ASTEROIDS, NOT MARS, ARE THE KEY TO HUMANITY'S SURVIVAL

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ABSTRACT

Colonizing Mars is a feasible idea, but the wrong idea. Building spacecraft out of asteroids provides a much cheaper and easier alternative to ensuring humanity's survival. Following a loose implementation of Musk's 5-step engineering process, we see that the current requirements are dumb, some of the most difficult challenges are removed, the entire process can be optimized, and the process progressively gets faster. We show that we can get thousands of tons of usable nickel-iron to Earth's orbit within a decade and that our limiting factor to moving all humans into space is our launch rate from Earth's surface. This is the fastest, cheapest, and easiest way to ensure humanity's survival.

Target audience: Elon Musk, Gwynne Shotwell, Jeff Bezos, Richard Branson, NASA

1. IDEA

We need to reevaluate our focus on colonizing planets, especially Mars. We have shown that humans can live above a planet's surface, so why settle for another planet's surface?

I propose that we move off of the surface of planets and move into outer space permanently, using asteroids as the primary construction material.

Plan:

1. Use "mining drones" to mine asteroids and send the metal to Earth's orbit.
2. Create spacecraft with this metal.
3. Establish a self-sufficient society with these spacecraft.
4. Move all of humanity off of the Earth's surface.

2. 5-STEP ENGINEERING PROCESS

1. **Make the requirements less dumb**

   SpaceX's (and many humans') current requirements: Establish an indefinitely self-sustaining colony on Mars.

   New requirements: Establish an indefinitely self-sustaining colony off Earth.

   The current requirements are unnecessarily restricted. The goal is to guarantee humanity's survival given any catastrophic event by establishing a society that can carry on without Earth.

2. **Try to delete parts of the process**

   Getting to the point where Mars is self-sustaining requires massive infrastructure investments both on Earth and on Mars. The key investments are:

   (a) Rockets
   (b) Landing and launching pads/towers
   (c) Propellant refineries
   (d) Power plants – solar or nuclear
   (e) Habitable structures
   (f) Environmental control systems
   (g) Distance between Earth and Mars (not an investment, per se)

Some are unnecessary and others are very easy to optimize.

Using asteroid spacecraft, we can eliminate a few challenging parts of the process while only introducing a couple simple parts.

We can eliminate:

(a) Landing and launching pads/towers on Mars

(b) Distance between Earth and Mars

   LEO, or even GEO, is so much closer to Earth that this part is essentially eliminated.

   Humans have never travelled to Mars, so we do not yet understand all of the consequences of being so far away. The distance will undoubtedly cause problems.

   The distance also makes the rocketry more expensive.

(c) Propellant refineries in space

   The proposed design in Section 7 uses solar sails so there is no propellant refining necessary

We introduce:

(a) Creating centripetal acceleration with rotating spacecraft.

(b) Manufacturing spacecraft out of asteroids.

3. **Simplify or optimize**

   Using asteroid spacecraft, we optimize in the following ways:

   (a) Reduce the amount of rockets we need

   We reduce the time it takes for a rocket to travel from Earth to the colony by months. The time savings let the rockets focus on launching and returning to Earth instead of housing humans for months as well.

   We will not have to time our journeys based off of launch windows. This allows for a more constant load on the launch systems, therefore we need fewer rockets.

   (b) Reduce the number of landing and launching pads/towers

   We have a more constant load on the launch facilities, so we need fewer launch facilities to put the same number of humans into space.

   (c) Reduce the size of the solar power plants in space by being closer to the Sun

   (d) Environmental control systems do not have to deal with Mars dust or the atmosphere.

   There are almost countless ways to optimize the currently outlined process. A few future optimizations would be:

   (a) A gateway between LEO and the colony can use a thruster with a high specific impulse.

   (b) Creating larger spacecraft. The volume increases linearly with the surface area of a sphere ($\frac{4/3*\pi r^3}{4\pi r^2} = \frac{r}{3}$). Optimizing this allows more humans per weight of spacecraft structure and shielding.

   (c) All of the processes will get more efficient as more humans move to space.

4. **Accelerate cycle time**

   The mining drones can have a very long lifetime, mining many tons of metal. By continuously creating drones, they will collect more and more asteroids. The mining drones also get faster the more they mine as I will explain later.

5. **Automate**

   (a) The system will undoubtedly become automated as it scales.

