Erebor

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Abstract

This paper presents a novel design for a mobile self-sustaining asteroid mining colony (population: 7500) that significantly improves upon previous designs' structure, energy requirement, total mass, and construction complexity. Mined ores are processed in-situ, adding value and facilitating distribution. Exports are carried out using secondary spacecraft. The structure itself is designed to minimize mass and mechanical complexity. Of note is the creation of a 'shell' structure around rotating torii, which is used for aeroponics, radiation shielding, rotation using magnets, and internal transport between rotating and non-rotating components via mag-lev trains. A pebble-bed nuclear reactor is the primary power source, and its heat used for nuclear thermal propulsion. Future prospects include diversifying export destinations and creating more colonies, aiding space colonization.

A Submission to the NSS Space Settlement Contest 2021

12th Grade
Small Group

This paper is dedicated to our parents: Mrs. Anuprita Kalgutkar, Mr. Jaideep Kalgutkar, Mrs. Sona Dube, and Mr. Vijay Nebhrajani.

Erebor is an entry to the 2021 NSS Space Settlement Contest. It was written by two high school students from Pune, India, (in alphabetical order): Aditya V. Nebhrajani and Arnav J. Kalgutkar.

Submitted to the 12th Grade Small Group category.

Contents

0.1 Acknowledgments

We're standing on the shoulders of giants. First, we'd like to thank the National Space Society, for organizing this contest, which has sparked interest in space settlement in young adults the world over, and given us the opportunity to express our passion. We'd like to thank the innumerable mathematicians, engineers, and physicists whose work we've used to create Erebor. This entire paper was written using free/libre and open source software, including GNU Emacs, TeX, Python, and Blender: whose communities and authors we are deeply indebted to. We'd also like to thank Garima Singh Ujlain for her invaluable help in creating the Blender diagrams for Erebor. Finally, we'd like to thank our families, parents, and teachers, whose support and love means the world to us.

0.2 Note on Paper Organization

This paper is divided into chapters and appendices. Perusing the chapters is sufficient to gain an understanding of Erebor's structure and functions. The table of contents and all references are hyperlinked. Some chapters have large tables at the end for better typesetting. Appendix A is a gallery of 3-dimensional models of Erebor, made using Blender, and other miscellaneous figures. Appendix B outlines the mathematics and physics behind some of the important concepts used, and us showing our work: a few non-trivial calculations are outlined here. Appendix C includes a prototype RSA encryption tool to be used on Erebor's software for security purposes.

0.3 Units, Acronyms, and Abbreviations

This paper uses SI units everywhere unless specified otherwise. All figures are to scale unless specified otherwise. Many of the acronyms are light-hearted backronyms. All acronyms that have origins are listed in Table 1.

Acronym	Full Form	Origin
Erebor	Extraterrestrial Resource Extraction Base including Operations for Refining	Lonely Mountain (Sindarian) [Tol91]
GHAR	Gravity Habitat for All Residents	'Home' in Hindi
RATHA	Reusable Atomic-powered Transport Habitat for Asteroid station	'Chariot' in Sanskrit
ALBATROSS	Autonomous Long-duration Bulk Article TRansporter Operated using Solar Sails	Seabird
TRAIL	Tether cum Rail on Asteroid for Improved Locomotion	'Trail' in English
VASP	Vehicle for Asteroid Surface Payload	Phonetic similarity to 'wasp'
DIMAAG	Data and Information Management for Asteroid station, including Astronautic Guidance	'Mind' in Hindi

Table 1: List of acronym origins

0.4 Executive Summary

Erebor is a mobile asteroid mining space station, processing ores in-situ. By providing resources, it serves as an activity enabling space settlement. However, it is also a settlement in its own right, housing a permanent population of 7500.

One of the fundamental advantages of in-situ mineral processing (instead of shipping raw materials and small asteroids to Earth orbit) is value addition at-site, generating more profit per unit mass exported vis-à-vis unprocessed ore, while also increasing the export volume. Moreover, not all destinations possess the facilities to process raw material. Further, as the entire asteroid is not transported there are no size constraints. No operations are carried out in LEO, avoiding additional debris. Once Erebor reaches its target, a net-like structure is deployed on the asteroid, along which extraction robots operate, akin to rappelling. This also increases the structural integrity of rubble-pile asteroids. Material is extracted mechanically (as opposed to sublimating volatiles or fragmenting the asteroid) to reduce wastage. Next, oxides, silicates and other impure forms are processed to produce pure metal. Magnesium is used as the reducing agent in the majority of processes. This greatly streamlines operations by utilizing a common reducing agent, even for metals traditionally processed via other methods. Wherever possible, operations are conducted in microgravity using specialized apparatus while those involving fluids (such as electrolysis) are carried out in centrifuges, as on the ISS.

Erebor's frequent movement necessitates a low mass. Two parallel contra-rotating human inhabitation torii are surrounded by a thick non-rotating shell (peek: Appendix A.3), which serves the dual purpose of aeroponic agriculture and radiation shielding. This shell allows internal transport using maglev trains running between the shell and the torii by matching velocities. Electromagnets are also used for spinning up the torii. Finally, such design reduces spinning mass and simplifies the axle mechanism, lowering mass and energy requirements.

Erebor uses a nuclear thermal rocket for propulsion, superheating and expanding liquid hydrogen to produce thrust. The specific impulse is high, enabling the large delta-V required for asteroid mining. Hydrogen is produced from water (abundant in asteroids), enabling self sufficiency. Two spacecraft have been designed for transport to and from Erebor: one which uses a nuclear thermal rocket for transporting time-sensitive cargo and passengers. The other uses a solar sail to export material without using any propellant, albeit with long travel times.

Erebor itself has far-reaching implications on the human condition. Moreover, bulk materials (iron, aluminium, etc.) delivered efficiently throughout the solar system are the key to space settlement. Future prospects are discussed in-depth in Section 5.3.2.

0.5 On the Name

Erebor, the Sindarian name of the Lonely Mountain, from JRR Tolkein's Middle-earth legnedarium is a Dwarvish kingdom that held one of the largest gold stores in all of Middle-earth, before being taken by dragons. In *The Hobbit*, Erebor represents Bilbo Baggins' quest and his ultimate maturation as an individual. The Dwarves were originally from the mines of Moria, which had *mithril*, a precious metal. Erebor is a home for those who mine the richest resources of our solar system, and has inside it a dragon dwelling, the pebble-bed nuclear reactor. Tolkein's Smaug breathes fire, our dragon spews flames of superheated hydrogen, the Nuclear Thermal Rocket. Finally, similar to Bilbo's journey to the Lonely Mountain, it represents humanity's progress and maturation, eventually growing to occupy the Solar System.

Chapter 1: Construction, Location, and Transport

1.1 Construction

Erebor is constructed in lunar orbit around the year 2035. A moon base with a large industrial complex is likely to have been constructed by then, and is a prerequisite to construction (design out of scope). Erebor is constructed in lunar orbit rather than LEO for the reasons listed below.

1. Resources such as Ilmenite ($FeTiO_3$, containing titanium and iron) anorthite ($CaAl_2Si_2O_8$ containing aluminium) and water (which can be electrolysed to obtain hydrogen gas) are abundant on the lunar surface.
2. Due to the lower gravity and no atmosphere, only 1.6 Km/s of delta-V is required to achieve lunar orbit from the surface as compared to 9.3 – 10 Km/s from Earth's surface to LEO.
3. Not just rockets, but rail guns and mass drivers can also transport material into lunar orbit.

Erebor's hull is mostly made of an aluminium and titanium alloy (metals which are both lightweight as well as extremely strong), since both metals are available on the moon. Hull plates are fabricated on the surface and launched into orbit using a combination of mass driver and rocket engines. Erebor is fueled for its maiden voyage using hydrogen obtained from lunar ice.

1.2 Location

Erebor is designed for asteroid mining operations. As such it has no permanent location and must travel from one asteroid to another once it has depleted the resources available at a given target. This requires a substantial propulsion system, which is explained in Section 1.3.1. Briefly, Erebor uses Nuclear Thermal Rocket (NTR) and has a maximum delta-V of 7.5 Km/s. This enables it to reach most NEOs (Near Earth Objects) and return to Earth without refuelling. However, Erebor may require refuelling for operations in the asteroid belt. As the fuel for an NTR is liquid hydrogen, Erebor can be refuelled at most asteroids by the electrolysis of water ice (which is abundant among asteroids). Large scale refuelling can also be carried out at the Ceres base which is elaborated below.

1.2.1 Asteroids

Erebor is capable of conducting operations both with Near Earth Asteroids (also known as Near Earth Objects or NEOs, these are defined as objects orbiting the Sun having an apoapsis of at least 0.983 AU and a periapsis less than 1.3 AU) well as in the asteroid belt.[Pol+17] Several NEOs such as Ryugu, 65803 Didymos, and 1943 Anteros all have values of over 50 billion USD, while the small (2.48 Km diameter) metallic asteroid 3554 Amun has been estimated to be worth 20 trillion dollars. M-type asteroids are found in the middle region of the asteroid belt, for example 16-Psyche, while C-type asteroids rich in water are abundant in the outer belt. The Martin L4 and L5 trojan asteroids are rich in olivine, a mineral that is rich in Magnesium and Iron.

Available Resources

Asteroids are the leftover debris from the formation of the solar system and are rich in volatile materials such as water and ammonia as well as metals like iron[Sco20], cobalt, nickel, aluminium and titanium. Many valuable metals rare on the Earth's surface including platinum, gold, silver, cobalt, rare earth metals and platinum group metals (ruthenium, rhodium, palladium, osmium, iridium and platinum) can be found at high concentration on asteroids, especially M-types. Due to the absence of oxygen and sulphur, metals are present in the native form making extraction more lucrative.

Asteroid Selection

Asteroids are selected for mining based on factors such as ease of access, commercial viability and availability of water. For example, metallic M-type asteroids are rich in metals but are poor in the water resources required for fuel production. Other factors such as ease of operations are also considered. For example, rubble pile asteroids which are not a single mass but smaller bodies held together by their mutual gravitational attraction or asteroids have a rapid spin rate, which makes it hard to land on the surface (such as 2011 UW158, roughly 300 m in diameter with a rotation period of only 36.6 minutes). Asteroids are identified by using space and ground-based telescopes such as NEOSM and the Roman Space Telescope. They can be broadly classified into three broad categories: C-types asteroids, M- type asteroids, and S-type asteroids.

C-Type Asteroids C-type asteroids are called carbonaceous asteroids (due to their high carbon content) and are the most common, accounting for 75% of all known asteroids. These comprise 80% of all asteroids at a distance of 3 AU from the Sun in the outer asteroid belt and about 40% at a distance of 2 AU from the sun. They have high levels of water (up to 22% percent according to some estimates) and are hence targets for refuelling operations. These asteroids also contain organic substances such as carbon, ammonia, and phosphorous, as well as volatiles such as helium. Some examples of large C-type asteroids are 101955 Bennu, 162173 Ryugu as well as the dwarf planet 1 Ceres.

S-Type Asteroids S-type asteroids account for 17% of all known asteroids. They are stony in nature and consist mainly of iron and magnesium silicates. These asteroids are poor in water but are abundant in metals such as nickel and cobalt. They also contain valuable metals such as gold, platinum and rhodium. Some large S-type asteroids are 1943 Anteros, 433 Eros and 4 Vesta.

M-Type Asteroids M-type or metallic asteroids are much rarer than S-type and C-type asteroids, although they have a higher concentration of metallic resources. These asteroids have high amounts of iron and nickel as well as rare metals. As such, M-type asteroids are the most commercially viable targets. Some notable M- type asteroids are 3554 Amun, 16 Psyche, and 21 Lutetia.

Distribution of Ice Ice is abundant among asteroids, especially C-type asteroids, at a distance of 3 AU or more from the sun known as the frost line (as ice can exist here without sublimating). This distance corresponds to the main belt of the asteroid belt. Ice is also present under the surface regolith and in the permanently shadowed polar regions of several asteroids. Comets with a higher water content are also present in the near solar system but they have highly eccentric orbits.

Planetary Defense Erebor can protect the Earth from Potentially Hazardous Objects (PHOs) such as 99942 Apophis and 101955 Bennu by altering the trajectories of these bodies slightly. This is done using the gravity tractor method. Erebor fires its engines slightly to accelerate and the mutual gravitational attraction pulls the asteroid along with it. The trajectory of the asteroid is carefully manipulated eliminating the chances of an impact even into the far future. Due to Erebor's high mass and thrust, the operation is much quicker as compared to a probe with an ion engine.

Asteroid Orbit The MPS is used during orbital insertion. Smaller station-keeping thruster are fired periodically to correct perturbations in Erebor's orbit. Some key orbital parameters are discussed below.

Eccentricity: Erebor orbits the target asteroid in an orbit with an eccentricity as close to zero as is allowed by the uneven mass distribution of the asteroid.

Inclination: A polar orbit with an inclination close to 90Âř is preferable as it enables access to all the latitudes on the asteroid surface. As asteroids typically have a low rotation period, Erebor is accessible from every location on the surface every few hours.

Radius: The smaller the orbital radius, the lower the gravitational potential difference between Erebor and the surface. The energy required to reach Erebor in orbit from rest on the surface of the asteroid is given by the formula:

$$E = G\left(\frac{1}{R} - \frac{1}{2r}\right)Mm \tag{1.1}$$

Where R and r are the radii of the asteroid and Erebor's orbit respectively, and M, m are the masses of the asteroid and the spacecraft respectively. Hence, even though orbital velocity is higher closer to the surface, it is overall more energetically favourable.
With decreasing radius, tidal forces increase. Tidal forces are experienced by a body when the gravitational force of another body acts differentially across it. The sections of Erebor closer to the asteroid experience a greater force than the sections further away. This has the potential to cause stress on the structure of Erebor. The limit at which tidal forces can disintegrate a celestial body held together by its own gravity is called the Roche limit. Even though Erebor is not at risk of being torn apart (since it is held together by tensile and compressive forces rather than merely gravitational cohesion), the Roche limit is chosen as the orbital radius to avoid straining the structure. The Roche limit is given by:

$$d = R_M \sqrt[3]{2\frac{\rho_M}{\rho_m}} \tag{1.2}$$

Where d is the distance from the body, R_M is the radius of the parent body, ρ_M is the density of the parent body and ρ_m is the density of the orbiting body. As asteroids have widely varying densities, the Roche limit has to be separately calculated for each asteroid. The density of Erebor is assumed to be 1.5 gm/cm^3, factoring in Erebor's metal construction as well as the large air and water spaces inside. Table 1.1 shows the Roche limits for different asteroids. In the case of Bennu, the Roche limit is less than its radius. The orbital radius is increased in such cases to provide a sufficient margin.

Asteroid Name	Type	Density (gm/cm^3)	Radius (Km)	Roche Limit (Km)
21 Lutetia	M	3.4	50	82.75
101955 Bennu	C	1.19	0.245	0.28575
433 Eros	S	2.67	8.42	12.85

Table 1.1: Roche limits of various asteroids

1.2.2 Other Locations

Ceres is the largest asteroid in the asteroid belt, accounting for one-third of the total belt mass and consists of 30% to 40% water ice. Hence, Ceres makes an ideal location for a refuelling station. This allows Erebor to operate in the asteroid belt almost indefinitely.

While Erebor does not mine the Martian surface nor Phobos or Deimos, settlements on the Martian surface play an important role as a market for mined resources.

1.3 External Transport

As Erebor is a mobile station and may operate very far away from Earth for years on end, it is vital to manage the transport of both people and materials to Erebor. Also, as Erebor must export mined material in order to financially sustain its citizens, there is a need for a proper system to transport the material back to Earth or any other destination. Erebor is also mobile and has its own propulsion system to move from one asteroid to another.

1.3.1 Erebor Main Propulsion System

Like the RATHAs, Erebor also uses a pebble bed reactor to power a nuclear thermal rocket which uses hydrogen as the reaction mass. The maximum possible delta-V between refuelings is 7 Km/s enabling round trips from even the furthest of asteroids.

