Feasibility Study for the Quantitative Assessment of Mineral Resources in Asteroids

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Abstract

This study was undertaken to determine if the U.S. Geological Survey's process for conducting mineral resource assessments on Earth can be applied to asteroids. Successful completion of the assessment, using water and iron resources to test the workflow, has resulted in identification of the minimal adjustments required to conduct full resource assessments beyond Earth. We also identify the types of future studies that would greatly reduce uncertainties in an actual future assessment. Whereas this is a feasibility study and does not include a complete and robust analysis of uncertainty, it is clear that the water and metal resources in near-Earth asteroids are sufficient to support humanity should it become a fully space-faring species.

Introduction

Why Asteroid Mineral Resources Matter

The long-term goal of the United States space program is establishing a human presence on Mars. This goal has been remarkably stable for decades, unfazed by changes in administration, geopolitical situations, economic conditions, and trends in public opinion. One can debate the merit of this goal, but it is a remarkably consistent aspect of our Nation's space policy.

Several major challenges must be overcome before there are human bootprints on Mars. The most problematic obstacle may be the price tag—a large fraction of which is in hauling material out of Earth's gravity well. Obtaining key resources (for example, water and metals) in the space between Earth and Mars could dramatically reduce the costs of a trip to Mars. The obvious way to obtain such resources is to mine near-Earth objects (NEOs). Such mining may be essential to sustaining a human presence beyond Earth's orbit.

Before a prudent mission architecture can rely on resources obtained in space, an unbiased, quantitative, and reliable assessment of those resources is needed. Creating such an assessment is the Congressionally mandated responsibility of the U.S. Geological Survey (USGS). The "Organic Act" of 1879 established the USGS with a few specific obligations, including "the classification of public lands and examination of the geologic structure, mineral resources, and products…" In 1962, Congress extended those examinations to "beyond the borders of the United States." In 2015, USGS management

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recognized that this applies to space, and especially to asteroids. At this time Congress has not provided funding specifically to assess asteroid resources. Nevertheless, the USGS Mineral Resources Program has decided it is prudent to fund a small feasibility study to examine if existing terrestrial methods can be applied to asteroids. This report details the steps taken as part of that study and its final results.

When it comes to asteroid mining, platinum and other rare metals have garnered the most public attention—with published reports suggesting that asteroids will provide trillions of dollars in return for the investment in asteroid mining infrastructure (Ostro and others, 1991; Gerlach, 2005). The methods we used in this study could be applied to platinum, but we have chosen to focus on two more practical resources: water and native metal (iron-nickel alloy). Water from asteroids has the potential to dramatically reduce the cost of long-term human presence beyond Earth’s orbit as a source of drinking water, radiation shielding, oxygen to breathe, and rocket fuel (Gerlach, 2005; Lewis, 2014). Iron-nickel alloy from asteroids could be directly used in space structures; 3D printing of complex parts from such materials has been demonstrated and should be possible in space. However, we emphasize that the objective of this study was not to complete a proper assessment of any asteroid resource, but instead to test the feasibility of doing such resource assessments in the future.

How USGS Conducts Quantitative Resource Assessments

The methodology used by the USGS is geared to produce unbiased and reliable results in a format readily understood by decisionmakers who are not technical experts in the field (for example, Singer, 2007). The methodology is often called the “three-part” model because it uses three separate quantitative models that are combined using numerical methods to produce the statistics for the final assessment (fig. 1). For each resource, a prerequisite for quantitative assessments is the development of qualitative “descriptive models” of each geologic setting in which the resource can be found. This is a description of the association among the resource, the geologic processes that form deposits of that resource and the rock assemblages that contain those deposits. For mineral assessments on Earth, the descriptive models are recorded in a standardized form to ensure consistent information content. This form includes key scientific references, type localities, geologic context, and typical alteration and weathering.

The first of the three quantitative models is the “spatial model,” which delineates tracts that contain the geologic setting described in the descriptive model. In other words, the spatial model is a map of the areas where the geology permits the existence of deposits of the resource (Singer, 2007). Thus, this model is not an attempt to map the resource deposits themselves. The spatial model can exclude areas inaccessible owing to technical, political, or legal reasons. A wide variety of relevant data, including information on known deposits, geochemistry of samples, geophysical surveys, geologic mapping, and remote sensing can be used in creating this model. The spatial variability in the quality of the data is also considered.

The second quantitative model is the “grade-tonnage model” for each geologic setting. “Grade” is the concentration (or quality) of the resource and “tonnage” is the mass (or quantity) of the deposit. These models are usually expressed mathematically as multivariate probability density functions for the resource concentrations and ore tonnages of the deposits in the assessment area. These functions are usually visualized in two plots: (1) a size-frequency distribution and (2) a quality-frequency distribution of the deposits. These models usually rely on previous in-depth investigations of localities analogous to the assessment area. The distributions are fit with a statistical model using a series of tests to ensure that the model correctly represents the typical highly skewed size distributions. This graphical analysis can also reveal if there are multiple populations of deposits. In such a circumstance, it is necessary to distinguish the geologic settings of the different populations and develop new descriptive and spatial models for each.

The third quantitative model is the “deposit-density model,” which provides an estimate of the expected number of deposits per unit area. This estimate is usually determined by examining a statistically meaningful number of localities in sufficient detail that the number of deposits in these areas is known with some certainty. Such studies take advantage of a wide variety of geologic and geophysical datasets, creating deep understanding that can be described as “geologic intuition” of the problem. Mathematically, this understanding is expressed as a probability mass function for the number of deposits per unit area, which can be calculated in conjunction with the development of grade-tonnage models. Again, there are a number of statistical tests to identify when multiple populations are being mixed and to provide a robust description of the uncertainty in the deposit-density estimates.

The deposit-density and grade-tonnage models are first statistically combined to calculate the expected size and quality distribution of deposits per unit area at various confidence levels (typically 10, 50, and 90 percent). Monte Carlo methods are the most commonly used statistical method because of their flexibility and mathematical simplicity. Then, an economic model that describes the cost to set up an extraction operation and then operate it can be applied. Even a simple parametric model can be sufficient to indicate whether the expected deposits are worth extracting. After combining with the areas identified in the spatial model, the final outputs are (1) the minimum number, size, and quality of economically viable deposits at various confidence levels and (2) a map of where these deposits may exist.

