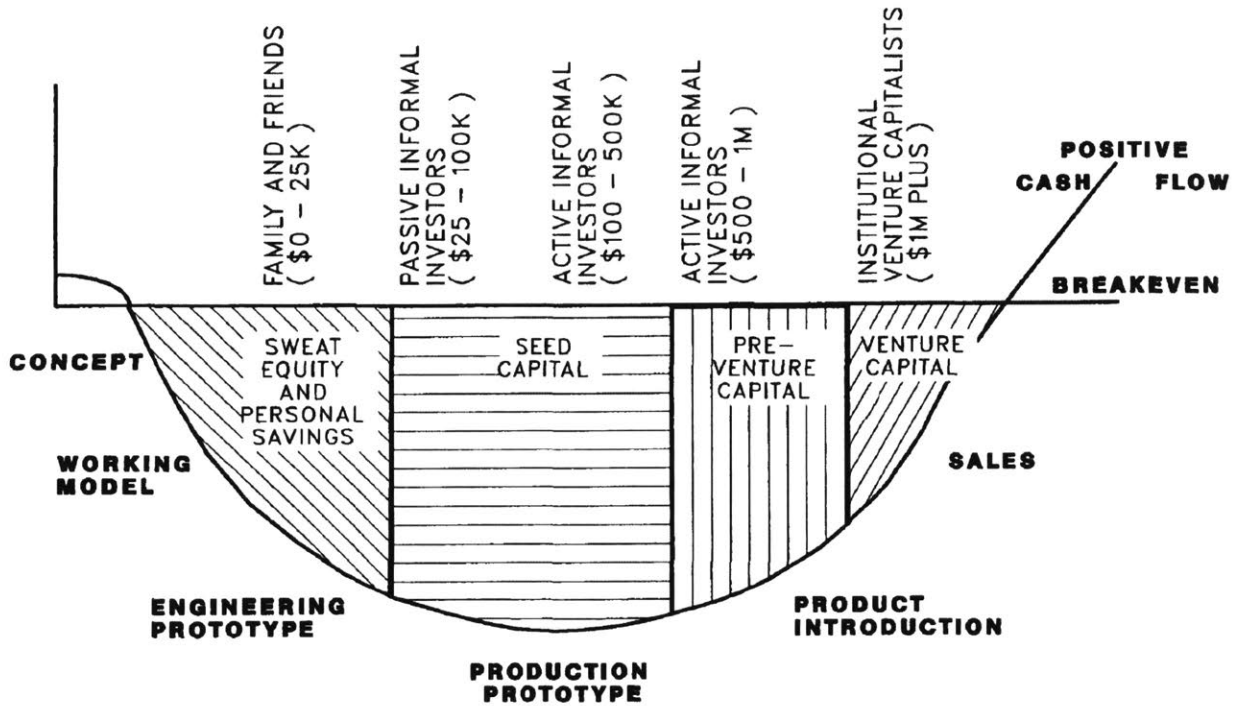
Figure 1: This is a plot of net cash-flow over time. In the early stages the cash is spent to develop a product without formal funding mechanisms or any means of profit generation. Developing a prototype is more expensive, and requires more formal funding mechanisms, but there is still no profit to be had. Only after sales have begun (and often after venture capital has become involved) does the product produce profit, finally paying back the initial investment and crossing the break-even point (U.S. Department of Energy, 1989)

Though the descent was certain – money cannot be made without first spending it, after all – the rise depended on the acquisition of sufficient funding. Many innovations, despite being technically feasible perished in that low cash-flow phase of development, hence the name Valley of Death.

Initial VoD Model:

1. Entrepreneur develops concept with market applications using self-funding
2. More significant and difficult to acquire funding is required to create prototype
3. Venture capital funds scaling and market entry of former prototype
4. Sale of product leads to positive cash flow

The concept proved to be quite compelling as a popular explanation for why certain promising products never made it to market. As is often the case with useful analogies, it was expanded beyond its initial meaning. This is fortunate because, in the initial conception, the Valley of

Death referred specifically to a private investor attempting to secure funding. NEA mining, the subject of this paper, differs from that initial configuration in several key ways. The following section shows the ways in which the Valley of Death framework was expanded from its initial form, in order to demonstrate that the application of the framework to NEA mining is reasonable.

2.2   Expansions of the Valley of Death model

A particularly prescient 1996 case study by Clyde Frank et al. expanded the use of the Valley of Death concept in many of the ways that are useful to the present analysis. That paper cited the government as the pre-VoD funder of research (Frank et al., 1996), a view confirmed by the government itself in a 2003 report on technology transfer in the National Renewable Energy Laboratory (Murphy et al., 2003).

Frank et al. also produced a useful explanation for the VoD itself.

> At this point, the government considers the technology too "applied" to continue to provide funding, since the government's role is to fund more basic research [research with no direct practical purpose], yet the private sector does not want to invest capital because the technology has not yet been implemented (Frank et al., 1996).

The first expansion takes the VoD from a model that applies solely to individual entrepreneurs attempting to commercialize their technology, to one that encompasses the challenges inherent in the transfer of technology from government research to private enterprise. This is a dramatic change, but the fundamental aspects of the VoD model are not altered. In place of an entrepreneur there is now the government, spending its own money on research, there is the decline of cash flow when the government ceases to fund development of the technology, there is the cash flow rise associate with the engagement of private funding, and finally there is the cresting of the break-even point and the ascent into profitability. In this conception the VoD model applies to the lifecycle of a single specific technology.

VoD Model Expansion One:

1. Government performs research with promising market applications
2. Non-governmental and difficult to acquire funds required for creation of prototype
3. Venture capital funds scaling and market entry of prototype
4. Sale of product leads to positive cash flow

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Another expansion of the model was to aggregate the VoD path for multiple similar technologies into a single overarching VoD path. Frank et al. came close to expanding to a field wide perspective in that they considered a bundle of technology from the pharmaceutical industries, drugs in that case, rather than the entire pharmaceutical industry as a whole. A more modern paper pushes the concept even further by developing a model by which new energy technologies compete with and displace older technologies (Hartley et al., 2017). By creating a generalized model which incorporates the Valley of Death faced by new technologies, they are broadening the scope of the framework to encompass more than merely a single technology (Hartley et al., 2017). However, even as a generalized case they are still using the framework primarily to apply to individual technologies rather than the energy sector as a whole.

VoD Model Expansion Two:

1. Government performs research with promising market applications
2. Non-governmental and difficult to acquire funds required for creation of prototype
3. Venture capital funds scaling and market entry of prototype
4. Sale of product leads to positive cash flow
5. [Aggregate 1-4 for multiple technologies in the same field e.g. pharmaceuticals]

A further expansion of the VoD model is inherent in the application of VoD to NEA mining as presented in this thesis. It is not possible to use the aggregation of NEA mining technology within the VoD model because individual NEA mining technologies – a device to extract water from a NEA for instance – cannot reach a positive cash flow in isolation. That is, as it currently stands, a device to extract water will never be profitable if a target is not identified and a craft to transport the device to the NEA is not developed. For this reason, the individual technologies never escape the VoD, so the aggregation is insufficient. Rather, the entire field of NEA mining must be considered as a single unit, because only together would it be possible for NEA mining to escape the VoD. One caveat to this, as will be discussed in the section on escaping the VoD, is that enabling components of NEA mining to escape the VoD in isolation is one of the methods to encourage the field as a whole to chart a path out of the VoD.

VoD Model Expansion Three (Proposed here):

1. Government performs research with promising market applications
2. Non-governmental and difficult to acquire funds required for creation of prototype
3. [Repeat 1 & 2 until all field components have been created. E.g. Spacecraft & water extraction method & engine using water as fuel, may occur simultaneously]
4. Venture capital funds scaling and market entry of prototype made from combined technologies
5. Sale of product leads to positive cash flow

This section has established the VoD model, specifically expansion three, for the purpose of using it in this thesis. The VoD model provides the map to the remaining chapters of the thesis will attempt to answer. Consider the plot below.

Valley of Death Model
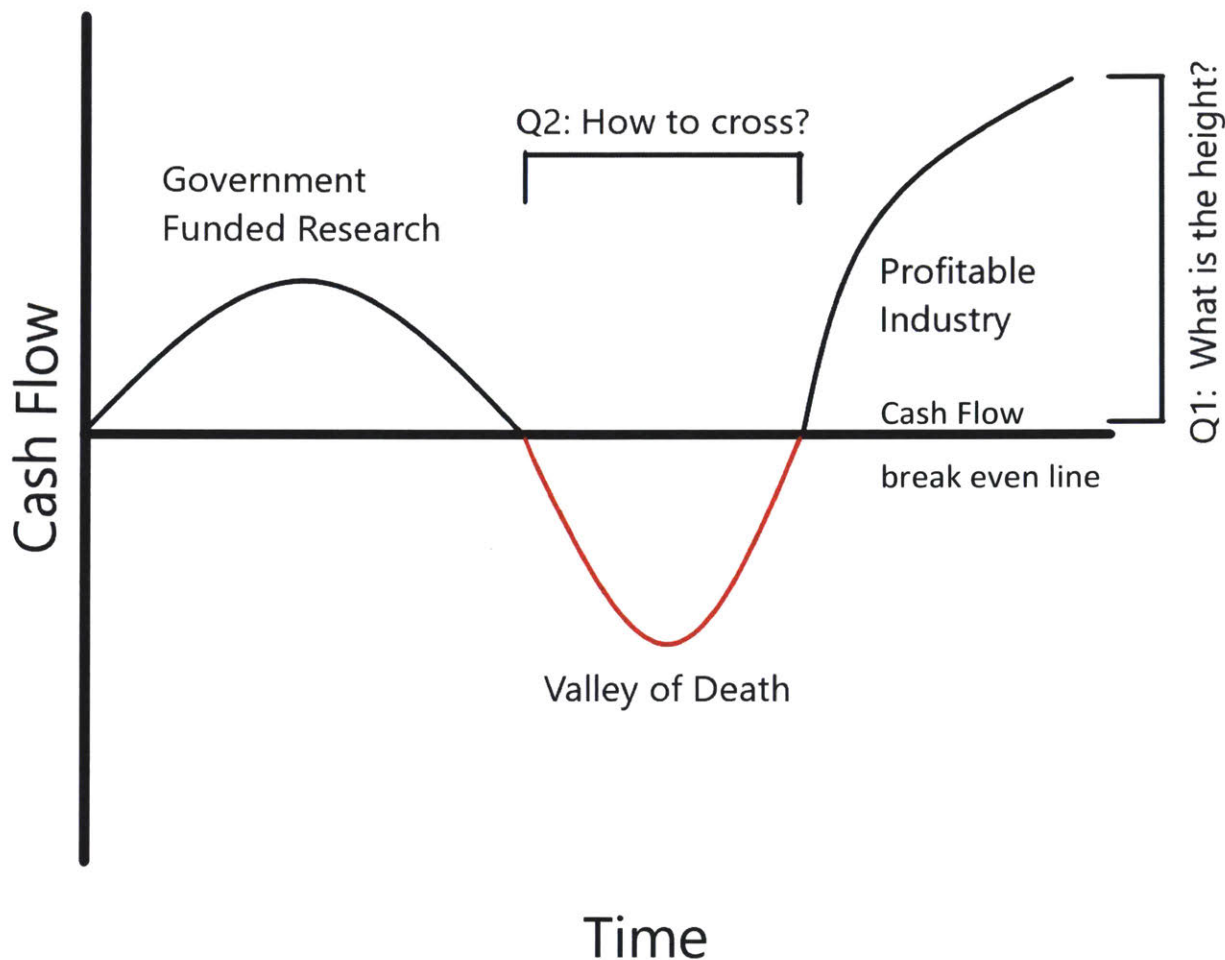
Figure 2: Simple depiction of the Valley of Death Model as used in this thesis. Y axis refers the amount of cash flow for the field. Positive while the government is funding research, negative while that research is being adapted for the market, and sharply positive again when then field has become a profitable industry. This figure will be used across the thesis to orient the reader as to which part of the VoD model is being discussed.

Question one, tackled by the next two chapters, is about the height of the peak on the other side of the VoD. Recall that the y-axis is the cash flow coming from the product, in this case NEA mining. Thus, the height refers to the overall profitability of the market for NEA resources. Those two chapters assess whether or not there are sufficient resources to support a highly positive cash flow in a NEA mining industry, provided the challenges of realizing that industry are met.

Question two, tackled by chapters five and six, is about the methods required to cross the valley. Even if NEA mining has sufficient resources to make it profitable, the VoD suggests that there

are still pitfalls which would prevent its realization. Only by exploring the VoD from multiple perspectives – law, economics, private industry, etc. – is it possible to chart a course across it.

By answering the two question posed above, this thesis assesses the feasibility of profitable NEA mining.

2.3   The Current Position of NEA Research in the VoD Model

Before tackling questions one and two, a final point needs to be demonstrated; namely, locating the position of NEA mining on the VoD model. This can be done by considering the history of research on near-Earth asteroids and how that field has changed over time.

The first near-Earth asteroid, Eros, was discovered in 1898 by Gustav Witt at Berlin and independently by Auguste H.P. Charlois at Nice, France (Yeomans, 2007). However, in terms of sheer quantity of discoveries, the field did not take off until the 1990s. As late as 1992 a workshop on the topic of near-Earth objects noted that "the total worldwide effort to search for NEOs amounts to fewer than a dozen full-time-equivalent workers, a number of whom are volunteers" (Morrison, 1992). The field's dramatic expansion in the 1990s was due in large part to the additional attention paid by the U.S. government.

Attention from the federal government came not solely for the sake of research, but for the specter of a catastrophic asteroid impact raised by scientists such as Luis Alvarez (Alvarez et al., 1980). This risk was brought home in 1994 when the comet Shoemaker-Levy 9 impacted Jupiter and dramatic images of the destructive power of the event, particularly from the Hubble Space Telescope were broadcast widely. Years later, Donald Yeomans, a manager of NASA's eventual NEO program, described in interviews that after that impact "we don't get the giggle factor nearly as much as we once did" (Boyle et al., 2005). The blatant demonstration of the damage an impact could cause led to several actions by the U.S. government to expand NEA research. First, in 1994 "Congress directed NASA to develop a plan to discover, characterize and catalog potentially hazardous NEOs larger than 1 kilometer in size" (Loff, 2014). Then in 1998, "NASA formally established a NEO program in response to the congressional directive to discover at least 90 percent of 1-kilometer-sized NEOs" (Loff, 2014). Finally, in 2005, Congress passed legislation requiring that NASA find 90% of the asteroids with diameters greater than 140

meters. (George E. Brown Jr. Near-Earth Object Survey Act, 2005). Placing these acts on a plot of NEA discoveries over time makes their impact clear.

Near-Earth Asteroids Discovered

Most recent discovery: *2019-Apr-28*

https://cneos.jpl.nasa.gov/stats/ — Alan Chamberlin (JPL/Caltech)
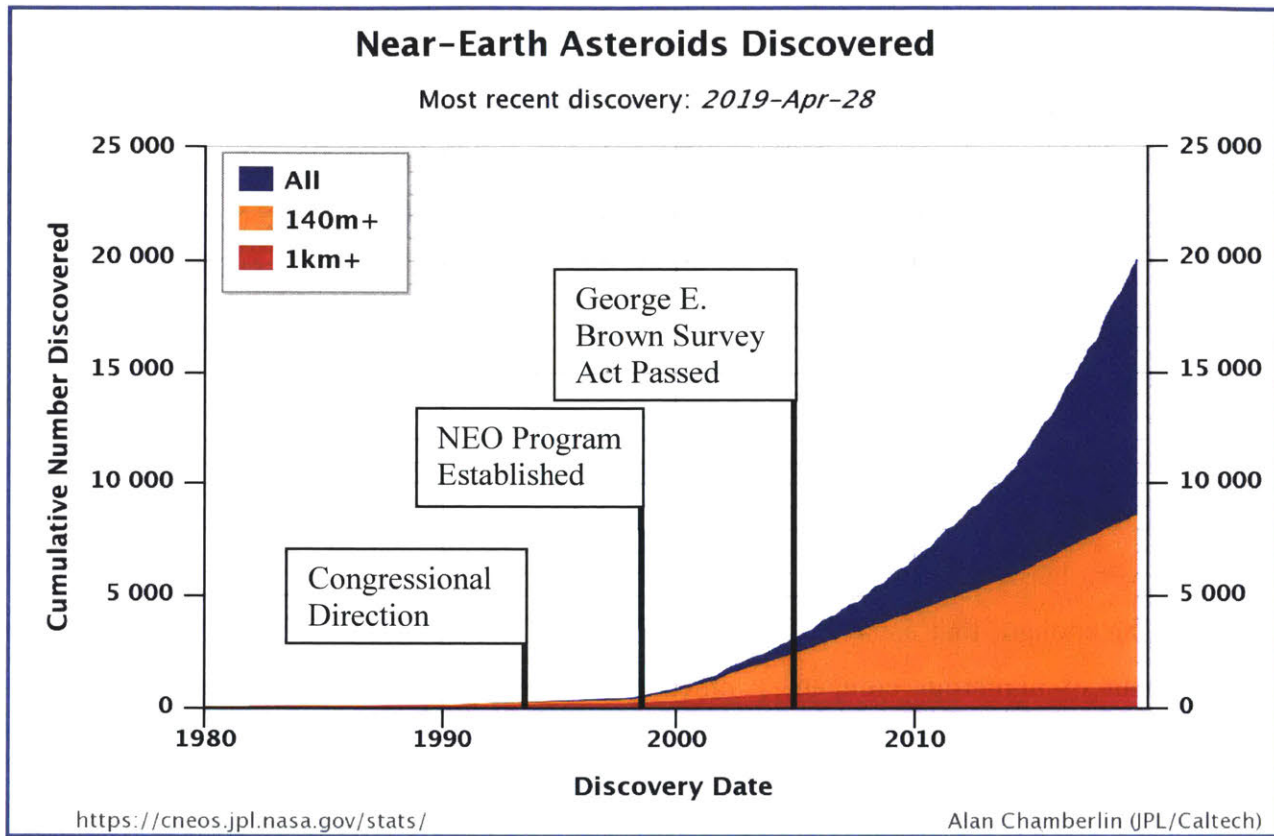
Figure 3: This is a cumulative plot of all NEAs discovered since 1980. Note that the trend begins to pick up with the first piece of legislation, hits an inflection point with the second piece of legislation, and that the "All" category begins to dramatically increase with the third piece of legislation. (CNEOS, 2019)

As the plot makes clear, legislative action, and the government support it produced, was a significant driver of NEA research. To drive the point home, as of 2019 more than 95% of NEAs were discovered by NASA-funded surveys (Talbert, 2019). While NEA research is obviously not confined to simply discovering NEAs, it is impossible to research undiscovered objects, and therefore this metric serves as a reasonable proxy of the field as a whole in making the point that the field itself is primarily government funded research.

While pure NEA research is firmly in the realm of government funding, it is the potential of mining resources from NEAs that pushes the field to the precipice of the VoD. The idea of mining NEAs developed concurrently with the field overall during the 1990s. In 1996, Dr. John Lewis published a book entitled *Mining the Sky* in which he laid out a fairly comprehensive plan

for utilizing space resources. He discussed in detail topics such as water extraction from C-type NEAs (Lewis, 1996) and placed the potential value of the metals in the smallest then-known metallic asteroid at around $30 trillion (adjusting for inflation) (Lewis, 1996). He also testified before Congress during the same hearing that led to the 1998 Congressional direction to find NEAs. At that hearing he testified that NEA resources "could support a human population of about one million times the population of Earth indefinitely" (House Report 105-847, 1998). However, despite this serious consideration the knowledge of the field simply was not sufficient for mining to move forward. In the figure above, the number of discovered NEAs in 2000 was roughly 5% of those known in the present. Disregarding technical challenges, the lack of knowledge prevented the development of NEA mining.

In the last decade that problem has been remedied. For the purpose of NEA mining a sufficient number of NEAs have been discovered to present a rich collection of potential mining targets. Or, at the very least, a sufficient number of NEAs have been discovered, and technology has advanced far enough, that some believe that NEA mining is feasible. This is clear from the establishment of numerous companies aimed at mining NEAs. In fact, not only are there companies attempting to mine NEAs, the first casualties of the VoD, Planetary Resources and Deep Space Industries, have already perished – or been acquired – in the attempt (Foust, 2018; Foust, 2019). Thus the deaths of these companies, and the existence of others, demonstrates that NEA mining is moving towards the Valley of Death.