Options for the Propulsion System

Erebor requires an efficient propulsion system for which there are three main options: Solar-Electric Propulsion (SEP), plasma thrusters and Nuclear Thermal Rockets (NTR). All of these have their own merits and demerits.
SEP is the only one of the three to be demonstrated in space. It has been employed on large number of spacecrafts, most notably on the Dawn and Hayabusa (1 and 2) probes. It is much more efficient than an NTR, however it is not practical for larger spacecraft. A large amount of energy is required to produce small amounts of thrust (experimental thrusters have produced only 5.4 N with 100kW power)[Hal18]. The propellants used are noble gases such as Argon and Xenon, which are not easily obtainable in space.
Plasma propulsion uses a magnetic field to accelerate plasma to high velocities in order to generate thrust. It has the highest efficiency of the three (the VASIMIR engine concept can achieve an I_{sp} of up to 10,000 seconds)[Dia+99] and also uses hydrogen as the propellent. However, it is extremely energy intensive (producing only 0.1 N for and input power of 10 kW) and is largely unproven.
A Nuclear Thermal Rocket (NTR) works by running liquid hydrogen through a nuclear reactor, where it is heated to a high temperature (3,000K) and expands rapidly. The hydrogen is then expelled out of a rocket nozzle at a high velocity (8.3 Km/s), generating thrust. Although none have flown in space, NTRs have been extensively tested on the ground since the 1950s. For example, the Nuclear Engine for Rocket Vehicle Applications (NERVA), tested in the early 1970s, attained an I_{sp} of 850 seconds in a vacuum. As Erebor already uses a nuclear reactor to generate power, a nuclear thermal rocket is thus the ideal choice.
The NTR uses a pebble-bed reactor, in which the fuel elements are contained in tennis ball-sized, spherical fuel elements called pebbles (further elaborated in Section 3.2.3). It has a higher operating temperature than conventional reactors (up to 900°C), which increases the efficiency of the engine as the kinetic energy of gases is directly proportional to the temperature (K = 3/2 RT per mole).

Engines

The MPS has a thrust of 3 MN so that Erebor, when fully fueled and having a mass of 3×10^6 tons, has an acceleration of at least 1×10^{-4} m s^{-2} or 0.1 mm s^{-2}. At this acceleration, a delta-V of 1 Km/s takes about 115.74 days. As Erebor is completely self-sufficient, these long-duration maneuvers are feasible. As fuel is drained, the acceleration increases upto a maximum of 0.24 mm s^{-2} (using a dry mass figure of 12,500,000 tons). Having a low acceleration reduces the structural stress on the GHARs which continue rotating even during engine firings. However, longer burn times increases wear on the reactor (which must increase its power and heat output) and engines. Also, the Oberth effect (maneuvers performed when going faster, such as perigee or perihelion, are more efficient) cannot be utilized due to the low thrust and less efficient trajectories must be used.

Delta-V Requirements

Erebor's delta-V of 7 Km/s is sufficient to rendezvous with and return from most asteroids, even in the absence of ice to refuel. In order to travel from Earth to a target asteroid, say 162173 Ryugu, Erebor must first escape the Earth's orbit and then transfer to the asteroid. As Erebor's thrust is low, the two phases can be considered more or less separately. Note that this is a simplified calculation which neglects inclination changes and other mid-course corrections. Hohmann transfers are not possible in many cases due to Erebor's low thrust, so the actual delta-V figure is almost certainly higher.

Escaping Earth Orbit

Erebor is initially co-orbital with the moon after having performed a separate burn to escape from lunar orbit. Further refueling is carried out in this orbit so that the hydrogen tank is at its maximum capacity, hence this is taken as the starting point for the delta-V calculations. Erebor now escapes from the Earth on a parabolic trajectory (i.e. $C_3 = 0$) and enters an orbit around the Sun co-orbital with the Earth. This is because Erebor's acceleration is extremely low making extended burns inside the Earth's sphere of influence impossible once it is already on an escape trajectory.

The semi-major axis of the moon's orbit is 384,400 Km and it has an orbital velocity of 1.022 Km/s. With a perigee at the moon's orbit, the escape velocity is given as:

$$v = \sqrt{\frac{2\mu}{r}} \tag{1.3}$$

Where μ is the standard gravitational parameter (GM, 3.986×10^{14} for the Earth) and r is the radius of the orbit (3.84×10^8 m). Evaluating, the escape velocity is found to be 1.440 Km/s. Subtracting the moon's orbital velocity, the minimum delta-V required to escape Earth from the moon's orbit is 418 m/s.

Transfering to the Asteroid

Erebor is now co-orbital with the Earth around the Sun and must perform a Hohmann Transfer. This is the most efficient method of transferring from one orbit to another, involving raising the aphelion to match the orbit of the final body while maintaining the perihelion at the initial orbit. The velocity of a body in an elliptical orbit is given as:

$$v^2 = \mu\left(\frac{2}{r} - \frac{1}{a}\right) \tag{1.4}$$

Where v is the orbital velocity, μ is the standard gravitational parameter (GM, 1.32×10^{20} for the sun), r is the current orbital radius and a is the semi-major axis of the orbit.

Erebor is in an orbit with $r = 1$ AU, $a = 1$ AU (1 AU = 1.49×10^{11}m). Calculating, we get an orbital velocity of 29.79 Km/s. Now, Erebor raises the aphelion to 1.41 AU, which is the aphelion of Ryugu. This orbit has a semi-major axis of $(1.4 + 1) \div 2$ or 1.2 AU. This orbit will have a velocity of 32.22 Km/s at perihelion. Subtracting, we get a delta-V of 2.43 Km/s. Once Erebor arrives at aphelion, the perihelion is decreased to 0.96 AU, which is the perihelion of 162173 Ryugu. Before the maneuver, the velocity at aphelion was 22.85 Km/s and afterwards it is 22.58 Km/s, hence the delta-V is 0.27 Km/s, bringing the total delta-V after Earth escape upto 2.7 Km/s.

Target	Delta-V (Km/s, from LEO)
Nereus	4.987
Bennu	5.096
Didymos	5.162
Anteros	5.440
Mars (orbit)	6.1
Moon (orbit)	4.8

Table 1.2: Delta-V Requirements

Thus, the minimum delta-V required by Erebor is 3.118 m/s, not accounting for plane change maneuvers and other corrections. An accurate delta-V figure to reach 162173 Ryugu has been calculated to be 4.31 Km/s for a one-way mission and 4.61 Km/s for a return mission, however LEO is used as a starting point here and hence the higher delta-V. Many targets have a higher delta-V requirement than Ryugu, such as 1943 Anteros (5.44 Km/s). Hence, a delta-V of 7 Km/s has been chosen for Erebor. Table 1.2 lists the delta-V requirements to reach several asteroids and other destinations.

Main belt asteroids are also accessible to Erebor; however, refuelling is required to return to Earth. As calculated by Anthony Taylor et al [Tay+93], when starting in LEO, 34,760 main belt objects are accessible with a delta-V of 8.5 Km/s, 3986 with a delta-V of 8 Km/s, 96 with a delta-V of 7.5 Km/s, 19 with a delta-V of 7.3 Km/s and just 4 with a delta-V of 7 Km/s. Erebor has only 7 Km/s of delta-V, although this is not a problem as it is constructed in lunar orbit and not in LEO. Hence, all of these targets can be reached without refuelling.

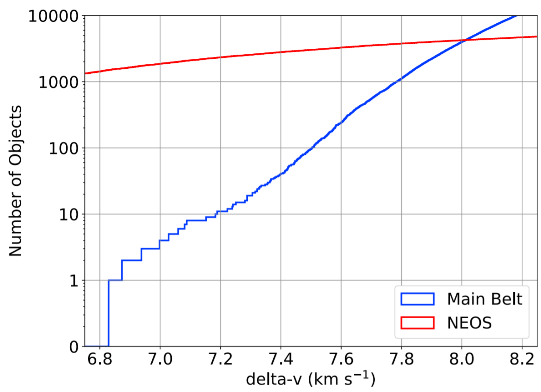


Figure 1.1: A Delta-V map of the known Main Belt Asteroids[1]

In practice, Erebor never returns back to Earth except once every few decades for reactor refueling. Most of the maneuvers are between asteroids with similar orbits hence the delta-V required is much lower. However these figures are applicable to craft such as the RATHAs and ALBATROSS which must return to Earth and head back out to Erebor again.

Power Consumption

It is difficult to estimate the power required to operate the nuclear thermal rocket as a lot of the thermal energy is not converted to heat. Hence, power consumption can be extrapolated

[1] Image credit: A Delta-V map of the known Main Belt Asteroids, Anthony Taylor et al[Tay+93]

from the NERVA XE engine. The NERVA XE engine, as tested in 1968, had an exhaust velocity of 8.3 Km/s in a vacuum, a thrust of 246.6 kN and a power consumption of 1140 MW. Scaling this up linearly to a thrust of 3,000 kN, we get a total power consumption of 13,868.61 MW.

Engine Efficiency

As derived in Appendix B.5, we can write the power of a rocket engine as $E = \frac{1}{2}Fv_e$. Plugging in these values for Erebor's propulsion system, we get a useful power output of 12,450 MW. This results in an efficiency of about 89.77%.

1.3.2 RATHA

The RATHA (Reusable Atomic-powered Transport Habitat for Asteroid station) is one of the two transport ship designs which supply Erebor. It uses a nuclear thermal rocket (NTR) which runs on liquid hydrogen fuel.[Fin91] As compared to the other ship (ALBATROSS) the RATHA utilizes short-duration trajectories when traveling to and from Erebor, it is used to transport crew and other valuable cargo, as opposed to bulk cargo (transported by the ALBATROSS).
The total payload capacity ofÂăeach RATHA is 100,000 tons with a maximum delta-V of 7 km/s. The normal crew capacity is 750 people (representing 10% of Erebor's total population). However, in the event of an emergency, each RATHA can accommodate 2,500 people by deploying inflatable habitats inside the unpressurized cargo compartment. Thus, the entire population of 7,500 can be evacuated onboard just three RATHAs.

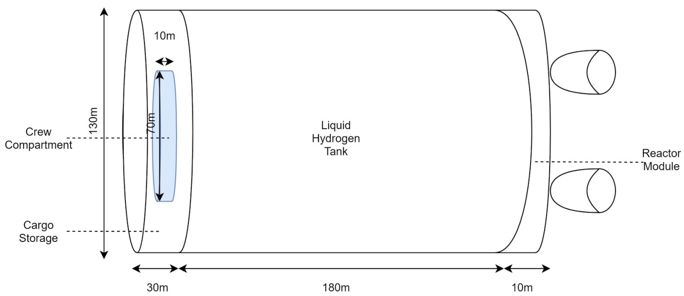


Figure 1.2: RATHA

Design

The RATHAs are a cylinder with a radius of 65 m and 220 m long. They are made out of an aluminium and titanium alloy (the same as Erebor) which provides structural strength while also keeping the dry mass low. The RATHAs are divided into three sections: the crew and cargo compartment, the hydrogen tank, and the nuclear reactor and engines.Âă

Crew and Cargo Compartment The forward section is the cargo and crew compartment. It takes the form of two concentric cylinders, the crew compartment contained within the larger cargo compartment. The pressurized crew compartment of the RATHA is 10 m long and can accommodate 750 people for the duration of the voyage. Each passenger is allocated 50 $m^3$of habitable volume, for a total of 37,500 m^3. Thus, the required radius is 34.54 m, rounded up to 35 m.
The unpressurized cargo compartment completely surrounds the crew compartment, thus protecting the crew from radiation. It is 30 m long, ensuring that the 10 m long crew compartment is completely encapsulated inside. The total volume of the cargo compartment has been chosen to be 3.5×10^5 m^3, allowing for bulky cargo such as replacement components for Erebor to be carried inside. Hence, after accounting for the volume of the crew compartment contained inside, the radius obtained is 64.12 m, rounded up to 65 m.

Hydrogen Tank The hydrogen tank is located between the cargo compartment and the nuclear reactor and hence also serves to isolate the crew from the reactor. Liquid hydrogen is extremely volatile and must be stored at 20 K. In order to reduce insulation requirements, the RATHA maintains an attitude with the cargo compartment towards the sun, keeping the hydrogen tank in shadow. The RATHA has a maximum delta-V of 7 Km/s. The fuel required is calculated using the Tsiolkovsky rocket equation:

$$\Delta V = v_e \ln \frac{m_0}{m_f} \tag{1.5}$$

Where v_e is the exhaust velocity (8.3 Km/s for a NTR), m_0 is the wet mass and m_f is the dry mass (Section 2.2). This is estimated to be 25,000 tons or 125,000 tons including the payload. Calculating, the value of the wet mass is 293,00 tons and hence the maximum mass of fuelÂăis 168,800 tons. As delta-V requirements decrease, the fuel required reduces exponentially. The length of the hydrogen tank is 180 m, obtained by dividing the mass of fuel (168,000 tons) by the density of liquid hydrogen (71 Kg/m^3) to get the required volume. As the tank is a cylinder with a radius of 65 m, the length is readily calculated.

Engines and Reactor The reactor compartment is 10 m long and houses the nuclear reactor and the thermal rocket units. The NTR itself is a scaled-down version of the pebble-bed design used in Erebor. It has a thrust of 293 kN, so that a fully fuelled RATHA has an acceleration of 1mm/s^2. The power consumption of the engine is 1,350 MW, extrapolating from the NERVA XE engine from 1968 (which had a power consumption of 1,140 MW for 246.6 kN). Some power is required for life support and communications; hence the total output of the reactor is 1,400 MW.

Aerobraking

Aerobraking or using the Earth's atmosphere to slow down enough to get captured by gravity is used to save fuel when returning to Earth. This explains the rationale of the cylindrical shape of the RATHA, with the large flat surface providing the required atmospheric drag. This surface is covered with heat-resistant tiles to protect the structure from the intense heat generated. As heat shields add excess weight to the RATHA, aerobraking is spread over multiple passes through the atmosphere to reduce the peak thermal load.
In order to escape from LEO and enter a $C_3 = 0$ orbit (zero characteristic energy, that is the trajectory which is parabolic and whose energy at infinity is 0), 3.2 Km/s of delta-V is required. Hence, an object on a similar trajectory also require 3.2 Km/s of delta-V to enter LEO, which is the minimum delta-V which can be saved by using aerobraking. In practice, RATHAs return to Earth on orbits with $C_3 > 0$ (hyperbolic trajectories) and hence the delta-V saved is even more.

1.3.3 ALBATROSS

The ALBATROSS (Autonomous Long-duration Bulk Article TRansporter Operated using Solar Sails) is the second class of spacecraft transporting material to and from Erebor. Its primary purpose is to transport material from Erebor across the solar system at a low cost. Hence, like its namesake which uses winds to soar for hundreds of kilometers without flapping its wings, it uses solar sails to produce thrust from solar radiation pressure without expending any propellant. Although the thrust produced is very low and hence the time taken to perform

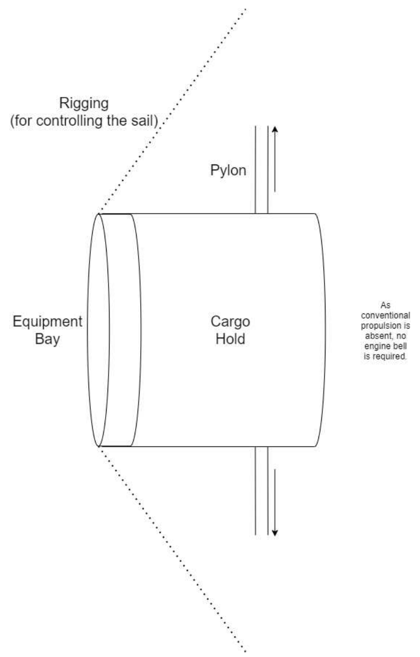


Figure 1.3: ALBATROSS

maneuvers is very long (on the order of a few years per km/s delta-V), it is irrelevant as the ALBATROSS is unmanned and transports cargo such as metals which are not time sensitive.
Since the ALBATROSSes do not require fuel or expensive equipment such as engines, it is feasible to build and operate a large fleet (as compared to the RATHAs). Hence, even though the journey may take several years, the ALBATROSSes arrive at Earth (and other destinations) at regular intervals (roughly every 50 days, see below) which ensures a continuous supply of material.

Design

The ALBATROSS has three main components: the hull, the pylons supporting the solar sail and the sail itself.

The Hull The hull is a cylinder with a radius of 50 m and a length of 100m. The majority of the internal volume is occupied by the cargo hold and the rest is the equipment bay containing the avionics, communication equipment, winches for manipulating the rigging and the fuel tanks for the hypergolic thrusters. Since the hull is unpressurized and does not need to withstand large structural loads, it is made out of thin sheet metal and reinforced using spars. This allows the dry mass of the ALBATROSS (including the sail but excluding cargo) to be kept under 25,000 tons.