   (b) It will become self-funding with asteroid mining, space tourism, and maintaining climate stability.

3. PROS AND CONS OF COLONIZING MARS COMPARED TO MANUFACTURING ASTEROIDS INTO SPACECRAFT

There are many pros and cons to colonizing Mars compared to manufacturing asteroids into spacecraft. The bold items below are the important reasons.

Pros

1. **Currently easier to create fuel and propellant from the Martian atmosphere.**
2. Easier to "plant a flag" on the only surface.
3. More research conducted on Mars than asteroids.
4. More total mass on Mars than all of the asteroids in our solar system combined.

Cons

1. **Most humans will still remain on Earth**
2. **Only 1 backup in case of disaster on Earth**
3. **More expensive**

   We can use asteroid mining to fund the entire process by sending asteroid samples down to Earth.

   Space tourism can't be achieved by colonizing Mars.

4. **No potential for luxury**
5. **Harder to make usable materials**

   The surface of Mars is covered in iron oxide, which is difficult to convert into usable iron.

6. **Lack of motivation**

   Besides exploration and ensuring humanity's survival, there is no reason to settle on Mars. Terraforming would be an incredible undertaking.

7. **Slower**
8. **Humans have never been to Mars**

   There is an inherent risk of the unknown.

9. **Acceleration due to gravity is 38% that of Earth's**

   Untested whether or not humans can survive for extended conditions in this environment.

10. **Static dust**
11. **Dust storms**
12. **Nights**

    This means larger solar panels will be needed for the same energy at the same distance from the Sun.

13. **Harder to scale**

    Does not easily lead to humanity being interstellar.

14. **Tougher on rockets**

    Landing and launching from Mars causes additional stress.

    Months of travel through outer space causes additional stress.

15. **Further distance from Earth**

16. **Further distance from Sun**

17. **More meteors pulled into the gravity well**

18. **Less livable surface area**

19. **Life might exist on Mars and more people would disturb it**

20. Marsquakes

21. Unchangeable orbit

22. Days are not exactly 24 hours

The cons far outweigh the pros. The only considerable pro for colonizing Mars is the feasibility of creating fuel from the Martian atmosphere. We will need to develop new mining equipment to create solar sails from asteroids.

The cons are significant and are completely avoided using metal mined from asteroids as spacecraft.

4. METAL PURIFICATION

We can create spacecraft out of silica, iron, nickel, and practically any metal found in the main belt.

M-Type asteroid compositions vary and are not as well studied as Mars. 16 Psyche is an m-type asteroid and is mainly composed of iron, nickel, pyroxene, and carbonaceous chondrite [1]. Hereinafter, I will assume that all other m-type asteroids have the same composition, which is a necessary extrapolation for simplicity. We are given the option to use the asteroid as-is, purify the nickel-iron, purify the pyroxene, or purify the carbonaceous chondrite. We will purify the nickel-iron because it is the most abundant material in m-type asteroids. It is also strong, malleable, and reflective.

There are many asteroids in the main belt. Some of these have a significant amount of acceleration due to gravity and others do not. If we want to mine the large asteroids, we have the advantage of being able to separate the materials by melting point, but there are significant drawbacks: we have to orbit the asteroid with the parabolic reflector at the same period the asteroid rotates, land on the asteroid, and launch from the asteroid.

If we mine asteroids without a significant acceleration due to gravity, ”0g” hereinafter, we have to separate based on boiling point.

Given the complications of landing on an asteroid with a significant acceleration due to gravity, we will focus on 0g asteroids.

Looking at the properties of the materials in Table 1 and the phase diagram of pure iron in Figure 1, we see that we can boil off the nonmetals in a low pressure chamber. We can vent off the pyroxene and chondrite gases to just be left with nickel-iron metal, ”metal” hereinafter, once we reach temperatures of around 2600°C at 1 bar.