Valley of Death Model
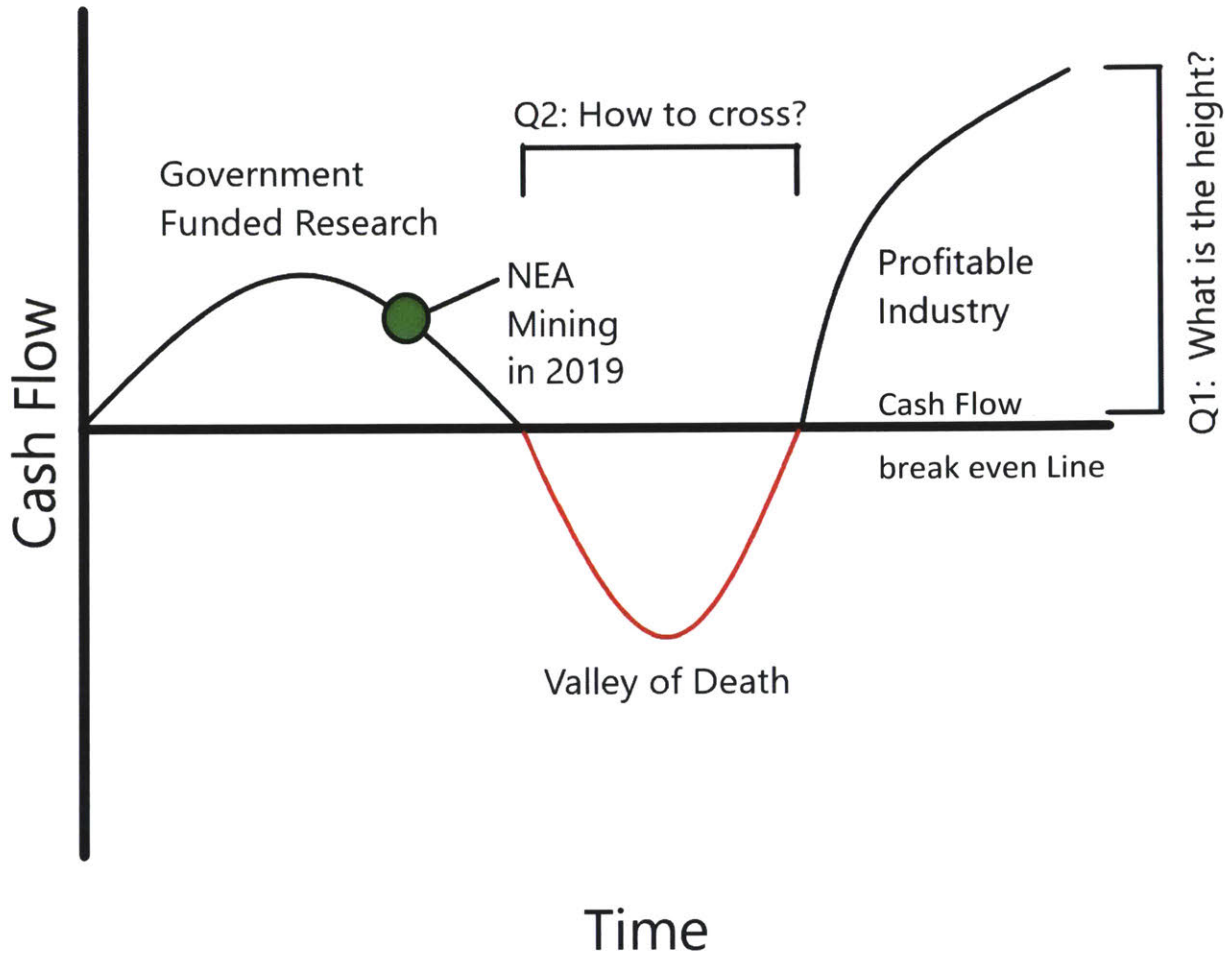
Figure 4: The Valley of Death model with the section just discussed (the current location of NEA mining) depicted in green.

From the above discussion we can place NEA mining at its position on the above plot, just before the full descent into the VoD. At this point it is still mostly government funded, but organizations now exist that are trying to commercialize the technology. By so doing, they will face the VoD and will benefit from the following exploration of question one (what is the cash flow of a successful NEA mining market?) and question two (how can the VoD be crossed?).

3 Water in NEAs

The aim of this chapter is to estimate the value of a market for water mined from NEAs. It begins with a brief discussion of the uses for water in near-Earth space, and hence the motivation for conducting this research. The first step in assessing the market for water mined from NEAs is to estimate the quantity of water in the NEA population. A number of previous estimates are recorded in the literature with various methods and priorities (Elvis, 2014; Rivkin et al., 2019). This chapter most closely follows the Elvis method, using the data specified in the appropriate section. An equation for the amount of water in the NEA population is created by summing across the probability that any given NEA has hydrated minerals. This is derived from known population values, e.g. that roughly 20% of NEAs are C-type NEAs (Binzel, 2019) and so have the highest likelihood of containing hydrated materials, as was mentioned in the introduction. The full equation is explained in the first phase of the Methodology Section. In the second phase of the Methodology Section the population derived in the first phase is constrained, most notably by a price estimate of shipping water to LEO, the substitution good – i.e. the other choice if one wants to buy water LEO – for water mined from NEAs. The Result Section begins by detailing the impact of the applied constraints on both the known and projected NEA populations. It finishes with a consideration of the relative value of pursuing less easily accessible NEAs in exchange for access to a proportionally greater quantity of resources. The chapter concludes with a summation of the five key findings produced by this research.

3.1 Motivation

Water can serve a number of useful functions in space. Naturally, water is a required resource for human survival and would be useful in supporting human life in Earth orbit and beyond. Additionally, experiments performed on the ISS have verified that water can be used for effective radiation shielding, making longer flights beyond Earth orbit safer for astronauts (Kodaira et al., 2014). Finally, water can be used as a fuel for inflight thrust, enabling greater mobility in orbit and beyond (Rabade et al., 2016). In combination, these three use cases demonstrate that the usefulness of water as a resource will grow in direct proportion to the development of the space industry. It is therefore worth considering the quantity of this resource

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which exists in near-Earth space, and the comparison of that capacity with the cost of launching it from the Earth's surface.

3.2   Data

Discovering and characterizing NEAs are two separate but equally important tasks. Large surveys such as Pan-STARRS and the Catalina Sky Survey observe significant portions of the night sky and are responsible for the majority of discoveries of new NEAs (Jedicke et al., 2015). These data are collected by both the Minor Planet Center and the Jet Propulsion Laboratory small-body database (Chamberlain et al., 2019). By contrast, characterizations are completed through targeted observations by instruments such as the Infrared Telescope Facility in Hawaii (Stuart et al., 2004). Those characterizations have most recently been assembled in a paper by Binzel et al. in 2019. The NEA database on which this analysis was performed was the total listing of NEAs found by the end of 2018 taken from the JPL database and matched to the characterizations recorded in the 2019 Binzel paper using the NEA designations. This produced a database of 19304 NEAs, of which 1044 had some form of characterization using the Bus-DeMeo taxonomy (DeMeo et al., 2009).

3.3   Methodology

This research had two main phases. The first was a building phase, in which the water mass present in the NEA population was calculated under known levels of uncertainty. In the second phase a number of constraining factors were used to restrict that population to profitable and accessible NEAs.

3.3.1   Phase I: Finding the mass of water in NEAs

The total water mass present in the NEA population was calculated using the following equation:

$$M_w = \left(\sum_{i}^{n} P_{hT} V_i \rho_T \right) f_w$$

M_w is the desired quantity, the mass of water in the NEA population, P_{hT} is the probability that an asteroid of a given type is hydrous, V_i is the volume of an asteroid, i is an indicator of the specific NEA, ρ_T is the average density of a given asteroid type, n is the total number of NEAs,

and finally f_w is the fraction of a hydrous asteroid's mass that is water. Each will be defined in turn.

Though it is not impossible for multiple asteroid types to possess hydrated minerals, this research aims to be conservative in its estimates and therefore restricts itself to an estimation of the quantity of water in C-type NEAs since, under the Bus-DeMeo taxonomy (DeMeo et al., 2009), those are most likely to have hydrated materials. Hydrated minerals have deep absorption in the 3.0μm spectral region (Feierberg et al., 1985; Jones et al., 1990; Rivkin et al., 2003). While that region is difficult to detect, absorption in the 0.7μm band strongly indicates the presence of the 3.0μm band. If the 0.7μm band is not present, the 3.0μm band is still present 50% of the time (Rivkin, 2012). Tying this back to the DeMeo typology, all NEAs with a "Ch" or "Cgh" type show absorption in the 0.7μm band. Thus, for Ch or Cgh NEAs P_{hT} is taken to be 1, for all other C-type NEAs it is 0.5, and for all other types of NEAs it is assigned to 0. Naturally, hydrated minerals do exist in non C-type NEAs, albeit in smaller amounts, and one avenue for future research could be to expand this work to include the appropriate P_{hT} for other NEA types.

Of the characterized NEAs, some are listed with multiple types representing ambiguity in the data. The types are listed in order of likelihood (Binzel et al., 2019). For this reason, NEAs with multiple types were assigned to a type with a 60% chance for the first type listed, and a 40% chance for the second type listed. Non-characterized NEAs were assigned to S-type, C-type, or other with percentages of 60%, 20%, and 20% respectively. This assignment is reported as consistent for the size range from 10km to 100m, (Binzel et al., 2019). At smaller sizes the percentage of C-types decreases to 10%. However, it is not clear if that decrease in prevalence is actual, and due to greater propensity for collision disruption owing to a lower overall strength, or a result of observational bias due to lower albedo (Binzel et al., 2019). NEOWISE, which was not biased against low albedo detections, found roughly 25% of the smaller NEA population had low albedos (Wright et al., 2016), providing weak evidence that the decrease in C-types at smaller sizes is due to observational bias. Due to the evidence, weak though it may be, a C-type prevalence of 20% was used for all NEA sizes.

The volume is calculated from the diameter, which is itself estimated from the albedo and the absolute magnitude of the NEA according to the following equation derived from the physical definitions of each of the terms:

$$D = 10^{.5[6.259 - \log_{10} a - .4H]}$$

D is the diameter of the NEAs equivalent sphere, a is an asteroid's albedo – the fraction of incident light that is reflected from the asteroid – and H is its absolute magnitude – a logarithmic measure of how bright the object would appear at a distance of ten parsecs (Bowel et al., 1989; Harris, 1997). Absolute magnitude is a known value for all NEAs in the database because it is derived from simple observation.

Unfortunately, albedo is more difficult to measure directly. Albedo is the ratio between incident and reflected light, while typical observations only measure the reflected light. Measuring albedo then requires atypical or additional observations to capture the ratio, and is therefore known for relatively few NEAs. In general, NEAs tend to have albedos from roughly 0.05 – 0.3, However, C-type NEAs tend to be on the darker end of the scale, roughly from 0.05 – 0.15 (Masiero et al., 2014; Masiero et al., 2011). Small changes in albedo can have a significant difference on the estimated size of a NEA. For this reason, I randomly assigned albedos to C-type NEAs along a normal distribution with a mean of 0.1 and a standard deviation of 0.05. As a lower bound I used 0.01 since very few NEAs are below that, and an albedo of less than zero would not be meaningful. Once the albedo and absolute magnitude are known, calculating the diameter of the equivalent sphere follows the above equation, and from the diameter finding the volume of the equivalent sphere is trivial.

The final two values, ρ_T and f_w were taken from the literature. The bulk density of C-type NEAs was found to be 1.41 +/- 0.069 g/cc. Ch and Cgh NEA had 1.70 +/- 1.1 g/cc and 3.48 +/- 1.06g/cc respectively (Carry, 2012). Similar to albedo, I took the given value as the mean of a normal distribution and the uncertainty as the standard deviation. I then assigned a value to each NEA from that distribution. Note that this is the bulk density, meaning it refers to the density of the NEA as a whole. Grain density refers to the density of the minerals themselves and is generally higher because the NEAs are porous, reducing the overall mass while keeping the volume the same.

There are a range of values in the literature for f_w, the mass of water in asteroids with hydrated components. One source divided C-type NEAs into two categories, those with less than 3% water content and those with greater than 7% (Rivkin et al., 2003). Another notes that meteorites well linked to C-type asteroids have from 5% to 15% (Rivkin et al., 2002). Again, since the objective is to be conservative in the estimate, and to preserve simplicity in the calculations, 10% was the value chosen for f_w. All the values discussed above are recorded in the table below.

Table 1: This table shows the components of the equation used to find the mass of water in the NEA population. Absolute magnitude is not included because each individual NEA has its own measured H value rather than an assigned one. Diameter is calculated from albedo and absolute magnitude and volume is calculated from that. Albedo and density are both randomly assigned based on a normal distribution with the mean at the center of the range and the uncertainty as the standard distribution.

Type	Probability of hydrated minerals (P_{hT})	Albedo (a) (where unknown)	Density (ρ_T) (g/cc)	Density uncertainty	Water mass as a fraction of NEA mass
C	0.5	0.05 – 0.15	1.41	0.069	0.1
Ch	1	0.05 – 0.15	1.70	1.1	0.1
Cgh	1	0.05 – 0.15	3.48	1.06	0.1

The above equations serve to find a single value for the total mass of water in the NEA population. Many of the components of that calculation depend on the random assignment of variables or values within a range. For this reason, a Monte Carlo simulation was chosen as an appropriate tool to assess the range of outcomes. The assignment of values and resultant calculation was repeated 500 times for the characterized NEAs, the non-characterized NEAs, and all NEAs in the database. Each iteration produced a NEA population with a water mass estimate for each NEA. Summing across those estimates provided an estimate of the total water present in the NEA population. Considering all 500 runs gave the range of possible values for the total amount of water in NEAs. Similarly, applying the constraints discussed in the next phase gave a range of possible values for the total amount of water in NEAs that can feasibly be accessed.

3.3.2 Phase II: Constraining the population of water- bearing NEAs

I used two factors to constrain the population of NEAs to those which might be useful for resource utilization. The first constraint was based on the delta-v of each NEA. Delta-v refers to the change in velocity required to perform an orbital maneuver, such as transitioning from an

Earth orbit to a NEA rendezvous orbit. Delta-v in this context refers to one way trips from lower Earth orbit to the desired asteroid. The one-way trip delta-v is a reasonable approximation for the accessibility of a given NEA (Rivkin et al., 2019). Where possible, the delta-v used was calculated by Lance Benner of JPL (Benner, 2019). When that could not be found, it was calculated using the method detailed by Shoemaker and Helin (Shoemaker et al., 1978).

For the sake of comparison, Benner provides the delta-v to the moon as 6 km/s. This is lower than some other estimates of the delta-v required to reach the moon (e.g. Rivkin et al., 2019), but for the sake of consistency between the source of delta-v to NEAs and delta-v to the moon, and due to a desire to be as restrictive as possible, 6 km/s was used throughout as the delta-v to reach the moon. This value was the first constraint applied to the NEA population generated in the previous phase. NEAs with a delta-v greater than 6 km/s were removed from consideration in the analysis. The rationale behind this constraint was that if it were easier to get to the moon than to the NEA, then the benefit of a planetary operating surface and consistent distance from the Earth would make the moon a more attractive target.

The second constraint was derived from the estimated value of the water present in the NEAs. Specifically, an upper limit was placed on the price per kilogram of the water within the NEAs. Any NEA with resources less valuable than the projected cost of mining would never be worth mining and could therefore be discarded from the analysis. That constraint was calculated using the following process.

To begin with, water launched from Earth was treated as a substitute good for water mined from a NEA. A substitute good, in this context, means that either good could be used in the place of the other, and customers decide between the two based primarily on the relative price. So, if it were always cheaper to launch water from Earth, then there would be no incentive to mine water from a NEA. More specifically, water launched to LEO was chosen as the comparison case. While it is impossible to know where in Earth orbit the demand for water will arise, comparing to LEO represents the cheapest case for launching water, and therefore provides the most restrictive cost comparison for mining water from NEAs. For similar reasons, the price chosen for launching water was that of the Falcon Heavy. SpaceX claims the Falcon Heavy will be able to lift 63,000 kg to LEO for a launch cost of $90M, for a cost per kg of $1410/kg (SpaceX,

2017). For ease of calculation, and given that this rocket has had relatively few flights, this was rounded up to $1500/kg. Applying this to the water mass quantities found in phase I gives a - maximum value for the water in a NEA sold in LEO.

The above value was then compared against the net present value of mining water from a NEA. Net present value takes into account the upfront costs and uncertain future benefits of a project to estimate that overall value of a decision in the present (Kenton, 2019). Since it is impossible to precisely estimate the cost of mining water from a NEA, I performed this calculation for a range of values. The ISS resupply contract per mission cost was taken as the lower bound at $200 million (NASA OIG, 2018), since that is arguably the simplest possible space mission. $150 billion was chosen as the upper bound. For context, the usual price of NASA's flagship missions is over $1 billion, and the James Webb Space Telescope, one of the most expensive flagship programs is above $8 billion and rising (National Academies Press, 2017). The International Space Station, counting the contributions of all relevant nations, cost $150 billion (not accounting for inflation since 2010) (Lafleur, 2010). Thus, $150 billion was a reasonable maximum for the amount for the amount that could possibly be spent on mining water from a NEA. Numerous intermediate values between $200 million and $150 billion were also used to compare against the net present value of the resources in NEAs.

Additionally, the net present value requires that a discount rate be selected. The discount rate is a way to mathematically represent that the certainty of a dollar in the present is worth more than the possibility of a dollar in the future. It also accounts for the opportunity cost of spending money on the present project as opposed to a hypothetical alternate one with better returns. Venture capital typically uses discount rates of 30-70% due to the inherent uncertainty and low cash-flow of new ventures (Bhagat, 2014). Since mining water from NEAs would certainly be both risky and take some time to yield any returns, a 50% discount rate was chosen. I further assumed that a year would be required for set up, and that income would begin to be generated after that first year for at least ten years. I then calculated the total amount of income required over that time period to break even with the initial investment. This dollar value was then compared to the maximum value of the NEA's water calculated above using the comparative price of launching water to space, and any NEAs for which the required amount of income was

higher than the maximum value of the NEA were removed from the population. This produced a list of NEAs which theoretically could at least reach break-even, and possibly generate a profit.

As with the previous section, each of the above cuts was performed for each of the 500 runs of the Monte Carlo simulation generated in the previous phase. This was done to limit the impact of uncertainty on the results. The results speak to the population of NEAs that could feasibly be mined for profit under a range of initial cost conditions.

3.4 Results

3.4.1 Water Quantity

There are a number of useful insights that can be drawn from this analysis. The first is a cumulative distribution function for the total mass of water across all 500 runs for characterized, uncharacterized, and all NEAs with a delta-v less than 6 km/s. It serves as a both a sanity-check and a justification for the simplification of later plots.

Water Content in NEAs with Delta-V <=6
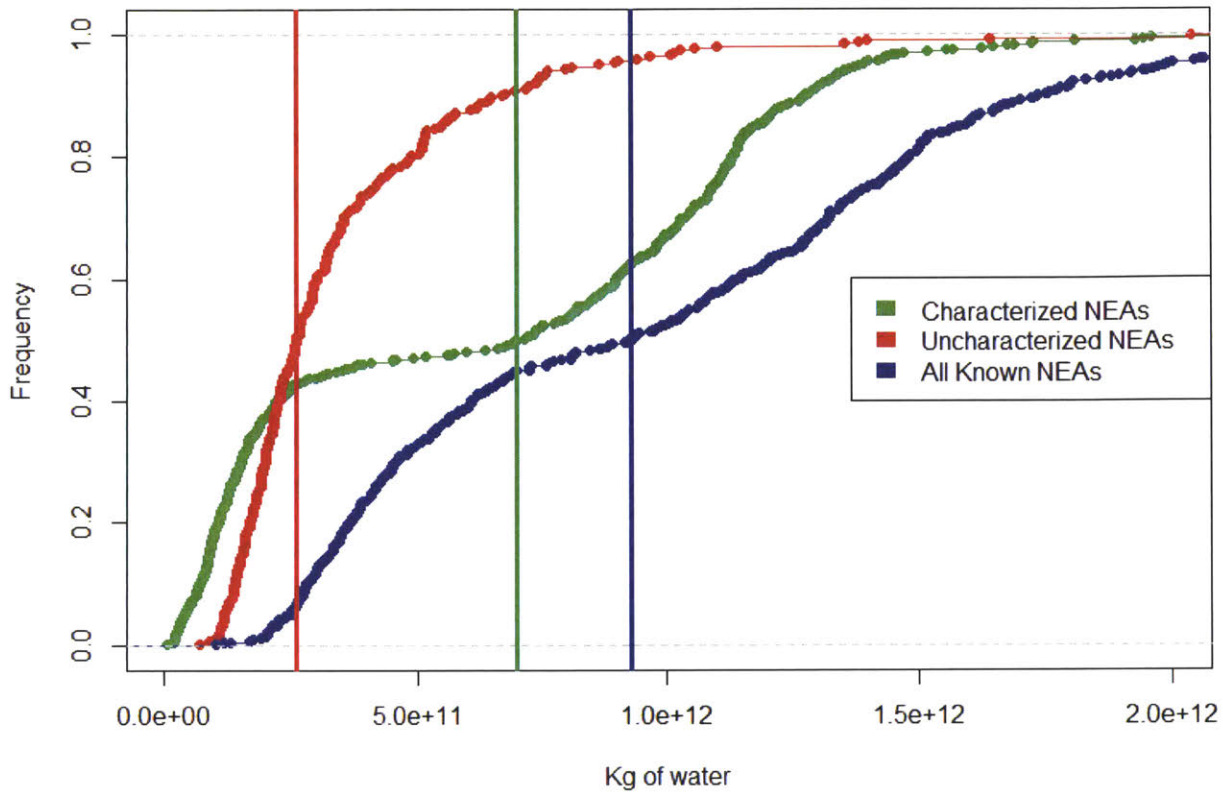
Figure 5: Plot of the frequency of different values for the water content of the delta-v constrained NEA population, with the median value marked by the vertical line. Uncharacterized NEAs are numerous and, due to the law of large numbers, cluster around a median water content of $3x10^{11}$ kg. Characterized NEAs are few in number, but large in size. The flat region is produced by a relative rarity of water content values around $5x10^{11}$ kg owing to the inclusion or exclusion of a handful of large NEAs. The known NEA population is a combination of the other two and thus exhibits a slight flat region ameliorated by the inclusion of the uncharacterized NEAs. It has a median water content of $9x10^{11}$ kg.