Solar Sail The solar sail is made out of matte aluminium foil, which is cheap, easy to produce on Erebor (allowing it to be repaired or replaced easily) and can be recycled at the end of its life. Due to aluminium's strength, the thickness of the sail can be reduced without impacting the integrity of the structure. Aluminium foil is also extremely reflective and hence no additional reflective coating is required, drastically reducing the cost. Accounting for the area occupied by the pylons and rigging, the total area of the sail is 700 km^2 (instead of 706.85 km^2 obtained from πr^2).
The aluminium foil used is 2.5 microns thick. As aluminum has a density of 2700 kg/m^3, the sail has a mass of 6.75 gm/m^2(for a total mass of 4,725 tons). To compensate for the fragile nature of the sail, it is reinforced using PBO (poly-p-phenylene-2,6-benzobisoxazole, commercially available as Zylon®) (see Section 4.1.1) cables, in addition to the rigging used for control.

Pylons The solar sail is attached between 8 pylons, each positioned at intervals of 45° around the hull. These are 15 km long and are constructed out of an Fe-Al-Ti alloy (which has a high specific strength). Despite the length of each pylon, as the pressure (and hence the acceleration) produced by the sail is low, the structural stresses are within the limits of the materials.
The solar sail is stabilized and reinforced using Zylon® cables. These are used to transfer the thrust of the solar sail to the ALBATROSS hull and also prevent oscillations in the pylons. Similar cables are used as rigging to manipulate the sail. The winches are located in the equipment bay of the ALBATROSS.

Payload

The payload capacity of an ALBATROSS is 125,000 tons, or the production output of Erebor every 25 days (500,000 tons of material every 100 days, elaborated in Section 4.1.4). As the dry mass is 25,000 tons, the maximum mass of an ALBATROSS is 150,000 tons.
Some of the advantages of having a relatively small payload capacity is that the unit cost of an ALBATROSS is reduced which in turn increases the number produced. Having a large number of ALBATROSSes is essential in ensuring a continuous supply of material. As they are filled up faster and can depart frequently, it reduces the gap between consecutive arrivals at any location. Also, due to physical constraints such as the properties of materials (for example, the tensile strength of the pylons), there is a limit to the size of a solar sail. Hence, the sails on a smaller craft can be made proportionally larger than those on a larger one which increases the acceleration and reduces the travel time.

Solar Radiation Pressure Thrust

The force experienced by a body due to solar radiation pressure is given by the formula:

$$P = \frac{2G_{sc}\cos^2\alpha}{cR^2} \tag{1.6}$$

Where r is the reflectivity of the material, G_{sc} is the solar constant of 1,361 kW/m^2, c is the speed of light, R is the distance of the body from the Sun and α is the angle of the body relative to the sun. Thus, at a distance of 1 AU or 1.495×10^{11} m, the pressure experienced by an ideal solar sail is 9.08 μPa.
The solar sail of an ALBATROSS is circular with a radius 15 km. Some of this area is occupied by the hull of the ALBATROSS, the pylons and rigging. Also, due to slight crumpling and curvature in the sail, not all of the sail produces ideal pressure. Hence, an effective surface area of 675 km^{2}is used instead of the total sail area.
The aluminium foil used as the sail membrane is not an ideal reflector either. As demonstrated by Victor Pozzobon et al [Poz+20], matte aluminum foil reflects 86% of light in the visible range and 97% of near infrared radiation. However, due to the degradation of the sail over several years of exposure to unfiltered solar radiation as well as micrometeorites, a total reflectivity of 85% is assumed. Thus, the maximum thrust produced (when the sail is perpendicular to the incident radiation) at a distance of 1 AU from the Sun is 5209.65 N (or 5.2 kN).

Acceleration Using the thrust of 5.2 kN, the acceleration when fully laden (125,000 tons) is 0.0416 mm/s^2 and 0.208 mm/s^2 when empty (25,000 tons).

Attitude Control

Attitude control is crucial for ensuring the stability of the solar sail and the correct orientation for maneuvers. The ALBATROSS controls its attitude in two ways: using the sail itself and with hypergolic thrusters.

1. As with sailing ships, Erebors's attitude is manipulated by the solar sail. A similar arrangement was pioneered on the Mariner 4 probe, which used solar pressure vanes to control its attitude, albeit on a smaller scale. The 8 octants of the sail can be extended and retracted, providing attitude control in the pitch and yaw axes. Limited roll control is achieved by warping the curvature of the sail.
2. Thrusters using hypergolic propellent are placed on the tips of the pylons, in order to maximize torque. These are required only in limited circumstances, such as when the solar sail cannot provide adequate torque or during rendezvous with other vessels. Due to the limited consumption and excellent storability of hypergolic propellants, refuelling is only performed upon returning to Earth.

Flow of Operations

The main function of the ALBATROSSes is to deliver material from Erebor to Earth or other destinations. The flow of this process is:

1. Once it arrives at Erebor, cargo is loaded in the hull of the ALBATROSS.
2. After loading is complete, it uses its solar sail to gradually alter its trajectory over a long period until it is coorbital with the Earth (or any other celestial body): i.e., its relative velocity has been reduced. This is necessary as the ALBATROSS lacks conventional propulsion and cannot perform orbital insertion burn. Instead, it must be captured by the Earth's gravity. Aerobraking is not possible due to the fragile solar sail.
3. Low Earth Orbit (LEO) is a highly congested environment with both active spacecraft and space debris present. Since the ALBATROSS cannot perform debris avoidance maneuvers and micrometeorite debris can damage the fragile solar sail, it is not practical for it to operate in LEO. Hence, cislunar space is used exclusively for ALBATROSS operations.
4. The ALBATROSS is unloaded at the L4 and L5 Lagrange points, as these do not require constant orbital adjustments like the L1, L2 and L3 points which are unstable.
5. Space tugs handle rendezvous and docking as well as any orbit changes required, since the thrusters on the ALBATROSS are not sufficiently powerful. It is unnecessary to include more powerful thrusters as these are required only when operating at Erebor or in Earth orbit. Most of the time, these would just be extra unnecessary mass.
6. The Earth escape maneuver may require several months or even years, although the acceleration is a lot higher without payload. This is performed beyond the orbit of the moon to avoid interfering in the operations of other spacecraft.

1.4 Internal Transport

1.4.1 GHARs

GHARs to NATASHA

From Figures 2.1 and 2.3, we see that the GHARs are adjacent to a non-rotating spoke of the NATASHA. Between each spoke and the GHARs, we run maglev trains. These speed up to the tangential velocity of the GHARs and reach a relative velocity of zero at a point where the GHARs have a train station on the margin. Citizens are free to take one of the trains on either 'level'. Trains are pressurized to 1 atm, to eliminate the need for airlocks when the trains are at the GHAR stations. These trains then slow down to zero velocity relative to the NATASHA at one of the spokes. Elevators then transfer people 'up' the spokes to the Logistics Hub. A similar process follows for goods. Note that the trains are pressurized to 1 atm to eliminate the need for airlocks in the GHARs.

Train	Time	Purpose
Rosalind Franklin Express	24/7	General-purpose people and goods train running every half hour, one per GHAR.
Richard Feynman Express	0200 hours	Nightly runs from NATASHA to GHARs, carrying food and essential everyday supplies.
Nikola Tesla Express	0230 hours	Bi-weekly maintenance train, carrying minor GHAR repair materials.
Copernicus Express	0300 hours	Nightly solid and liquid waste transport to the MIU.
Johannes Kepler Express	24/7	Transports compressed O_2 from NATASHA to the GHARS and compressed CO_2 from the GHARs to NATASHA. Runs every half an hour, one per GHAR.

Table 1.3: Details of GHAR to NATASHA trains

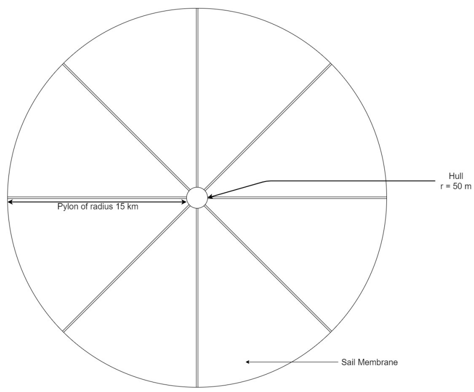


Figure 1.4: ALBATROSS sail (hull not to scale)

Within the GHAR

From Figure 2.4 it is clear that the top level of the GHARs is reserved for trains. These are slower maglev trains which serve purely to transport people from one location within the GHAR to another.

1.4.2 NATASHA

NATASHA exports its crop produce via elevators to the Logistics Hub, then to MIU-A2 for further processing. The processed food is then transported back to the GHARs via NATASHA spokes and the maglev trains.

1.4.3 MIU and Logistics Hub

Within the MIU and Logistics Hub, modified robots are used for transport. These are very similar to trams with rails and transport both humans and goods. Further information is in Section 3.3.

Chapter 2: Structure

The structure of Erebor is optimized for movement. The aim is to minimize the mass of the station, and ensure that the station can bear the internal forces due to acceleration. Moreover, areas for living, agriculture, and most importantly, industry also need to be included. This is achieved while minimizing mass and the complexity of the systems. Erebor has four major components: rotating torii for inhabitation (1g), a zero gravity area for agriculture which doubles as radiation shielding, another larger zero gravity area for industry and metals processing, and the hydrogen fuel tank.
While reading this section, the reader is encouraged to refer to Appendix A.3 to gain a better understanding of the structure.

2.1 Dimensions

Component	Dimensions	Value
Erebor	Dry Mass	12,500,000,000 Kg
NATASHA	Toroidal (inner) radius	250 m
	Semi-major axis	50 m
	Semi-minor axis	20 m
	Cross sectional area	1,470.2 m^2
	Volume	2,309,384.76 m^3
GHAR (Unit)	Torodial (inner) radius	250 m
	Height	21 m
	Breadth	21 m
	Cross Section	412.72 m^2
	Circumference	1,570.79 m^2
	Volume	648,300 m^3
	Usable Area	230,790 m^2
Hydrogen Tank	Radius	400 m
	Capacity	247,175,141.24 m^3
MIU	Radius	130.7 m
	Length	200 m
	Volume	1.07×10^7 m^3
Logistics Hub	Radius	130.7 m
	Length	150 m
	Volume	8.05×10^6 m^3
Reactor	Radius	130.7 m
	Length	50 m
	Output	5.5 GW

Table 2.1: Component Dimensions

2.2 Mass Estimation

It is essential to know the mass of Erebor in order to calculate the volume of hydrogen fuel required for a delta-V of 7 Km/s. In order to calculate the total mass of Erebor, an average value for the density is used. This value, or the bulk density (ρ), is a weighted average of the densities of the various materials constituting the interior of Erebor. We have calculated two separate bulk densities: one for the pressurized areas (the NATASHA and GHARs) and another one for the unpressurized segments (the Logistics Hub, MIU and reactor). However, this represents just the interior and excludes the mass of the hull. The hull is considerably more heavy as it must:
(a) Hold pressure,
(b) Protect the interior from micrometeorite impacts, and
(c) Provide structural integrity.
For the hull, a surface area density (σ) has been calculated. This represents the mass of a one m^2 section of the hull. Again,

Area Type	Components	Percentage by Volume	Density of Component (kg/m^3)
Pressurized Areas	Air	85%	1.225
	Intermediate Density (Water, Plastics)	10%	≈ 1000
	Metals (Ti, Al)	5%	Al: 2700 Ti: 4500 Mean: 3000
			246.04 kg/m^3
Unpressurized Areas	Vacuum	90%	0
	Metals	10%	3000
			300 kg/m^3

Table 2.2: Volume density

Hull Type	Component	Thickness	Density (kg/m^3)	Mass per Area kg/m^2
Pressurized	Outer Hull (Ti-Al Alloy)	5mm	3000	15
	Kevlar Layer (Whipple Shield)	10cm	138	138
	Pressure Hull (Ti-Al Alloy)	2cm	3000	60
				213 kg/m^2
Un-pressurized	Outer Hull (Ti-Al Alloy)	5mm	3000	15
	Kevlar Layer (Whipple Shield)	10cm	138	138
				153 kg/m^2

Table 2.3: Area density

the pressurized hull and the unpressurized hulls have separate densities.

Multiplying these densities by the volumes of the relevant parts yields a mass of 12,099,586,593.3 Kg. There are many factors which have not been accounted for in the above mass estimates. The given figures are also purely theoretical and are bound to change once actual construction begins. Hence, the dry mass is taken as 12,500,000 tons.

2.3 Hybrid Structure

Description

Humans live in two contra-rotating torii, the GHARs, with 3,750 of the total 7,500 in each. Naturally, these torii have the highest level of radiation shielding. The non-rotating area surrounds these two torii, forming a protective shell.

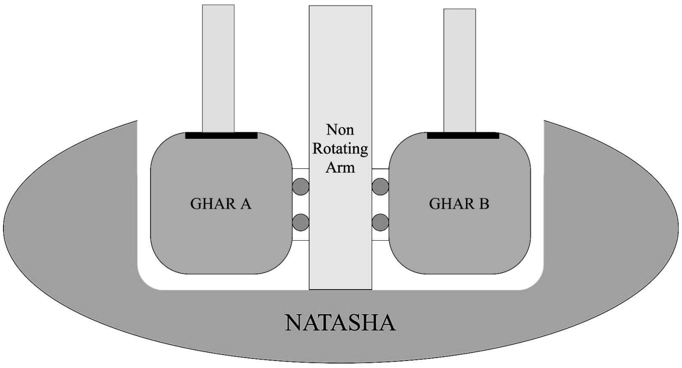
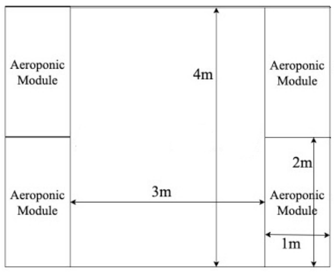
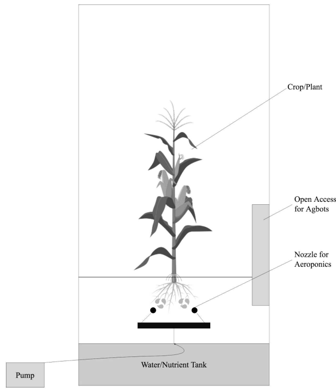


Figure 2.1: Hybrid torus cross section with maglev trains.



(a) Pathways in NATASHA



(b) Single aeroponic module

Figure 2.2: Aeroponics

Rationale

In the aim to reduce mass, the rotating and one of the non-rotating areas are integrated into a single structure, in a manner such that the latter provides radiation shielding for the former. The advantages of such design are:

1. The presence of an uninhabited structure around the GHARs allows NATASHA to serve as radiation shielding. This eliminates the need for separate materials and structures, thus significantly reducing mass.
2. Moreover, such a system places the radiation shielding in a non-rotating structure, reducing the mass which the rotating systems have to power.
3. Spinning up is simple, using sets of magnets between the non-rotating shell and the torus to be rotated, similar to the propulsion of maglev trains.
4. Such a structure allows internal transportation to have a simpler design, which can readily be achieved by having high-speed maglev trains that match speeds with the torus, load up, and slow down again to zero velocity (further described in Section 1.4.1).

Spoke Design

Location	Dimensions	Comment
GHAR (Unit) Spokes	Radius: 7 m, Height: 240 m	These are rotating arms. These 5 arms are hollow and do not have any internals. They do not bear any load, as the centripetal force is borne by the GHAR itself. They only bear load when Erebor is accelerating, and the resultant reaction forces of the electromagnets.
NATASHA Spokes	Radius: 11 m, Height: 120 m	These are 5 non-rotating arms. They transport materials and people from the Monorail Maglev Train Stations and NATASHA to the Erebor. These arms do not have to bear any load when the station is at rest. They bear the forces/load applied by NATASHA and the electromagnets when Erebor accelerates.