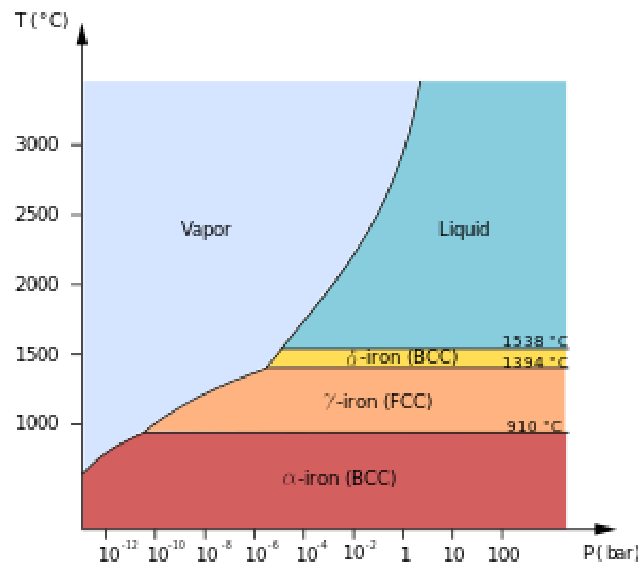

Fig. 1: Low-pressure pure iron phase diagram [2]

0g asteroids are easier to mine but have the flaw that they are smaller, so there’s less usable mass. This will prove to be a small problem.

This purification design of boiling off the nonmetals in 0g may not work. Another solution would be to separate the metals and nonmetals by melting point with centripetal acceleration. For the rest of this paper, assume that the boiling design will be used as it may have fewer moving parts.

5. MINING AND PURIFICATION PROCESS

M-Type Asteroids are metal-rich, so they will be the focus of our metal mining.

Process:

1. Use mining equipment to get a sample of the asteroid.

2. Heat the sample to boil off the nonmetals in a boiling chamber.

Material	Melting Point (°C)	Boiling Point at 1 ATM (°C)
Iron	1538	2862
Nickel	1455	2730
Silica	1710	2230
Pyroxene	1000	Could not find data. Assume similar to silica.
Carbonaceous Chondrite	Could not find data. Assume similar to pyroxene.	Could not find data. Assume similar to pyroxene.

Table 1: Boiling and Melting Points of Common M-Type Asteroid Materials

Use the light absorber/parabolic reflector to heat the chamber and sample.

Maintain a small pressure by venting the gases.

Continue heating until approximately 2600°C.

The boiling chamber compartments have a few requirements:

(a) Made from a material with a high melting point, high thermal conductivity, and minimal chemical interaction with iron, nickel, pyroxene, and carbonaceous chondrite. There are a few suitable materials, such as hafnium diboride [3], titanium diboride [4], zirconium diboride [5], titanium carbide [6], or silicon carbide [7].

(b) Capable of holding 1 bar.

(c) Each compartment holds a solid/liquid sample of asteroid.

(d) Have direct contact with the sample, so we do not need rely on radiation to heat the sample.

At the end of this two step process, we are left with liquid nickel-iron.

6. MANUFACTURING PROCESS

After the mining and purification process, we are left with liquid nickel and iron to be crafted. For the early part of the operation all of the metal will be put into manufacturing reflective panels for our parabolic reflector. After the manufactured parabolic reflector suits our energy needs, we will manufacture solar sails and spacecraft.

To create the **parabolic reflector**, we:

1. Create wire by pushing the metal through a hole, similar to injection molding.
2. Create foil strips by flattening this wire.
3. Align these foil strips into panels using wire frames and an assembling robot following a wire.

Our process to create **solar sails** is the same as the parabolic reflector, but shaped differently.

To create our **spacecraft**, we can take advantage of cold welding. If we don't flatten the wire into foil, we can use the assembling robot to lay the wire in the shape of spacecraft. The wire will weld together upon contact.

7. MINING DRONE DESIGN

Manufacturing drone components:

1. Computers
2. Communications equipment
3. Solar panels
4. Solar sail / parabolic reflector
5. Sample collector
6. Light absorber and boiler
7. Structural components
8. Manufacturing setup

Assume that a rocket and a high impulse thruster will be able to put 100 tons into GEO.

Computers and communications equipment are standard and weigh 260 kg since each Starlink weighs 260 kg and this is not much more complicated [8].

Solar panels are required to power the computers, communications equipment, sample collector, and manufacturing setup. Assume they weigh approximately 500 kg.

A simple **sample collector** design would be a drill with a core sample head attached to an arm. This should weigh less than 2 tons.

Assume the **structural component** weighs 5 tons.

The **manufacturing setup** should be incredibly simple. The wire is created using pressure to push out a stream of molten metal, similar to injection molding. The foil is manufactured by flattening this wire. The assembly robot applies slight pressure between two metal surfaces and welds them together via cold welding. This whole setup should require less than 2 tons of mass, including the backups in case of failure.