There are several important takeaways from this plot of the application of the delta-v constraint. First, the median water content in the constrained NEA population is $9x10^{11}$ kg. To put that quantity in perspective, it is equal to roughly three and a half years of the outflow from the Charles River in Boston (US Geological Survey, 2019). For comparison, Rivkin and DeMeo estimated $8\pm4x10^{11}$ kg of water in the 1-km NEO population with delta-v less than 8 km/s (Rivkin et al., 2019). The estimate produced here has a delta-v constraint of 6 km/s, was not size limited, and used 10% water content rather than 7%. Despite the slightly different conditions, the similarity in estimates suggests that this method produced a similar value to those in the literature and permits proceeding to the next stage of the analysis with a measure of confidence

The second takeaway from this plot is that the median values of these distributions, represented by the vertical lines, are reasonable approximations of the overall distribution. Even when considering all NEAs, the uncertainty is $\pm 7 \times 10^{11}$ kg of water, yielding a range only slightly larger than an order of magnitude. This is not a bad result considering both the numerous sources of uncertainty in this calculation and the vast quantities under discussion. Additionally, since the majority of runs are clustered by the median, future plots will simply use median values instead of the full distribution in the interest of graphical clarity.

Finally, this plot lists 2×10^{11} kg of water as the minimum likely estimate of the total amount of water in the NEA population with lower delta-v than the moon, with values as large as 1.6×10^{11} kg of water. Estimates for the amount of water on the moon vary – one source gives 1×10^{11} kg water (Mitrofanov et al., 2012), another 6×10^{11} kg of water (Spudis et al., 2013) – but they are of the same order of magnitude as this estimate. Thus, there is roughly as much water in the known NEA population with less delta-v than the moon as there is on the moon itself. Whether or not it is as accessible is indeterminate, because neither lunar nor asteroid mining techniques have been developed, but NEAs are comparable to the moon from a pure quantity-of-resource perspective.

3.4.2 Mineable NEA Population

The above comparison does not take into account the constraint of cost. Using the method discussed above, the NEA population was evaluated to determine which NEAs could be mined profitably assuming a range of initial costs. This was first used to produce a comparison between the initial cost and the smallest NEA which contained sufficient resources to break even. Note that this comparison is mostly run-agnostic. There is a one to one correlation between cost and NEA size, and differences between runs were due to variations in which specific NEA was the smallest over the cutoff size for each point. For this reason, the range around the median is very small and the median values are very good representations of the overall trend.

NEA Size Required to Break Even with Initial Cost
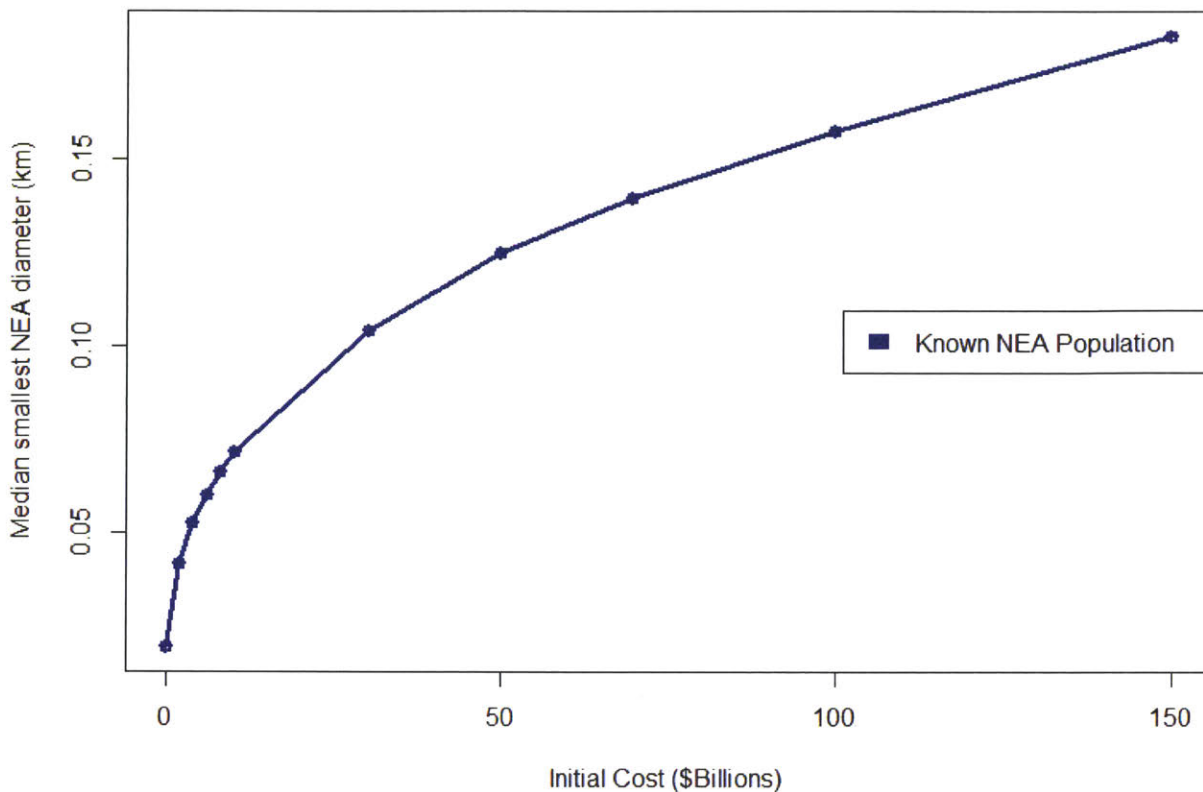
Figure 6: Plot of the smallest NEA which has a net present value equivalent to the initial cost. As expected, the smallest profitable NEA increases exponentially as cost increases. The initial increases in cost require the greatest increases in size from the NEA to be mined. After roughly $10 billion, the size increase as a result of cost increases becomes linear rather than exponential.

As expected, increasing initial cost leads to an increase in the minimum NEA size worth mining. It is important to note that this relationship is exponential. The initial increases in cost produce dramatic increases in size of the NEA required for profitable mining, but that affect attenuates over time. Even at the extreme of $150 billion for upfront costs, NEAs larger than 200 meters are still worth mining. Thus, high costs do not completely deplete the population of potential NEA mining targets.

By applying the minimum size worth mining found above to the delta-v limited population, it is possible to estimate the number of NEAs in the mineable population for a given cost. This was performed for each of the runs of the Monte Carlo simulation and the median population numbers are displaced on the plot below.

Additionally, the minimum NEA size worth mining was applied to the projected total population of NEAs. This total population estimates were taken from the 2017 Science Definition Team report on the effort to search for and characterize NEOs (Stokes et al., 2017). In that report, the population was estimated for a number of different bins based on size. The size of the minimum mineable NEA corresponds to some fraction of a specific bin. For example, a minimum mineable NEA of 20 meters would correspond to ½ of a bin containing NEAs ranging in size from 10 meters to 30 meters. If there were 100 NEAs in that bin, then 50 of them would be considered mineable. To create the plot below, the number of NEAs in the fractional bin for a given size was summed with all larger bins. So a minimum mineable NEA of 20 would have a number of mineable NEAs equal to half of the 10-30 meter bin, all of the 30-50 meter bin, and so on up to the bin with the largest NEA sizes that contained undiscovered NEAs. This produced the following plot comparing the number of mineable NEAs for a range of costs for both the known and the projected NEA population.
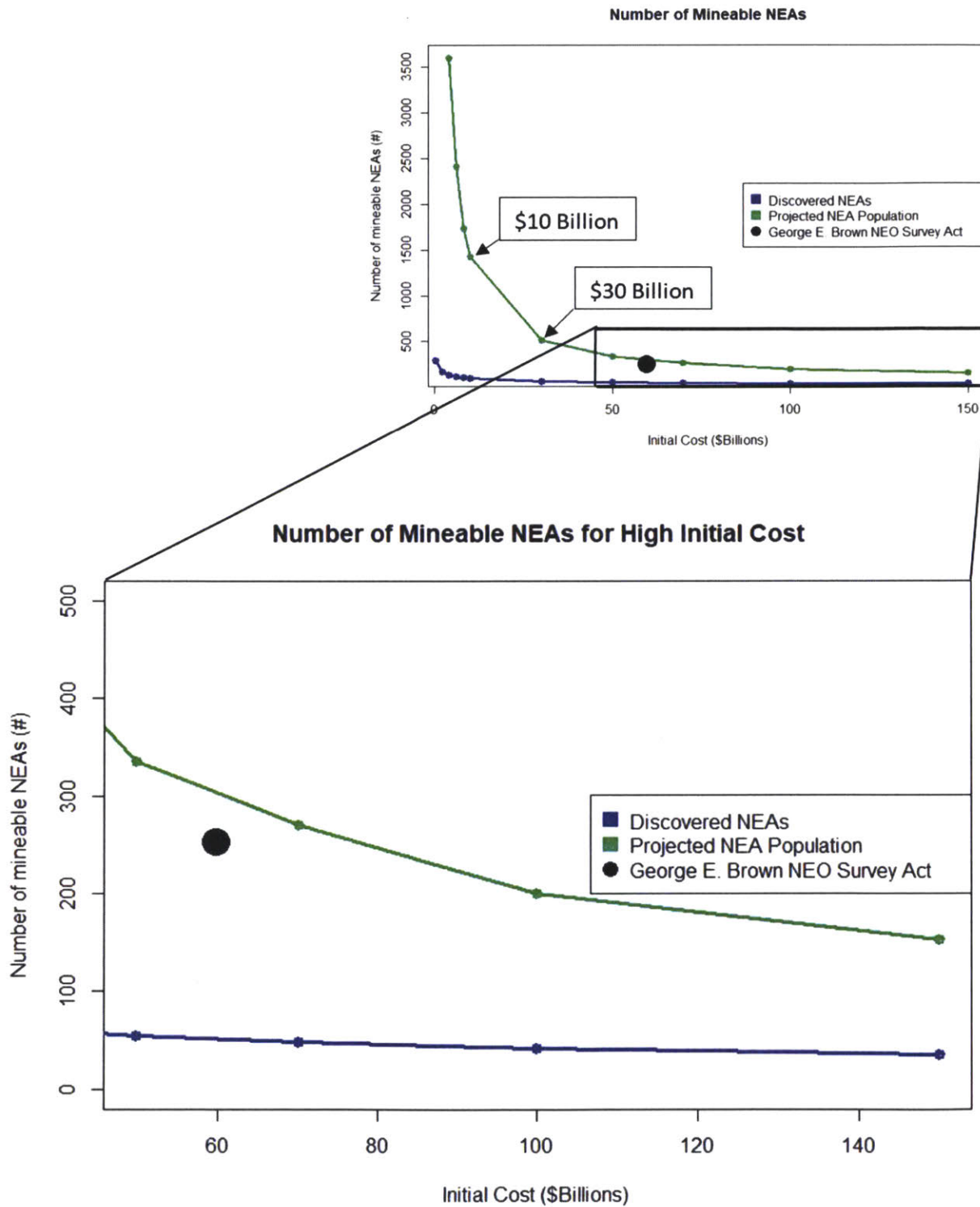
Figure 7: Based on current completeness levels, there are at least 100 undiscovered mineable NEAs for an initial cost of $150 billion, and exponentially more as cost decreases. The full size plot depicts the number of NEAs with sufficient resources to break even with a given initial cost across the entire cost range, and shows an extreme increase in the number of mineable NEAs when the cost goes below $10 billion. The zoomed in plot depicts the

upper end of the cost range and shows the number of mineable NEAs that remain undiscovered at high cost. The George E. Brown Survey Act point is derived from the initial cost for which a 140 meter NEA breaks even, roughly $60 billion. The number of NEAs at that point is simply 90% of the projected population, the stated goal of the survey act. The position of the point demonstrates that even accomplishing the goal of 90% detection for sizes larger than 140 meters would still leave many undiscovered mineable NEAs, particularly at lower initial costs.

Applying the minimum mineable NEA to the known and projected NEA population makes it clear that at high costs there are dozens of mineable NEAs in the known population and over one hundred in the projected NEA population. Unsurprisingly, as the cost decreases the number of mineable NEAs increases, reaching a maximum of 290 NEAs for the known population at an initial cost of $200 million. The projected population contains nearly 100,000 mineable NEAs for an initial cost of $200 million, but this would require finding millions of 20 meter NEAs, which may not be feasible in the near future. The projected population plot was limited to the number of mineable NEAs for an initial cost of $4 billion, which was a more manageable 3500.

Additionally, as was mentioned in the previous chapter, the George E. Brown Jr. NEO Survey Act requires NASA to find 90% of NEAs larger than 140 meters. A 140 meter NEA with hydrated minerals has a break-even point at roughly $60 billion, hence the existence of that point the plot. This means that if the Survey Act goal was met and no other NEAs were discovered (an admittedly unlikely proposition), the blue line to the right of the point would rise to the intersect the green line, while on the left it would remain as it is. Essentially, for initial costs less than $60 billion mineable NEAs would remain undiscovered even if the Survey Act goal was met. This speaks to the importance for mining of both fulfilling the current survey goals and expanding them as technology and political will allow.

Finally, as depicted on the full range plot in the upper right, the dramatic uptick in number of mineable NEAs occurs at an initial cost between $10 billion and $30 billion for both the known and the projected populations. A cost lower than $10 billion yields thousands of projected and more than one hundred known mineable NEAs. In contrast, a cost higher than $30 billion yields less than 500 projected and 66 known mineable NEAs. This suggests that at costs lower than $10 billion the sheer quantity of mineable NEAs is the overwhelming factor, while at costs than $30 billion the quantity of water in a single mineable NEA is the dominant factor.

This plot speaks to the number of mineable NEAs, but it does not address the amount of water present in the population. The dramatic losses in the number of mineable NEAs depicted above

raises the question of whether those lost NEAs contain the lion's share of the total water in the NEA population, or if they make up a relatively small fraction of it.

Water in NEAs Rendered Inaccessible by Cost Increases
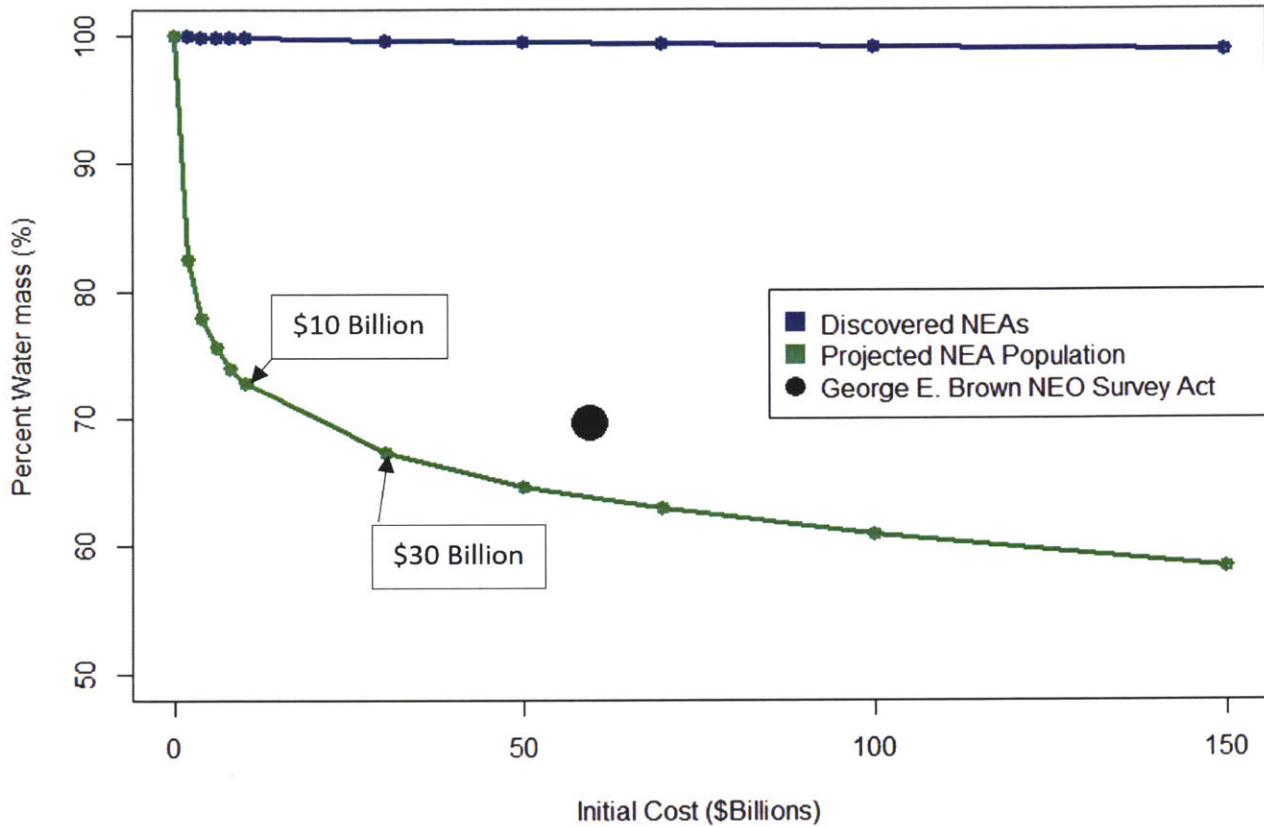
Figure 8: In the known NEA population the loss of water due to increasing costs is negligible. By contrast, the loss of water in the projected population can reach as high as 40% of the total amount present in the population. Note that the dramatic loss of accessible water mass occurs for costs less than $10 billion, and that the loss of water for the range from $30 - $150 billion is less than 10% of the total.

This plot reveals a key difference between the known and projected NEA populations. The water content of the known population is dominated by the largest NEAs, to the point that going from 290 mineable NEAs to less than 40 has a negligible impact on the total mass of water that can be profitably mined. In fact, the median sum of the water mass of the three largest NEAs is 80% of the total water mass in the population. Thus, for the known NEA population the key factor in accessing the largest amount of resources is choosing to mine the handful of largest NEAs.

By contrast, the projected population loses access to up to 40% of the total water present in NEAs as cost increases. Again, the key initial cost values are $10 billion and $30 billion. 30%

of the loss of access to water happens by the time the cost hits $10 billion, and less than the remaining 10% occurs after $30 billion dollars. So, for the projected population, the choice of whether to go for a single large NEAs or multiple smaller ones depends on the cost required to mine the NEA.