Table 2.4: Spokes

2.3.1 NATASHA

Description

The NATASHA (Figure 2.1) surrounds the GHARs. The NATASHA's cross section is elliptical with a rectangular cut-out, which maintains equal thickness and provides enough volume for required crop growth. Its total mass is 630,000 tons It has multiple 'stories' for aeroponics and internal transport systems for the movement of harvested crop. The NATASHA also includes the maglev train system described in Section 1.4.1. NATASHA relies on three levels of shielding: the hull, aeroponic water systems, and the air and plants. This system is further explained in Section 2.3.1. NATASHA is divided by bulkheads into several compartments, each dedicated to a different crop. This allows for the climatic conditions such as humidity, temperature, photoperiod, carbon-dioxide content, etc., to be adjusted for each individual crop to achieve maximum yield.

Dimensions

1. **Radius:** The radius of the NATASHA is 250 meters.[1]
2. **Cross section:** The cross section is an ellipse with an area taken out, where the GHARs rotate. The cross sectional area comes out to be 1,470.2 m^2.
3. **Arable volume:** Not all of the total volume can be utilized. Robots need to be able to access each plant from all sides for harvesting and maintenance operations; necessitating a system of pathways, which will affect the arable volume. From Section 2.3.1, each aeroponic module is 2 m^3. Pathways of height 4m and width 3m are created, such that two 'floors' may be accessed, as shown in Figure 2.2a. In a single NATASHA cross section, we can fit an effective 70 units of pathway and four modules, or 109,956 modules (219,912 plants) in total. This coincides perfectly with the Table 3.3 estimate of 217,500m^2, and leaves room to spare.

Aeroponics

Aeroponics is the method of growing plants in an air medium, using sprays to provide nutrients directly to the roots.

Aeroponics is carried out in the NATASHA by creating cuboidal cells of 2m^3 for each plant[2] (1m × 1m × 2m). Two plants are grown in each module following a companion planting system.[3]

Shown in Figure 2.2b is one aeroponic unit cell, which contains two plants (one visible, other behind).

The nutrient-water tanks for all the modules on one level are interconnected, forming one large tank. The pump for the nozzles is shared between eight unit cells, four on one level and four on

[1] The rationale for this value is relevant more to the GHARs than to NATASHA, and is covered in Section 2.3.2.

[2] Median crop height is approximately 2 meters, averaged over a Erebor's variety of crops.

[3] Companion planting has many benefits, and has been carried out in the Himalayas to improve yield.[Git15]

the level below. A part of the cell is left open for access to the agricultural robots (Agbots, described in Section 3.3). Agbots have access to both the aeroponic machinery and the plant.

Seasons

The NATASHA is biodynamically lighted (described in Section 3.1.5). Biodynamic lighting is exploited to have different seasons in different parts of the NATASHA by varying humidity, photoperiod, and temperature. Crops can be divided into three types by season of growth: monsoon, winter and summer. The arrangement of seasonal sections by crop is shown in Figure A.2.

2.3.2 GHARs

Description

The GHARs (Gravity Habitat for All Residents) are the set of two rotating torii used to house the population of 7,500, divided equally between the two. The GHARs have radii of 250 meters each, and have a gravitational acceleration of 9.8 m^2. From the density tables, the total mass of a single GHAR is 190,000 tons. The radius of rotation is large enough to neglect Coriolis forces, and the resulting angular velocity is within human comfort levels. One of the salient advantages associated with the smaller dimensions of the GHAR (as compared to a traditional toroidal habitat) is its ability to bear its own structural load through tension in the ring as opposed to tension in the spokes. Hence, the reinforcement in the spokes can be reduced, saving valuable mass. The GHARs are contra-rotating to minimize internal torque on Erebor. The two GHARs are in time zones differing by 12 hours. This makes late night shifts in vital areas such as the MIU and piloting unnecessary, as it is always somebody's daytime. The lighting within is biodynamic.

Dimensions

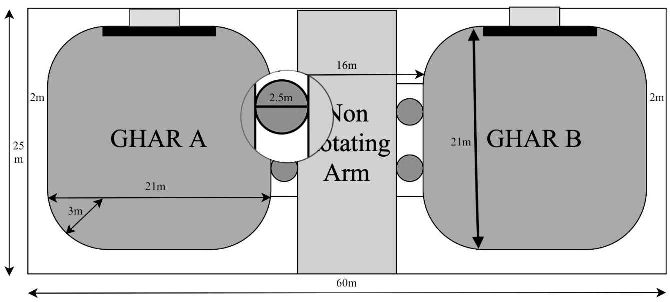


Figure 2.3: Detailed GHAR dimensions

The foremost concern of any space colony is the comfort and well-being of the residents. A large part of this comfort is determinable by the amount of space each citizen should have. Allocating living area is a delicate balance, too much area is wasteful, and too little is a study in overpopulation. On a more serious note, around 60 square meters of space per citizen is an ideal balance (with reference to urban vs rural area/citizen). A torus with a rounded square cross section (internal side 21 meters) is ideal for this application, as it allows the torus to be relatively light and yet provide enough living area. These 21 meters are divided into 7 floors of 3 meters each.

Internal Design

As shown in Figure 2.4, a GHAR is divided into seven floors, each of three meters total height. Some premium flats, sports complexes, restaurants, hotels, etc., have a double or triple height ceiling. In addition to this, the large central main road

To find	Calculations
Angular Velocity	We know, $a = \omega^2 r$, where a=acceleration, ω=angular velocity, and r=radius Thus, $\omega = 0.191321$ rad/s. This is equal to 1.83 rpm, which is well within the values for human comfort as estimated by Graybiel's 1960 experiment[CG61]. We assume the radius to be 262.5 meters to give Earth gravity at the middle floor of the GHAR. This reduces the variation between the floor for which acceleration is 9.8 m/s^2 and any other floor.
Tangential Velocity	We know, $\omega = 0.191321$ rad/s, and $r = 250$ meters at the level of the trains. Hence, $v = \omega r = 47.83$ m/s = 172.19 km/h. This is the speed the trains must reach to match with the GHARs.
Tension in GHAR	Tension in a rotating ring (which bears its own load) is given by $T = mv^2/2\pi R$. Since v^2/r is g, the tension after substitution is 592,693,008 N $\approx$ 593 MN.
Tensile Strength and Area Requirement of Material per Cross Section	The total tension in the GHAR is $\approx$ 593 MN, we need to find the area of load bearing material in a given cross-section. The load bearing material chosen is titanium, which is readily obtainable on the moon in the form of ilmenite or $FeTiO_3$. Titanium has an endurance limit of 223 MPa, but stress is restricted to 200 MPa. This gives the total area of titanium required as 2.965 m^2 per cross section, rounded to 3 m^2.
Maximum Total Area	490,197.96 m^2
Area per citizen	The area per citizen is given by: total area/-total number of people = 65.35 m^2

Table 2.5: GHARs Dimensions

and some park areas also have larger ceiling heights. At the top level, trains run for transport within the GHARs. These are also maglev, but slower and with the purpose of public transport, similar to an underground or metro system. Also, there are tracks on the Main Road for Transport Robots which run small scale transport, ambulances, etc.
Apartments are of two types: premium and economy, depending on the means of the citizen. In addition, citizens can buy multiple floors depending on availability and with permission from the government. The apartments closer to the parks naturally have more demand and greater prices, whereas those near train stations are cheaper. All apartments are 21 meters wide by a length of 60 meters for Premium (1260 m^2) and 40 meters (840 m^2) for Economy apartments. The internal layout of these apartments is similar to those on Earth.

Everyday Life

Other than the apartments for residence, the GHARs have public parks, hotels for tourists, restaurants, sports complexes, hospitals, and schools. There are 4 hospitals in total, 2 per GHAR. Also, there is one school and one college per GHAR. Since Erebor has a student populace of around 2,000 (from Section 5.1) each school/college has around 500 students. There are 3 office blocks in each GHAR, or a total of 6 office blocks. This where the engineers, scientists, pilots, and other citizens whose occupations do not require leaving the GHARs work. There are

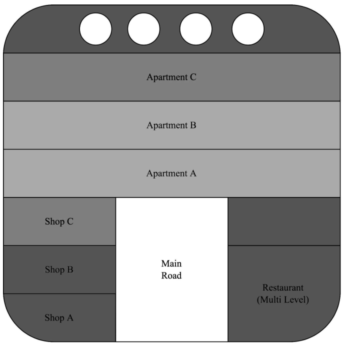


Figure 2.4: GHAR cross section

chemical, industrial, and genetic laboratories. The exact layout of these sections is given in Appendix A.

Spinning Up

The GHARs have a mass large enough that mere motors at the center cannot spin it up to the required angular velocity. Generally, this problem is solved using thrusters on the hull of a rotating ring. However, this creates unnecessary stresses at specific points along the hull, which, on stress analysis, often require further reinforcement. Fortunately for Erebor, the GHARs are surrounded by the non-rotating NATASHA. This makes spinning up almost as simple as internal transport: magnetic propulsion is used to spin up each of the GHARs. In Figure 2.1, these electro-magnets are located at the 'bottom' of the GHARs.
The GHARs are slowly spun up after construction. Once the GHARs are up to speed, this system is used only to maintain the required momentum. As is evident, a surrounding non-rotating shell is a useful and innovative feature of Erebor.

2.4 Hydrogen Tank

Erebor's hydrogen tank is a vital component which enables liquid hydrogen to be stored at temperatures as low as 20 K. Storage of hydrogen at such low temperatures is vital as liquid hydrogen has a density of 70.8 Kg/m^3, compared to only 8.3×10^{-2} Kg/m^{3}for gaseous hydrogen. Storing hydrogen as a liquid helps to decrease the volume required for storage but extra precautions have to be taken to maintain hydrogen at cryogenic temperatures. In order to maintain these temperatures, Erebor's hydrogen tank is kept out of direct exposure to sunlight. This is done using the Thermal Protection System (TPS) sunshade which a reflective coating further discussed in Section 3.1.4. This keeps the hydrogen tank in complete darkness and prevents direct sunlight from boiling off the hydrogen. As the temperature of space in the shade is only about 2.7 K due to the cosmic background radiation, the hydrogen tank loses enough heat through radiation in order to maintain the temperature at 20 K. The loss of heat due to radiation is balanced by heat absorbed from the other parts of Erebor. Hence, little to no boil off is required to maintain the temperature of the hydrogen tank. However, when Erebor performs maneuvers, it may have to change its orientation which exposes the hydrogen tank to sunlight. However in this case, some boiloff is acceptable.

2.4.1 Internal Structure

The hydrogen tank has a double walled structure. One side of the outer wall is covered with a layer of multi-layered insulation or MLI while the other side is covered with black paint to increase radiation. The same black painted side has louvres to increase surface area for radiation. Both walls are made out of aluminium and titanium, just like the rest of Erebor. The distance between these walls is 5 m. Hence, the tank is comprised of a pair of two concentric spheres, one with a radius of 130.7 m and the other with a radius of 125m. The space between these walls also stores fuel. Normally, as space is cooler than liquid hydrogen, a single layered hull is all that is needed. However when Erebor changes its attitude for maneuvers, the tank is exposed to direct sunlight. Thus, the space between the two tanks is drained first and a vacuum layer is formed between the inner layer and outer layer. This slows the transfer of heat from the outer wall to the liquid hydrogen, reducing boiloff.

2.4.2 Volume Calculations

In order to calculate the dimensions of the hydrogen tank, we first consider Erebor's fuel requirements. Erebor's dry mass is estimated to be about 12,500,000 tons. Erebor has a maximum possible delta-V of 7 Km/s with engines that have an exhaust velocity of 8.3 Km/s. Using Tsiolkovsky's rocket equation (see Appendix B.2), we get a total wet mass of 2.905×10^{10} Kg rounded up to 3.0×10^{10} Kg for a total fuel mass of 17,500,000 tons. The density of liquid hydrogen is 70.8 Kg/m^3, and dividing we get a total volume of 247,175,141.243 m^3.
Note that such a large quantity of fuel is only required when Erebor needs a delta-V of 7 Km/s, which is rare. Normally, Erebor does not need a full load of fuel as ice is readily available at most asteroids. Also, as the delta-V decreases, the mass of fuel goes down exponentially.

Why a Sphere?

The hydrogen tank is spherical in shape. This has been chosen as a sphere has the highest volume to surface area ratio of all 3-dimensional solids.Âă This provides three main advantages:

1. Less surface area of the sphere is exposed to the space, meaning less heat is absorbed by the tank in the event that it is in direct sunlight, for example during maneuvers.
2. Less material is required for the tank, reducing the dry mass.
3. A sphere is one of the strongest shapes, as there are no weak points such as corners thereby uniformly distributing the forces. This is important as the tank walls must bear the load of the hydrogen fuel when the engines are firing.

Radius Calculations The volume of Erebor's hydrogen tank is known, at 247,175,141.24 m^3. Hence, the radius of the hydrogen tank is 389.3 m, or 400 m for the whole double-walled structure including the insulation and vacuum space between the walls.Âă

2.4.3 Struts

There is a network of struts located between the NATASHA and the hydrogen tank. When Erebor accelerates these serve the purpose of extra support and structural integrity, along with taking away sideways forces on the spokes. These are made of PBO (poly-p-phenylene-2,6-benzobisoxazole/Zylon®) due to its high tensile strength (5.8 GPa), and are arranged in a uniform lattice structure to maximize efficiency. We use a total of 125 struts. The calculation of this value is given in Appendix B.7.

2.5 Industry and Support Components

The MIU and the Logistics Hub have the same radius and together form a cylinder 350 meters long. The MIU is the industrial unit, and the Logistics Hub is where the arms are mounted, along with other miscellaneous purposes such as docking.

2.5.1 Main Industrial Unit (MIU)

The MIU or Main Industrial Unit is a cylinder divided into four segments parallel to its circular faces (A, B, C, D) and four

quadrants perpendicular to these faces (1, 2, 3, 4), giving in effect sixteen distinct zones in the MCU. All of these are used for various industrial and maintenance activities.
The MIU has a radius of 130.7 meters (equal to that of the Hydrogen Tank), and a length of 200 meters. Each of the sixteen zones in the MIU is purposed as in Table 2.6. The locations are chosen such that functions which need more than one space are in a continuous block. Both humans and robots perform operations in the MIU. Some have centrifuges to create acceleration where it is required. Humans are not allowed entry in the sections adjacent to the nuclear reactors when they are online.

Unit	Location	Comment
Robotics Workshop	A1	Robots are assembled, reworked, repaired, maintained, etc. in this location.
Agriculture Processing	A2	Harvested crops are brought in at one end, and finished products such as dough from wheat, rice from the husks, etc. are received at the other. This food processing unit is similar to those currently in use on Earth.
3D Printing/Sheet Formation	A3, A4	This unit involves the final processing of the metal and its production into sheets. 3D printing is done in zero gravity to produce finished products at the metal processing site.
Metals Processing	B1, B2, B3, B4	The concentrated material from the asteroid is processed into crude metal ingots. Centrifuges are used to carry out processes which are infeasible in microgravity. Some of the processes carried out include vapor phase refining (such as the Mond process and Kroll process for nickel and titanium respectively as well as reduction using magnesium or hydrogen).
Refining	C1	Crude metals are purified for export. Copper and aluminium are purified electrolytically whereas zone refining is used to purify silicon, gallium, germanium and indium.
Electrolysis of Water	C2, D1	Described in Section 3.2.1.
Electrolysis of Molten Silicates	C3, C4	Described Section 4.1.4.
Incoming Metal Processing	D2, D3, D4	The drones are unloaded and refueled here. The ore from the asteroid is concentrated using various methods, including centrifugation and magnetic separation.

Table 2.6: MIU Zones

2.5.2 Logistics Hub and Docking

The functions of the Logistics Hub and their details are in Table 2.7. Note that parts of the Logistics Hub are open to the vacuum of space (docking, etc).

Function	Comments
NATASHA Arm Load Bearing	When Erebor accelerates, the weight of NATASHA is borne by the struts and the arms. The arms apply load on the Logistics Hub, which is made with enough structural strength to bear this load in conjunction with the struts.
Transport (Arm Lifts)	The lifts in the NATASHA's non-rotating arms end at 5 stations in the Logistics Hub. From here, Class C Transport Robots (refer to Section 3.3) carry people and material to the MIU and the rest of Erebor.
DIMAAG	Erebor's supercomputer, DIMAAG, is located in the Logistics Hub. It is housed in a separate enclosure, and is used for complicated orbital calculations and maneuvers. DIMAAG has direct control over Erebor's engines, thrusters, and robots.
Servers	The storage servers are located adjacent to DIMAAG, and are used to store data on population, governance, history, recreation etc.
Docking: RATHAs and VASPs	The RATHAs dock four at a time to the Logistics Hub, each at right angles to one another and in one plane. The payload is extracted and transported using the Class C Transport Robots
Docking: RATHAs and VASPs	The VASPs dock to the MIU, and deliver their payload to the metal processing units. The VASP design is given in Section 4.1.3.