At this point, we are left with optimizing the light absorber and boiler vs. the solar sail / parabolic reflector. We only need enough of a solar sail / parabolic reflector to get to an appropriate asteroid in a reasonable time. Assuming we want to get to an asteroid within 5 years, we need a **solar sail** of mass 27.66 tons. Refer to Appendix subsection 15.1 for the calculations. Now we have (100 - 0.26 - 0.5 - 2 - 5 - 27.66 = 64.58) tons to allocate for the light absorber and boiling chamber.

Appendix subsection 15.2 shows that we have 64580 **boiling chambers**, each with an averaged mass of 1kg. This means we have a total volume of $64580 * 0.1^2 * \pi * 0.5m$ = 1014m^3 and a surface area of $64580*2\pi*0.1*0.5$ = 20288 m^2. The total purification rate is now based upon the heat transfer rate between the asteroid sample and the boiling chamber walls. This part of the entire process is the most complicated and has a higher throughput the more surface area.

8. SPACE CITIES

Let's assume that people will live in cities with 1 million people with 9.81 m/s^2 of centripetal acceleration. The easiest way to have centripetal acceleration on a spacecraft would be to rotate two spheres attached by a cable. For 1 million people, each sphere will hold 500k people. Appendix subsection 15.3 shows that this would require 5.84E6 tons of iron, or a comparable weight in nickel-iron. Housing all 8 billion humans would require 4.672E10 tons of iron.

Assuming the metal purification process is limited only by the energy output, we can estimate how long it will take both to house the first million humans and to house all humans. Appendix subsection 15.5 shows that if this is the case, then we can purify enough metal to house the first million humans in less than 3.5 hours and we can house all humans in less than 6.5 hours. Obviously energy output will not be the limiting factor in this mining and purification process. So what are the limiting factors?

Possible limiting factors:

1. Boiling chamber: Limited by the heat transfer between the container and the samples.
2. Sample collector: Limited by the mass collection rate.
3. Manufacturing: Limited by any of the processes:
    (a) Cooling
    (b) Pushing into wire
    (c) Flattening
    (d) Assembling the wire and foil, which is limited by the "coordination" of the robot or the travel speed on the wire.

Given the complicated nature of the boiling chamber, it is safe to assume that it will be the limiting factor.

If each sample chamber purifies its sample in 1 hour, we get 812 m^3 of metal per hour. This is approximately 7200 tons of metal per hour. Converting this into foil we get 150 km^2 per hour, assuming nickel-iron foil weighs 0.0484 kg/m^2 (see Appendix subsection 15.5).

We want to ensure that humans don't just survive, but are happy. 16 Psyche, estimated to contain about 1% of the mass in the asteroid belt has an estimated mass of 2.41E16 tons. With 80% of the asteroid's mass as metal, we get 1.93E16 tons of metal in 1% of the asteroid belt [9]. (Note: we are using 16 Psyche because it is well studied.) Using just the metal from 16 Psyche and the assumption that 5.85 tons of metal can provide 136m^3 of suitable living space, we can provide every human with 5.6E7m^3. That translates to every human having 412k studio apartments, using them however they please. This is more than enough space for every human to live luxuriously.

9. FUNDING

The sheer amount of nickel-iron can be used to fund this operation.

Another massive source of revenue is space tourism. This will be the cheapest way to build vacation resorts in space.

The final source of revenue would be to maintain a solar mirror that restores climate stability. Given the high cost of the effects of climate change, this may be a large source of revenue.

10. ESTIMATED LOGISTICS

We are aiming to move all humans into space as quickly as possible. For this estimate, use the assumption that the boiling chamber is the limiting factor for the first drone.

The logistics for the early parts of the process are:

1. Design the collector drone. We have the generic satellite design with a few new parts, which are:
    (a) Solar sail / parabolic reflector
    (b) Boiling chamber
    (c) Sample collector
    (d) Foil manufacturing equipment
    (e) Assembler

    None of these new parts require any new research. It is safe to assume that a rapidly innovating entity could design and produce a drone within a year.
2. Launch the drone on a standard rocket to GEO. This should only add about a month of time.
3. Since we did not go into the orbital mechanics, it is safe to say that the journey to the asteroid will take approximately 4 years using a continuous thrust.
4. Attaching to the asteroid and getting set up will take about a week.