The analysis performed in this section allows us to set up a simple decision tree with regards to mining NEAs.
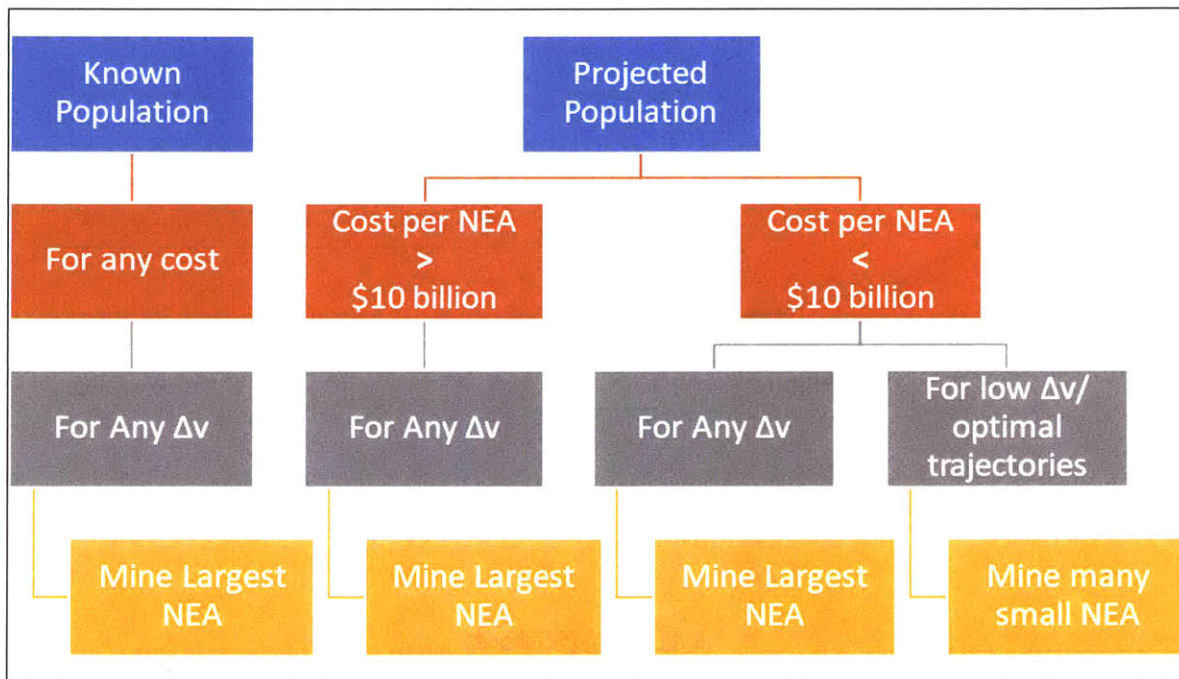
Figure 9: Decision tree for mining water from NEAs. If the cost of mining a NEA is less than $10 billion per NEA and the known population is significantly expanded, then it is possible to access nearly as much water by maximizing the number of NEAs mined compared to simply mining the largest NEAs. Choosing quantity works especially well in scenarios with numerous low delta-v NEAs or when low delta-v trajectories which encompass multiple NEAs can be found.

Naturally, the water content in the projected population is larger than the content in the known population. So another key takeaway is the importance of at least meeting the George E. Brown Jr. Survey Act goal, and ideally surpassing it to enable all the options currently under the "projected population" part of the decision tree.

3.4.3 Delta-V and Resource Access

The methodology used here allows for one other interesting analysis to be performed. The previous analysis simply cut off all NEAs that had a delta-v higher than 6 km/s. However, the precise delta-v of a NEA is considered one of the key data points in determining its suitability as

a target (Elvis et al., 2011). For this reason, it is also worth exploring the relationship between delta-v and the percent of water available. To do so it is useful to borrow a concept from economics, that of marginal utility.

In economics marginal utility is the quantification of additional satisfaction derived from consuming an additional unit of a good (Bloomenthal, 2019). The net satisfaction of the good could be said to be the benefit of the good minus its cost. When marginal utility is positive, overall wellbeing is increased by additional consumption, and vice versa when it is negative. To apply this concept to mining water from NEAs, consider water to be the good, and delta-v to be the cost of the good. The marginal utility of NEA mining is positive so long as each additional unit of delta-v allows for access to progressively greater amounts of water. For example, if 1 km/s of delta-v allowed for access to 10 kg of water, and 2 km/s of delta-v allowed for access to 25 kg of water, that increase in delta-v from 1km/s to 2 km/s would have positive marginal utility. If 3 km/s allowed for access to 30 kg of water, the marginal utility in reaching 3 km/s would be negative. As long as marginal utility is positive, it makes sense to bear the cost of additional delta-v in exchange for access to additional water. This concept can be applied to a plot of available water per km/s to assess the marginal utility across the full range of delta-v.

Water Content by Delta-v
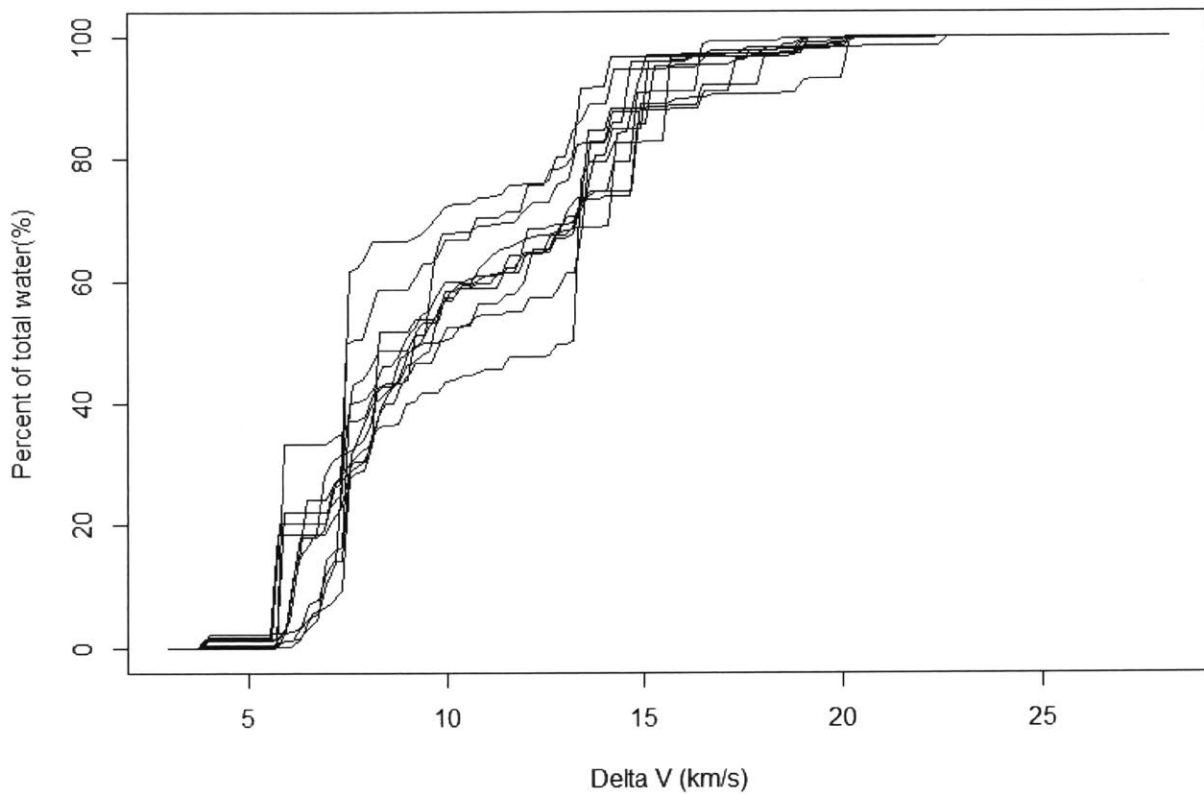
Figure 10: Water content per delta-v increases exponentially until ~10 km/s where it hits an inflection point and increases logarithmically. From this, we can see that the marginal utility of additional delta-v is positive until ~10 km/s and negative after that.

Water mass per delta-v for ten runs of the Monte Carlo simulation is plotted on the above chart. The key takeaway from this is the shape of these runs. The accessible amount of water curves upwards before hitting an inflection point around 10 km/s and leveling off. So, up until roughly 10 km/s the marginal utility of additional delta-v is positive. Recall that the moon-based delta-v constraint applied to the population was 6 km/s. This cutoff is clearly less than the inflection point, suggesting that, for the delta-v constrained population, the marginal utility is strictly positive.

Marginal utility being positive means that the optimal business case would be to select the NEA with the largest reserve of resources closer than the moon, rather than the one that is easiest to access. Delta-v is a linear value – each additional 1 km/s is exactly as hard to traverse as the previous one. Resource value is also linear, 100 kg of water is worth exactly half that of 200 kg

of water, disregarding the impact of increased supply on pricing. Since increasing from 4 km/s to 5.5 km/s yields access to dramatically more of the water in the NEA population, it makes sense to prioritize the increased water mass despite the increased delta-v.

Admittedly, certain exceptions to this conclusion apply. The first attempt to mine water from NEAs will likely be cash starved due to the risk of the venture, and might very well not be able to bear the added burden of a higher delta-v, even in exchange for a significantly greater return. Additionally, this analysis is based purely on the supply side of the equation. It does not consider the size of the market for NEA-mined water, or the impact a newly opened NEA mine might have in driving down the cost of in-space water. Nevertheless, it does strongly suggest that, if a NEA mining industry is established, it will focus more on the quantity of water available and less on the delta-v required to access it.

3.5   Findings

This chapter aimed to consider the cash flow from water resources within the population of mineable NEAs. Five results from this research were articulated:

1. The known population of NEAs approaches – and the projected population surpasses – one trillion metric tons of water, an amount equal to or slightly greater than the quantity of water on the moon itself.

2. No matter how high the initial cost of mining water, there are at least tens of known NEAs which could produce a profit if fully mined. Even an extreme initial cost of $150 billion would only require the resources of a 180 meter NEA to break even.

3. There are undiscovered NEAs which could profitably be mined, regardless of the initial cost of mining. Accomplishing the goal of the George E. Brown Jr. NEO Survey Act would be an excellent first step toward locating those NEAs, but additional survey efforts, particularly for smaller NEAs, will be necessary to find all or most of the NEAs worth mining.

4. For the projected population, an initial cost of $10 billion is the threshold below which a multi-NEA approach is feasible. No such threshold exists for the known population, wherein mining the largest NEAs is the only way to gain access to significant quantities of water mass.

5. Every increase in delta-v capacity has a correspondingly greater increase in water mass contained in NEAs more accessible than the moon. As a result, for the delta-v constrained population, the bigger NEAs are worth more than would be saved by choosing a NEA with less delta-v.

These five results were based on the planetary science research performed above. Results one and two directly speak to the overarching question one of this thesis (what is the cash flow of an industry mining water from NEAs?). Results 3-5 guide the priorities in developing that industry, and will be used in later chapters to inform policy recommendations.

4 Platinum Group Metals

After considering water, the other NEA resource worth investigating is the platinum group metals (PGMs): iridium, osmium, palladium, rhodium, ruthenium, and platinum itself. Kilogram for kilogram, PGMs are some of the most valuable resources on Earth. Since they are found on NEAs in higher quantities than in PGM mines on Earth – albeit still on the order of parts per million – it is worth considering whether or not a business which mined PGMs from NEAs and sold them on Earth could have a positive cash flow, i.e. what the answer to overarching question one would be with regards to PGMs on NEAs. This chapter of the thesis tackles that question by first laying out the case for mining NEAs for PGMs, drawing heavily from the historical literature and current best knowledge in the process. It will then develop the context for comparison between a hypothetical NEA mine and a terrestrial platinum mine. Third, this chapter will explore the challenges in mining NEAs revealed by that comparison to terrestrial platinum mines. Finally, this chapter concludes by directly answering question one with regards to the mining of PGMs from NEAs.

4.1 The Case for Mining Platinum Group Metals

Throughout the chapter, platinum will often be considered in the place of the full complement of the six platinum group metals. It is common to refer to terrestrial mines as "platinum mines" even if they produce more than just the one PGM. Additionally, previous studies of meteorites commonly assessed platinum content, while assessments of all six PGMs are less common. For this reason, moving forward, when the term "platinum" is used, it refers specifically to the metal platinum, but can be thought of as an indicator of the relevant metric for the full spread of PGMs. By contrast, when the term "PGM" is used, it refers to multiple or all of the six metals and will be noted as such.

The rationale for mining platinum from NEAs is straightforward. Platinum is useful as a chemical catalyst in the automotive industry. It also has valuable properties for electronics and additional miscellaneous industrial purposes. Beyond its practical uses, it is a component in fine jewelry and it is used as a speculative investment (Sverdup et al., 2016). As a result, at the time of this writing in 2019, it has a market price of roughly $25,000/kg (Business Insider, 2019). The discovery of new sources of platinum peaked between 1980 and 1985 (Sverdup et al., 2016),

meaning that, as far as humans are aware, there is a diminishing amount of undetected platinum that exists within economical mining distance of the Earth's surface. Looking elsewhere for additional platinum to meet demand is a natural next step.

Platinum is a siderophile element, meaning that it dissolves easily in molten iron. As a consequence, during the formation of the Earth the vast majority of platinum on the planet sank to the Earth's core. Less than 1% of platinum on Earth is in an accessible location in the Earth's crust (Yeomans, 2013). In comparison, NEAs are expected to possess concentrations of platinum more in line with its solar-system element abundance of one part per million(ppm) or 0.0001% of all solar-system matter (Anders et al., 1982). Naturally, due to the range of NEA types the abundance of platinum is likely to vary significantly between different NEAs.

The case for mining platinum from NEAs is then fairly easy to construct. Assuming M-type NEAs – a subset of X-type NEAs – have a similar composition to iron meteorites, one can take the calculated parts-per-million of platinum in those meteorites, multiply it by an estimate of the NEA's mass, and multiply that by the price of platinum to arrive at a dollar value for the platinum in a NEA. John Lewis, in his book *Mining the Sky,* uses this back of the envelope method to arrive at a value of $6 trillion for the PGM in the asteroid Amun (Lewis, 1996). Working backwards, this implies a concentration of PGM of 8 ppm at platinum prices.

The subject was considered in greater depth by Kargel in 1994. Kargel took research on the abundance of PGMs in various types of meteorites, and used that to produce an estimate of the value of a 1 km metallic NEA. He used a value of 29 ppm for platinum, and 100 ppm for PGMs overall. The following table compares those assumptions with the literature both before and after Kargel published his paper.

Table 2:*Range of platinum and full platinum group metal concentration values in iron meteorites from a variety of sources. Early research assessed many types of iron meteorites, while later research tended to focus on specific types, most notably IVB meteorites which tend to have high platinum concentrations. The Hoashi high concentration value is likely erroneous considering the differing values found by both Campbell and Walker. The bottom two rows provide platinum and PGM concentrations for terrestrial mines for the sake of comparison.*

Source	Year	Low Pt Concentration (ppm)	High Pt Concentration (ppm)	PGM Lowest Concentration (ppm)	PGM Highest Concentration (ppm)	Meteorite Type Assessed
Wesson	1989	-	16	-	31	Various iron meteorite

					(Pt and Ir)	types
Hoashi	1993	0.1	86	5 (Ru, Pd, Pt)	111 (Ru, Pd, Pt)	Highest in IVB iron meteorites
Campbell	2005	29	31	104 (All PGM)	166 (All PGM)	IVB iron meteorites
Walker	2008	30	33	99 (All PGM)	151 (PGM)	IVB iron meteorites
McCoy	2011	2	7	9 (Missing Rh)	22 (Missing Rh)	IVA iron meteorites
Worsham	2016	-	11	7 (Missing Rh)	36 (Missing Rh	IAB iron meteorites
Cawthorn	1999	1.3	3.2	-	-	Terrestrial mine
Zientek	2017	-	-	5	15	Terrestrial mine

The biggest takeaway from this table is that platinum and PGM concentrations vary widely across iron meteorite types. PGM rich groups, such as the IVB meteorites, do indeed have platinum concentrations around 30 ppm and PGM concentrations above 100 ppm, but other groups such as the IVAs tend to be much lower. There is currently no way to link a given NEA to a specific meteorite type. However, since IVB meteorites do exist it is safe to assume that NEAs with equivalent richness of PGMs exist as well, though extensive searching and prospecting might be necessary to find them. Kargel's PGM and platinum concentrations are therefore in agreement with the modern literature, given the reasonable assumption that a NEA selected for PGM mining would be rich in PGMs.

Similarly, Kargel's estimate of the density of a metallic NEA is also relatively accurate. He states that 29 ppm of platinum in a 1-km asteroid would yield 117,000 metric tons of platinum. This carries an inherent assumption about the density of a metallic asteroid given the typical density equation.

$$\rho = \frac{M_{plat} * \frac{1000000}{29}}{V_{nea}} = 4.03 g/cm^3$$

The derived density of the NEA is 4.03 g/cm^3. While the elements on an iron asteroid tend to have a density in the range of 7.3 – 7.7 g/cm^3, iron meteorites also exhibit macroporosity, making the bulk density of those asteroids significantly lower (Housen, 2002). A recent study analyzed a number of different M-type asteroids and found they ranged in density from 2.5-5 g/cm^3 (Hanuš et al., 2017). Thus the density Kargel uses also fits comfortably in the modern range. From this confirmation of the platinum concentration and the density of metallic asteroids, it is clear that, broadly speaking, Kargel's estimate of the value of platinum is in a 1-km diameter NEA is correct. A 1-km NEA possess sufficient platinum to be worth on the order of trillions of dollars.

The literature values found above and compiled in the table below are used when estimates of the value of a PGM-rich NEA are performed below.

Table 3: Literature values used to calculate the dollar value of a NEA given that NEA's radius. Density is used to calculate the overall mass. This is multiplied by concentration to get the mass of platinum or PGMs. Finally, this is multiplied by the cost of a kilogram of platinum to get the value of the NEA. The cost of platinum is used because at $25,000/kg it is a medium among the price of the six PGMs – Ruthenium is $10,000/kg while Rhodium is $100,000 (Metals Daily, 2019) – and because it is often the largest component of the PGM concentration.

Platinum Concentration (ppm)	PGM Concentration (ppm)	Density (kg/km^3)	Platinum Price ($/kg)
30	150	3.75x10^{12}	25,000

In summation, the apparently extreme value of large NEAs is, in fact, reasonably accurate. However, that is not sufficient to guarantee that NEAs should be mined for PGMs. Even terrestrial mines are not always mined to exhaustion because the cost of accessing certain reserves is higher than the value of those reserves (Sverdup et al., 2016). The following section creates the framework for determining whether or not NEA PGMs are out of reach due to price limitations by establishing the basis for comparison between NEA and terrestrial mines.

4.2 NEA Platinum in context

In the previous chapter the focus was primarily on the water content of the population of NEAs more accessible than the moon. Platinum requires an altogether different approach. To begin with, the moon is notoriously lacking in PGMs (Day et al., 2017), so the analysis does not consider accessibility. Additionally, the full population of PGM-rich NEAs is not the most useful factor to consider. This is for two reasons. First, an individual large NEA is comparable in terms of platinum content and total ore mass to a terrestrial mine. Second, the complexity required to mine and refine platinum on a NEA produces a strong preference for mining a single NEA, rather than multiple. This second reason will be explored in detail in the following section on the challenges of mining platinum from NEAs.

To develop the comparison between a single NEA and a terrestrial mine, the plot below shows the platinum grade and amount of ore for a 140 meter NEA and the largest known M-type NEA, the asteroid Amun. Platinum concentration was chosen rather than PGM concentration because that data exists for both NEAs and terrestrial mines. All also possess other PGMs, but the relative concentrations are not consistent or easily comparable. Two platinum mine complexes are included in the chart: Stillwater and Bushveld. A platinum mining complex is comprised of several individual mines in the same geographic area. Those mines can have differing grades of platinum and ore contents. The large circles refer to the average platinum concentration and summed ore content of the individual mines that make up the complex and are represented by the smaller circles.