Table 2.7: Logistics Hub Functions

2.6 Radiation Shielding and Hull Design

Radiation shielding is one of the most crucial aspects of a space settlement. While on Earth, the magnetic field and the atmosphere provide shielding against solar and cosmic radiation. However, no such protection is available in space and hence arrangements must be made to ensure sufficient protection from radiation for the inhabitants of Erebor. Hence, in order to protect the residents of Erebor, special measures have to be taken to shield them from radiation.

2.6.1 Sources

The two main sources of radiation are the Sun and Galactic Cosmic Rays (GCRs). The Sun emits charged particles such as protons, electrons and charged helium nuclei (α-particles) in the form of the solar wind as well as gamma and X-rays. GCRs also consist primarily of charged nuclei such as hydrogen (85%), helium (14%), as well as highly ionizing heavier nuclei. The Sun can also occasionally eject a large amount of plasma in an event called a Coronal Mass Ejection, which can pose a serious danger to the residents of Erebor. All of these are highly ionizing and can cause damage to cell tissues and DNA. However, the real danger is not these charged particles but rather the secondary radiation such as gamma rays produced on interacting with shielding. These are extremely penetrating and ionizing and must be stopped before reaching populated areas. The measures taken to reduce the impact of this secondary radiation is discussed in Section 2.6.3.

2.6.2 Health Risks

The effects of radiation can be felt on a daily basis while living in space. Astronauts report seeing flashes of light due to the interaction of radiation with the retina. In the long run, exposure to ionizing radiation can lead to damage to DNA. Smaller quantities of radiation increase the risk of cancer while doses of radiation above 4 Sieverts (Sv) in a short duration can be fatal. In contrast, the maximum allowed radiation exposure for NASA astronauts over the course of their career ranges from 1 Sv for females of the age of 25 and 4 Sv for males of the age of 55. These limits are chosen such that there is no more than a 3% increase in the lifetime rates of cancer mortality. Onboard Erebor, the radiation shielding is designed such that radiation levels in the GHARs are the same as the background radiation levels on the Earth. Other areas such as the MIU or NATASHA however, may have significantly higher radiation exposures and hence the amount of time spent in these areas per head is closely monitored. Apart from this, monthly health checkups are mandated in order to monitor any radiation-related health issues.

2.6.3 Protection

Radiation protection can be achieved by using a high-density material such as lead or a thick layer of water or packed soil. However, these are extremely heavy and Erebor must be as low mass as possible in order to move from one target to another as efficiently as possible. Hence, the radiation shielding must be as efficient as possible in order to save mass. That is why radiation shielding for the GHARs has been combined with agriculture, as plants have higher radiation tolerances than humans due to their slower cell division rates and can adapt or be genetically engineered to survive high radiation environments. The water in the aeroponics systems also makes an excellent radiation shield. This arrangement provides radiation shielding against all major types of radiation, as discussed in the following sections.

Gamma Rays

Gamma rays are highly penetrating and are best stopped by high density materials such as lead. But this using heavy materials such as lead is impractical due to the aforementioned mass considerations. Hence, gamma rays are stopped over a larger distance as they pass through the air, water, plants and structural material in the NATASHA, as well as the aluminium and titanium hull layers.

Charged Particle Radiation

Beta particles, protons, and other heavier ions can be stopped using traditional shielding materials and metals of high atomic mass and density. However, this produces a secondary radiation which is highly ionizing and damaging. For example, beta particles produce Bremsstrahlung X-rays upon being decelerated. However, the generation of this secondary radiation is avoided when shielding made from lower atomic mass elements such as hydrogen is used. Erebor takes this into consideration, as the water in the aeroponics systems and the plants themselves have a high hydrogen and carbon content and can prevent any secondary radiation generation.

Alpha Particles and Neutrons

Alpha particles or doubly charged helium nuclei are of least concern as they are stopped by even a thin layer of metal. Neutrons on the other hand, are more of a concern. They are also best stopped by low atomic mass elements such as hydrogen, but produce dangerous secondary radiation in the form of gamma rays. These get dissipated on further passage through the NATASHA.

2.6.4 Radiation Shielding

Requirements

According to the Mars Radiation Environment Explorer (MARIE) instrument aboard the Mars Odyssey spacecraft and the Radiation Assessment Detector (RAD) on the Curiosity Rover, a human being in deep space away from the Earth's magnetic field receives about 1.84 ± 0.33 mSv per day from GCRs. This results in about 671.6 ± 120.45 mSv/annum. This is similar to another estimate of 400 mSv to 900 mSv for unshielded humans in interplanetary space for a year. Comparing this to the annual background radiation of 1.5 to 3.5 mSv on average for the Earth and 6.2 mSv in the USA in particular we find that levels of radiation on Erebor are about 100 times higher. However, we desire to shield Erebor by a factor of a 1000, to protect against even high-energy particles.

Erebor's Shielding

In order to know if Erebor has sufficient radiation shielding, we need to see if the incoming radiation is reduced to a level comparable to the natural background radiation on Earth. To do this, we utilize a concept known as the halving thickness, which is the thickness of a given material needed to halve the value of radiation. As we want to reduce incoming radiation by a factor of a 1000, roughly 10 half-value layers are required to provide 2^{10} or 1024 times shielding. The half value layers of some materials along with their densities are given in Table 2.8. Looking at the table, we can see a trend that regardless of the material, about 80 gm of material is required to shield a 1 cm^2 cross section. As any radiation has to pass through several meters of the NATASHA, it is inevitable that they encounter at least 80 gm of material per cm^2, be it air, water, the aluminium hull, plants, etc.

Another important consideration is that most gamma rays and for that matter all other radiation must pass through three hull layers before reaching the GHARs: two layers while entering and exiting the NATASHA and another layer again while entering the GHAR. Only the radiation impacting the roof of the GHARs is not so strongly shielded by the NATASHA. Additional shielding is also implemented here, in the form of a layer of lead.

Reactor Shielding

So far, we have discussed only external sources of radiation. However, Erebor also possesses a large internal source of radiation, namely the nuclear reactor. As the nuclear reactor is not isolated from the rest of Erebor due to the structural instability of a long and thin structure under acceleration, the reactor is directly adjacent to the MIU. There is a thin layer of lead about 1 cm thick between the MIU and reactor. Apart from this, section A of the MIU, i.e. the section directly adjacent to the nuclear reactor, is a robot-only zone when the reactors are online. All maintenance is carried out using robots. Another point is that the GHARS have a 1000 times radiation reduction, whereas cosmic radiation is only a 100 times more than the background radiation on Earth. This helps to further reduce the impact of the reactors on the population of Erebor.

2.6.5 Hull Design

Erebor's hull must fulfill several functions. It must be able to hold 1 atm of pressure, protect against micrometeorite strikes and provide radiation shielding while also being as lightweight as possible. Erebor's hull is made primarily out of titanium

Material	Half Value Layer	Density (g/cm^3)	Mass (1 cm^2 area)	10 Layer Mass
Air	6189 cm	0.001225	7.58 gm	75.81 gm
H_2O	7.15 cm	7.15	7.15 gm	71.5 gm
Al	3.05 cm	2.7	8.235 gm	82.35 gm
C	3.54 cm	2.26	8.00 gm	80.00 gm
Fe	1.06 cm	7.87	8.34 gm	83.46 gm

Table 2.8: Materials for radiation shielding analysis

and aluminium due to their high strength and low mass. Both of these are abundant on the lunar surface where they are constructed: the crust comprises of 28.5% Al_2O_3 and 0.22% TiO_2.[Dem+07] There are three main layers in Erebor's hull: the innermost pressure hull about 2 cm, an intermediate layer of kevlar 10 cm thick to absorb any impacts, a thin outer metal layer only a few millimeters thick made from the same Ti-Al alloy and finally a coating of Multi-Layer Insulation (MLI). Thus, the total hull thickness is about 12.5 cm. Together, the kevlar and outer metal layer form a Whipple shield. This is more mass efficient than traditional spacecraft shielding, due to lower mass requirement. As impact velocities are much higher than in LEO, the extra thickness of the pressure hull helps to withstand impacts. The pressure vessel is maintained at a constant temperature of 293 K, so thermal expansion is not a problem. The outer metal layer however, has expansion joints to deal with thermal expansion when Erebor reorients for maneuvers.

2.7 External Communication

Erebor communicates with the Earth and other stations using a Laser Communications Relay. This technology has been demonstrated by NASA in their Laser Communications Relay Demonstration (LCRD), offering transmission speeds 10 to 100 times greater than 'standard' radio. While the demonstration was on satellites in Earth orbit, it is conceivable that this technology be used for much longer distances, albeit with refocusing and redirectioning units at set intervals, which receive and reemit the laser beam. These units could be the moon base, other Erebors in a system of stations, or simply units set up solely for this purpose. This technology facilitates all external communication. The actual relays are located at the endpoints of the pylons used to hold up the TPS. Hence, we have a total of four relays, arranged in a square. Their directions can be varied using attached motors controlled by on-board computers.

2.8 Attitude Control

Attitude control onboard Erebor is performed via small thrusters located across Erebor's surface. However, the largest thrusters are present on the pylons of the Thermal Protection System, as more torque is available to the thrusters the further away they are from the center of Erebor. However, reorienting Erebor is difficult due to the large angular momentum possessed by the two rotating GHARs. The thrusters used are hot gas thrusters due to their higher specific impulses. Hypergolic propellants cannot be used due to their rarity in space and their toxicity, while cold gas thrusters lack efficiency. Hence, the thrusters of Erebor combust a small amount of oxygen and hydrogen to produce thrust.

Chapter 3: Support Systems

Support systems encompass all the processes and systems that facilitate life onboard Erebor. These are not directly related to industrial activities but sustain the crew and the vessel itself, indirectly enabling everything else. The support systems onboard Erebor can be broadly divided into three main categories, namely life support, power and automated systems.

3.1 Life Support

Life support is one of the most essential aspects of any space colony. It encompasses all the procedures and systems required to sustain life in the inhospitable environment of space. Space is a vacuum, and there are large temperature fluctuations between areas in direct sunlight and shade. Gases like oxygen, which is necessary for life, are absent in space. All of these factors combined, space is one of the most inhospitable environments for life to exist. If Erebor is to support a permanent population of 7500, along with the food crops required to sustain it, several systems are necessitated. These include efficient methods of food production, a water management system which minimizes any loss, a climate control system which sustains the delicate balance of gases in the atmosphere, a thermal control system to ensure a stable temperature no matter what, and a lighting system to simulate a day-night cycle even in 24-hour sunlight or darkness. All these subsystems collectively constitute the life support onboard Erebor.Âă

3.1.1 Food Production

Food is a crucial resource required for the sustenance of life hence it is essential that food can be produced as efficiently as possible for the population of 7500. The average adult human has a daily caloric requirement of 2550 – 3400 Kcal per day [Jon03], depending on sex, weight, height and physical activity. Assuming an average value of 3000 Kcal, the total calorie production of Erebor is 2.25×10^7 Kcal or 9.414×10^7 KJ. This energy, in turn, comes from the nuclear reactor, which powers the lights needed for photosynthesis. This value, however, does not reflect the total energy consumption as plants do not have a 100% energy conversion efficiency, nor the LED lighting system used to provide energy for the plants (see below). In addition to calories, humans also require vitamins, minerals, proteins, etc. Food sources have to be chosen accordingly in order to satisfy these requirements. The two most common sources of food are plants and animals.

Plants are autotrophs and can synthesize their own food using water and carbon dioxide. However, solar energy cannot be relied upon entirely. Light diminishes by the inverse square of the distance from the sun. To illustrate this, let us take the example of the asteroid Ryugu. Ryugu has a semi-major axis of roughly 1.2 AU. That means that on average, by the inverse square law, Ryugu receives only $\frac{1}{1.2}^2$ of the solar radiation received by Earth at 1 AU. This amounts to only 0.7 of the solar energy received at 1 AU, which is about 1.361 kilowatts per square meter (kW/m^2). Thus, Erebor receives only 9.527×10^2 watts per square meter. For asteroids in the asteroid belt, the intensity of solar radiation is even lower. Thus, efficient artificial LED lighting is required, powered by the nuclear reactor. Another advantage of artificial lighting is the ability to simulate a day and night cycle even in space.

Animal husbandry is not practiced due to the inherent inefficiencies in the conversion of feed to usable protein. For example, a broiler requires 20.7 units of feed per unit of protein. Hence, soya-based alternatives are used instead of meat.

Aeroponics in Erebor

The growth of crops requires a substrate or a medium. On Earth, this is usually soil. Traditional agriculture requires heavy soil and extensive water inputs. This is naturally unfeasible for Erebor. However, aeroponics can be used instead. Aeroponics is viable in zero-gravity and has been demonstrated on the ISS. Aeroponics involves growing plants without a medium. The plants are suspended in the air and their roots are sprayed with water and dissolved nutrients in the form of a mist. This results in efficient utilization of water and minerals. Thus, aeroponics eliminates soil and limits the spread of diseases. Soil is also heavy and bulky, and would thus not be practical onboard Erebor, where it is of the essence to keep the mass low. One disadvantage of aeroponics is that plants cannot be grown directly from seeds in an aeroponic setup. Plants are first required to grow in tissue culture. Only then they can be transplanted into the aeroponics facilities.

Aeroponics Infrastructure Aeroponics is carried out in the NATASHA. This enables the radiation shielding for the GHARs to be combined with the agricultural facilities, thus saving mass. Plants have a higher radiation tolerance than humans, and so are not at extreme risk if exposed to higher amounts of ionizing radiation. Water is an excellent radiation shield as well. The water present in the piping and the aeroponic vats also helps to add another layer of radiation shielding. The air present in the NATASHA also serves to block radiation.

The plants are grown in modular vats, allowing them to be replaced and transported easily. Each vat is 5 m long and 2 m wide, for a total area of 10 m^2. They are 2 m high and thus can accommodate even the taller cereals. The vat contains both the plants as well as the mist system and nutrient tank. The plants are placed in a substrate with the roots exposed. A central computer controls the mist system and nutrient management. The nutrient tank is connected via piping to the central system. The central system consists of a series of piping connected to a centralized tank. The nutrient solution is stored in the main tank and the wastewater is purified before recirculation. The nutrient concentration can be increased by the vats system by dissolving nitrogen or other minerals in the tank. This allows for certain crops to receive higher concentrations of certain minerals than the standard nutrient solution. This is again controlled by the central computer after receiving agricultural data from the robots.

Automation and Robotics As the cropped area is large and the population of Erebor is very low, it is essential to automate agriculture. Aeroponics is easier to automate than traditional agriculture, due to its industrial nature. Hence, robots are used to save labor as well as increase the efficiency of operations. The robots run along a central, electrified track and use a robotic arm to collect samples of both plants and of the nutrient mixture for analysis in the lab. They are also used to harvest the crops and plant seedlings, as well as deliver the harvested plants to a collection point. The robots are controlled by a central computing system. Robots, however, are unable to properly process the harvests on the spot. Instead, the harvested plants are delivered whole and processed in the industrial segment.Âă

Nutrient Management Nutrients for the aeroponics systems are recycled and are not wasted, as they are not obtainable from space. Nitrogenous wastes from humans are processed and reused. Wastes from the agricultural processing facility are also reused. Thus, Erebor aims to achieve as high an efficiency as possible. Even water is recycled for both humans and plants.

The nutrients used in the aeroponics solution is recycled from human wastes in photobioreactors. The algae are processed to manufacture the agricultural additives necessary.

Area Estimation Agriculture is an extremely complicated process and it is difficult to obtain a proper estimate for the area required to sustain the population of 7,500 onboard Erebor. Assuming an average cropped area of 29 m^2 per head, we get a total of 217,500 m^2 of area required for aeroponic cultivation. This area is not as much as it initially seems, as aeroponic modules are compact and can be stacked in many levels. The design of this cropped area in the structure of Erebor is shown in Section A.1.