5. After a couple days we will have reached the point where the boiling chamber is the limiting factor and we are producing 7200 tons of metal per hour.
6. Now we send massive solar sails and spacecraft back to Earth.
7. These solar sails start to arrive in Earth's orbit within 1 year, given their large continuous thrust. Refer to Appendix subsection 15.6.
8. 6 years in, we are limited by the number of humans we can launch from Earth's surface.

11. HOW CAN THIS HELP THE EARTH?

Asteroid mining currently has a few benefits for the Earth, namely ending climate change, ending nickel and iron mining on Earth, and reducing the number of humans on Earth.

11.1. End Climate Change with a Space Mirror

One of the potential solutions to ending climate change is a space mirror, which lies between the Earth and the sun and reflects sunlight before it gets into Earth's atmosphere. This reduces the amount of heat energy entering the Earth's atmosphere and thus reduces the ultimate temperature on the surface of the Earth. This has been theorized but never put into practice because of the cost of putting the reflective materials into Earth's orbit. By mining asteroids we have more than enough metal to create an effective space mirror. Lowell Wood calculated that a 1.6E6 km^2 space mirror orbiting at Lagrange point L1 would restore climate stability [10]. With our throughput of 7200 tons of metal per hour, or 149km^2 of foil per hour, it would take a 450 days to restore climate stability.

The solar mirror is essentially a solar sail, so placing it in Lagrange point L1 would immediately push it towards Earth. Placing it closer to the Sun and balancing the force of the thrust from the solar sail and the force of gravity by adjusting the weight-to-thrust ratio could allow the sail to remain in place indefinitely. A potential design for this would be to have a foldable or rotatable solar mirror.

11.2. End Nickel and Iron Mining on Earth

Nickel and iron mining cause ecological disruption. By transporting our metal down to the Earth's surface, we reduce the need for mining these metals on Earth. This saves ecosystems from being destroyed.

11.3. Reduce the Number of Humans on Earth

Humans are inherently ecosystem disrupting. By moving humans off of the planet we will reduce the impact they have on the planet. The biggest planet destroyers are the richest humans, who will be the first to inhabit interplanetary space. Ultimately, with most humans off of the planet, nature will slowly heal.

12. SUGGESTIONS FOR EACH MEMBER OF THE TARGET AUDIENCE

Elon Musk and Gwynne Shotwell: Keep Starship the #1 priority, but make a team dedicated to making asteroid mining drones a reality. Launching from Earth will always be the limiting factor in this plan.

The new goal for Starship should be to get all humans into space as quickly as possible. We need at least 5 million launches for this to happen.

Given the goal change, we should apply the 5-Step Engineering Process for Starship:

1. **Make the requirements less dumb**

   New requirements: Get all humans to LEO as quickly as possible.

   At this point, we can reevaluate the overall design of Starship. In the past we have seen propulsive landings, spaceplanes (entering the atmosphere, not leaving it), and parachute landings. Of all of these, spaceplanes might be the easiest to scale. For the rest of this process, assume we are switching to a spaceplane design from the current propulsive landing design.

2. **Try to delete parts of the process**

   The tower to catch the upper and lower stages is no longer necessary. This was one of the hardest parts of the design and is certainly the hardest to scale.

   With this change, we do introduce:

   (a) Creating suitable runways.
   (b) Wings and landing gear for the upper and lower stages. This will add considerable weight to Starship.

3. **Simplify or optimize**

   This change simplifies the entire process into a design created in the 1970s.

4. **Accelerate cycle time**

   The most important aspect about this change is the launch rate increase. The limiting factor for a propulsive landing design for Starship was always going to be the availability of launch towers. The entire launch cycle for the spaceplane design is:

   (a) Launch vertically from a launch pad
   (b) Stages separate
   (c) First stage glides into a landing

(d) First stage is refurbished as needed
(e) First stage is stood up, refueled, and put on the launch pad
(f) A different second stage glides into a landing
(g) This second stage is refurbished as needed
(h) This second stage is stood up, refueled, and stacked
(i) Repeat

The launch pad and "standing up" mechanism have been standard components of rocket design for 70 years. They are not complicated and can be built quickly and cheaply.

We can build dozens of runways for our gliders in desolate areas.

Overall, this switch in design changes the limiting factor from the launch towers to the Starships themselves. This will undoubtedly increase the cycle time tremendously.