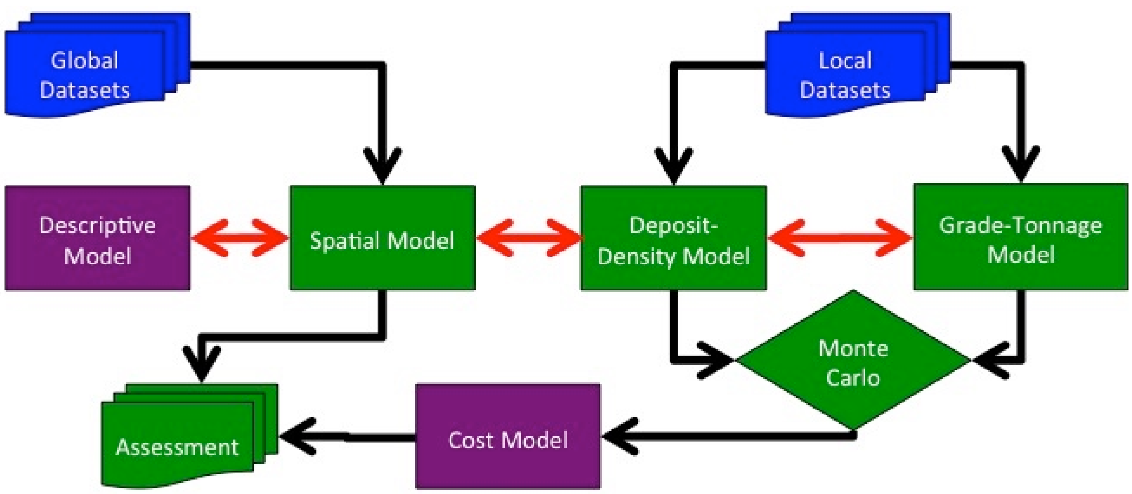

Figure 1. Flowchart for USGS resource assessments. Blue boxes are datasets, green boxes derive from USGS processes with minor modification, and purple boxes require some conceptual adjustments to apply to Solar System exploration and science. Black arrows represent the flow of information. Red arrows indicate iteration and research.

Descriptive Model for Asteroids

The first part of an assessment is to describe the geologic settings in which concentrations of the relevant resource can be found. Each geologic setting on Earth has a characteristic mineral assemblage. For asteroids, this emphasis on petrology is similar to meteorite classes. To link meteorites to asteroids, we rely on the Small Main-belt Asteroid Spectroscopic Survey (SMASS) taxonomy (Binzel and others, 2004). For this feasibility study, we simplify the problem by only considering the three main spectral categories (C, S, and X). We further simplify matters by equating C asteroids with carbonaceous chondrites, X asteroids with iron meteorites and pallasites, and S asteroids with all other meteorites (which are mostly stony). This simple translation from spectral data to meteorite type is a gross oversimplification that ignores many important categories of asteroid spectra and types of meteorites. In fact, we are aware of a few cases where this oversimplification associates an asteroid with the wrong type of meteorite. However, it is sufficient to demonstrate the general approach that could be used in a real assessment of asteroid resources. Some key steps needed to provide more reliable input to an assessment are discussed at the end of this report.

Spatial Model for Asteroids

The first quantitative model, the spatial model, describes where ore bodies can be found within boundaries set by political and technical limits. In our case, each asteroid can be thought of as an ore body. We limit this initial analysis to NEOs based on change in velocity (Δv), a measure of the effort needed to move between two objects (or orbits) in space. We limit our analysis to objects that can be reached from low Earth orbit with a Δv of ≤7 kilometers per second (km/s), which includes most objects between Earth and Mars, but excludes the main-belt asteroids. The objects and their orbital parameters are taken from the Minor Planet Center database (minorplanetcenter.net) and Δv is calculated using the methods of Shoemaker and Helin (1978). We prefer to analyze NEOs, with their slightly more generic definition than near-Earth asteroids (NEA), because they can include remnants of comets.

Deposit-Density Model for Near-Earth Objects

The second model, the deposit-density quantitative model, is used to determine how many deposits (that is, asteroids) are in the study area. This part of the assessment takes advantage of activities driven by the George E. Brown, Jr. Near-Earth Object Survey Act of 2005 that requires the National Aeronautics and Space Administration (NASA) to identify ≥90 percent of potentially hazardous NEAs greater than 140 meters in diameter. The catalog of NEAs with diameters greater than 1 km is now 90-95 percent complete, but there are differing estimates on how many smaller bodies remain undiscovered (for example, Mainzer and others, 2011; Stuart and Binzel, 2004). However, because more than 99 percent of the volume of NEAs is in objects ≥1 km in diameter (fig. 2), we are able to ignore the smaller asteroids for this initial assessment.

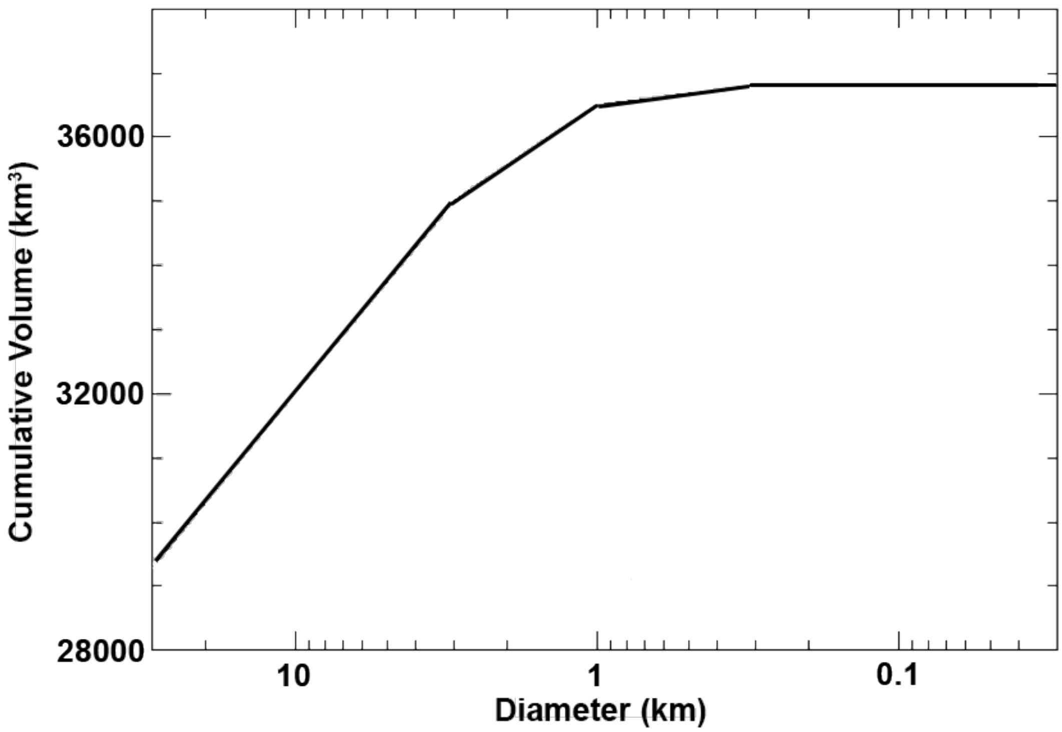

Figure 2. Cumulative volume of near-Earth objects (NEOs) versus NEO diameter calculated from observed brightness.

Grade-Tonnage Model for Near-Earth Objects

For NEOs, we divide the third quantitative model into its two components. The "tonnage" part describes the size distribution of deposits (that is, asteroids). Whereas there are some questions about the size distribution of the smaller bodies, the ≥1 km diameter objects are well characterized (fig. 2). However, there are significant uncertainties in the mass represented by these bodies, especially because the densities of asteroids are highly variable and difficult to estimate (Chesley and others, 2002).