Platinum Grade in Asteroids and Terrestrial Mines
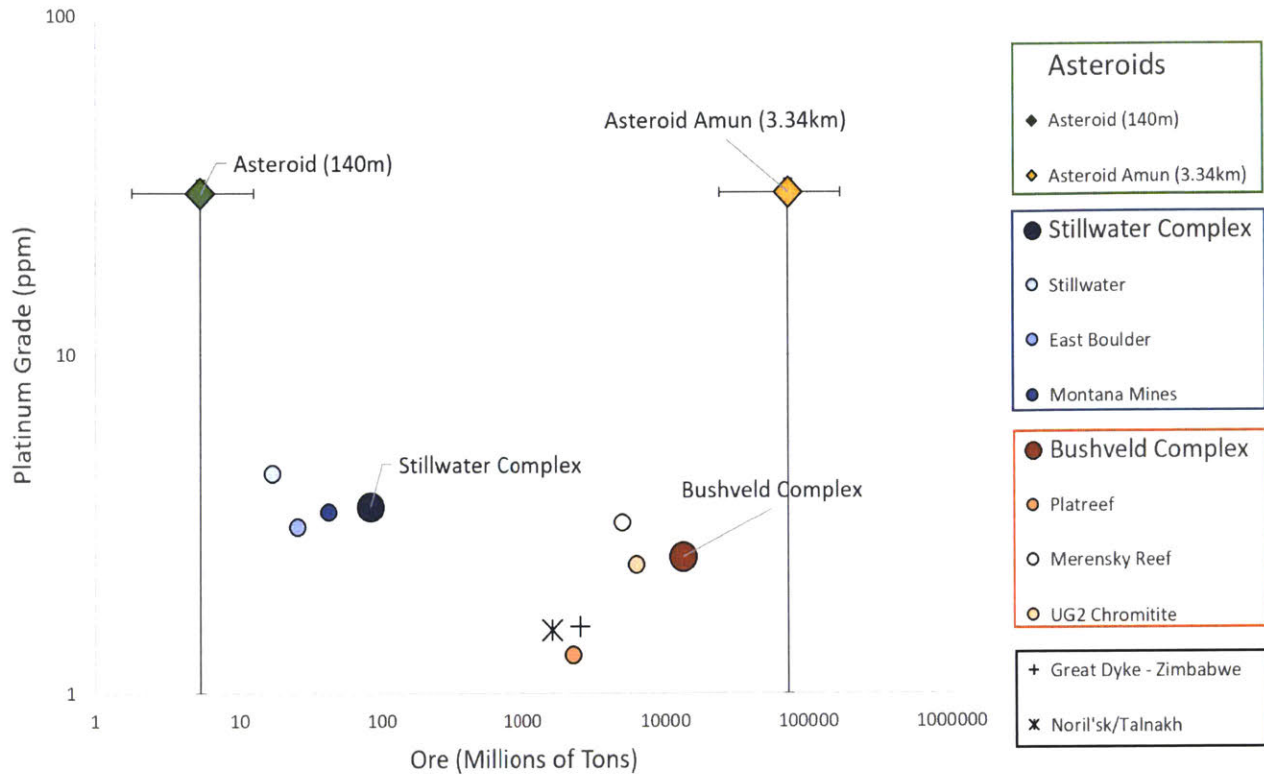
Figure 11: In terms of both the amount of ore and the platinum content, large NEAs are comparable to terrestrial mines. A platinum rich-NEA would have roughly an order of magnitude higher platinum concentration than a terrestrial mine. Depending on the size of the NEA it would range from smaller than the smallest existing mine to ~5 times the largest. For terrestrial mines the chart above was constructed from the technical documents and articles on the productivity of those mines and mine complexes (Abbott et al., 2017; Cawthorn, 1999; Page et al., 1976). The hypothetical 140-m metallic NEA was chosen to correspond with minimum size NASA is congressionally mandated to find (George E. Brown Near-Earth Object Survey Act, 2006). As mentioned above, a density range from 2.5 g/cm3 – 5 g/cm3 was chosen to provide the horizontal NEA error bars (Hanuš et al., 2017). The NEA platinum concentration values were chosen to correspond to IVB meteorites, but the vertical NEA error bars are for all meteorite types. All are taken from Table 1 above.

The reason the asteroid Amun was chosen for the chart, aside from Lewis' discussion of its value above, requires some explanation. Determining if a NEA is metallic is a challenging task. Under the Bus-DeMeo taxonomy (DeMeo et al., 2009) potentially metallic NEAs are classified as X-type, because they have featureless spectra. As a result, the primary tool planetary scientists use for determining asteroid composition is not a diagnostic for identifying metallic objects. A previous taxonomy of NEAs, the Tholen taxonomy, partially used albedo to classify NEAs. Given that metal is more reflective than stone, higher albedos, along with neutral spectral features defined the M-type or metallic-type classification. Unfortunately, this not a unique

identifier either. Other NEA types, under either taxonomy, do occasionally exhibit a high albedo, possibly because of metal mixed with silicates (Magri et al., 2007; Shepard et al., 2010). It is not known if high albedos outside the M-type truly represent NEAs with a high metallic content, or if those objects have a different composition producing a similar result. Harris et al. (2014) take this analysis one step further by looking for enhanced thermal conductivity in a NEA, which is indicative of high metal content. This proved effective at identifying metallic NEAs, even ones that were not previously characterized as M-type or X-type. The final step of that paper was to identify 18 NEAs which passed the paper's established threshold for a metallic composition. Of those NEAs, (3554) Amun was the largest. For that reason, Amun was selected as the largest well-vetted metallic NEA and a reasonable maximum size for a platinum-rich NEA.

Now that the origin of the data in the chart above have been explained, it is possible to discuss what it reveals. The immediate takeaway is that a very large platinum rich asteroid would have more ore at a higher grade than the largest or most concentrated terrestrial platinum mines. In the case of Amun, it has five times the ore of the Bushveld complex and up to an order of magnitude richer concentration of platinum. This places a frame around the question of the cash flow of NEA PGM mining. Namely, can a NEA be mined with less than an order of magnitude increase in cost compared with a terrestrial mine? While this question is impossible to answer in its entirety, it is possible to use the similarity in size and resources between NEA and terrestrial mines to assess whether the challenges associated with constructing a mine in space are an order of magnitude costlier than those associated with mining on Earth.

4.3 Challenges of NEA Mining

The previous two sections demonstrated conclusively that there is a significant amount of valuable metals present in the largest members of the NEA population. If mined in their entirety, certain NEAs would be worth trillions of dollars, far more than even the best terrestrial mines. However, the mere presence of valuable resources is not sufficient to prompt mining activity. Earth's core has a platinum concentration of 5.7ppm (McDonough, 2014) which equates to 34 quintillion kilograms of platinum. At current prices that would be worth almost $1 septillion dollars. Despite this excessive value, no one is seriously considering mining the core of the Earth because of the extreme challenge that would represent and the fact that traditional platinum

mines are capable of meeting demand at a more viable price point. Less hyperbolically, the Duluth Complex in Minnesota could have up to $1 trillion of resources, but has not yet been mined because of extraction costs and pollution concerns (Myers, 2010). Similarly, the challenges inherent in mining PGMs from NEAs raise serious obstacles to profitably mining the admittedly vast resources in the NEA population.

4.3.1 Mission Architecture

The challenge of finding promising metallic NEAs has already been discussed. However, beyond simply finding promising targets it is necessary to determine how one might select a specific NEA from among a number of targets. More specifically, the precise nature of a promising NEA remains to be determined, and with it the ideal mission architecture. Two specific cases deserve to be considered: small vs. large NEAs and on-NEA refining vs. transportation to a mining station. Previous sections have focused on large NEAs, and this section will justify that focus.

The case one might make for a small NEA is quantity over quality. The idea here would be to collect a significant number of low delta-v metallic NEAs instead of mining a single larger and more difficult to reach NEA. Fortunately for the sake of comparison, one of the versions of the NASA Asteroid Retrieval Mission (ARM) had a very similar mission architecture. ARM would have returned a seven-meter diameter object, with an estimated mass between 250,000 kg and one million kg, to a high lunar orbit. The estimated full life-cycle cost of this capture and return mission was $2.6 billion (Glenn Research Center, 2015). A solid metallic object would be at the upper end of the scale for mass. Generously assuming that the object is at the upper end of possible platinum concentrations depicted in Figure 11, an object with that mass would have $500,000 worth of platinum, or three orders of magnitude less than the mission would cost. In essence, the complexity of space missions produces high mission costs which produce a distinct preference for a single large object instead of many smaller ones.

The examples above from the ARM mission weighs against the prospect of a central mining facility in orbit to which ore from a NEA might be brought. However, there is another comparison that can be made to demonstrate that on-site mining is the preferable option. As was established in the previous section, the quantity of ore in a large NEA is comparable to a terrestrial mine on a one to one basis. That is, a *single* sufficiently large NEA has more ore than

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a terrestrial mine. A technical report of the Stillwater mining complex estimated that the likely reserves of the Stillwater mine would last until 2035, and the East Boulder Mine would last until 2061. Stillwater began commercial mining in 1986 and East Boulder began in 2002 (Abbott et al., 2016). This gives an average ore processing per year between 0.34 and 0.42 million tons per year. As shown above, the amount of ore in Amun is around 70,000 million tons, so at those rates it would take over 150,000 years to fully mine the NEA. The largest platinum mine in the world, the Bushveld Complex, only processes 30 million tons of ore per year (Anglo American Platinum Limited, 2017). Even at the pace of the highest capacity mine in the world, it would still take over 2000 years to mine Amun to exhaustion. Unless mining in space can be performed dramatically faster than on Earth, a single large NEA would be a productive mine far into the future. For this reason, using a centralized location for NEA refining simply adds unnecessary transit costs to the overall proposition. Mining and refining on a large NEA is the optimal mining mission architecture.

4.3.2 Prospecting

Due to the impossibility of assessing platinum concentration from a distance, prospecting will require either onsite composition analysis or a sample return mission to assess the PGM concentration of a metallic NEA. This analysis has two natural comparison points: terrestrial prospecting operations and scientific missions to asteroids.

Considering the terrestrial side of prospecting first, according to the US geologic survey, terrestrial resources with an estimated quantity of PGMs less than one metric ton ($25 million) are not considered worth prospecting to determine precise tonnage and grade (Zientek et al., 2017). IVB meteorites have concentrations of PGMs between 100-150 ppm (Campbell et al., 2005), so one metric ton of PGMs would require a NEA diameter with a diameter of at least 15 meters. Note, this is not the size at which a deposit becomes valuable, it is the size a deposit necessary for it to be worth investigating in a terrestrial context. In space, the prospecting cost must be higher and consequently the minimum size NEA worth prospecting would be larger as well, likely by a factor of two at a minimum to account for the separate mining and prospecting missions.

By considering the costs of previous missions to NEAs it is possible to get a sense of the cost of a prospecting mission. Historically, the cost of spacecraft designed to visit a NEA has varied

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widely. Full spacecraft designed for sample return have costs ranging from $150 million for Hayabusa 2 (Howell, 2018)) to nearly $800 million for OSIRIS-REx (OSIRIS-Rex, 2019). Smaller missions which do not return a sample to Earth are less expensive, on the order of $70 million for the DART mission, including the launch cost (Karen et al., 2019). Adding the cost of the launch vehicle to each of the other two missions results in an estimated overall cost between $70 million and $1 billion dollars.

This equates to a minimum size between 11 meters and 30 meters just to break even on a prospecting mission. The upper end of the scale is likely more accurate given that the prospecting mission would need to acquire comprehensive information on the NEA to enable a follow-up mining mission. Also, considering that the above size range only breaks even with the prospecting mission, it would be fair to double the range in acknowledgement of the fact that a mining mission would be at least as expensive as a prospecting mission. Note that this is the cost to assess a *single* NEA for potential value, so it should also be increased to account for the likelihood of sending a prospecting mission to NEAs that turn out not to be PGM-rich. Taking these multiplicative factors together, NEAs below 100 meters quickly become infeasible to mine profitably.

In essence, prospecting missions are crucial because of the wide range in PGM concentrations even among iron meteorites – and presumably among metallic NEAs as well. However, the cost of prospecting missions restricts the minimum viable size of mineable NEAs. Technological advances might expand the range of viable NEAs to some degree, but the traditional minimum quantity of PGMs worth prospecting for, which is borrowed from terrestrial mines, places a hard cap on how small a NEA can be before it is not worth prospecting, let alone mining.

4.3.3 Mining and Refining Process

Earlier sections assumed it, but it bears noting explicitly that transporting ore to Earth en masse more closely resembles a natural disaster than a business plan, so some degree of mining and refining must occur in space. Yet mining and refining PGMs is no easy process, and space rarely makes anything easier. There is no way to know exactly what the process for mining in space will be, but by taking terrestrial mines as a point of comparison and noting areas where a different process might be required it is possible to gain a first order understanding of the challenges facing a prospective NEA platinum miner.

Per the US Geological Survey of Platinum Group Elements (Zientek et al., 2017), terrestrial PGM mining and refining has several stages:

1. Creation of ore via explosives in holes bored by handheld pneumatic or mechanized drills
2. Transportation to surface
3. Crushing of ore to free PGM-particles from the rest of the rock
4. Concentration of ore via froth flotation circuits wherein water and air are used to make bubbles to which PGM minerals adhere
5. Smelting of ore at temperatures over 1500 °C, producing sulfur dioxide as a waste product
6. Use of blown air to separate base metals from PGMs
7. Refining of PGMs into individual platinum group metals via hydrometallurgical techniques involving solvent extraction, precipitation, and dissolution using chloride solutions

A full in-depth study of metallurgical processes in space is beyond the scope of this thesis, but high level observations can be made based on the steps out lined above. Further work might delve deeper into what alterations would be necessary to perform these actions in space.

Step 1-3: Step one involves creating manageable chunks of ore to feed into the refining process. The drilling and explosions of traditional techniques may be complicated by the vacuum of space. However, metallic asteroids tend to have significant macroporosity, making them potentially more like rubble piles than solid objects (Housen, 2002). If this is the case, extracting ore might be as simple as choosing which boulders to move. The possibility of rubble piles is significant for steps two and three as well. Transportation overall may be easier in a zero-gravity environment, but if the substance of the NEA is small grains, that might require the development of new methods to move significant amounts of ore at once. Similarly, if the rubble is uniformly rich in PGMs that could aid the crushing process, or it could complicate determining the correct quantities to crush. Overall, steps one through three simply require more information and experimentation before it can be determined if performing these steps in space would present unique challenges.

Step 4: Step four allows for a return to quantification. Of the seven steps it is the only one with significant water usage. The water use per kilogram of PGM of some platinum mines ranges from 270 to 1800 metric tons per kg of PGM (Abbott et al., 2016). In the water resources section, the estimate of $1500 per kg of water to LEO was given. This gives a range of $404 million to $2.7 billion to transport the water to orbit necessary to mine a single kg of PGM. This is four to five orders of magnitude higher than the value of a kg of PGMs (Business Insider, 2019).

A caveat must be made to this analysis. A significant component of water usage is due to mine water contaminated with nitrates from explosions which must be processed to prevent mine waste from polluting the surrounding area. In space, this may not be necessary, either because explosions are not needed in mining or because pollution is not a concern. The Stillwater mine has an expected mine water inflow of 2.08 cubic meters per minute, and produces on the order of 10 kg of PGMs per day. Assuming a 12-hour workday this gives a mine water estimate of 150 cubic meters per PGM. This improves the cost of water calculation, but even in the best possible case where the waste water is entirely nonexistent and the water usage is at minimum, that still leaves a cost of $179 million for transporting the necessary water to LEO, and significantly more if it must be transported beyond LEO to the NEA to be mined.

This raises an interesting possibility for future research. As was mentioned earlier, it is possible for non-M-type NEAs to have high radar albedos indicative of high metallic content (Magri et al., 2007). This includes the C-types which can possess hydrated minerals. Kargel estimated that chondrites could have platinum concentrations ranging from 8 – 25 ppm for different types of chondritic meteorites (Kargel, 1994). More recent research suggests it might be closer to 1 ppm (Brandon et al., 2005), but that does not entirely close off the possibility. The significant quantity of water required for PGM mining and refining might imply that the optimal NEA for mining has a lower concentration of PGMs in exchange for sufficient hydrated minerals to make PGM mining possible. This is an area for further study once more is known about the composition of specific metallic NEAs.

Step 5: Step five from the list of terrestrial mining refining stages, smelting at 1500 °C, is a highly energy intensive procedure. The energy consumption of the entire PGM mining and

refining process will be considered separately in the following section, rather than piecemeal here. However, this stage does produce a significant amount of sulfur dioxide. Rather than release it into the atmosphere, terrestrial mines use a dual alkaline scrubbing system to produce gypsum and sell it as an agricultural product (Abbott et al., 2017). This process may be unnecessary in space, and the opportunity to sell gypsum for agricultural reasons also may not exist. Simply venting the sulfur dioxide into space may provide a cost saving opportunity.

Step 6-7: Steps six and seven involve the removal of base metals and the division of PGMs into component metals. At some point in these steps it might make sense to ship the material to Earth for the final refining processes. The final refining stages requires acids, reagents, and other highly specific techniques and materials (Zientek et al., 2017), all of which would have to be shipped to space at high costs per kg. Moreover, by this stage in the refining process the ore is down to PGMs and elements such as copper, selenium, tellurium, iron, and nickel (Abbott et al., 2017). None of these materials is entirely without value, so, despite the cost of shipping, it may make sense to do so over attempting to refine on-site. As an additional point of evidence, once the ore in question reaches 50% platinum + palladium the Stillwater mining complex ships it out for further refining at a secondary location (Abbott et al., 2017). Presumably that is a result of a cost benefit analysis on the optimal amount of refining onsite. A similar analysis should be conducted on NEA mining once a more detailed process for refining in space is developed.

One final challenge of the mining and refining process is worth considering. PGM mines are not automated enterprises. In 2016 the Stillwater mine had 791 employees, and East Boulder had 402 (Abbott et al., 2017). Only 24 people have ever traveled beyond LEO (NASA: Apollo 50th Anniversary, 2019). Putting sufficient people in space to run a PGM mine is no small feat. Automating large portions of the mining process would decrease the number of people required, but those same automations might be applied to terrestrial mines, potentially decreasing the cost to produce PGM and therefore decreasing the cost for which it is sold. Alternatively, since PGM prices tend to be driven more by demand than supply (Sverdup et al., 2016), automation might be fueled by terrestrial concerns and then applied to NEA mining after it is developed.

In summation, steps 1-3 may be transferable to space without excessive difficulty, and certain parts might even be easier. Steps 4-6 contain processes for which a space analog may be very

challenging to develop, or which have resource demands which may be prohibitively expensive unless a new and creative tact is taken. Step 7 may be most efficiently performed on Earth, pending more detailed mining plans. Finally, launching the personnel required to complete steps 1-7 is a challenge in and of itself. Either advanced automation or significantly increased human spaceflight capacities will be necessary for profitable PGM mining to occur.

4.3.4 Energy requirements

This is a relatively small challenge compared to the others listed above, but it is worth considering because of the easily quantifiable nature of the comparison. As part of an environmental report, researchers analyzed the energy consumption of a platinum mine. When considering the mine, concentrator, smelter, and refinery the energy consumption per kilogram of PGM was on the order of 200 GJ per kilogram of PGM produced (Mudd, 2012). By contrast, the full battery capacity of the International Space Station (ISS) stores on the order of 2 gigajoules (Dalton et al., 2004; Harding, 2017). In other words, an energy capacity 100 times what is currently used on the most advanced and expensive pieces of space equipment would be necessary for every single kilogram of PGM at the scale of a terrestrial mine.

One might wonder if producing PGM on a smaller scale than a terrestrial mine would help make it more efficient. However, as Mudd notes, there is a "minor negative scale effect for unit energy consumption for stand-alone mine-concentrator-smelter projects with low throughputs" (Mudd, 2012). In other words, much like the refining process discussed above, trying to scale down from terrestrial sizes makes the energy budget more expensive per kilogram of PGM produced.

4.3.5 Down-mass costs

Finally, the transportation to market of any platinum produced also represents a unique challenge. Deep space shipping has not been previously attempted and no easy comparisons exist. The most obvious comparison in terms of both consistency and complexity is the resupply missions to the ISS. Admittedly these missions do not go beyond LEO, and therefore are easier and cheaper than transportation from a NEA mine to an Earth-based market actually would be. Despite these discrepancies, it is instructive to look at current capabilities to gain perspective on the scale of the problem.

Unlike in the water resource chapter, in this case the interesting component is the down-mass of the resupply mission. Of the three ISS resupply contractors only two have the capability for returning cargo to the Earth. Sierra Nevada's Dream Chaser, launching on the Atlas V returns 1750 kg to Earth. SpaceX's Dragon 2, launching on a Falcon 9, can return 2507 kg to Earth. Since the Dream Chaser has a lower return capacity and requires a launch vehicle configuration costing $175 million it can be dismissed as strictly worse than the Dragon 2 for this analysis (NASA OIG, 2018). For the initial round of resupply missions SpaceX had a cost of $152.1 million per mission. The second round of resupply missions have a projected overall price per mission of $300.6 million per mission, due largely to a 50% increase in price per kilogram on the part of SpaceX (NASA OIG, 2018). Considering the huge cost of launching a vehicle it is likely the craft would be filled both on the way up and the way down. One cost saving measure might be splitting the mission cost between the cost to bring materials up to LEO and the cost to bring them down. Alternatively, both costs might be borne the NEA mining company due to the necessity of refining materials discussed above. To make this analysis as restrictive as possible, we will consider the situation in which the NEA mining company carries the full cost. This gives us a cost of $300 million for carrying 2507 kg from orbit to Earth.