5. **Automate**

Does not apply here.

Jeff Bezos: Focus on making the space planes as outlined above.

Richard Branson: Partner with SpaceX, ULA, or any other orbit-capable entity to get the collector drones into orbit. Put your entire operating budget into making this a reality. The estimated logistics can easily be handled by $250 million per year.

NASA: Keep Artemis alive, but start researching asteroids more intensely.

13. CONCLUSION

We have shown that we need to switch our focus from Mars to asteroids. Building spacecraft out of asteroids is the fastest and cheapest way to move all of humanity to space. Using Musk's 5-step engineering process, we show that the current requirements are dumb and switching to creating spaceships from asteroids is better. Please reconsider colonizing Mars.

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15. APPENDIX

15.1. Solar Sail Mass

Assume:

1. Solar pressure: 5N per 6.4E5 m^2 at 1 AU [11]
2. Aluminum foil thickness of 6 micrometers
3. Aluminum reflects 95% of light
4. Average Δv for the entire duration
5. Δv of 9.96 km/s from LEO to the asteroid [12]

$$a = 9960m/s/5years = 6.31E-5m/s^2$$

$$F = ma = 100000kg * 6.31E-5 = 6.31N$$

$$6.31N * 6.4E5m^2/5N = 8.08E5m^2$$

Aluminum foil mass for 1m^2 area:

$$6E-6m^3 * 2710kg/m^3 = 0.01626kg$$

8.08E5 m^2 * 16.2 kg / 1000 m^2 * 1/0.95 = 13.83 tons of aluminum foil if at 1 AU the entire time. If the solar sail is at 2.7 AU the entire time, it will take 36.45 years to get to an asteroid. Neither of these distance assumptions are true, so assume this mass of solar sail gets to the asteroid in 20 years. Let's double the size of the solar sail to 27.66 tons to get to the asteroid in 10 years. This timing assumption is complicated and ignores the $\frac{1}{r^2}$ relationship of radiation and it also avoids the orbital mechanics. Further analysis should study this section much more. For now, we will continue with the 27.66 ton solar sail assumption.

15.2. Boiling Chamber Mass

Assumptions:

1. Maximum pressure will be 1 bar
2. The core sample sizes will be 10cm diameter cylinders 0.5m long.
3. Material tensile strength = 45 bar. This is the tensile strength of silica [13].

Thin-walled assumption

$$\sigma = \frac{Pr}{t} \tag{1}$$

Solving for thickness of tungsten required for each sample chamber:

$$t = \frac{Pr}{\sigma} = 2.22E-3m \tag{2}$$

The thickness will not depend on the pressure in the chamber. The thickness will depend on the mechanical durability of the chosen material. Let's assume the material weighs 1kg total weight per boiling chamber. This is including the light absorber and the support equipment for the boiling chamber averaged out.

15.3. Million Person City

Assumptions:

1. 500k people per sphere
2. 1 ATM of pressure
3. The outside walls are 0.5m thick, made from pure iron.
4. Everyone has 100 kg of possessions.
5. Each person's net wall mass is 50 kg.
6. The average person weighs 62 kg.
7. Everyone is suspended using iron wires.
8. Each person gets 136m^3, which is about the size of a studio apartment in the United States (600 ft^2) [14].

9. Iron has a tensile strength of 540 MPa [15].
10. Assume 8 billion total humans.

Calculations:

- Total volume required per sphere: 68E6 m^3
- Radius of the sphere = 253m

$$SA_{sphere} = 4\pi r^2 = 8E5m^2 \tag{3}$$

- Everyone has an average suspension cable length of r = 253m.
- Cable area required per person = F / P = $212*9.81/540000$ = 0.00385 m^2.
- This translates to $0.00385m^2*253m*500000$ = 4.87E5 kg of iron
- The walls require $8E5m^2 * 0.5 * 7300$ = 2.92E9 kg of iron
- In total, this design requires 5.84E6 tons of iron.
- This translates to 5.84 tons per person.
- Housing all humans requires 4.672E10 tons of iron.