The final quantitative model we use describes the probability distribution of the quality (that is, grade) of the deposit. Resource quality is primarily governed by the concentration of the resource, but is also secondarily affected by how the resource is bound in the rock. Native iron-nickel alloys make up nearly all of metallic asteroids and as much as 25 percent of carbonaceous chondrites. The primary source of uncertainty is that only 5–20 percent of the asteroids in the X spectral group are actually metallic (Thomas and others, 2011).

For water, we do not expect pure water ice to be found on NEOs in any meaningful concentration. Instead, we focus on hydrated minerals. Whereas some primitive carbonaceous chondrites have more than 20 percent by weight bound water, most have been heated sufficiently to contain only a few percent water (Mason, 1963). Furthermore, the concentration can vary significantly with depth if an asteroid has been heated for a geologically short time. Because of processes that affect meteorites as they pass through the Earth's atmosphere and while they sit on the Earth's surface, there may be a sample bias against the most primitive chondritic bodies in the meteorite collection. In other words, there are significant issues, and thus large uncertainties, in estimating the water content of carbonaceous asteroids from samples in the meteorite collection.

Modeling

The final step is to combine the models in a statistically rigorous manner to obtain the total amount of each resource expected at the 10, 50, and 90 percent exceedance quantiles. Because the statistical distributions in the locations, sizes, and compositions of ore bodies (and asteroids) do not fit simple statistical models, it has proven necessary to utilize Monte Carlo methods to do this combination correctly. For this step, we created a simple Monte Carlo model in FORTRAN that we have named ASTRA1. The code for ASTRA1 is included as appendix 1 of this publication.

As input, we start with the list of known asteroids with Δ*v* less than 7 km/s and absolute magnitude (M_H) brighter than 18, which approximately corresponds to a diameter of 1 km for dark objects. Figure 3 shows the distribution of the brightness of the 428 objects in this list. Because this list may be only 90 percent complete, an additional 43 entries are added with their M_H coded as "0". This is our deposit-density model.

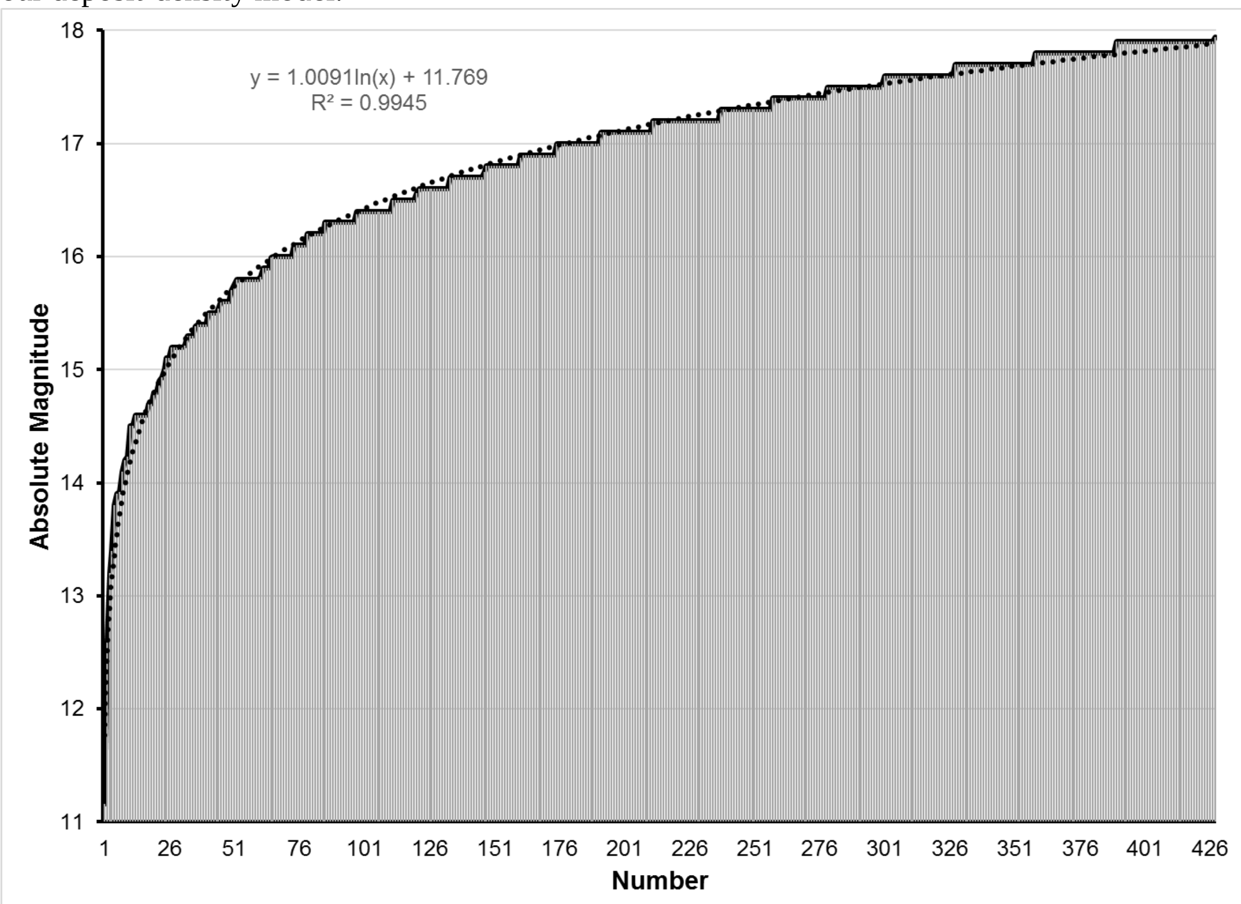

Figure 3. Cumulative distribution function of absolute magnitude (M_H) of the 428 known objects with Δ*v* less than 7 km/s included in this study. The logarithmic fit is used to obtain brightness values for the undiscovered objects also included in this study.

For composition, we rely on the SMASS spectral classification from Binzel and others (2004) and relate spectral class to meteorite group as described in table 1. Of the 428 asteroids listed, 8 are annotated as metal-rich, 16 as carbonaceous, and 76 as stony. The remainder could not be matched to an object in Binzel and others (2004) and were classified as unknown with a numerical code of "0". The input data file is provided as appendix 2 of this publication.

Table 1. Association among spectral types and meteorite groups in this study.

Assumed Meteorite Group	SMASS Spectral Type from Binzel and others (2004)	Numerical Value in input file
Stony	A, K, K:, L, Ld, O, Q, R, S, S:, S(IV), Sa, Sk, Sl, Sq, Sq:, Sr, U, V, V:	1
Carbonaceous	B, C, C:, Cb, Cg, Ch, D, T	2
Metal-rich	X, X:, Xc, Xe, Xk,	3

We ran 100,000 cases through ASTRA1 to investigate the range of water and metal that might be available in the NEO population. Here, we explain the steps used to generate each of these possible cases.