3.1.2 Water and Waste Management

Water is an essential aspect of life and is vital for many biological processes not just in humans but also plants. As water has a chemical composition of H_2O, it is a source of both hydrogen and oxygen, both of which have many uses. Per capita water usage is capped at 100 L of water per day, compared to 300 L per citizen per day in the US (about 80 gallons). The average human requires 3.52 Kg of water daily for biological processes [Jon03]. Water is also present in the air in the form of water vapor, at an average concentration of 1% at sea level on Earth (this concentration is maintained onboard Erebor as well).Âă
Although water is abundant in space in the form of water ice on asteroids, it is still a limited resource that must be conserved. Hence, water is recycled and water usage is minimized (for example, using aeroponics instead of hydroponics). Many technologies for the conservation of water in space have already been pioneered on the ISS, such as recycling water from moisture in the air and from human waste. On the ISS, only 90% of water is recovered, but through advancements in technology this figure can be brought close to 100%. The small quantities of water inevitably lost are recovered by mining ice from the asteroids Erebor visits.

Drinking Water and Sewage

The purified water onboard Erebor is stored in a centralized tank onboard the GHARs. Chlorine is not added, germ control is instead carried out using UV lamps. These facilities are located onboard the GHARs, as the presence of gravity simplifies operations. Sewage is directed to a treatment facility, where it is broken down by algae in photobioreactors. The algae are harvested periodically and processed in the Main Industrial Unit (MIU). There, the nutrients are extracted and used in the aeroponics solution. The water from the photobioreactor is then distilled at low pressure so that the water can boil below 373K. The residue obtained after distillation mostly consists of organic material and is again added to the photobioreactor.ÂăAfter distillation, the water is refilled in the potable water tank and is recirculated. For greywater, a similar distillation process is employed. However, the distillation process is carried out in separate equipment so that the organic residue from sewage is not contaminated by inorganic wastes.

Humidity

Humidity is kept at 1% of the atmosphere in the GHARs and varies depending on the crop in the NATASHA. The water in the air is maintained at a stable level using humidifiers and dehumidifiers. The excess water in the air is diverted into the grey water system after condensation. Thus, no water is wasted.

Water Handling Outside the GHAR

Water is used in other parts of the station such as the MIU, the 0g areas, etc., for both human activities as well as industrial processes. In the manned 0g areas, the water is sent to the GHARs for processing and then sent back to the 0g areas again. Water used for industrial processes however is not recycled, as it is usually heavily contaminated after usage. The required purification equipment would be heavy, bulky and energy-intensive. Distillation is impractical in 0g (hence the ISS Urine Processor Assembly uses centrifuges) and another large-scale centrifuge in the crowded MIU used for water purification is not reasonable. Industrial water cannot be processed in the GHARs, as long-distance transportation is unfeasible. Besides, industrial processes are carried out only when Erebor is at an asteroid. After the water from ice on the asteroid is used in industrial processes, it is electrolyzed to produce hydrogen and oxygen.

3.1.3 Atmospheric Management

Atmospheric management is one of the most fundamental issues of any space settlement. It involves maintaining the composition of different gases in the atmosphere in their correct proportions. The atmosphere onboard a space station must also be maintained at an appropriate pressure. Atmospheric pressure is required for the sustenance of human life. The atmospheric pressure at sea level on Earth is 1 atm or 101,325 Pascals. The pressure chosen for Erebor is 100 KPa, or just slightly below 1 atm. This reduces the need for separate systems capable of functioning at a lower pressure than on Earth. This also eliminates any potential health complications caused by spending long durations at reduced pressure, especially among children and the elderly. Air circulation, air quality, dust, particulate matter, and humidity are also necessary aspects that must be considered.Âă

Gas Composition

The three main gases present in Erebor are oxygen (O_2) (21%), carbon dioxide (CO_2) (0.05%) and nitrogen (N_2) (78%). Water vapor and trace gasses such as argon and helium make up the balance 1%, as they do on Earth. Thus, the composition of Erebor's atmosphere is largely similar to that of Earth's. Each gas has a vital role to play in the life support system.

Oxygen Oxygen is one of the gases crucial for life as it is used to produce energy by oxidizing glucose. The typical human being consumes 0.84 Kg of oxygen in a day and exhales 1 Kg of carbon dioxide. This gives a total of 6,300 Kg oxygen consumed and 7,500 Kg carbon-dioxide produced daily by the crew of Erebor. It is essential to maintain the appropriate concentration of oxygen in the Erebor atmosphere, as oxygen levels of greater than 50 KPa can cause oxygen toxicity over a long duration. A pure oxygen atmosphere at a lower pressure is an alternative used mainly for Extravehicular Activities (EVAs), however, it would be impractical to operate the entire station at reduced pressure. Also, a high-pressure oxygen atmosphere is a fire hazard. Oxygen is an oxidizer and promotes combustion. As in the case of Apollo 1, such an arrangement could lead to a fire that can quickly prove fatal in the confined environment of space.

Carbon Dioxide Carbon-dioxide is excreted during respiration. As it is toxic to humans, CO_2 levels in the GHARs must be strictly regulated. Even a concentration of 5,000 ppm (0.5%) can cause headaches, drowsiness, sleep disruption, etc. Hence, a CO_2 concentration of 0.05% (500 ppm) must be maintained on Erebor. This is slightly higher than the concentration in the Earth's atmosphere (409 ppm), although considering the difficulty of scrubbing carbon dioxide from the atmosphere artificially, this a reasonable level.ÂăCO_2 is required for the growth of plants and thus can be recycled onboard Erebor itself.
In order to remove CO_2, Erebor uses Direct Air Capture (DAC). First, air is run through a series of filters to remove

the dust and then is sent to the support sector. Unlike the ISS which uses a zeolite adsorbent, CO_2 in Erebor is removed using sodium hydroxide (NaOH) and calcium carbonate ($CaCO_3$).ÂăThe flow of the process is given in Figure 3.1.
The process can be carried out an unlimited number of times, as it regenerates the NaOH and $CaCO_3$ through the process itself. Calcination is carried out using waste heat from the nuclear reactor. The carbon dioxide is then bottled at a high pressure and sent to the NATASHA for agriculture. In the NATASHA, carbon dioxide is similarly filtered from the oxygen-rich air and is then bottled and sent to the GHARs. Thus, the reduction of carbon dioxide to oxygen is done via photosynthesis.

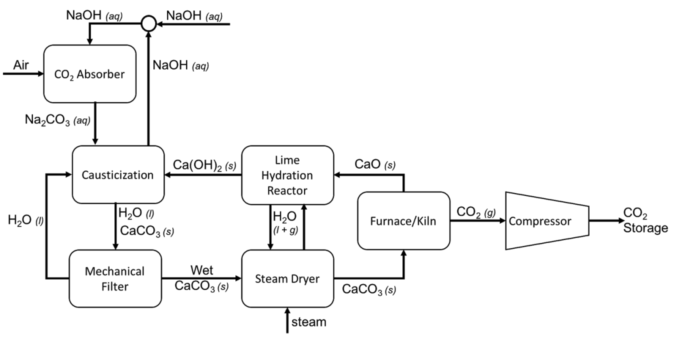


Figure 3.1: Direct air capture[1]

Nitrogen Nitrogen makes up 78% of Erebor's atmosphere. As Apollo 1 reminds us, the atmosphere cannot consist of pure oxygen, due to the fire and health hazards. Nitrogen does not support combustion like oxygen. Nitrogen is also an important element in organic molecules, such as proteins. These are mainly obtained from crops such as pulses, which in turn obtain nitrogen from nutrients supplied by the aeroponics system. Many legumes, however, have root nodules that house nitrogen-fixing bacteria. Thus, the nitrogen levels in the NATASHA deplete gradually. The nitrogen can be re-obtained from human and agricultural wastes, which contain nitrogen. The excess nitrogen which is not used in the manufacturing aeroponics solution can be reintroduced into the atmosphere, thus maintaining the composition at 78%. Despite recycling procedures and high efficiencies, some nitrogen is bound to be lost over time. However, many C-type asteroids have ammonia which contains nitrogen. Trace amounts of nitrogen-containing amino acids have been found in C-type asteroids [KN17]. However, nitrogen may have to be imported from Earth, for example when operating at an S-type or M-type asteroid.

Atmospheric Climate Control

The GHARs have centralized climate control via the ventilation system. Air is heated using the waste heat of the nuclear reactor. For cooling, the air is exposed to the ammonia pipes running along the exterior of Erebor. As given below in Section 3.1.4, Erebor uses a Thermal Protection Sunshield (TPS) to block out sunlight, leaving the station in the shade. Thus, the exterior of the station is at an extremely low temperature. This can be used to cool down the air using a series of heat exchangers. Heated or cooled air is circulated using convection currents.

[1] Image credit: Wikimedia Commons: Direct Air Capture Process Flow Diagram using Caustic Soda (`https://commons.wikimedia.org/wiki/File:Direct_Air_Capture_Process_Flow_Diagram_using_Caustic_Soda.png`)

3.1.4 Thermal Control

Thermal control is essential for a space station. On Earth, the atmosphere absorbs solar radiation during the day and radiates it out to space during the night. The atmosphere, however, manages to maintain the temperature variation at the surface to a minimum. However in space temperature can vary between 260°C in direct sunlight to -100°C in the shade, compared to an average temperature of just 15°C on Earth. This is mainly because of the Earth's atmosphere. The atmosphere helps to absorb solar radiation before it reaches the surface and acts as an insulating blanket keeping heat from being radiated into space. Life, barring a few exceptions such as extremophile bacteria, can only survive in a narrow temperature range. It is thus essential to ensure thermal regulation for Erebor. The temperature onboard Erebor is maintained at a uniform 20°C throughout all pressurized areas. This has been chosen as the temperature of 20°C is usually regarded as comfortable room temperature.
Thermal regulation can be mainly divided into two main operations: heating and cooling. Heating is a relatively simple operation, as only a heating element and electricity is required. Cooling, however, is more complicated. It involves a series of heat exchangers to absorb heat from the crew and machinery compartments and large radiators in order to dissipate heat in the vacuum of space, not to mention the pumps and piping systems required. Ammonia or NH_3 is the most common coolant used in space applications, but it is toxic in nature and hence any leaks must be quickly controlled. Considering all of this, it is easier to heat a spacecraft up than to cool it down. In order to do this, a spacecraft must be kept in shadow, so that it is not exposed to any solar radiation. It then begins to rapidly radiate heat away to the surrounding vacuum. As long as heat is supplied at the same rate as it is lost to the environment, thermal equilibrium is maintained. Thus thermal regulation on Erebor has two main components: a sunshield to isolate the station from sunlight as well as a system of heaters.

Thermal Protection System

The Thermal Protection Sunshield (TPS) on Erebor is the sunshield system that blocks out the solar radiation. It is a lightweight sheet made out of polymers (such as polyamide) with a reflective aluminum coating. This material is similar to that of a solar sail, which uses the radiation pressure of the Sun to generate thrust. As the TPS is reflective, it ensures that most of the solar radiation is reflected rather than absorbed. This ensures that the temperature of the sheet does not remain too high. The radiation that is absorbed by the TPS is radiated away from the rear face in the shadow. Five layers (each only a few μm thick) of material is used to ensure that the solar radiation is completely blocked out. This arrangement is similar to the sunshield used on the upcoming James Webb Space Telescope.
The TPS is in the shape of a square stretched between four pylons mounted on the rear end of the MIU, near the engine bells of the main propulsion system. The TPS must completely protect the hydrogen tank (which has a radius of 400 m) from direct sunlight. Hence, the total side length of the TPS is equal to the diameter of the hydrogen tank, or 800 m. The length of each pylon is half the diagonal, ($\sin \pi/4 \times 800$ m) or 565.68 m. The pylons themselves are lightweight and are made out of an aluminum-titanium alloy. This ensures that they are both strong and lightweight. The pylons have cables inside them, which are connected to high power winches inside the main body of Erebor. These help to extend and retract the TPS. It can be adjusted depending on the energy available for heating. In case the heating system fails or is short of power in an emergency, the

TPS is slightly retracted. This allows for some solar radiation to fall on the hull and takes the burden off the heating system. One main drawback of this arrangement is that the station will have to maintain a constant attitude with respect to the Sun, that is, the engines pointing toward the Sun. This is not much of a problem except when Erebor is maneuvering when it must change its orientation. Heating is stopped for this period in the areas facing the sun, while those in the shadow side can function normally. Erebor also rolls along its axis slowly to ensure that all surfaces are uniformly exposed to the Sun and shadow (where they radiate heat). This also provides attitude control while firing the engines due to the gyroscopic effect.
Solar panels are also mounted on the TPS, although they are present only to provide power in an emergency scenario.

Solar Radiation Pressure Because of the solar radiation pressure on the TPS, a small force is experienced. The force experienced by a body due to solar radiation pressure is given by the formula:

$$P = \frac{2G_{sc}\cos^2\alpha}{cR^2} \tag{3.1}$$

Where G_{sc} is the solar constant of $1,361$ kW/m^2, c is the speed of light, R is the distance of the body from the Sun and α is the angle of the body relative to the sun. Thus, at a distance of 1 AU or 1.495×10^{11} m, we get a pressure of 9.08 μPa. Hence for the 800×800 m^{2}TPS, the total radiation pressure comes out to only 5.81 N at a distance of 1 AU from the sun.
As this force is of such a low magnitude (only 9.08 μPa at 1 AU), it can usually be neglected. However, this force is continuous and tends to add up over a long period of time to produce a noticeable Δv. Solar radiation pressure also depends on the intensity of solar radiation which decreases with the inverse square of the distance from the sun. Combined with the large mass of Erebor and the great distances of many large asteroids from the sun, solar radiation pressure from the TPS can be safely neglected. Periodical firings of the main engine are used to compensate for any gradual drift.

Heating Systems and Insulation

The heating system forms the other part of the thermal regulation system. Artificial heat is important in the absence of solar radiation. The temperature in the shadow is about -100 C, far below the 20 C maintained onboard Erebor. Without artificial heat, the temperature can fall below safe levels and fatal hypothermia can set in at body temperatures below 35 C. Maintaining a stable temperature can be further divided into two main methods: heating and insulation.

Heating Heating is one of the most essential elements to the thermal control on Erebor. It is used to compensate for the loss of thermal energy via radiation from Erebor. The heating system is necessary both for sustaining life as well as for the mechanical components, which do not work at extremely low temperatures. Heat is most commonly generated by using electric heating elements, which use high resistance wires to convert electrical energy to thermal energy. However, this conversion is not completely efficient and some energy is bound to be lost. A more efficient method would be reusing the waste thermal energy produced by the different systems on Erebor. Most electrical systems do not have efficiencies of a hundred percent. The lost energy is dissipated as heat. Rather than radiate this thermal energy into space and waste it, electricity can be saved on heating by instead repurposing it for this purpose. The main source of waste heat is the nuclear reactor. The latest Generation IV reactors only have maximum thermal to electrical conversion efficiencies of 45%. This means that 55% percent of the reactors' energy output is not converted to electricity but remains as thermal energy, which must be removed, either for disposal or for reuse.

Insulation Insulation involves minimizing the loss of heat from Erebor. As the temperature of the vacuum of space is the temperature of the cosmic background radiation (2.7 K) when not exposed to direct sunlight, an object will tend to lose heat very rapidly. The temperature of Erebor is about 20 C, or 293 K. Thus, there exists a 290 K difference in temperature. Insulation helps to prevent the loss of heat from the spacecraft. The hulls of the pressurized compartments absorbs heat from the interior via convection of the air inside and conduction from the surfaces in contact. Thus, in order to prevent heat loss, the hull contains a layer of insulating material. Usually, a material with poor thermal conductivity is used for this purpose. A good material is expanded polystyrene (EPS) foam. It is 95 – 98% air and has an extremely low density of 11 – 32 Kg/m^3. This reduces the mass penalty imposed by thermal insulation. It has a thermal conductivity of only 3.2 $\times 10^{-2}$ to 3.8 $\times 10^{-2}$WmK, minimizing the heat loss. Thus, as thermal equilibrium is to be maintained, the heat supplied by the heating system has to be only equal to the amount of heat lost. By reducing the thermal energy radiated away, Erebor saves on the power requirement of heating.