15.4. Energy Required to Purify Metals

Assumptions:

1. The asteroid's temperature is approximately -73 C [16]
2. The composition by mass of the average m-type asteroid is [1]:

   82.5% metal Assume 80% iron, 20% nickel

   7% low-iron pyroxene

   10.5% carbonaceous chondrite
3. Solid iron specific heat = 0.450 J/g°C [17]
4. Iron's latent heat of fusion = 11.7 kJ/mol [18]
5. Liquid iron specific heat = 0.820 J/g°C [19]
6. Solid nickel specific heat = 0.444 J/g°C [20]
7. Nickel latent heat of fusion = 17.47 kJ/mol [21]
8. Liquid nickel specific heat = 0.73 J/g°C [22]
9. It is hard to find data on pyroxene and chondrite, so assume they have the same properties as silica.
10. Solid silica specific heat = 0.71 J/g°C [23]
11. Could not find silica's specific heat as liquid or gas. Assume the same as when a solid.
12. Silica latent heat of fusion = 50.55 kJ/mol [23]
13. Silica latent heat of vaporization = 384.22 kJ/mol [23]
14. Heating from -73°C to 2600°C

For 1 kg sample of an m-type asteroid:

Iron (0.66 kg):
Q = m($c_{solid}\Delta T + \Delta H_{fus} + c_{liquid}\Delta T$)

= 800g*(0.450 * (1611°C) + 11700 J/mol * 1 mol / 55.845g + 0.820*(2600°C-1538°C))
= 1.2E6 J

Nickel (0.165 kg):
Q = m($c_{solid}\Delta T + \Delta H_{fus} + c_{liquid}\Delta T$)
$= 165g(0.444 * 1528$°C + 17470 J/mol * 1 mol / 58.693 g + 0.73*(2600°C-1455°C))
= 2.98E5 J

Silica (0.175 kg):
Q = m($c_{solid}\Delta T + \Delta H_{fus} + c_{liquid}\Delta T) + \Delta H_{vap} + c_{gas}\Delta T$)
$= 175g(0.71 * 1788$°C + 50550 J/mol * 1 mol / 60 g + 0.71*(2230°C-1788°C) + 384220 J/mol * 1 mol / 60 g + 0.71*(2600°C-2230°C))
= 1.59E6 J

Total energy to bring an asteroid sample to 2600°C = 3.09E6 J/kg

15.5. Exponential Metal Purification

Assuming the metal purification process is limited only by the energy output, we can estimate how long it will take both to house the first million humans and to house all humans.

Assumptions:

1. Metal purification requires 3.09E6 J/kg.
2. Main belt asteroids get 187 watts of sunlight per m^2 (2.7 AU from the sun)
3. Our metal reflects 95% of light
4. Our metal is 6 micrometers thick
5. Iron has a density of 7850 kg/m^3 [24]
6. Nickel has a density of 8908 kg/m^3 [24]

Foil calculations:

- 1 m^2 is a volume of 6E-6 m^3
- which is a mass of (0.8*7850+0.2*8908)*6E-6 = 0.0484 kg
- Which translates to 20.66 m^2/kg nickel-iron.

To avoid the calculus required for precise rough estimations, we can assume the metal production is a 2^n function where n is the number of iterations of the process of using the foil to make more foil.

20.66 m^2 of sunlight at 2.7 AU from the sun translates to 3863 watts.

3.09E6 J / 3863 watts = 800 s

It takes 800s to create enough energy to double in size.

We are starting with 16.2E5 m^2 of parabolic reflector area, which would be 78 tons if our nickel-iron foil was the equivalent area.

$$m_i * 2^n = m_f \tag{4}$$

$$n = log_2 \frac{m_f}{m_i} \tag{5}$$

Number of iterations required to house 1 million humans:

$$n = log_2 \frac{m_f}{m_i} = log_2 \frac{5.84E9kg}{78E3kg} = 16.2 iterations \tag{6}$$

This means that it takes 3.6 hours to get enough metal to house 1 million humans.

Number of iterations required to house all million humans:

$$n = log_2 \frac{m_f}{m_i} = log_2 \frac{9.35E13kg}{8.6E3kg} = 30.16 iterations \tag{7}$$

This means that it takes 6.7 hours to get enough metal to house all humans if we are only limited by the power output of our parabolic reflector.

15.6. Solar Sail Disclaimer

Solar sails have seen limited use and there is not much literature on their practicality, especially at distances further than 1 AU from the sun. We might have to use another form of transportation to move the solar sail from the asteroid to Earth's orbit. A solar sail's orbit is also much different from the normal Hohmann transfer orbit used to get to the main belt.