First, a brightness (M_H) was assigned to each of the 43 potential undiscovered objects. Figure 3 shows the brightness distribution of the 428 known objects and a logarithmic fit to those data. The undiscovered objects are assumed to have the same brightness distribution as the known objects. This is incorrect because the undiscovered objects will be biased toward being fainter than the known objects (since brighter objects are easier to discover). Furthermore, because the survey on large NEOs may be 95 percent complete, we assign each of the potential undiscovered objects a 50 percent chance to not exist. Numerically, this is done by giving a non-existent object an M_H of 100, making them far too small to affect subsequent calculations.

Next, for the objects that were not spectrally classified, a composition was assigned randomly with a probability of 39 percent to be stony, 27 percent to be carbonaceous, and 34 percent to be metal-rich. These are the proportions found in the broader NEO population reported in Binzel and others (2004) and bias-corrected by Stuart and Binzel (2004). The bias is significant because spectra are much easier to obtain for the brighter (typically stony) objects. The raw (that is, biased) proportions for the known objects in our list with SMASS spectra are 83 percent stony, 8 percent carbonaceous, and 9 percent metal-rich. Given the relatively small number of objects with SMASS spectra, the magnitude of this bias is unsurprising. However, it is important to note that there are more infrared spectra of asteroids available today than are included in Binzel and others (2004). A proper assessment of asteroid resources would need to take all those data into account, but the data we use are sufficient to demonstrate the feasibility of the approach we are taking.

In the software, the next step is to calculate the mass of each object. The brightness is converted to diameter using the relationship from Harris and Harris (1997). There is insufficient data to determine empirical probability distribution functions for the albedos of NEOs. Canonical values for albedo are about 5 percent for carbonaceous objects and about 20 percent for other asteroids. Whereas better information is available for some objects, we simulate uncertainty in these canonical albedo values by varying them by ±50 percent with a simple linear distribution.

Carry (2012) conducted an extensive study of various physical properties of asteroids, including density. The tabulated information for each spectral class is condensed into the three compositions we consider in table 2. In the ASTRA1 program we assume a simple linear distribution between the minimum and maximum densities. An alternative, and possibly more self-consistent, method for estimating density would be to use values obtained for each meteorite class (for example, Consolmagno and others, 2008 but the differences in values are small (nearly 10 percent).

Table 2. Density range for each composition group derived from data compiled by Carry (2012).

[kg/m^3, kilogram per cubic meter]

Composition Group	Minimum Density (kg/m^3)	Mean Density (kg/m^3)	Maximum Density (kg/m^3)
Stony	1468	2704	3940
Carbonaceous	577	2086	3595
Metal-rich	1391	3482	5574

From diameter and density, it is straightforward to calculate the mass of each object, assuming that they are spheres. While asteroids are not spherical, the method for calculating diameter gives an effective diameter that results in errors much smaller than the other uncertainties we have already discussed. This completes the tonnage part of the grade-tonnage model.

For our grade model, we use the compositional data from Nittler and others (2004). We consider only whole-rock analyses and are only interested in the metallic iron (FE_M in their tables) and hydrogen concentrations. We multiply the hydrogen concentration by 9 to obtain the mass of water instead of hydrogen. In asteroids, hydrogen may mostly exist in the form of hydroxyl (OH) but we assume the extraction technology will convert this to water (the “waste” product would be oxygen—itself a potentially desirable resource, but one we do not examine in this report). Table 3 shows the meteorite classes that were included in each of our composition groups. Figure 4 shows the distribution of metallic iron and water concentrations for each of the three composition groups and the empirical expressions fit to them. In ASTRA1, the metallic iron and water concentration is randomly selected for each object using these mathematical expressions.

Table 3. Mapping among compositional groups for this study and meteorite classes from Nittler and others (2004).

Compositional Group	Meteorite Classes from Nittler and others (2004)
Stony	ACA, ANG, AUB, BENC, DIO, E, EH, EL, EUC, H, HOW, L, L/LL, LL, LOD, LUN, R SHE, URE
Carbonaceous	C, CI, CK, CM, CO, CR, CV
Metal-rich	IAB, IIE, MES, PALL