Heat Loss Calculations As Erebor is maintained at a constant temperature of 20 C or 293K, the heat supplied to Erebor is equal to the heat lost. Thus, in order to determine the power required for heating, the heat radiated away by Erebor must be found. Heat is lost by a body in three forms: conduction, convection and radiation. However in the absence of an atmosphere, Erebor radiates heat away only through radiation. Conduction and convection however take place internally. The heat lost by a body through radiation per unit time is given by the Stefan-Boltzmann Law.

$$q = \epsilon\sigma(T_A^4 - T_S^4)A \tag{3.2}$$

Where q is the heat transfer per unit time (W), ϵ is the emissivity coefficient of the body, σ is the Stefan-Boltzmann constant (equal to 5.67×10^{-8}Wm^{-2}K^{-4}), T_A is the absolute temperature of Erebor (293K), T_S is the absolute temperature of space (2.73K), and A is the surface area of the body.

NATASHA The calculations here deal with the NATASHAs only as the heat radiated by the GHARs is immediately absorbed by NATASHA and hence is not considered. The NATASHAs are in the form of a torus with an elliptical cross section. The major radius of the torus is 250m. The semi-major radius of the ellipse is 50m and the semi-minor radius is 20m. The total surface area of the torus is approximately equal to the circumference of the ellipse into the circumference of the torus. The circumference of the ellipse can be calculated to be 230.13m. Even though the NATASHA has a significant portion cut out to accommodate the GHARs, the GHARs themselves radiate heat as well. So the tops of the GHARS can be approximated to be a part of the ellipse. Thus the total surface area is approximately $2\pi \times 250 \times 230.13$ m^2 or 361,487.35m^2. As Erebor is constructed on the moon where aluminium is abundant, the outer hull also is made out of Aluminium sheets. The hull is coated with Aluminium foil which has a low emissivity coefficient of 0.04. This minimizes radiation and hence the energy required for heating. Using these values, we get a value of 6,042,680W or roughly 6.04MW of heat loss. Hence, 6.04MW of waste heat from the nuclear reactor is consumed in heating the NATASHA.

Logistics Hub and MIU The logistic hub and MIU together form a cylinder of radius 130.7 m and length 350 m. One of the ends is a common bulkhead with the nuclear reactor, while the other end is exposed to space (the hydrogen tank is only attached at a small area). Thus, we get a total surface area of 34,0666.23 m^2. Assuming the same aluminium foil as the NATASHA with an emissivity of 0.04 and the temperature maintained at 20°C or 293K, as with the rest of Erebor, we get a total heat loss of 5.7 MW.

Hydrogen Tank The hydrogen tank also radiates heat, but to a much lesser degree. This is due to the low temperature of the hydrogen tank, of only about 20 K. The hydrogen tank is mostly covered with MLI or Multi-Layered Insulation. This has an effective emissivity of between 0.003 and 0.006 [Moe+], so we assume an average value of 0.0045. The hydrogen tank has a radius of 400 m. This gives us a total surface area of 2.01×10^6 m^2. Now using the Stefan-Boltzmann law, we get a total heat loss of only 79.6 W. This is insufficient to reject the heat which gets transferred to the hydrogen tank from the other parts of Erebor. Hence, two workarounds are presented:

1. Remove MLI on certain sections of the hydrogen tank, preferably all on one side of the tank. This is so that when Erebor reorients to fire its engines and the TPS cannot block sunlight, the sunlit side of the tank is insulated while the shadowed side can radiate into space. This side can be painted black, so it radiates more heat.
2. The surface area can be increased. Louvres can be added to one side of the tank in order to increase the surface area for radiation. Since they are all on one side, they remain shadowed even when Erebor reorients.

Reactor Module The reactor module is different from the rest of Erebor. As the nuclear reactors produce a large amount of waste heat that must be rejected, the reactor module has large louvers which can be opened to:

1. Increase the surface area available for radiation.
2. Directly expose the reactors to space to increase radiation.

Also, it is difficult to calculate the heat lost as the reactor is at a much higher temperature than the rest of Erebor. This temperature is the equilibrium temperature such that waste heat produced is equal to the heat radiated away.

Ammonia Pipe System The ammonia pipe system carries waste heat from the reactor to other parts of Erebor where it can be reused or simply radiated into space. Liquid ammonia (NH_3) is used because ammonia has a high specific heat capacity of 1.133 cal/g K, and is liquid at relatively low pressures, even though it is toxic to humans. It has adverse effects at concentrations as low as 50 ppm and can be fatal at 2,500 ppm. The possibility of ammonia leaking into the atmosphere can be altogether eliminated by placing the piping outside the main pressure vessel, but inside the insulation layer to trap the heat. Ammonia is also used as a coolant on the ISS. The ammonia absorbs heat using a system of heat exchangers. The heated ammonia is then circulated through Erebor, where it dissipates the heat. Thus, waste heat is repurposed and energy is saved both on heating as well as on a cooling system for the reactor and other machinery. A pumping system and plumbing network are required for this, although it would have been necessary for cooling anyway had the TPS not been implemented.

In the GHARs, this system of ammonia pipes is not used for heating. This is because of the difficulty in transferring the fluid from the non-rotating spire to the rotating GHARs. Hence, the GHARs rely on the traditional electrical heating elements. These are strategically placed around the station in the air ventilation system. This allows the hot air to be evenly circulated, ensuring uniform temperature. In the NATASHA however, the ammonia pipe system is used as there is no obstacle to transferring ammonia.

Cooling Systems

There are several reasons why a cooling system is also required on Erebor. First, a redundant system is always required in case the TPS malfunctions. Secondly, in case of a mechanical failure, the temperature in inhabited areas may rise to dangerous levels. Thirdly, the waste heat produced may exceed the demand for heating. And lastly, the TPS cannot block out the Sun when Erebor changes its attitude while maneuvering. The main form of heat rejection is ammonia pipes running along Erebor's exterior which radiate directly into space. Since a large portion of waste heat is reused for heating, a dedicated cooling system is not required and a simpler passive cooling system can be used. A passive cooling system does not use energy to cool down the spacecraft but instead increases or decreases the heat passively radiated by the spacecraft. An example of such a system is thermal control louvers. These are door like structures placed on the exterior of the spacecraft and can be opened or closed to regulate the temperature. When opened, they expose radiators which increases the heat radiating area. On Erebor, another type of louvre is also used. These are doors which form a part of the hull when closed and have thermal insulation on their inside. When opened, they expose the pressure vessel directly to the vacuum of space, drastically increasing the rate of radiation. This system cannot be used for long durations as the temperature decreases rapidly. However, it can be used to quickly eliminate a large amount of heat, in the case of temperatures rising to unsafe levels.

3.1.5 Lighting

Due to the Thermal Protection System (sun shield), Erebor is perpetually in the dark, hence, lighting onboard Erebor is carried out entirely artificially using LEDs. Each part of Erebor requires different types and durations of lighting. We will take each of these on a case-by-case basis, and finally, we will calculate the entire power requirement, as shown in Table 3.4.

3.2 Power

In this section, the total power consumption of Erebor is calculated and the arrangements for providing said power are discussed. Briefly, the maximum power consumption is 20.5 GW and this energy is supplied by a pebble bed nuclear reactor.

3.2.1 Total Power Consumption

Thermal Regulation As discussed in Section 3.1.4, Erebor is shielded from direct sunlight by the Thermal Protection Sunshield (TPS), exposing it to near absolute zero temperatures which necessitates heating. This is provided by a system of ammonia pipes carrying away waste heat from the reactor, doubling as cooling for the reactor and industrial machinery. Hence, the energy required for heating does not need to be factored into the total power output as it is repurposed waste heat. There is no shortage of waste heat for all heating demands, as even generation IV reactors are only about 50% efficient. The amount of power required for heating Erebor is equal to the power radiated away, as Erebor is in thermal equilibrium. As estimated in Section 3.1.4, the total heat radiated away by Erebor is 11.74 MW, excluding the reactor.

Application	Power (MW)
Thermal Regulation	11.74
Life Support	150
Lighting (Table 3.4)	4.6
Metals Production	2014.28
Hydrogen Production	18,287.51
Total	20,438.13

Table 3.1: Power requirement

CO_2 Capture The average human exhales about 1 Kg of carbon dioxide per day. This accounts for a total of 7500 Kg of CO_2 produced daily. It takes around 250 – 300 KWh to remove a ton of CO_2, for a total requirement of around 2250 KWh per day or an average power consumption of 93.75 KW.

Life Support It is difficult to estimate the power used in life support due to the large number of factors involved. It can be safely assumed that a maximum of 20 KW is used per head, extrapolating from the ISS which produces 120 KW for a crew of 6. Hence, 150 MW is required for life support.

Metals Production Erebor produces about 60 Kg of metal every second (refer to Section 4.1.4). It is hard to calculate the exact power usage due to the large number of processes carried out. One process for which there is an accurate power estimate is the electrolysis of iron silicate. As per a design proposed by Russel O. Colson and Larry A. Haskin, in order to produce about 1400 Kg of iron-silicon metal from iron silicate, 47 GJ of energy is used. Extrapolating from these numbers, 2014.28 MW is required for metal processing.

Hydrogen Production Hydrogen is the propellant used by the nuclear thermal engines hence its production is essential. 17,500,000,000 kg of hydrogen is required by Erebor in order to achieve a delta-V of 7 Km/s. As mentioned in Section 4.1.4, Erebor aims to fully refuel itself in about 2000 days with at 20 hours per day of operations. This equates to 4000 tons of water processed per hour or 123.46 Kg of hydrogen produced per second. Current hydrogen production methods such as alkaline water electrolysis have an efficiency of 80% and the theoretical minimum energy for the electrolysis of water is 237 kJ per mole of water (2 grams of hydrogen).[SH19] Thus, the specific energy for hydrogen is 148.13 MJ/Kg and the total power consumption is 18,287.51 MW.

Propulsion During engine burns, industrial processes are not carried out hence most of Erebors power can be diverted to the nuclear thermal engine. The total power consumed by the engine is 13,868.61 MW, as calculated in Section 1.3.1.

Hence, Erebor consumes around 20.5 GW when at an asteroid and 14.04 GW (NTR and life support) when maneuvering. Power usage drops even further to under 500 MW when traveling through interplanetary space with the engines shut off. Due to the highly variable power output, Erebor has several smaller reactors each of which can be switched on or off on demand rather than a single large reactor. In total, the maximum achievable power output for Erebor is 20.5 GW.

3.2.2 Power Generation Options

Since Erebor's total power requirement is 20.5 GW, there are only two viable options for generating electricity on such a scale: solar power or a nuclear reactor.

Solar Power Area Estimation

The amount of energy radiated by the Sun per square meter at a distance of 1 AU is known as the Solar Constant or GSC and it is 1.3611 kW/m^2. Hence, the required area for 20.5 GW is 15,007,320.64 m^2, or a square with a side of 3873.93 m. Also, this assumes 100% efficient solar panels and these figures are only applicable at a distance of 1 AU from the sun. Ceres, for example, is at a distance of 2.7 AU from the Sun and hence receives 7.29 times less sunlight, according to the inverse square law.

Nuclear versus Solar

Table 3.2 compares nuclear and solar power.

Category	Nuclear	Solar
Compactness	A nuclear reactor is a compact source of a large amount of power.	The area covered by solar panels is greater than 15 km^2.
Versatility	A nuclear reactor is not dependent on the distance from the sun.	Solar panels depend on the distance from the Sun and hence are unreliable in the outer solar system.
Maintenance	A nuclear reactor is a high-tech piece of machinery that must be almost constantly maintained but it can run for years without refueling.	Solar panels do not require as much maintenance. The need for fuel is eliminated completely. However, given their large size, they experience micrometeorite impacts frequently.
Propulsion	Due to the high temperatures produced, thermal rockets can be used which have a higher thrust but lower efficiency than SEP. Hydrogen fuel can be easily produced from water.	Solar Electric Propulsion (SEP) has a lower thrust but is more efficient than an NTR. However, noble gases such as xenon, argon or krypton which are rare in space are required as fuel.
Waste Heat	A nuclear reactor produces a lot of waste heat that must get rejected.	Solar panels produce less waste heat. The rear face of the panels also acts as a radiator,
Hazardous Materials	A nuclear reactor has highly radioactive fuels that must be handled carefully during fueling and disposal.	Solar panels do not require dealing with any hazardous material.
Danger	Subjects the residents of Erebor to ionizing radiation and the danger of a meltdown.	Solar panels do not subject the crew to any additional risks.

Table 3.2: Nuclear vs Solar power

After reviewing the advantages and disadvantages of both, a nuclear reactor has been chosen for Erebor due to its constant power output regardless of distance from the Sun or attitude, less bulk as compared to solar panels and ability to generate high temperatures for the thermal rocket engine. This outweighs the higher risk as well as the inconvenience associated with fueling and increased maintenance.

3.2.3 The Nuclear Reactor

Erebors nuclear reactor is a pebble bed reactor. This reactor is a Generation IV Very High Temperature Reactor (VHTR), as it can achieve temperatures of up to 900°C. The nuclear fuel, which can be Plutonium, Uranium or Thorium, is contained in small pebble-shaped elements with a graphite casing doubling as the moderator. These pebbles cycle through the reactor, ensuring continuous operations even during refueling. Such reactors can have around 450,000 pebbles.
Helium is used both as a coolant and the working fluid, As helium is inert and remains a gas all the time, pebble bed reactors are safer to operate than traditional designs.
The reactor onboard Erebor uses thorium as a fuel, due to its abundance on Earth, ease of extraction and inherent safety over uranium. The thorium pebble bed reactor combination is a proven design based on the THTR-300 (Thorium High Temperature Reactor) operated in Germany between 1987 and 1989. The reactor has 8 smaller modules, each with a power output of 2,562.5 MW, for a total of 20.5 GW.

Individual Nuclear Reactors

Each reactor module is housed in an octant in the reactor block. These octants are isolated from each other by armoured bulkheads to protect the other units from damage in the extremely unlikely event of an explosion, with the blast being diverted to empty space instead. Each reactor unit does not have a permanent hull section but is instead covered by a louvre, allowing the module to be exposed to space in order to radiate excess heat away. This is shown in Figure A.4.
The reactor vessels themselves are large cylinders with a radius of 20 m and a length of 40 m. It is rotated with an angular velocity of $\omega = 0.1$ rad/s for an acceleration of 0.2 m/s^2 at the outermost edge. Thus, the pebbles stay firmly against the walls of the reactor vessel allowing them to be smoothly rolled in and out continuously. After extraction from the reactor core, the pebbles are thoroughly inspected using robotic sensors before they are reinserted into the reactor.
Liquid helium coolant is passed through a system of pipes inside the reactor vessel, where it absorbs heat from the pebbles. The superheated helium is then used to drive the turbine, generating power. This is shown in Figure A.5.

Reactor Efficiency

All thermal power plants operate on the same fundamental principle, that is the transfer of energy from a hot reservoir to a cold reservoir or heat sink. Thus, the greater the temperature between the heat source and heat sink, the higher is the efficiency. The theoretical efficiency of any thermodynamic process is given by the Carnot equation:

$$\eta = 1 - \frac{T_C}{T_H} \tag{3.3}$$

Where T_C is the absolute temperature of the heat sink, T_H is the absolute temperature of the heat source and η is the theoretical efficiency of the cycle.
On Earth, thorium pebble bed reactors can achieve an efficiency of upto 50% (much higher than conventional reactors) on account of the high operating temperatures of upto 900°C (1173.15 K). Water is used as the heat sink at a temperature of 28°C (or 301.15 K), giving a maximum theoretical efficiency of 76.71%. However, Erebor radiates excess thermal energy directly into the vacuum of space (2.7 K) which enables a theoretical efficiency of almost 100%. Thus, the reactor aboard Erebor is more efficient as compared to its terrestrial counterparts which enables a smaller size (and hence lower mass) as well as less waste heat, for the same power output.
In practice, 100% efficiency is obviously not achievable due to losses from friction, imperfect heat transfer and inefficiencies in the conversion of mechanical energy to electrical energy. The reactor itself also consumes some energy which must be deducted from the net electrical power output.

The Reactor as an NTR

In a nuclear thermal engine, hydrogen gas is heated from 20 K to 3000 K within a fraction of a second. The higher core temperatures of a pebble bed reactor are advantageous here, as the kinetic energy of a gas is directly proportional to its temperature ($K = \frac{3}{2}RT$). The hydrogen gas is passed through the reactor centrifuge, making use of the same plumbing as the helium cooling system. Thus, the cryogenic liquid hydrogen doubles as a coolant during engine operation.