As mentioned elsewhere, the current price of platinum is roughly $25,000/kg (Business Insider, 2019), so the gross income from bringing 2507 kg of platinum to market is $62 million dollars. Even in the unlikely circumstance that the mission was carrying solely Rhodium, the most valuable of the PGMs at a current price of $100,000 (Metals Daily, 2019), the gross income would be $250 million, still short of the established cost of simply bringing the PGM to market. Moreover, even setting aside the complexities of resupplying the ISS, a mission returning with a full load of platinum only breaks even with the minimum launch cost of the Falcon 9 at $62 million (SpaceX, 2017). In essence, even if bars of perfectly pure platinum were discovered floating in LEO, it would still be impossible to return them to Earth profitably with current capabilities. However, there has not previously been a reason to develop significant down-mass capabilities, so it is likely to see rapid improvement if there are opportunities for profit.

The above discussion only considers the challenge of transporting from LEO to the Earth's surface. Current space shipping capabilities are entirely unable to transport the products of a NEA mine to LEO. As a demonstration of this fact, Amun has a higher delta-v than the surface

of the moon, and travel to the moon has been very limited in the past decades. The complexity of moving large quantities of mass over those distances has no parallel among existing capabilities and would need to be developed from scratch.

4.4   Findings

This chapter aimed to consider the cash flow of PGMs, particularly platinum, when mined from a PGM-rich NEA. Five results from this research were articulated:

1. NEAs can be reasonably valued at or above trillions of dollars.
2. A single large NEA contains an amount of platinum comparable to or greater than the largest terrestrial mines.
3. In a best case scenario, at current rates, it would take more than 2000 years to extract all the resources from a single large PGM-rich NEA.
4. NEAs can have wildly different amounts of PGM, even after selecting the most promising. Prospecting missions would be required to select a NEA for PGM mining.
5. Half of the steps to mine and refine platinum, producing the energy required, and transporting the product to Earth markets either cannot be done profitably with current capabilities or cannot be done at all.

Results 1-3 paint a rosy picture of the potential of a NEA PGM market. However, results 4&5 demonstrate that the technology and knowledge required to profitably mine NEAs simply does not yet exist, and there is no guarantee that it can or will be developed in the foreseeable future. Policy recommendations in this space must consider the possibility that investments in this space will never yield returns. Mining PGMs from NEAs may be analogous to mining platinum from the Earth's core: impossible with all current and foreseeable technology. That is not to say PGM mining should not be pursued, rather it is simply not possible to assess if platinum mining can ever be profitable until the technologies discussed above advance further.

5 Status of NEA Mining in Law and Private Industry

Previous chapters have established that there is value in NEAs, but that that value is difficult to access. The natural next step of the analysis is to consider how that value might be made available. To do so, it is necessary to first depict the current law of the land with regards to mining NEAs. This chapter will explain the status of existing laws and private enterprises which are relevant to NEA mining. The first section will cover the two international treaties and two national laws which have bearing on asteroid mining efforts. The section on the private sector will be a brief overview of the companies that are active, or have recently been active, in the NEA mining space.

5.1 Relevant Laws

Though there are a broad number of treaties and laws which might serve as a precedent for NEA mining, there are only four documents which have direct legal bearing on the subject: The Outer Space Treaty (OST) of 1967, the Moon Agreement of 1979, U.S. Commercial Space Launch Competitiveness Act (SPACE Act) of 2015, and the Government of the Grand Duchy of Luxembourg's Law on the Exploration and Use of Space Resources of 2017.

5.1.1 Outer Space Treaty of 1967

As of 2019, the OST has been ratified by 109 countries (Committee on the Peaceful Uses of Outer Space, 2019). Due to that high acceptance rate, the OST is likely to fall under the heading of customary international law and is therefore binding on all countries, regardless of their signatory status (Lyall, 2017). As the product of the Committee on the Peaceful Uses of Outer Space (COPUOS), the OST was an idealistic document containing high-minded language citing the "common interest of all mankind" and stating that the "use of outer space should be carried on for the benefit of all peoples irrespective of degree of their economic or scientific development" (United Nations, 1967).

The use of this idealistic language is significant because, according to Article 31 of the Vienna Convention on the Laws of Treaties (United Nations, 1969), there must be a "good faith" effort to interpret the text of the treaty in the context of its object and purpose, as may be found in its

preamble and annex (United Nations, 1969). The stated context of the OST deals with the good of mankind as a whole, which weighs against an interpretation of the treaty permitting the mining of an asteroid for the good of one country or company.

Moving from the general object of the treaty to its specifics, there are two articles within the OST which are directly relevant to asteroid mining.

Article two states:

> Outer space, including the Moon and other celestial bodies, is not subject to national appropriation by claims of sovereignty, by means of use or occupation, or by any other means. (United Nations, 1967)

Article six states in part:

> State Parties to the Treaty shall bear international responsibility for national activities in outer space, including the moon and other celestial bodies, whether such activities are carried on by governmental agencies or by non-governmental entities, and for assuring that national activities are carried out in conformity with the provision set forth in the present treaty. The activities of non-governmental entities in outer space, including the Moon and other celestial bodies shall require authorization and continuing supervision by the appropriate State Party to the Treaty. (United Nations, 1967)

Article two clearly forbids a *nation* claiming an asteroid and mining it as a national effort. Article six specifies that non-governmental entities – such as a hypothetical asteroid mining company – would be the responsibility of the governments from which they launched their equipment. It is not clear if the term "responsibility" should be taken to cover just liability for damages, or if it is meant to imply that those companies must be held to the same standard of action as a state. If the former, then the OST would permit asteroid mining, if the later it would not. Some (e.g. Feinman, 2014) believe that the former interpretation is correct, while others (Sarnacki, 2014) hold that the OST does not forbid the extraction of resources by non-governmental entities. An interesting third interpretation is that article six creates an obligation for countries with launch capacity to create legislation governing the extraction of resources (Hobe et al., 2016). Under this third interpretation the US SPACE Act – to be discussed in greater detail later – would not only be legal, it would be required under international law. However, one point made clear by the multiple potential interpretations of the OST is that the

treaty – taken in isolation and without judicial rulings – does not settle the question of the legality of mining asteroids.

A final point of importance is that Article one of the treaty describes the exploration and use of outer space as the "province of mankind" (United Nations, 1967). There are multiple possible interpretations of the term "province". In this context, province could mean that outer space is owned by everyone, that outer space must be managed by everyone, or the act of exploration and use of outer space is an area of activity open to everyone (Reed, 2018). The first interpretation would prohibit private ownership, while the latter two would not. Again, whether or not the treaty forbids asteroid mining on the basis of the term "province of mankind" is not clear. However, the term itself is useful for comparison to the next relevant piece of legislation: The Moon Agreement of 1979.

5.1.2 Moon Agreement of 1979

The Moon Agreement of 1979 was ratified by only 18 countries, and the U.S., China, and Russia were not among the ratifying countries (COPOUS, 2019). For this reason, it is not currently binding on the three nations which possess the most active space programs – i.e. the countries that are most likely to host an asteroid mining company. However, the Moon Agreement did receive enough ratifications to become international law and is therefore at least marginally relevant to the legal status of future mining endeavors. Additionally, unlike the OST which covers the general "use" of space, the Moon agreement specifically considers the use of space resources. It is therefore instructive to consider the terms of the Moon Agreement both for the precedent it represents and for the impact it may have on future mining efforts.

Note that, though the treaty in question is called the Moon Agreement, the first Article of the treaty states that "the provisions of this Agreement relating to the moon shall also apply to other celestial bodies within the solar system, other than the Earth" (United Nations, 1979). Thus, for everything that follows, the term "moon" may be replaced with "near-Earth asteroid" with no loss of accuracy.

Article eleven of the Moon Agreement states:

1. The moon and its natural resources are the common heritage of mankind…

2. The moon is not subject to national appropriation by any claim of sovereignty, by means of use or occupation, or by any other means

3. Neither the surface nor the subsurface of the moon, nor any part thereof or natural resources in place, shall become the property of any State, international intergovernmental or non-governmental organization, national organization or non-governmental entity or of any natural person. The placement of personnel, space vehicles, equipment, facilities, stations and installations on or below the surface of the moon, including structures connected with its surface or subsurface, shall not create a right of ownership over the surface or the subsurface of the moon or any areas thereof. The foregoing provisions are without prejudice to the international regime referred to in paragraph 5 of this article.

4. …

5. State Parties to this Agreement hereby undertake to establish an international regime, including appropriate procedures, to govern the exploitation of the natural resources of the moon as such exploitation is about to become feasible…

6. …

7. The main purposes of the international regime to be established shall include:
   a. The orderly and safe development of the natural resources of the moon;
   b. The rational management of those resources;
   c. The expansion of opportunities in the use of those resources;
   d. An equitable sharing by all State Parties in the benefits derived from those resources, whereby the interests and needs of those countries which have contributed either directly or indirectly to the exploration of the moon shall be given special consideration.

(United Nations, 1979).

Paragraph two is functionally identical to article two from the OST. Paragraph three expands on that limitation to specify that natural resources cannot be owned except in accordance with an international regime to be established by the treaty itself. As far as that goes, the Agreement is clear. If the Moon Agreement were binding and no action were taken to establish that international regime, then asteroid mining would be illegal under international law.

The nature of that hypothetical international regime then becomes the key question. Paragraph seven lists fairly expected restrictions on the management of the resources, as well as the requirement that those resources be a last partially redistributed to less developed countries. Paragraph one's use of the phrase "common heritage of mankind" also contains a hint about the nature of the proposed regime. In contrast to the poorly defined "province of mankind" the idea

of common heritage can also be found in the UN Convention on the Law of the Sea (UNCLOS), which was the result of a conference lasting from 1973 to 1982.

In many ways, the sea represents a comparable entity to an asteroid. In both cases, no one country or company can lay claim to sovereignty, but there are still resources worth extracting so long as a mutually agreed upon legal framework exists. In the case of UNCLOS the entity formed in accordance with the treaty was the International Seabed Authority (ISA) and it was invested with powers ranging from setting the price of extracted minerals to transferring deep-sea mining technologies to less developed countries (Sarnacki, 2014). Moreover, it does so with the same justification as the Moon Agreement. Article 137 of UNCLOS states that "No State or natural or juridical person shall claim, acquire or exercise rights with respect to the minerals recovered from the Area except in accordance with this Part" (United Nations, 1982). Thus, if an International Outer Space Authority were to be formed from this model, it might have similar far-reaching authority.

The relationship between the ISA and the United States is instructive to consider as well. Though the treaty came into force in 1982, it was only signed by President Clinton in 1994 and still has not been ratified by the United States Congress (Sarnacki, 2014). However, much like the OST, the sheer number of other countries that follow the Law of the Sea has rendered parts of customary law and therefore binding to all countries, including the US (Roach, 2014). In practice, the US attempted to defy the treaty and extract resources off the coast of Hawaii without the license of the ISA, and international pressure eventually forced it to shut down the attempt (Sarnacki, 2014).

The point of this digression into UNCLOS is to show that it is entirely possible for an internationally sanctioned regulatory authority to be put in place against the wishes of a major international power. When applied to the Moon Agreement, it raises a dangerous possibility for the future of asteroid mining. Recall from the previous chapters that the most valuable handful of NEAs for both water and platinum may be orders of magnitude more valuable than any other NEAs. This gives a strong incentive for any space-faring nation to prevent other nations from claiming the choicest NEAs for themselves, though future search efforts might uncover such a bounty of NEAs that the competition for the largest becomes less fraught.

However, given the current state of the search for NEAs, the Moon Agreement provides a relatively easy way to slow or halt the progress of a competitor within the framework of international law. If one of the big three – U.S., Russia, or China – signed on to the Moon Agreement, they could use its clear prohibition against asteroid mining without an international regulatory regime to prevent the others from gaining an edge in asteroid mining (Listner, 2011). In an extreme case, a regulatory agency might even require the public disclosure of any and all asteroid mining and refining technology, just as the ISA does with regards to ocean mining technology. Naturally, this possibility would drastically curtail the potential profit from successfully mining a NEA, and it would therefore have a dramatic chilling effect on the nascent asteroid mining industry.

Despite this dire possibility, the Moon Agreement is not currently binding on any countries where asteroid mining companies exist, and its onerous provisions make the strategy outlined above unlikely. Instead of an obstacle, it is simply an extra uncertainty. However, in an industry already plagued by technical uncertainty, the existence of international law capable of destroying the industry might be sufficient to scare away any potential investors. If the asteroid mining industry is to get off the ground, then the Moon Agreement must either be fully embraced and an international regulatory body created, or it must be excised entirely.

5.1.3   U.S. Commercial Space Launch Competitiveness Act of 2015

In contrast with international law, the US regulation on the subject of asteroid mining is wonderfully straightforward. According to § 51303 of the SPACE Act:

> A United States citizen engaged in commercial recovery of an asteroid resource or a space resource under this chapter shall be entitled to any asteroid resource or space resource obtained, including to possess, own, transport, use, and sell the asteroid resource or space resource obtained in accordance with applicable law, including the international obligations of the United States. (SPACE Act, 2015)

Additionally, Section 403 of the SPACE Act states that:

> It is the sense of Congress that by the enactment of this Act, the United States does not thereby assert sovereignty or sovereign or exclusive rights or jurisdiction over, or the ownership of, any celestial body. (SPACE Act, 2015)

This language explicitly permits the private mining of asteroids and the sale of any resources derived thereof. It also expressly denies any claim of sovereignty, which would be illegal under the OST, and states that the law itself does not violate the international obligations of the United States. Taken on its own, this law would safely settle the legal question of asteroid mining for companies based in the United States.

Unfortunately, simply stating that a particular national law does not break international law is no guarantee that that is actually the case (Reed, 2018). Since, as was discussed in earlier sections, it is not clear to what degree the OST forbids asteroid mining, it is similarly not clear if the Space Act violates it. On the one hand there are law professors who hold the opinion that "A United States grant of exclusive property rights in extracted space resources (even if not territory itself) is incompatible with the commitments to free access and common benefit that are central to the OST" (Reed, 2018). On the other hand, organizations such as the International Institute of Space Law (IISL) put out a position paper after the law was passed stating that "in view of the absence of a clear prohibition of the taking of resources in the Outer Space Treaty one can conclude that the use of space resources is permitted. Viewed from this perspective, the new United States Act is a possible interpretation of the Outer Space Treaty" (IISL, 2015). Without clarity around the application of the OST, the legality of the SPACE Act is impossible to determine.

5.1.4 Luxembourg Law on the Exploration and Use of Space Resources of 2017

Luxembourg's legislation on the subject of asteroid mining goes even further than that of the United States. Their Law on the Exploration and Use of Space Resources contains the following relevant articles:

Article one:

> Space Resources are capable of being appropriated

Article four:

> The authorisation for a mission shall only be granted if the applicant is a public company limited by shares (société anonyme) or a corporate partnership limited by shares (société en commandite par actions) or a private limited liability company (société à responsabilité limitée) of Luxembourg law or a European Company (société européenne) having its registered office in Luxembourg.

Article seven:

(2) The operator to be authorised shall have a robust scheme of financial, technical and statutory procedures and arrangements through which the exploration and utilization mission, including the commercialisation of space resources are planned and implemented. The operator to be authorised shall furthermore have a robust internal governance scheme, which includes in particular a clear organisational structure with well defined, transparent and consistent lines of responsibility, effective processes to identify, manage, monitor and report the risks it is or might be exposed to, and adequate internal control mechanisms, including sound administrative and accounting procedures, as well as control and security arrangements for its technical systems and applications.

Article thirteen:

For each application for an authorisation, a fee shall be set by the ministers in order to cover the administrative expenses incurred in relation to the processing of the application. Such fee shall range from 5.000 to 500.000 euros depending on the complexity of the application and the amount of work involved.

Article fourteen:

(1) The authorisation shall be withdrawn if the conditions for the granting thereof are no longer met.

(2) The authorisation shall be withdrawn if the operator does not make use thereof within thirty-six months of it being granted, renounces to it or has ceased to carry out its business for the preceding six months.

(Law of 20 July 2017 on the Exploration and Use of Space Resources)

Article one is the simple approval of asteroid mining and other utilizations of space resources. Articles seven and fourteen are concrete standards which an asteroid mining company must meet to be permitted to mine an asteroid. This includes a requirement that the authorization be used, i.e. the asteroid be prospected or mined, within thirty-six months. Considering the time required to travel to an asteroid, the precise definition of "use" in this context might have to be more precisely defined to insure that companies making a good faith effort to mine a NEA do not lose their rights because of the delays inherent to space missions. However, the law at least represents a reasonable first effort at a set of guidelines to encourage asteroid mining without allowing companies to claim and camp on the rights for asteroids they have no intention of mining. Future legislation will be able to build on this foundation.

Additionally, article four and article thirteen demonstrate what might happen if there is an asteroid mining gold rush. Article four requires that a company looking to mine asteroids under Luxembourg's authorization be based in Luxembourg, and article thirteen levies a price on that company for the evaluation of the authorization to begin mining. Naturally, Luxembourg is too small to support a fully homegrown asteroid mining company. With this regulation, they hope to incentivize asteroid mining companies to base themselves in Luxembourg. By doing so, Luxembourg gains access to resources the nation might otherwise miss out on, both directly in the form of fees for authorization, and indirectly via jobs and additional economic impact. If other countries follow suit, it raises the possibility of a "race to the bottom" in which countries deregulate their space industry in the hopes of attracting asteroid mining companies (Smith, 2017). Much like there are countries that serve as tax havens, there might become countries with favorable regulation that become asteroid mining havens. Again, as with the U.S. SPACE Act, international law will be required to limit this, if extensive regulation is chosen as the optimal choice of action.

5.1.5 Findings

There are three takeaways from this discussion of the current legal status of asteroid mining.

1. There is ambiguity as to whether or not a private company mining asteroids is legal under the Outer Space Treaty.
2. The Moon Agreement does not permit the mining of asteroids without an international regulatory regime, and therefore provides a perfect context through which any sufficiently influential country could put pressure on the asteroid mining plans of others.
3. Existing national laws simply permit asteroid mining, they do not provide the detailed regulatory structure that will be necessary to enable asteroid mining

The combination of finding one and two create a highly precarious international situation for NEA mining. Ideally this ambiguity would be resolved prior to serious attempts to mine asteroids. Once an international regulatory regime is in place (or deemed officially unnecessary) additional national laws will need to expand on the Luxembourg law to build a comprehensive legal structure explaining what approvals and agencies are responsible for which aspects of the mining process. In sum, the potential for legal asteroid mining exists, but the current status of

international and national laws is likely to be insufficient to support the industry at best and an active hindrance at worst.

5.2 Private Efforts

Despite the legal morass described in the previous section, there are a number of companies bravely forging ahead with an attempt to mine asteroids. It is worth taking a moment to review the status of the field and the major players in it. While not exhaustive and obviously subject to change, the table below details many of the relevant asteroid mining companies along with their current goals and status.

Table 4: List of Asteroid Mining Companies with their stated goal, current status, and amount of funding if publicly available.

Name	Goal	Status	Total Funding ($ millions)
Asteroid Mining Corporation Ltd. UK	Prospecting -> Mine an Asteroid by 2030	Active	?
Aten Engineering	NEA Prospecting	Active	?
Deep Space Industries	Mining and Manufacturing in space	M&A - Series A	$3.5
Kleos Space	Secondary focus on in-situ manufacturing	IPO	$1.57
NEO Resource Atlas (NEORA)	Hi-fidelity mapping of NEAs	Active	?
OffWorld	Industrial robotics for space environments	Active	?
Planetary Resources	Map and Mine NEAs	M&A - Series A/Grant	$50.3
Planetoid Mines Company	Mining of moon, mars and asteroids	Seed	?
TransAstra	Develop optimal mining technology	Active	$.5 TTM Revenue

At first glance, the nine companies listed here give the impression of a thriving young industry. However, that impression is overly optimistic. To begin with, consider Planetary Resources,

which had the highest known funding amount at $50.3 million dollars. Not only would that level of funding be insufficient to even approach mining a NEA based on the discussion in the resource chapters, it also was insufficient to keep the company independent. A large number of employees were laid off in the summer of 2018, and the company was bought by ConsenSys – a blockchain company with no prior experience in outer space (Foust, 2018). Similarly, Deep Space Industries removed any mention of asteroid mining from the Deep Space Industries website in June of 2018 (Web Archive of Deep Space Industries from June 4, 2018), and it was officially acquired by Bradford Space in early 2019 (Foust, 2019). While Bradford Space is a space company, their focus is on propulsion and attitude control capabilities. They may someday return to asteroid mining but it is not a near term focus (Foust, 2019). Planetary Resources and Deep Space Industries were the most widely known and best established of the asteroid mining companies and they both moved away from asteroid mining within a year of one another.