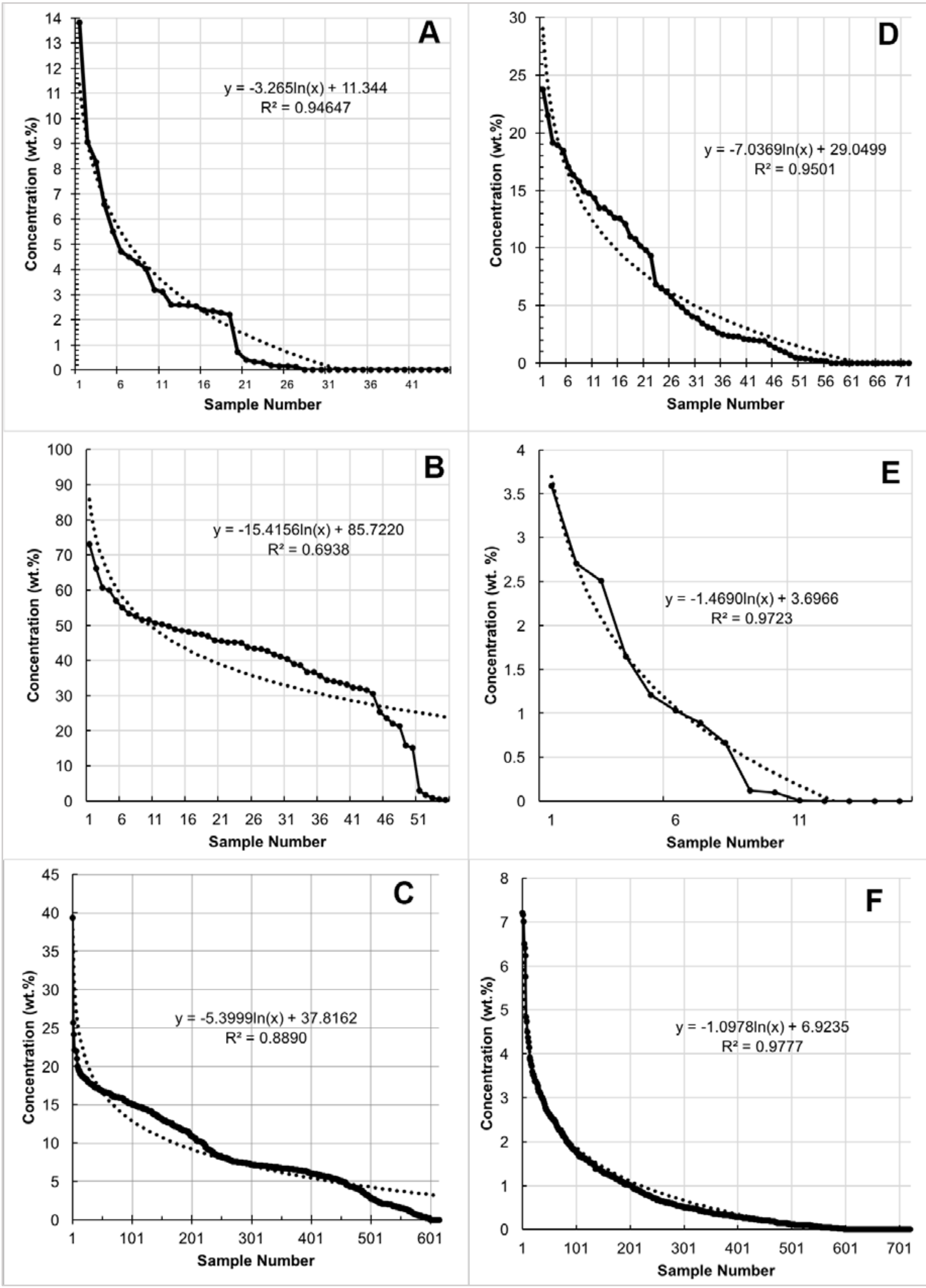

Figure 4. Curve fits (dotted lines) to the meteorite composition compilation of Nittler and others (2004; line with black circles). Iron and water concentrations, in percent by weight (wt. %), are shown for the three major meteorite

categories as described in table 3. (A) Iron-nickel alloy in carbonaceous meteorites, (B) iron-nickel alloy in metal-rich meteorites, (C) iron-nickel alloy in stony meteorites, (D) water in carbonaceous meteorites, (E) water in metal-rich meteorites, and (F) water in stony meteorites.

There remain serious questions about how representative these data are of the compositions of meteorites. Additionally, there are further serious questions about how representative meteorites are of the NEO population. We do not address these issues in this feasibility study.

The final step in ASTRA1 is to sum the amounts of free metallic iron and water in the entire simulated NEO population. To facilitate obtaining statistics, the 100,000 runs are sorted and summaries are output. The results are presented in the next section.

Discussion

Figure 5 shows the probability distribution of water and metallic iron expected based on the parameters discussed above. The information is summarized in table 4.

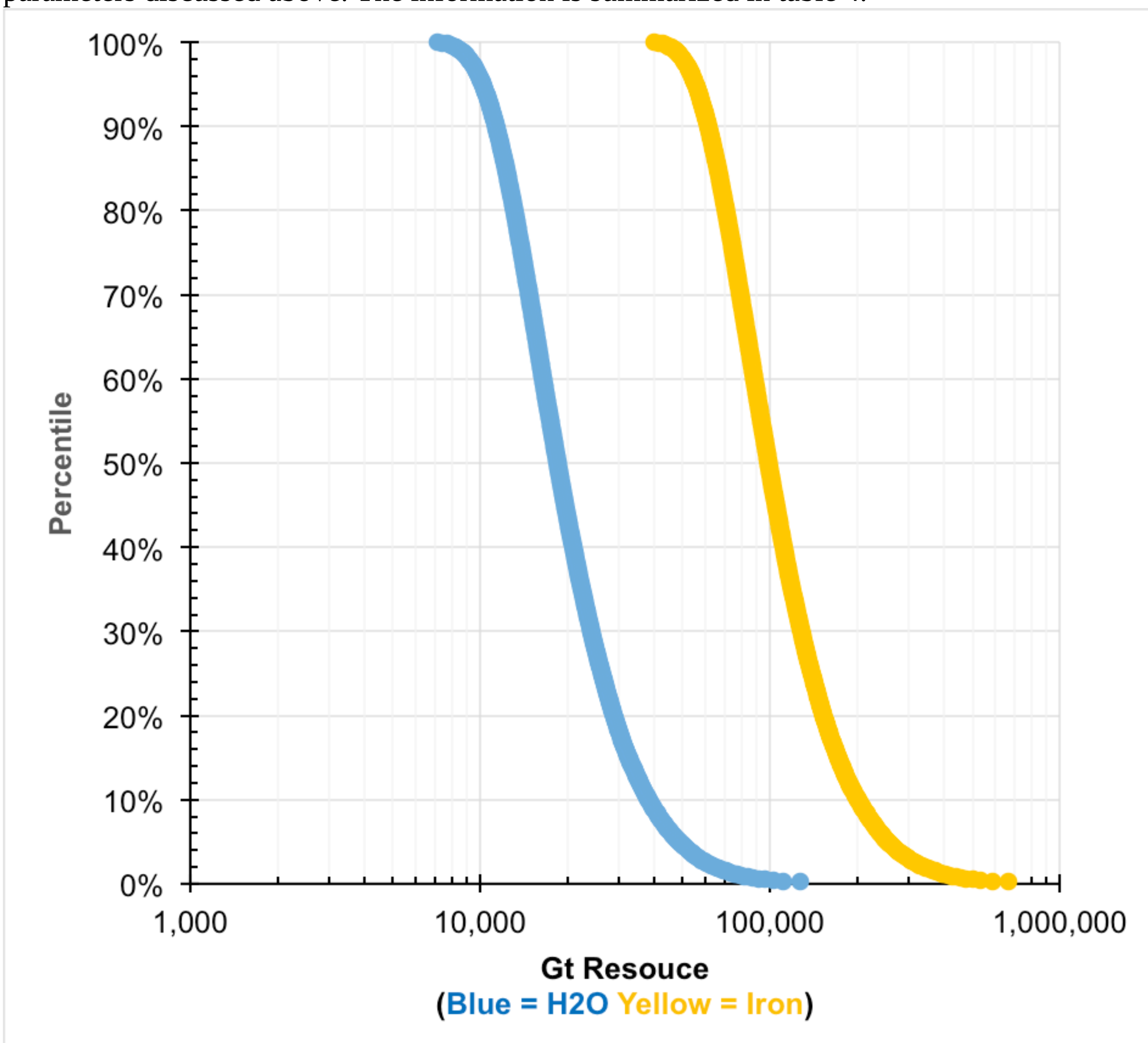

Figure 5. Output of ASTRA1 modeling showing how the minimum amount of water and metallic iron resources (in gigatons, Gt) in near-Earth objects would be represented in a USGS resource assessment.

Table 4. Minimum amount of water and metallic iron resources in near-Earth objects.

[Gt, gigatons]

	90% probability (Gt)	50% probability (Gt)	10% probability (Gt)
Water	11,000	18,000	38,000
Metallic iron	61,000	99,000	200,000

On face value, these results suggest we have assessed the likely amount of resources available in NEOs to about a factor of 4. However, we reiterate that the objective of this study was not to produce an accurate and reliable assessment of NEO resources. As we have discussed, there are major sources of uncertainty that are incorrectly modeled or not included at all. For example, the linkage between spectral classes and meteorite groups is assumed to be perfect when we know it is a gross oversimplification. It is plausible that values presented in table 4 and figure 5 may be off by a factor of a hundred or more.

Even given these caveats, it is clear that the amount of useful resources in NEOs is immense when compared to current needs. For example, the International Space Station has a mass of less than 400 tons and the crew of 6 uses about 5 tons of water per year. The numbers in table 4 could sustain a million-fold increase in human activity in space for a million years. Even if the numbers are too large by a factor of a thousand, or even a million, there appears to be a significant amount of useful resources in NEOs.