Of the remaining companies, the two aiming to perform all parts of an asteroids mining process are Asteroid Mining Corporation Ltd. UK. and the Planetoid Mines Company. Both are little more than web pages at the moment (Asteroid Mining Corporation Ltd. UK., 2019; Planetoid Mines Company, 2019). The lack of public information does not prove that these companies are not good faith efforts to mine NEAs. However, an assessment of the companies based on publicly available information would have little to distinguish them from scams.

Adding to that less than stellar impression, Asteroid Mining Corporation Ltd. UK was started by a freshly graduated BA of International Relations and History. They estimate a value of almost $1 billion for the platinum contained in a 25-meter asteroid. In contrast, based on the values expressed in the platinum resource chapter above, this thesis finds a value on the order of $25 million for a 25-meter asteroid. Even generously assuming a typo on their part and that they are referring to the value of all platinum group metals, the value is on the order of $100 million, a full order of magnitude less than their stated estimate. Perhaps the Planetoid Mines Company is more capable, but even less public information exists about them, so no assessment of their competence can be made.

The remaining companies fit into two categories: prospecting and technology development. The prospecting companies, Aten Engineering and NEO Resource Atlas, both aim to become experts

at identifying NEAs with high value and then selling that information to other asteroid mining companies (Aten Engineering, 2019; NEO Resource Atlas, 2019). The technology development companies, Kleos Space, OffWorld, and TransAstra Corp, all aim to develop technology that will be crucial for some phase of the asteroid mining process. OffWorld and TransAstra are focused on robotic resource extraction, while Kleos Space is aimed at using space resources for in-space manufacturing (Offworld, 2019; TransAstra, 2019; Kleos Space, 2019). These more modest goals require correspondingly more modest funding, and it is perhaps for that reason that these companies have survived their more ambitious and more famous brethren.

5.2.1 Findings

The profitability of the final five companies depends on the existence of other companies also engaged in other aspects of the asteroid mining process. While that certainly is less glamorous than the tempting prospect of netting trillions of dollars by being a vertically integrated asteroid mining company, it is also more feasible. Planetary Resources and Deep Space Industries were both acquired long before they could raise a sufficient amount of money to seriously consider mining an asteroid. The companies which are still active in the industry and have a greater appearance of legitimacy are those aimed at claiming one small piece of an asteroid mining industry, rather than the entire industry. Given the scale required for profitable NEA mining discussed in the resource chapters, it is likely that the successful approach will be one in which numerous companies identify their own specialties and all contribute to the overall industry goal.

6 A Bridge to the Future

All the preceding chapters have covered the current state of resources, law, or private efforts. Question one has been answered as well as current knowledge permits, and the previous chapter has paved the way for the investigation of question two, namely, how the Valley of Death can be crossed.

To extend the Valley of Death metaphor, the suggestions that follow are the supports for a bridge across the Valley of Death. There are two columns which hold up the bridge, and an underlying foundation which makes those columns possible. All must be developed before NEA mining on a grand scale reaches feasibility. To map this clearly see the figure below.
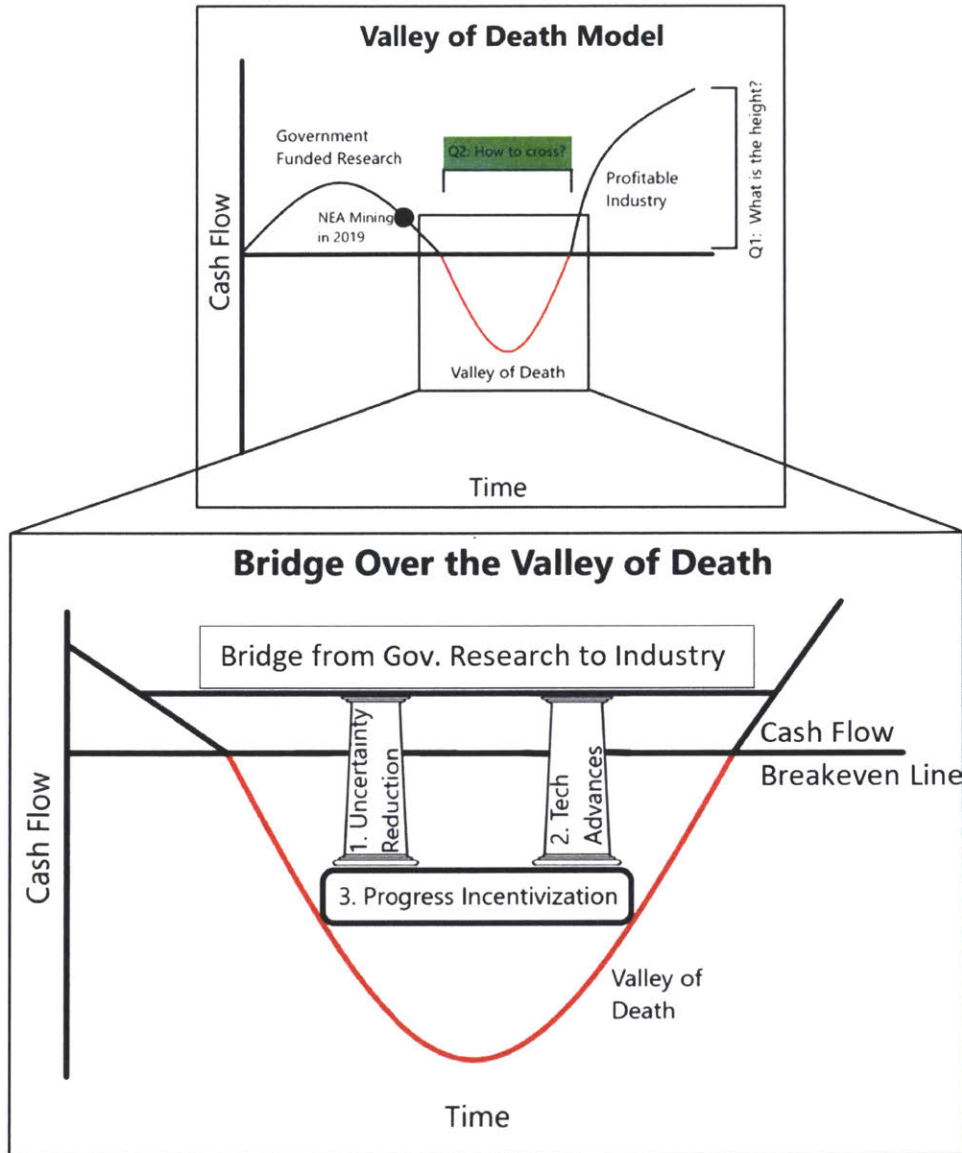
Figure 12: The bridge over the Valley of death is supported by uncertainty reduction and technological advances on a foundation of progress incentivization. The upper image is the map of the Valley of Death model from chapter two. The lower image zooms in on the Valley of Death and places the three supporting categories in their rightful places.

The supports and foundation are:

1. Uncertainty Reduction
2. Technological Advancement
3. Progress Incentivization

A key aspect of these supports is that they do not place an undue cost on those not in the NEA mining community. That is, given how remote the returns from NEA mining ventures currently are, it is unlikely that actions will be taken solely for the benefit of future NEA miners. Instead,

the actions discussed are those which either are low cost, or which offer a benefit to some other discipline in addition to the value offered to NEA mining. Each support will be discussed in terms of the actions in tangential disciplines that would increase the feasibility of a NEA mining industry.

Note that the points discussed in this section fall into two broad categories: actions that can be taken to increase the feasibility of NEA mining, and sign posts that, having occurred, indicate that NEA mining has taken another step toward feasibility. This chapter will first explore the two pillars – uncertainty reduction and technological advancement – that support the bridge over the Valley of Death. Next it will explain how the foundation – progress incentivization – enables those pillars to function. Finally, the chapter concludes with a summarization of the methods to cross the Valley of Death.

6.1   Uncertainty Reduction

6.1.1   Scientific Uncertainty

The resource chapters established that there is a significant quantity of valuable resources contained in the near-Earth asteroid population. However, if one were asked where specifically to start mining those resources, it would be impossible to answer. Specifically, the sources of scientific uncertainty are as follows:

1. Unknown NEAs
2. Earth-based detection of resources
3. Precise prospecting information

6.1.1.1   Unknown NEAs

As was touched on briefly in the resource section, knowledge of the NEA population is still incomplete, and hundreds of NEAs are discovered every year (Minor Planet Center, 2019). From the water resource chapter recall the finding that, regardless of initial cost, there are still undiscovered NEAs that can profitably be mined. Additionally, discovering a significant percentage of the projected population expands the options one has when deciding the optimal water mining strategy. Since the minimum mining size only considered resource amount and not ease of access, those NEAs may well represent very tempting targets for early water mining efforts. For platinum, the need to discover additional NEAs is less clear since a single large

PGM-rich NEA would possess sufficient resources to justify mining if the technological challenges could be solved.

Reinforcing the perspective on large NEAs for platinum and serving as a caveat to it for water, is the fact that the majority of NEAs above around 1.5 kilometers are projected to have been found (Stokes et al., 2017). For this reason, while the unknown NEAs might serve as proving grounds for demonstrations of mining technology, or be used for a quantity over quality approach to water resource extraction, they are unlikely to be the subject of the large scale mining efforts when larger NEAs with more resources have already been discovered.

In the short term, the efforts of the asteroid research community are likely to reduce the uncertainty around undiscovered NEAs. The goal of the George E. Brown Jr. near-Earth Object Survey Act of 2005 dovetails nicely with the needs of the asteroid mining community. The largest danger here is that, after 90% of NEAs larger than 140 meters have been discovered, support for continuing the search wanes and promising NEAs small and close enough to serve as technological stepping stones go undiscovered. On the whole, while the pace of discovery might slow, the prospect of it ending entirely seems unlikely. While additional focus on finding NEAs would be ideal, action is already being taken to mitigate this particular source of uncertainty. Any progress that is made on this front can only be to the good of a future NEA mining industry.

6.1.1.2   Earth-based detection of resources

Beyond simply locating NEAs, further work must be done to identify which NEAs possess useful resources. Without this knowledge, it is impossible to even begin to compare potential targets for mining operations or technology demonstrations. Both water and platinum represent unique challenges when it comes to detecting their presence on NEAs from Earth.

For water the challenge is straightforward. The current characterization taxonomy uses data from the 0.45 to 2.45 μm spectral region, which includes the 0.7 μm that indicates the presence of hydrated minerals (DeMeo et al., 2009; Rivkin et al., 2003). Once a NEA has been characterized it is relatively straightforward to place it in one of three categories: definitely possesses hydrated minerals, may possess hydrated minerals, or does not possess hydrated minerals. That is enough to begin considering other factors such as which NEAs are easy to access or otherwise promising enough to pursue more seriously. The problem is that only 5% of

all known NEAs have been characterized, and the rate of characterization is only 100/year, roughly 1% – 5% of the yearly discoveries (Elvis, 2014; Binzel et al., 2019). Without a more comprehensive knowledge of the NEA population it will be hard to commit to a target given the not insignificant chance that a better NEA could be discovered at any moment.

One complicating factor to the characterization question is that the NEA characterization process is not random. Characterization efforts such as the SMASS program at MIT consider ease of access when choosing characterization targets (Binzel et al., 2004). On the one hand, this may make it more likely that the most promising targets have been characterized, on the other hand, since NEAs are asymmetric in their resource quantities, it could mean that a NEA which is twice as hard to access and contains ten times the resources remains uncharacterized despite potentially being a preferable target.

With regards to platinum, the situation is more complicated. There is no easy way to detect platinum group metals on a NEA from Earth. In the resource section a method relying on analysis of the albedo of a NEA was discussed (Harris et al., 2014). However, that method relies on precise knowledge of albedo, which is relatively uncommon, and it has only been applied to dozens of NEAs at best. Additionally, that method was only able to detect metallic NEAs. The wide variety in platinum content among metallic meteorites demonstrates that not all metallic NEAs possess significant quantities of platinum group metals (e.g. Hoashi et al., 1993). Simply put, there is very little firm information to guide target selection toward a platinum-rich NEA.

To move forward in this area additional characterization efforts must be made. One way to do so which would fit within the current paradigm would be to highlight the importance of compositional knowledge in impact prevention. Knowing the composition of NEAs is crucial when selecting an impact prevention method, i.e. some methods would be ineffective against a rubble-pile but effective against a cohesive block, or vice versa (Dachwald et al., 2007). For this reason, one could argue that, after the completion of the George E. Brown Jr. NEA Survey Act goal, it would be prudent for a follow-on act requiring NASA to characterize a certain percentage of NEAs above a certain size. This would both serve the obvious goal of mitigating impact dangers, while also advancing scientific understanding of NEAs and paving the way for future

NEA mining efforts. Without a more comprehensive database of NEA compositions, target selection is like picking a spot to drill an oil well by eyeballing the soil.

6.1.1.3 Precise prospecting information

The holy grail of scientific uncertainty reduction would be actionable knowledge of the composition of a NEA. Terrestrial mines undergo years of mapping and precise surveying to locate and characterization the minerals present. This is not always sufficient. As was mentioned in the platinum resource chapter, the Duluth Complex in Minnesota has been extensively surveyed, and both the general geography and the precise location of nickel, copper, and platinum group metal deposits is known (Piatak et al., 2015). Despite the potential $1 trillion value, mining operations have yet to commence, partially due to environmental concerns (Myers, 2010). However, that precision of surveying information is certainly a necessary precondition to mining.

Ideally, an asteroid mining company would possess equivalently detailed information before launching a mining mission. To be profitable, asteroid mining requires operations at a very large and expensive scale. Without precise prospecting information, there is significant risk that the huge investment required will be lost. This particular information is challenging to acquire, but also presents unique opportunities.

Historically, all of the precise information about NEA composition has been gathered by government space agencies. Globally, there have been twelve missions which performed some analysis of NEAs. Future missions of this type will almost certainly occur, and three are currently planned (Williams et al., 2019). However, fifteen missions in fifty years is an insufficient pace to provide a basis of information for an asteroid mining industry. Government space agencies have proven that information on asteroids can be collected, now may be the time for private organizations to try their hand at collecting the information the NEA mining community so desperately needs.

As a demonstration that this task is headed to the private sector, recall that two of the private space companies discussed in the previous chapter – Aten Engineering and NEO Resource Atlas – were aimed straight at this problem. Their business plan is to acquire prospecting information and then sell it to the companies that would actually perform the mining. This is a demonstration

of the specialization of different companies that is likely to be crucial if asteroid mining is to succeed. Fundamentally, the task of prospecting a significant number of previously identified-as-promising NEAs requires a different skillset than setting up a full scale mining operation on a single NEA. There are similarities, most notably launch and travel requirements, but for truly industrial scale space companies to exist, launch and travel must become mundane. Government support for NEA prospecting companies might speed things along, but an industry that can only exist by the grace of government support is not truly an independent industry in the first place.

Transitioning prospecting to the private sector follows the path of traditional technology transfer. First the government develops the original bespoke version of the technology at great cost. Then, once it has been demonstrated, the private sector standardizes performance and reduces cost. The government has demonstrated via the asteroid missions that have already occurred that it is possible to gather concrete information about asteroid composition. Now it is the role of the private sector to determine how to gather this information cheaply and easily enough that a profit can be made on the selling of that information. Of course, transitioning prospecting to the private sector faces a Valley of Death of its own. There are methods to incentivize the development of this technology which would help it traverse the Valley of Death and will be discussed in the third section of this chapter. If those incentives are properly constructed, then these burgeoning private companies may be able to profitably prospect NEAs, reducing uncertainty in the process and freeing other companies to face the challenges of NEA mining armed with all relevant scientific information.

6.1.2 Legal uncertainty

The legal uncertainty was explored in greater detail in the previous chapter, but the sheer damage mismanagement of this sector could do to a hypothetical NEA mining industry bears repeating. As it stands, the act of NEA mining is of questionable legality under the Outer Space Treaty (OST) which is considered customary international law and binding on all countries (Lyall, 2009). If, despite the OST, a country does attempt to mine NEAs and an influential country takes exception to that, then the Moon Agreement – which clearly forbids asteroid mining –could be used to pressure the adventurous country into compliance.

The international legal situation must be resolved. Ideally, it would be resolved soon, before any one country pulls ahead in this space and engenders pushback from other countries. Indeed, the

"veil of ignorance" is a philosophical/political theory which suggests that the fairest regulations come when no party is aware of their stake in the matter (Rawls, 1971). NEA mining is currently behind that veil of ignorance. While certain countries have a small head start, any major power stands a reasonable chance of being the first to reap the rewards of mining asteroids, if they choose to pursue it. The legal conflict should be resolved before that veil tears entirely and the countries locked out of benefitting from asteroid mining use international law to prevent the success of the countries that pursue it.

6.2   Technological Advancement

To begin with, there are obvious advances in technology that would be beneficial to nearly any space venture. This category includes advances in propulsion, communication, manufacturing, and anything else that makes it cheaper and easier to build a spacecraft and move it from point A to point B. Since these technologies are so widely useful and of interest to anyone operating in space, R&D in these sectors can be taken as a given. Instead, this section of the analysis will focus on the advancement of technologies specific to NEA mining. Specifically, this section focuses on two separate areas: mining technology, and resource utilization technology.

6.2.1   Mining Technology

All the prospecting and uncertainty reduction in the world is useless without technology capable of extracting resources from an asteroid at scale. Water and platinum group metals (PGMs) are at different stages of technological development and must be considered separately.

6.2.1.1   Mining Water

Arguably, the first step to developing technology that can extract resources is developing asteroid regolith simulants to allow for the development and testing of asteroid mining technology. Simulants for water-rich asteroid minerals are fairly well established, and researchers have extended the NASA Figure of Merit grading system from Lunar simulants to asteroid simulants (Metzger, 2019). The knowledge gained from the Osiris-Rex and Hayabusa 2 sample return missions has already begun to enhance knowledge of asteroid compositions vis-à-vis the presence of hydrated minerals (OSIRIS-Rex Team et al., 2019), and future studies can only enhance that knowledge and contribute to an ever more accurate simulant.

The extraction of water from hydrated minerals is not an overly complicated process. A number of different organizations have made prototype devices which are capable of extracting water from hydrated minerals. At the moment these devices are small, on the order of grams of water produced with an hour of function (Zacny, 2017). This may produce a final device sufficient for NASA's short-term ISRU goals around enabling a broader range of mission architectures (Mahoney, 2017), but it is not enough to support an industry. In theory, there is no reason these technologies could not be scaled to larger sizes, the research and development simply has not yet reached that stage. Overall the development of water mining technology is proceeding at a reasonable pace, and considering the wide-ranging interest in ISRU, there is every reason to expect it to continue to advance without the necessity of outside intervention.

6.2.1.2 Mining Platinum

Unfortunately, the technology to mine platinum group elements is in a much less promising position. No efforts to make a simulant of a PGM-rich asteroid could be found in the literature, possibly because there has never been a sample return mission to a metallic asteroid. Even on Earth different platinum mines require different procedures to operate due to the different compositions of soil containing platinum (Bernadis et al., 2005). Without precise knowledge of the composition of PGM-rich soil a simulant cannot be developed, rendering the testing of mining techniques and equipment challenging.

The technology used to mine platinum on Earth has also never been used in space. Recall from the platinum resource chapter that the refining process is long, complicated, and uses a significant amount of specialized equipment (Zientek et al., 2017). As that chapter demonstrated, at least some of that process must be performed in space to make asteroid platinum mining profitable. Therefore, any progress made toward altering mining equipment for use in space would be useful for asteroid mining.

However, making space-ready mining equipment has very few alternate uses or motivations. Given how far in the future any return on mining efforts is likely to be, the motivation to conduct this R&D is low. That said, there are other aspects of the mining process which can benefit both terrestrial mines and asteroid mining. Specifically, any technology which automates the mining process or makes it less energy intensive would be beneficial to an asteroid mining project.

As was mentioned previously, even a relatively small platinum mine requires hundreds of employees and a significant amount of energy to function, both of which are far beyond anything that has ever been available in space. Efforts to automate mines would decrease the number of people needed to work in space, and decreases in energy requirements lower the amount of equipment or fuel that need to be launched to power an in-space refinery.

Terrestrial platinum mines have also faced automation challenges. Research has found that under certain circumstances traditional mining methods outperformed automated mining methods (Musingwini et al., 2008). Efforts were made to implement automation with little initial success. (Ferreira-Marques et al., 2013). Only in the last few years, pushed partially by findings that conventional platinum mining – in South Africa in this case – would not remain economical in perpetuity, has progress been made (Stoddard, 2018). This conflux of needs may present an opportunity to produce technology that benefits both terrestrial and asteroid mining, possibly funded in part by those terrestrial mines for whom profits are not many years and millions of kilometers away. It is impossible to say where rising in-space capabilities might meet falling mining energy and personnel requirements. However, as platinum grows scarcer on Earth and the space industry expands, the eventual overlap between the infrastructure and personnel necessary to mine a NEA and what can be economically launched into space will be a key sign that platinum asteroid mining has reached feasibility.