Of course, one must also consider humanity's ability to extract those resources. Based on the technology that is deployed in space as of this writing, the amount of extractable water and metallic iron in NEOs is known with great certainty to be zero. The immense promise of NEO mineral resources is currently untappable. Unsurprisingly, there are a number of efforts underway to change that.

As resource extraction technology is developed, the actual amount of usable resources in NEOs is likely to increase slowly. For example, if water is extracted by putting an entire asteroid in a plastic bag, the km-scale objects we focused on in this feasibility study would be useless. Instead, the focus would need to be on much smaller objects, perhaps only tens of meters across. Those small objects constitute a miniscule fraction of the volume of all NEOs, but they may be sufficient to enable human space activities for decades or centuries to come.

To be economically viable, processed and delivered asteroid resources would need to cost less than having the same need supplied from Earth. For reference, the cost of platinum on Earth has been about $30,000 per kilogram (kg) in recent years. The cost of water and base metals is trivial on Earth, but transporting them to users in space is expensive. The nearly $200-million Atlas V launch of the Mars Science Laboratory put just over 3,000 kg on a transfer orbit to Mars, suggesting a cost in the ballpark of $50,000/kg for water (or any other resource) to support a human crew traveling to Mars. It is worth emphasizing that the USGS does not assess the technologies or economics of resource extraction. Instead, the USGS assessment supplies the input data for others who examine those types of issues.

None of these issues should detract from the fundamental point of this study. We have successfully demonstrated that the USGS resource assessment methods can be applied to asteroids. The natural next question concerns what is needed to do a proper assessment. Modest improvements can be made by correcting some simplifying assumptions and using additional datasets we did not incorporate into this feasibility study. However, there are key sources of uncertainty that require new fundamental scientific research. We have identified three areas of research that are needed to produce an accurate and reliable assessment of NEO resources.

First, too few NEOs have high-quality spectral observations, especially in the mid-infrared range. This is especially true for the smaller objects that are more likely to be targets for initial resource extraction. At the same time, this feasibility study does not make full use of all the data that are currently available. For example, in the absence of full infrared spectra, even basic albedo data can provide some useful constraints on the composition of an asteroid.

Second, our ability to link spectral classes of asteroids to meteorite samples is tenuous. Returned samples from asteroids are the best way to ground-truth these linkages. However, it is unrealistic to expect returned samples from a statistically significant portion of the NEO population. It is important to support the study of returned samples with spectral classification of meteorites (and analog materials) in realistic settings. This requires laboratory measurements of appropriate materials in vacuum, at a range of temperatures, subjected to the radiation environment in space, and with a range of realistic particle sizes. Even with improved spectral libraries, telescopic observations from Earth will have limited ability to positively identify the composition of the asteroid underneath the weathered surficial layer. Missions that analyze the composition of asteroids at a depth of at least several centimeters are essential. One possible way to accomplish this is a fleet of small spacecraft that insert reusable probes into many locations on multiple asteroids, as suggested by Asphaug and others (2017).

Finally, attempts to collate the available compositional and mineralogical data for meteorite samples have highlighted important deficiencies in this critical dataset (for example, Nittler and others, 2004). It is always difficult to compare results from different laboratories using different techniques over the span of many decades. Furthermore, most research on meteorites is focused on specific scientific problems that do not require comprehensive knowledge or data for the entire meteorite—the ratios of a few elements, or even just isotopes of a key element, suffice. Thus, there is a need for systematic and consistent whole-rock and modal-mineralogy analyses of meteorites.

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Appendix 1. ASTRA1.f

```
      REAL    R,A(500,10),ABS,ABC,ABM,AB,Ro,D
      REAL    PI,HTOT,FETOT,CH,CFE,OUT(1000,2),X
      REAL    WORK(100000,2),SORT(100000,2)
      INTEGER N,M,J

c   A(*,1)=brightness (Magnitude)
c   A(*,2)=SMASS class (0=unknown, 1=S, 2=C, 3=M)
c   A(*,3)=volume (km3)
c   A(*,4)=mass (Gt)
c   A(*,5)=dV (km/s)
c   A(*,6)=mass H2O (Gt)
c   A(*,7)=mass metal (Gt)
c   A(*,8)=not used
c   A(*,9)=brightness with guesses for undiscovered asteroids
c   A(*,10)=spectral class with guesses for unknowns

c   Set constants
      PI=3.1415926589

c   Set mean albedo for S, C, and M
      ABS=0.20
      ABC=0.05
      ABM=0.20

c   Initialize random number generator
      WRITE(*,*)'Hello'
      WRITE(*,*)'Please give me an integer?'
      READ(*,*)M
      DO N=1,M
         CALL RANDOM_NUMBER(R)
      END DO

c   Read input file
      OPEN(UNIT=1,FILE="ASTRA_INPUT.csv",STATUS="OLD")
         DO N=1,471
            READ(1,*)A(N,5),A(N,1),A(N,2)
         END DO
      CLOSE(UNIT=1)

c   Run the model 100,000 times
      WRITE(*,*)'Starting the 100,000 runs'
      DO M=1,100000

c   Reset total H and Fe to zero
            HTOT=0.
            FETOT=0.

c   Start work on asteroid input data
            DO N=1,471
c   Add asteroids we have not detected yet (50% chance they exist)
               IF(A(N,1).EQ.0) THEN
                  CALL RANDOM_NUMBER(R)
                  IF(R.LT.0.5) THEN
                     A(N,9)=100.
                  ELSE
                     A(N,9)=(1.0091*LOG(R*428))+11.769
                  ENDIF
               ELSE
                  A(N,9)=A(N,1)
```

```
            ENDIF
c Add spectral class for asteroids that don't have observations
c Relative abundance of C, S, and X from Stuart J. S and Binzel R. P. (2004).
c Bias-corrected population, size distribution and impact hazard for near-Earth
c objects. Icarus 170, 295-311.
             IF(A(N,2).EQ.0) THEN
                 CALL RANDOM_NUMBER(R)
                  IF(R.LT.0.39) THEN
                    A(N,10)=1
                  ELSEIF(R.LT.0.66) THEN
                    A(N,10)=2
                  ELSE
                    A(N,10)=3
                  ENDIF
               ELSE
                 A(N,10)=A(N,2)
               ENDIF
c   Generate albedo, density, and concentrations of H and Fe
            IF(A(N,10).EQ.1) THEN
              CALL RANDOM_NUMBER(R)
              AB=ABS*(0.5+R)
              CALL RANDOM_NUMBER(R)
              Ro=1.468+(R*2.472)
              CALL RANDOM_NUMBER(R)
              X=R*720.
              CH=(-1.098*LOG(X))+6.9235
              IF(CH.LT.0) CH=0.
              CALL RANDOM_NUMBER(R)
              X=R*615.
              CFE=(-5.3999*LOG(X))+37.8162
              IF(CFE.LT.0) CFE=0.
            ENDIF
            IF(A(N,10).EQ.2) THEN
              CALL RANDOM_NUMBER(R)
              AB=ABC*(0.5+R)
              CALL RANDOM_NUMBER(R)
              Ro=0.577*(R*3.017)
              CALL RANDOM_NUMBER(R)
              X=R*72.
              CH=(-7.037*LOG(X))+29.05
              IF(CH.LT.0) CH=0.
              CALL RANDOM_NUMBER(R)
              X=R*45.
              CFE=(-3.265*LOG(X))+11.344
              IF(CFE.LT.0) CFE=0.
            ENDIF
            IF(A(N,10).EQ.3) THEN
              CALL RANDOM_NUMBER(R)
              AB=ABM*(0.5+R)
              CALL RANDOM_NUMBER(R)
              Ro=1.391+(R*4.183)
              CALL RANDOM_NUMBER(R)
              X=R*15.
              CH=(-1.469*LOG(X))+3.6966
              IF(CH.LT.0) CH=0.
              CALL RANDOM_NUMBER(R)
              X=R*55.
              CFE=(-0.001276*(X**3))+(0.09227*(X**2))-(2.56*X)+69.64
              IF(CFE.LT.0) CFE=0.
            ENDIF

c   Calculate diameter, volume, and masses
          D=1329*(10**(-0.2*A(N,9)))/(AB**0.5)
          A(N,3)=4*PI*((D/2.)**3)/3.
          A(N,4)=Ro*A(N,3)
          A(N,6)=A(N,4)*CH
```

```
            A(N,7)=A(N,4)*CFE

c   Add amount of H and Fe to the running total
             HTOT=HTOT+A(N,6)
             FETOT=FETOT+A(N,7)
          END DO

          WRITE(*,*)'RUN ',M
          WORK(M,1)=HTOT
          WORK(M,2)=FETOT

       END DO

c   Sort output
       WRITE(*,*)'Starting to sort'
       SORT(1,1)=WORK(1,1)
       SORT(1,2)=WORK(1,2)

       DO M=2,100000
            WRITE(*,*)'SORTING POSITION ',M
            DO N=1,M-1
                 IF(WORK(M,1).LT.(SORT(N,1))) THEN
                      DO J=M,N+1,-1
                           SORT(J,1)=SORT(J-1,1)
                      END DO
                      SORT(N,1)=WORK(M,1)
                      GOTO 100
                 ELSE
                      SORT(M,1)=WORK(M,1)
                 ENDIF
            END DO
100         CONTINUE
            DO N=1,M-1
                 IF(WORK(M,2).LT.(SORT(N,2))) THEN
                      DO J=M,N+1,-1
                           SORT(J,2)=SORT(J-1,2)
                      END DO
                      SORT(N,2)=WORK(M,2)
                      GOTO 200
                 ELSE
                      SORT(M,2)=WORK(M,2)
                 ENDIF
            END DO
200    CONTINUE
       END DO

c   Output
       DO M=1,1000
            OUT(M,1)=SORT(M*100,1)
            OUT(M,2)=SORT(M*100,2)
            WRITE(7,*)OUT(M,1),OUT(M,2)
       END DO

       WRITE(*,*)'90% chance of exceeding ',OUT(100,1),' Gt of H2O'
       WRITE(*,*)'50% chance of exceeding ',OUT(500,1),' Gt of H2O'
       WRITE(*,*)'10% chance of exceeding ',OUT(900,1),' Gt of H2O'
       WRITE(*,*)'90% chance of exceeding ',OUT(100,2),' Gt of metal'
       WRITE(*,*)'50% chance of exceeding ',OUT(500,2),' Gt of metal'
       WRITE(*,*)'10% chance of exceeding ',OUT(900,2),' Gt of metal'

       END
```

Appendix 2. ASTRA_INPUT.csv

5.188	11.16	1
6.968	15.5	1
6.503	13.4	0
5.816	17.7	0
5.482	15.6	1
5.87	13.2	1
6.135	14.23	1
6.551	15.54	1
6.829	14.93	1
6.094	13.9	1
4.82	15.75	1
5.456	13.92	1
6.179	16.56	0
5.129	16.8	1
6.444	17.2	1
6.289	17.94	0
6.443	17.2	0
6.999	14.5	0
6.594	15.21	0
6.567	17.52	0
6.491	16.1	1
5.133	15.38	3
5.309	14.1	1
6.704	16.5	0
6.063	15.2	1
6.114	15.8	1
6.043	16.75	0
6.536	15.82	0
5.939	16.4	2
6.266	14.6	3
5.678	17.3	1
5.016	17.8	0
6.472	15.99	0
6.166	14.5	1
6.601	15.3	1

6.757	15.9	0
6.007	17.4	0
5.639	17.1	0
6.007	12.6	1
6.171	16.4	0
6.114	17.8	0
6.47	14.6	0
6.472	13.8	1
6.706	17	0
6.587	14.2	1
5.632	17.1	0
6.549	15.2	1
6.211	16.1	0
6.512	14.7	3
6.66	14.7	1
6.281	15.6	0
6.172	17.2	0
5.584	17.4	0
4.969	17.8	1
6.73	14.8	0
5.903	14.8	1
6.874	15.9	0
6.006	16.4	1
5.883	16.8	1
6.335	16.7	0
5.761	17	0
5.9	16.7	1
5.67	17	0
6.243	14.6	1
5.133	17	1
6.042	17.8	0
6.599	15.1	1
6.747	16.9	0
5.657	17.9	0
6.509	17.1	0
6.168	16.4	0
6.164	15.3	0
4.818	17.8	0
6.784	17.4	0
6.688	16.2	0
5.345	17	1
5.918	17.5	0
6.683	17.2	0

5.941	16.9	0
5.893	16.1	1
5.34	16.3	1
5.409	15.2	2
5.341	15.8	1
5.58	15.8	1
6.491	16.3	0
4.846	17.6	1
6.204	17.2	1
6.764	16.6	1
5.904	15.5	1
5.958	17.1	3
6.824	17.7	0
6.126	17	0
6.812	15.4	0
6.772	15.8	1
6.59	16.8	1
6.754	15.9	0
6.233	17.6	0
5.943	17.6	0
6.622	16	0
4.758	17.4	0
5.527	17.8	1
6.576	16.8	1
6.404	17.3	1
5.924	16.7	0
5.956	14.6	0
5.963	16.3	1
4.848	17.2	0
4.96	16.6	2
6.611	17.9	0
6.143	17.1	0
6.219	17.1	0
6.45	17.3	1
6.24	17.2	1
6.334	16	0
6.826	15.8	1
6.651	16	0
4.062	16.8	1
6.454	16.9	3
5.804	16.5	0
6.629	15.8	0
5.758	17.7	0