6.2.2 Resource Utilization technology

Considering the quantity of water present on Earth, the only use-case for water mined from NEAs is as an in-space resource. For this reason, the status of space technologies utilizing water is a key question when considering the overall market feasibility of mining water from asteroids. There are three reasonable uses of water in space: human consumption, radiation shielding, and as a fuel. The first two uses do not require any technological development to fulfil those purposes. The status of technology for using water as a fuel then becomes the crux of the issue.

There are two types of propulsion which use water as a fuel. The more common method is to electrolyze the water and then combust the resulting hydrogen and oxygen to produce thrust. An alternative process is to simply heat water and use the resulting steam for propulsion (Rabade et al., 2016). Per the following table, both methods have been demonstrated to produce a specific

impulse comparable to many other common propulsion systems, albeit less than electric propulsion.

Table 5: Methods of water-based propulsion produce similar specific impulses to other commonly used propulsion methods. It is less than powerful than electric propulsion, but it also consumes much less power (Wertz et al., 2011).

Propulsion System	Specific Impulse (s)
Water – Electrolysis	350 – 420
Water – Steam	190 – 320
Cold Gas	45 – 73
Solid	290 – 304
Liquid – Monopropellant	200 – 235
Liquid – Bipropellant	274 – 467
Electric	500 – 3000

To summarize, while water based propulsion is not certainly not commonplace, it does perform well on paper. Given this fact, it is likely that the competitiveness of water as a fuel would not be a limiting factor in creating a market for water in near-Earth space. That is not to say a market will exist for water as a fuel – that would require other agents desiring to reach destinations in near-Earth space – but it does mean that if those people exist, and if water were mined, the technology to use water as a fuel would likely keep pace with demand.

In contrast with water, platinum is not meant to be used in space, and the existence of the platinum industry on Earth demonstrates that the technology for utilizing this resource already exists. Admittedly, the ideal case for asteroid mining might well be the use of platinum and other metals for large scale production in space, where one would gain from both the value of the materials and from avoiding the cost of launching significant weight to orbit. However, in-space manufacturing is in its infancy, and NASA does not plan to use metals from celestial bodies for in-space manufacturing until 2025 at the earliest (Prater et al., 2017). In essence, the technology to use platinum in-space is not anywhere near complete, but that should not matter for the first use case for platinum. If technology advances rapidly to the point where in-space platinum can be used, that would be a strong indicator of asteroid mining's feasibility, but it is an unlikely to be the initial direction for the technology.

6.3   Progress Incentivization

It is important to consider what should and should not be incentivized with regards to NEA mining. For instance, given the current state of the field it would be premature to attempt to

incentivize NEA mining in its entirety. Too many obstacles remain for such incentives to be anything more than a waste of the investment. However, as the uncertainty reduction and technological advancement sections above detail, there are small concrete steps that can be taken to improve the feasibility of NEA mining. This section discusses methods of incentivizing those steps, to enable a NEA mining industry to one day be developed.

Two categories of incentives are discussed here. First is the legal incentives that are perpetual once enacted, and second are policies which serve their purpose each time they are implemented or renewed.

6.3.1 Legal Incentives

In the uncertainty reduction section, the importance of clarifying the legal standing of asteroid mining was discussed. From an uncertainty reduction standpoint any legal clarification would be beneficial and almost any action would be preferable to inaction. However, not all legal regimes are equally beneficial in developing the NEA mining industry. Naturally, the debate over the optimal set of legal statues to support an industry is long-running, and one that will not be settled by this thesis. What can be done here is to place potential options, specifically around property rights, in the context of asteroid mining to recommend potentially beneficial approaches.

The crux of the issue is developing a legal structure that ensures the benefits from any work done in this field accrue to the company performing the work, specifically in the area of uncertainty reduction. Until the modern era the field was primarily scientific, so both discoveries and characterizations were made public (Planetary Spectroscopy Group, 2018; Minor Planet Center, 2019; Chamberlin et al., 2019). The problem with relying on public research for mining information is that NEA characterization is a relatively slow process, and scientific researchers should not and would not spend their time producing data solely for the good of private industry. While the goals of public researchers and private mining companies are similar at the moment, they do not perfectly align and are likely to further diverge in the future (Krolikowski et al., 2019). Hence the appearance of companies such as Aten Engineering, which are trying to make a profit off of performing the types of characterizations necessary for NEA miners (Aten Engineering, 2019).

This raises the question of what form of legal protection would enable a prospecting/characterization company to reap the rewards of their work. Two methods are worth considering, one simple and one complex. The simple method would be to assign the property rights to a NEA to any company that determines the composition of the NEA to actionable levels of precision. That is, if a NEA mining company could launch a mission on the strength of the information, then the prospecting company should have ownership over the NEA and license it to the mining company.

There are a number of advantages to strict property rights in this style. Traditionally, strict property rights are thought to create an incentive for economic growth (Gould et al., 1996). In this case, property rights would create an incentive for prospecting, which is a necessary precondition of mining that might not otherwise be performed because of the inability to capture the profits associated with the work. The existence of this incentive allows for specialization. Instead of every company performing the full prospecting and mining process, they are incentivized to focus and excel in one area. It also creates an asset in the NEA mining industry long before any concrete resources are extracted. This asset, and the added certainty of the prospecting itself, might well ease the way to financing a NEA mining company, both because there will be a clearer picture of the resources present and because the rights to the NEA could serve as collateral for loans to fund the establishment of a mine.

There are a number of downsides to strict private property as well. It might well exacerbate the already significant first mover advantage in NEA mining. The first NEA miners are likely to develop a position of technological leadership. That is, they will possess the technology and experience to successfully mine a NEA where other companies might lag behind. Additionally, the strong preference for established technologies and organizations in space mission architectures will privilege the first company to successfully produce such goods. Strong property rights would allow for the preemption of scarce assets, i.e. the claiming of the few large and valuable NEAs. Considered together, this means that NEA mining would display a strong presence for all three factors which can lead to a first-mover advantage (Lieberman et al., 1988).

To limit the impact of strong property rights while still incentivizing prospecting, the precise requirements to claim a NEA would have to be carefully considered. Failure to do so would lead

to rapid NEA claiming without the production of any useful information. In the worst case, it might produce a class of companies analogous to patent trolls – companies whose entire business strategy is to use patents to sue companies, rather than to try and profitably utilize them (Reitzig et al., 2007). Additionally, similar to the practice of offensively patenting an invention to prevent a competitor from using it (Blind et al., 2009), a company might claim a NEA it has no intention of either mining or licensing to others to mine to prevent any progress in an unwanted area. These downsides could be limited by restrictions built into the law, such as a limit on the number of NEAs one company can own or a requirement – similar to patent licensing requirements (Tandon, 1982) – that prospecting companies mine or license a NEA within a certain period of time.

Beyond simple property rights, a more complicated legal incentive could be constructed from the Moon Agreement. That treaty proposed the creation of an international authority similar to the International Seabed Authority (ISA). The ISA has a number of features which, if implemented, would incentivize uncertainty reduction. To begin with, in the Law of the Sea there is a requirement that when a contractor applies to explore a given area they must also provide survey information of another area of equal value to the ISA (ISA, 2001). A similar strategy could be employed, essentially a mine-an-asteroid share-an-asteroid plan. This would limit ownership and provide for countries beyond the first to undertake asteroid mining. To make it fair, the ISA also had "Pioneer Investors", countries which had already spent significant effort mapping seabed resources and were given special consideration in the ISA's approach to deep sea resources (ISA, 2001). A similar provision could be designed to make sure initial prospectors are rewarded for any work they do before such an agency is set up.

The precise nature of legal incentives is beyond the scope of this paper. The two methods laid out, property rights and an international agency, are simply a first pass at the mechanisms by which those incentives might be created. Property rights are straight forward and, assuming international law is clarified, could work on a national scale. An international agency would be more challenging to set up, but would also provide for more countries at different stages of space development and could thus promote buy in from the international community. Regardless of which specific option is chosen, legal strategies should be employed to make sure that the prospecting asteroids generates value for those who undertake the task.

6.3.2 Prize Competitions

While the legal incentives proposed were aimed primarily at incentivizing uncertainty reduction, prize competitions would be aimed at technological advancement. In general, prize competitions are a fast-growing policy tool for technological development, one which has already produced a number of noteworthy successes. The most dramatic success of prize competitions in the space industry was the Ansari XPRIZE in 2004. The winner of that competition built a spacecraft which was bought by Richard Branson and became the technological basis for Virgin Galactic (XPRIZE, 2019). DARPA also held a noteworthy prize in autonomous vehicle design in 2004/2005 which contributed to a dramatic acceleration of the technology (DARPA, 2019). In the present, tools such as Challenge.gov (U.S. General Services Administration, 2019) serve as a central location for prize competitions for agencies across the U.S. government.

The aspect of asteroid mining that makes it particularly ripe for prize competitions is that the overall goal of mining can be deconstructed into smaller tasks which a private team could legitimately tackle. Additionally, many of the most useful challenges would not produce an immediately saleable product, so the prospect of a prize purse would serve as an incentive when traditional market forces might not. Below are the outlines of two areas of asteroid mining that are ripe for a prize competition. These prize designs follow the XPRIZE prize design structure, particularly the idea of a "winning team will" statement (Diamandis, 2018), which precisely states what is required for a team to win the prize.

6.3.2.1   NEA Resource Extraction

The first potential prize design area is centered around NEA resource extraction. Challenges remain in the process of developing the technology to extract a resource from a NEA for both water and platinum. With regards to water, progress has been made in both developing extraction prototypes and in developing simulants to test it on. However, with the recent arrival of OSIRIS-REx at the asteroid Bennu, the potential will soon exist for a simulant that perfectly matches the composition of samples returned from an asteroid possessing hydrated minerals. For this reason, the optimal "winning team will" statement for water mining might be:

> The winning team will develop a device capable of extracting water with 95% efficiency from an asteroid simulant compositionally identical to samples returned from asteroid Bennu.

By phrasing the statement in such a way, with both simulant and mining requirements, teams might have to cooperate and develop the diverse skillsets necessary for both simulant development and resource extraction. Additionally, current water extraction from a simulant has only reached 67% efficiency (Zacny, 2017), so reaching 95% is an ambitious but achievable goal. Due to the NASA interest in in-situ resource utilization, participating in or funding a prize of this nature would dovetail nicely with their stated goals (Mahoney, 2017).

NEA platinum mining is not in as developed a state. The technology to mine platinum from a platinum-rich asteroid does not currently exist, nor is there a reasonable simulant for testing purposes. Additionally, developing a simulant is more challenging because platinum itself is more expensive. It would do little good to develop a simulant for testing purposes if the simulant itself were extremely expensive. With this in mind, the "winning team will" statement of an asteroid platinum mining competition might be:

> The winning team will demonstrate the capability to mine platinum group metals at 80% efficiency from a fair approximation of a metal-rich asteroid.

This formulation leaves open options such as using returned samples form a future mission to a metal-rich asteroid, developing a metal-rich asteroid simulant, using an iron meteorite, or any other alternative that the team can develop. In the Stillwater Complex, the refining efficiency is 80% – 85%, hence the choice of 80% for the prize efficiency (Abbott et al., 2017). In this way, the possibility of creative solutions is preserved without losing sight of the ultimate goal. Finding a sponsor for a platinum mining challenge might be difficult. There is no direct overlap with other industries or scientific goals. However, if such a prize were to be run, it might push the industry closer to firmer financial footing.

6.3.2.1   Automated Traditional Mining Technology
The second potential prize idea is centered on automating traditional mining technology. It might build on the simulants or resource extraction technology developed in the previous prize. From the resource chapter, the extraction of platinum resources from a mine requires hundreds of people (Abbott et al., 2017), so this prize should be aimed at facilitating platinum asteroid mining with less human intervention than is required terrestrially. Automation is currently a popular topic across broad sections of society, meaning that there is a significant workforce with automation-related skillsets looking for new applications for the technology. Automation has

proven successful in a wide variety of mine types (e.g. Rubin et al., 2015), though platinum mines have lagged behind and are only now beginning to catch up (Stoddard, 2018). Advances in this area would naturally benefit mine owners because they would have to employ fewer workers, so traditional mining companies might be interested in funding the prize.

Note that the successful completion of this prize would not make asteroid-mined metals less attractive compared to terrestrial ones. This is because the price of labor in space is far higher than on Earth. As a result, increased mine automation would benefit terrestrial mines in the short term, while making asteroid mines more feasible in the long term. Following the XPRIZE prize design architecture, and carrying over the 80% efficiency from the previous platinum prize design, the "winning team will" statement might be:

> The winning team will develop a device capable of producing 1 kg of platinum from both platinum rich soil taken from a terrestrial mine and from a platinum-rich asteroid simulant with 80% efficiency and without any human involvement.

If this prize design were successfully completed, terrestrial mines would profit, and a potential asteroid company would have a strong technology base to scale up from. Depending on the circumstances, this prize, and the others, could be altered to require that the device in question pass spaceflight readiness checks such as thermal and vacuum testing.

6.4 Findings

No valley can be crossed without a bridge, and no bridge can be built without supports and a foundation. The Valley of Death is no different. In this chapter the supports and foundation of a bridge across the Valley of Death for asteroid mining were laid. The supports were uncertainty reduction and technological advancement, and they rest on a foundation of progress incentivization. In each case actions that could help build the bridge were discussed. Certain advances that would be beneficial, but probably do not make sense to specifically aim for were also considered. By tracking which supportive aspects have been achieved, it is possible to estimate the progress that has been made towards developing asteroid mining into a fully realized private industry.

7 Further Research and Conclusions

This thesis has concerned itself primarily with the simplest possible asteroid mining concept: i.e. where a single asteroid with resources is located, traveled to, mined, and the resources extracted are then sold in orbit or on Earth. Alternatives to this default structure, along with explanations of how they might affect the feasibility of the overall enterprise, are briefly raised below. Further research could delve more deeply into whether any of these edge cases provide an opportunity where typical asteroid mining does not.

7.1 Opportunities for Future Research

7.1.1 Mars Crossing Asteroids

This analysis of asteroid mining has been predicated on the idea that resources extracted from NEAs will be used in Earth orbit or sold on Earth. However, there is a class of aptly named asteroids, Mars-crossers, which pass through both Earth's and Mars' orbits. They raise the interesting possibility of extracting a resource, most likely water, from an asteroid for use as a fuel on a Mars mission. Having additional fuel available at Mars could open up a wide variety of different mission options. Due to the absence of traditional fuels on Mars, water produced in this fashion could be worth much more than the maximum of $1500/kg for water in LEO. Higher prices for the water would lead to higher profits or a wider range of asteroids sizes which could be profitably mined.

Naturally, there are a number of different avenues of research that would have to be conducted before any such mission could be planned. To begin with, only around 350 Mars crossing asteroids have been characterized (Binzel et al., 2019). That number is not enough to guarantee that a promising target exists in the characterized population. More research would be necessary to expand the list of known Mars crossing asteroids and to characterize the known asteroids. Additionally, the mining technology for the mission would have to be well demonstrated and in place prior to a Mars mission. No Mars mission is going to rely on technology without a long history of successful operation. Despite the remaining difficulties, the higher price fuel would fetch in Mars orbit might make this method of asteroid mining feasible even if others are not.

7.1.2 Mining Multiple NEAs per mission

Another mission architecture that was raised briefly in the water resource chapter, but was not considered in depth, was the idea of mining multiple NEAs with a single spacecraft. As that chapter and the platinum resource chapter showed, NEA mining is much more likely to be profitable when performed at scale on the largest NEAs. However, for water specifically, sufficient discoveries of unknown NEAs could make a quantity-over-quality approach profitable.

The value of this alternate mission architecture would depend heavily on identifying promising trajectories for moving between NEAs while expending relatively little fuel. After all, every bit of fuel expended is fuel that cannot be sold. Since the number of NEAs the can profitably be mined increases exponentially as the cost to mine decreases, the likelihood of low delta-v trajectories between NEAs similarly increases dramatically as the cost to mine decreases. This strategy also might be more promising if there is a significant market for water-based fuel in multiple near-Earth orbits, creating a market for bringing the fuel to the customer. Essentially, under this model the spacecraft would be like a refueling truck, where under the traditional model the mine would be more like a gas station. The presence of a wide variety of customers would be a crucial indicator of the success of this strategy. Future research is needed to locate and characterize the smaller water-rich NEAs, and to calculate fuel-conserving trajectories.

7.1.3 Cross-Resource Mining

As was mentioned briefly in the platinum-mining chapter, though metallic NEAs have the highest concentrations of platinum group metals (PGMs), meteorites corresponding to other NEA types also possess concentrations of PGMs equal to or higher than terrestrial mines. This raises the interesting possibility of profitably mining a single NEA for both water and PGMs. The typical platinum mining and refining process requires significant quantities of water, and transporting the refined platinum also requires fuel. There is a clear opportunity for a platinum mine to benefit from supplementary water extraction capabilities. This could make PGMs much cheaper to mine and potentially help them cross the line into profitability.

Limitations exist of course. Hydrated minerals only occur in a small fraction of NEAs, and knowledge of PGM prevalence in NEAs is based primarily on meteorite information. Just finding and correctly identifying a NEA that is rich in both metals and hydrated minerals would be a challenging task, possibly one that could only be accomplished via prospecting mission.

Additionally, the technology to mine both resources on a single NEA and have the output of one mine feed into the other would have to be developed, requiring additional research and development. These two complications would increase the initial price, meaning that the NEA would likely have to be fairly large to make a reasonable return, further lowering the chance of finding a suitable NEA in the first place. For this reason, it may be best if technological research along this avenue waits to proceed until – and unless – a metal and water rich NEA is identified.

7.2   Conclusions

7.2.1   Question 1: Can the resources of the NEA population support a positive industry cash flow?

Water: Yes. The results section in chapter three demonstrated that there is enough water in the NEA population to support profitable mining operations. The number of known mineable NEAs ranges from hundreds at an initial cost of $200 million to over fifty for a cost of $150 billion. Additional NEA discoveries will only improve this calculation and open up new mission options. Technology is still in the prototype phase, but early results suggest that it can be developed to the necessary point. The largest remaining question is whether or not sufficient demand will develop to justify the industry.

Platinum Group Metals: Maybe. The first section of chapter four demonstrated that values above $1 trillion dollars for PGMs in NEAs are reasonable. However, the section considering the challenges of platinum mining showed that every stage of the mining process – prospecting, mining, refining, and transporting to market – presents clear technological obstacles that have no apparent solution and for which no R&D is occurring. Unless dramatic technological advancements occur, platinum group metals cannot be profitably mined from NEAs for sale on Earth.

7.2.1   Question 2: How can the Valley of Death be crossed?

The Valley of Death can be crossed through **uncertainty reduction** and **technological advancement** with progress incentivization as the underlying foundation.

Uncertainty Reduction: Section one of chapter five depicts the international legal situation as a dagger pointed at the heart of NEA mining. Unless a clear international regime, possible one of

the two recommended in the section on legal incentives in chapter six, is implemented, the legal status of the field is too uncertain for investors to want to engage.

From section one of chapter six, methods for reducing uncertainty with regards to the specific content of resources on a NEA are also required for NEA mining to proceed. These methods include both the continuation of detection efforts – ideally up to and beyond the goal of the George E. Brown Jr. NEO Survey Act – and the application of increased attention to the task of NEA characterization. Prospecting missions, though expensive, would go a long way toward reducing uncertainty to a tolerable point so that NEA mining operations could proceed with confidence.

Technological Advancement: The section of chapter five on platinum mining challenges, particularly the subsection on mining and prospecting, revealed that the technology to profitably mine platinum in space does not exist and is not in development. Setting up incentives such as the prize designs from section three of chapter six would encourage progress in this area. Some aspects of the prize competitions may attract interest from terrestrial mining companies, but large swaths of the necessary technology have no other obvious use and are unlikely to be developed.

As discussed in section two of chapter six, the technologies needed to mine water and to use it as a fuel in space are in various prototype stages and give every indication of developing at a reasonable rate. An additional push via the prize design in section three of chapter six would help impel the industry out of the Valley of Death

7.3   Final Statement

Asteroid mining cannot proceed in a (metaphorical) vacuum. The primary selling point the industry offers is access to plentiful resources without the cost associated with launching out of the gravity well. Early efforts *might* manage to make a profitable company out of selling water in LEO or returning platinum to earth, but ultimately the true value of the industry will be found in supporting a broader space ecosystem. Asteroid mining must be placed in the context of space industry and manufacturing. If a space industry develops, then resources will be mined from NEAs. If humanity does not develop outer space to any great extent, then asteroid mining will not be the industry to drag it there.

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