6.798	17.6	0
5.484	16.5	0
5.851	17.6	3
5.965	17.7	0
4.361	17.8	0
6.987	16.4	0
6.586	17.5	0
5.655	17.9	0
6.211	15.8	0
6.669	15.2	3
6.144	17.1	0
6.68	14.6	1
4.613	17.2	0
6.137	17.1	0
6.241	14.9	0
6.373	16.5	2
5.731	16.9	0
6.624	16.6	1
4.384	17	0
6.949	15.5	0
5.106	16.4	0
5.523	16.8	0
5.784	17.8	0
5.343	16.5	0
6.518	16.4	0
5.655	16.2	0
5.154	17	0
5.357	15.8	0
5.585	15.3	0
5.976	16.4	0
6.859	16	1
5.708	17.4	1
6.411	16.4	0
6.42	16	0
6.443	17	0
5.704	17.6	0
6.165	15.6	1
6.324	15.2	0
6.867	17.7	0
4.933	17.6	0
6.291	16.4	0
5.871	16.3	0
6.483	17.8	0

6.074	16.2	1
5.478	16.7	1
6.305	17.5	0
6.743	16	0
5.599	17.9	0
5.771	17.7	0
5.258	17.7	0
5.146	16.8	0
6.488	16.3	0
6.356	17.7	1
6.963	16.6	0
5.337	16.6	1
4.704	16.9	0
6.635	17.6	0
6.177	17.2	0
6.426	15	1
6.208	17.9	0
6.223	16.7	1
6.124	15.8	0
5.56	16.9	0
5.933	16.6	0
4.787	16.7	0
5.951	17.3	0
6.89	16.6	0
6.085	17.8	0
5.403	16.2	0
6.856	16.2	0
5.381	17.1	0
6.863	16.8	0
6.49	17.9	0
5.895	16	0
5.442	16.3	0
6.241	16	0
6.093	16.6	0
6.414	17.4	0
6.695	17.3	0
6.964	16.4	0
6.01	16.6	2
5.736	16.7	0
5.568	17.6	0
5.259	17.2	0
6.778	17.2	0
5.747	16.9	0

6.033	17.9	0
6.41	17.3	0
6.219	17.5	0
5.634	17.9	0
6.834	16.4	0
6.975	16.3	0
6.395	16.9	0
6.231	16.2	0
6.186	16.1	0
6.782	17.2	0
6.546	16.5	0
5.714	17.6	0
6.764	17	0
6.373	17.9	0
6.383	15.4	0
6.916	16.3	0
4.816	17.1	0
5.479	16.6	0
6.347	17.8	0
5.913	17.4	0
6.682	15.1	0
5.772	17.1	0
4.93	17.5	0
6.806	15.7	0
6.625	17.3	0
6.852	17.6	1
6.44	16.7	0
5.559	17.9	2
5.313	17.5	1
6.128	16.3	0
6.479	17.7	0
6.01	17.2	0
5.104	17.6	0
6.187	17.2	0
5.775	17.4	0
6.45	16.8	0
6.253	17	0
4.255	17.8	0
6.556	17.2	0
6.662	16.6	0
5.995	17.5	0
6.687	17.4	0
6.175	17.6	0

6.376	17.9	0
6.657	17.4	0
6.883	15.6	0
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6.704	16.5	0
6.229	17.1	0
5.568	17.3	1
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6.872	15.4	1
5.976	17.7	0
6.819	17.5	0
5.982	16.3	0
5.866	17.1	1
6.757	16.7	0
6.837	17.3	0
6.444	17.7	1
6.93	17.9	0
6.983	16.5	0
5.61	17.1	0
6.718	17.2	0
6.154	17.7	0
6.914	17.5	0
6.383	17.9	0
5.104	17.4	0
6.014	17	0
5.793	17.5	0
6.792	17.9	0
6.681	17.3	0
6.679	15.5	0
6.778	17.4	0
6.108	17.9	0
5.635	16.8	0
6.543	17.7	0
4.909	17.4	0
6.131	17.8	0

5.985	16.9	0
6.922	17.1	0
6.024	17	0
6.742	17.7	1
6.582	17.5	0
6.337	16.2	0
6.578	17.1	0
5.74	17.7	0
5.617	17.9	0
6.547	17.9	0
6.653	17.4	0
6.334	17.3	0
6.565	17.8	0
6.588	17.6	0
6.829	17.5	0
6.809	16.7	0
6.636	17.9	0
6.977	17.6	0
6.583	17.8	0
6.209	17.5	0
6.52	17.1	0
6.832	16.9	1
6.011	16.9	0
6.576	17.2	2
4.863	17.6	0
5.903	17.9	0
6.981	17.6	0
5.441	17.7	0
6.929	16.3	0
6.017	17.3	0
6.969	16.4	0
5.168	17.9	0
6.407	17.4	0
6.048	17.8	0
4.309	17.6	0
6.064	17.1	0
5.93	17.3	0
6.958	17.9	3
6.671	16.6	0
6.724	17.3	0
6.775	17.7	0
6.731	15.4	0
6.693	17.1	0

6.069	17.8	0
6.332	17.7	0
5.325	17.7	0
6.619	16.5	0
5.796	17.8	0
5.618	16.7	0
6.953	17.3	0
6.572	17	0
6.79	17.3	0
6.435	16.8	0
6.879	17.2	0
6.605	17.5	0
6.582	17.7	0
3.947	17.5	1
6.39	17.9	0
5.719	17.2	0
5.246	17.8	0
6.821	16.9	1
5.772	17.9	0
5.564	17.5	0
5.719	17.9	0
6.776	17	0
6.774	17.8	0
6.35	17.4	0
6.966	17.5	0
6.765	17	0
6.452	17.9	0
6.924	17.7	0
6.55	17.8	0
6.797	17	0
6.662	17.2	0
6.763	17.6	0
6.891	17.7	0
6.441	17.9	0
6.253	17.4	0
6.547	16.8	0
6.373	17.9	0
6.709	17.9	1
4.476	17.8	1
6.197	17.6	0
6.957	17.9	0
6.349	17.7	0
6.585	17.3	0

5.921	17.9	0
6.981	17.4	0
6.814	17.6	0
6.486	17.6	0
6.128	17.3	0
6.7	17.9	0
6.874	16.7	0
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6.852	17.7	0
6.773	16.3	0
6.245	17.9	0
6.556	17.1	0
6.572	17.5	0
6.711	17.2	0
6.981	17.7	0
6.616	17.8	0
6.567	17.8	0
6.865	17.7	0
6.485	17.8	0
6.957	17.3	0
6.903	17.9	0
6.796	17.2	0
6.395	16.9	0
6.7	17.4	0
4.893	17.8	0
6.486	17.2	0
6.952	17.2	0
6.332	17.8	0
6.789	17.9	0
6.099	17.2	0
6.742	17.7	0
6.153	17.7	0
6.515	17.8	0
6.278	17.8	0
6.514	17.4	0
6.635	17.8	0
6.443	17.4	0
6.771	17.5	0
5.798	17.6	0
6.264	17.9	0
5.683	17.5	0
6.707	17.6	0
6.376	17.8	0

6.923	17.2	0
5.829	17.3	0
5.524	17.7	0
6.922	17.9	0
6.313	17.9	0
6.662	17.9	0
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