Fuel Cycle Management

Fuel pebbles drastically simplify the fuel cycle management of the reactor. Fuel pebbles are regularly cycled in and out of the reactor to check for damage to the casing after which they are reinserted. When a pebble has been depleted, it is first sent to Earth for reprocessing and then returned to Erebor.

Reactor Cooling

Even highly efficient Generation IV reactors are only about 50% efficient, meaning that roughly the same amount of heat must be rejected as the energy produced, i.e. about 20.5 GW at peak capacity. A small fraction of this waste heat (about 11.74 MW) is circulated across the structure of Erebor using the ammonia coolant lines (further discussed in Section 3.1.4) to overcome radiative heat loss. The rest of the waste heat is radiated directly into space. The reactor modules are exposed directly to space and run at much higher temperature than the rest of Erebor. As radiation is proportional to T^4, the rate of heat loss is much higher than the rest of the structure.
Gigawatt level power is only required either when industrial processes are taking place or the engines are being fired. In both cases, material from Erebor is being vented: in the former the oxygen from electrolysis and in the latter hydrogen fuel. Both serve to cool the reactor by carrying away heat. Hydrogen is run through the reactor as a part of the NTR while oxygen absorbs heat from the helium coolant through heat exchangers. The oxygen vent valves are located on the opposite side of Erebor to balance out the thrust and torque produced.

3.3 Robotics

Robots perform various functions on Erebor. The BaseBot is the basic robot on which every other robot is based in a modular design. BaseBots can run on rails or on wheels, depending on the application. One large multifunctional arm is attached to the front of the robot, similar to the ones used in factories to assemble cars. They have a small toolbox in the front and a large storage compartment at the rear. The toolbox has various modular attachments for the arm, and its contents vary with each application. Since the robots are all of different widths, the gauge of each class (A, B, or C) of railed robot is different. Thus, most tracks are gauntlet tracks, which allow robots of different widths to run on them while using the same sleepers. The BaseBots are made in three classes, listed in Table 3.5. Table 3.6 summarizes all robots used.

Crop	Notes	Nutrients	Area
Wheat (Triticum aestivum)	A cereal crop and a source of carbohydrates. Wheat is used mainly for baking bread.	Carbohydrates (72%), Proteins (13.2%) and Water (11%)	10% Total: 21,750 m^2
Rice (Oryza sativa)	A cereal crop and a source of carbohydrates. Rice is a staple in many Asian cuisines.	Carbohydrates (90%), Proteins (8%) and Fats (2%)	10% Total: 21,750 m^2
Maize (Zea mays)	Maize is an important cereal crop and a source of carbohydrates. It can be used to make a variety of products such as corn flour and cornstarch.	Water (73%), Protein (3.4%), Carbohydrates (21%) and Sugar (4.5%)	5% Total: 10,875 m^2
Tomatoes (Solanum lycopersicum)	Tomatoes are a vital part in many cuisines. They have an extremely high yield in an aeroponic environment.	Water (95%), Protein (0.9%), Carbohydrates (3.9%), Sugar (2.6%) and Fiber (1.2%)	5% Total: 10,875 m^2
Potatoes (Solanum tuberosum)	Potatoes are a source of carbohydrates and starch, and as such is a vital source of energy for the residents of Erebor.	Water (77%), Carbohydrates (20.1%) and Protein (1.9%)	5% Total: 10,875 m^2
Soya (Glycine max)	The most vital crop grown onboard Erebor. As there are no cattle, soya is also used to manufacture dairy products and meat substitutes. Soya is also an important source of protein.	Water (63%), Protein (16.6%), Carbohydrates (9.9%) and Fat (9%)	20% Total: 43,500 m^2
Legumes	Legumes are an important source of protein and fats, especially in the absence of meat. The main legumes which are grown onboard Erebor are- Chickpeas, Green Gram, Groundnuts and Pigeon Peas.	Chickpeas (Cicer arietinum): Water (60.21%), Carbohydrates (27.42%), Protein (8.86%), Iron, Phosphorus, and Folate Groundnut (Arachis hypogaea): Fat (48%), Carbohydrates (21%), Protein (25%) and Niacin	10% Total: 21,750 m^2
Vegetables	An important source of vitamins, minerals, and fiber. The main vegetables which are grown onboard Erebor are- Onions, Carrots, Peas, Eggplants, Green Beans, and Beetroot. Beetroot is also grown to produce sugar.	Onions (Allium cepa): Water (89%), Protein (1.1%), Carbohydrates (9.3%), and Sugar (4.2%) Carrots (Daucus carota): Water (88%), Carbohydrates (9.6%), Sugar (4.7%), Fiber (2.8%) and Vitamin A. Beetroot (Beta vulgaris): Water (88%), Carbohydrates (9.6%), Sugar (6.8%), and Protein (1.6%)	20% Total: 43,500 m^2
Leafy Vegetables	These are grown mainly to supplement the diets of Erebor residents with important vitamins and minerals. Green, leafy vegetables can be eaten directly or converted in other forms of dietary supplements. The main leafy vegetables grown are- Spinach, Kale, Lettuce, Cabbage, and Broccoli.	Vitamins A, C, and K, Dietary fiber, Potassium, Manganese, and Folate	10% Total: 21,750 m^2
Misc	Other miscellaneous crops, such as medicinal plants, garnishing, spices, etc.	N/A	5% Total: 10,875 m^2
Total			217,500m^2

Table 3.3: Crops

Location	Duration	Color Temp.	Average Irradiance	Lit Area	Total	Comment
GHARs (Public spaces such as the central walkway and internal transport system)	Biodynamic lighting	Varies similar to daylight	**5 W/m^2** Assuming lamps of luminous efficacy 200 lm/W, and 1000 lx. These values are high since they mimic daylight and are used in outdoor areas.	197,920.33 m^2	989,601.65 W	All public spaces in each GHAR are lit biodynamically. Biodynamic lighting is artificial lighting which mimics the color and intensity curve of daylight on the Earth. It also allows, over time, to show a shift in seasons (each season has a different curve).
GHARs (Private spaces such as homes and restaurants)	16 hours	4000K	**3 W/m^2** Assuming lamps of luminous efficacy 90 lm/W and 270 lx of average luminous flux per unit area.	197,920.33 m^2	989,601.65 W	The private, âĂŸindoor' spaces in the GHARs have a 24/7 power supply, similar to how homes are supplied with 24/7 power via grids on Earth. While people can switch their lights and appliances on at any time, it is expected that they will sleep for approximately seven to eight hours. Hence, light will be used for an average of 16 hours.
NATASHA	Biodynamic lighting	Varies similar to daylight	**10 W/m^2** Assuming lamps of luminous efficacy 200 lm/W, and 2000 lx. These values are high since they must give plants energy. This is nowhere close to the sun's irradiance (164 W/m^2), but plants do not use the entirety of the Sun's energy and much of it is lost as heat. LEDs do not have nearly as much heat loss	219,912 m^2	2,199,120 W	The plants in the NATASHA are biodynamically lighted, with different seasons in different sections. Such lighting allows plants to grow in a lighting environment which is similar to that of Earth.
MIU and Logistics Hub	24/7	6000K	**4 W/m^2** Assuming lamps of luminous efficacy 200 lm/W and 800 lx of average luminous flux per unit area.	100,000 m^2	400,000 W	The MIU, train stations, Logistics Hub, and other areas are lit 24/7 since people will commute and work at all times due to the 12 hour time gap.
Other areas	24/7	5000K	**3 W/m^2** Assuming lamps of luminous efficacy 180 lm/W and 540 lx of average luminous flux per unit area.	20,000 m^2	60,000 W	
Total					4,638,323 W $\approx$ 4.6 MW	

Table 3.4: Lighting

Class	Dimensions (lbh)	Application
A	$3 \times 1 \times 1$ m^3	Transport, Repair
B	$9 \times 2 \times 3$ m^3	Agriculture, Asteroid Surface Operations, Transport
C	$15 \times 5 \times 3$ m^3	Transport

Table 3.5: BaseBot classes

Type	Class	Functions	Location	Details
Agbot (Agriculture)	B	Harvesting, planting, monitoring, adding fertilizer and pesticide, etc.	Aeroponics in NATASHA	Agbots have a long arm with harvesting/planting attachments. These are located in the toolbox. Substrate and plant monitoring via pH testing, sampling of sap and air, infrared analysis, etc is carried out using more attachments. Lastly, a sprayer and pipette which gives plant-specific pesticides based on analysis. Agbots can also carry out small aeroponic machinery repairs and maintenance. The storage compartment is used to store harvested plants or seedlings to be planted. Run on rails in the NATASHA.
Astrobot (Asteroid Surface Operations)	B	Harvesting and analysing surface minerals, deploying and removing rails, ice harvesting, building surface infrastructure, etc.	Asteroid (External)	Astrobots have a reinforced arm with three major purposes: analysing the surface, extracting surface minerals, and building the surface infrastructure. To achieve this, the arm has attachments which allow it to drill the surface and collect minerals in the storage compartment, or to take materials from the storage compartment and build infrastructure. The astrobots run along tracks in the TRAIL. Surface infrastructure is built by many Astrobots working together. These activities are either automated or controlled remotely by humans from Erebor. Run on the TRAIL (Tether cum Rail on Asteroid for Improved Locomotion).
Hull Repair Bots (Repair and Maintenance)	A	Hull repair, prevention of leaks, etc.	Hull	The Hull Repair Bots are fairly simple. They have X-Ray and Infrared imaging to check the hull for inconsistencies, damage, and leaks. The storage box contains temporary leak patchers and permanent riveters to fix leaks. It also has tools to fix other basic hull problems, and can be controlled remotely. The toolbox has all the required attachments. Like all other robots, their activities are coordinated. Run on single gauge rails along the hull.
Industrial	B	Industrial Functions	MIU	These robots have multiple arms and toolboxes, and vary with the industrial application. These robots do not have any storage compartment as the Transport Class C robots fulfil this purpose in the MIUs. They run on the gauntlet rails system in the MIU.
Transport Class B (Small-scale transport of materials and humans)	B	Human Transport	MIU, GHARs	Human Transport Class B robots are used primarily by workers in the MIU, emergency services in the GHARs, etc. These are modified to carry a maximum of four people on a smaller set of tracks, optimised for speed and efficiency due to smaller size. The toolbox contains medical equipment in the case of ambulances or industrial equipment, depending on the application. Run on gauntlet rails or treads.
		Material Transport	MIU, GHARs	Small-scale material transport within the MIUs and NATASHA. Run on rails or treads.
Transport Class C (Bulk Transport of materials and humans)	C	Human Transport	MIU, Logistics Center	These are used as buses and public transport in the MIUs. Workers are generally expected to use Class C transport.Run on gauntlet rails.
		Material Transport	MIU, Logistics Center	These are used as vans are cargo movement in the MIU. They also move large equipment and other materials for industrial activity. Run on gauntlet rails.

Table 3.6: Robotics

Chapter 4: Industry and Materials Processing

4.1 Mining Operations

Production of pure metal is the primary economic activity onboard Erebor. The main steps are the extraction of metals from the asteroid surface, transport to Erebor, processing and finally, export. Erebor is designed with the capacity to produce 5,000 tons of pure metal per day (57.87 Kg produced per second, rounded up to 60 Kg to account for any stoppages in production).

4.1.1 Asteroid Surface Infrastructure

Before mining can begin, infrastructure on the asteroid surface must be established. The asteroid surface is a hostile environment with hazards including radiation, micrometeorites, an unstable surface and heavy machinery at work. Hence all surface operations are uncrewed and are controlled from Erebor. Robots are transported to Erebor for maintenance to avoid having humans on the asteroid.

The main components of the surface infrastructure are as follows:

1. A control center for all surface operations.
2. Logistics facilities such as temporary storage, a landing pad and loading/unloading platform for the VASP drones.
3. A system of cables (known as the TRAIL) to stabilize rubble pile asteroids (asteroids consisting of debris loosely held together by its own gravity) and anchor vehicles to the surface
4. Temporary shelters (known as SHADE) which are constructed on the surface to protect equipment from the hostile environment of space.

Command and Communications Module

The command and communications module is the first module to be deployed on the asteroid surface. It acts as the foundation for all following infrastructure (for example, the initial anchor point when constructing the TRAIL) and also houses the computer systems for managing surface operations. The module is a modified VASP drone (see Figure 4.1), with the chassis housing the computing equipment and the arms modified by adding harpoons and hooks (as used on the ill-fated Philae lander). These penetrate to a depth of 10 m after landing to firmly anchor the module in the low-gravity environment while also stabilizing the local area (for rubble-pile asteroids). Thrusters (identical to the ones used on the VASP drones) prevent it from flying off if harpoon deployment is unsuccessful. The landing site is always the pole of the asteroid, as there is zero rotational velocity here which facilitates easier landings by the VASP drones as they come to unload more equipment.

TRAIL

The next step is to establish the TRAIL system: Tether cum Rail on Asteroid for Improved Locomotion. It is a system of cables running along the surface of the asteroid, akin to the lines of latitude and longitude on a globe. These cables are made of PBO (poly-p-phenylene-2,6-benzobisoxazole/Zylon®), a synthetic fibre with an extremely high specific strength (strength to weight ratio) of 3,766 KNm/Kg. Thus, it is lighter than metal for a wire of given strength which aids in transporting the many kilometers of cabling required. It is also thermally stable which is required due to the high temperature variation in space. The cables are connected between pylons which are driven deep into the asteroid, located every 50 m or so. This holds the asteroid together while also firmly anchoring equipment to the surface.

Some important functions of the TRAIL are:

1. All the vehicles on the asteroid surface run along the TRAIL cables, much like abseiling along a sheer rock face. Due to the low gravity on the asteroid, the escape velocity is extremely low (for example, 101955 Bennu has an escape velocity of only 0.7 Km/h) which means that a vehicle driving over rough terrain could accidentally get ejected from the surface. Hence, all vehicles are tethered to TRAIL. As the pylons are driven deep into the regolith, they can stop even a heavy object from flying off.
2. Electrical wires are bundled with the TRAIL cables, eliminating the need for surface vehicles to carry large battery packs. Energy is supplied by wireless power receivers mounted at regular intervals along the TRAIL which absorb microwaves transmitted by Erebor.
3. Many asteroids are ‘rubble piles’ or a collection of debris loosely held together under its own gravity. The TRAIL holds the debris together and prevents it from disintegrating, especially as materials are mined and the mass (and thus the gravity) reduces.

The TRAIL is deployed using VASP drones. First, the asteroid is surveyed and optimal locations for the anchor points are located. Second, the lines of longitude are constructed by running cables from the command and communications module on one pole and an anchor point on the other. Finally, the lines of latitude are laid.

Resource Depot and Landing Pad

The resource depot and landing pad is located at the pole of the asteroid (which makes landing on the asteroid easier as there is no tangential velocity). It stores extracted resources until they are transferred to Erebor and acts as a platform for loading and unloading the VASP drones. A flat surface is provided which eliminates the need to land on uneven terrain.

SHADE

The SHADE (Safety from Hostile Asteroid Daylight Environment) is a structure erected on the asteroid over resource deposits in order to protect surface operations from direct sunlight. The rationale behind the SHADE is explained below:

1. It protects machinery from overheating in direct sunlight, eliminating the need for heavy cooling equipment on each vehicle.
2. Ice sublimates when exposed to sunlight at distances from the Sun less than 3 AU. Hence, if subsurface ice is accidentally exposed, the water escapes into the vacuum and is lost. This is prevented by performing mining operations in the SHADE.
3. The SHADE is partially airtight, hence any ice inadvertently sublimated (by heat sources such as waste heat from machinery) is temporarily trapped inside. In this time, the vapor is reclaimed by vacuum pumps which drastically reduces wastage.

The SHADE is a geodesic dome with lightweight aluminium-titanium pylons as the edges. This modular construction allows the radius to be varied as per the size of the deposit. The faces of the dome are made with a lightweight polyamide fabric held taut between the pylons (the same material used in the TPS, refer to Section 3.1.4). The fabric is coated with a thin layer of aluminium, which is highly reflective and hence increases the fraction of incident radiation reflected rather than absorbed.

The interior of the SHADE is a vacuum, although the polyamide skin is airtight. Despite the junction between the SHADE and the asteroid not being completely sealed, gases are retained inside for a short duration. Thus, any ice accidentally sublimated is temporarily trapped and the vapor is reclaimed using vacuum pumps.

4.1.2 Materials Extraction

The main materials extracted from the asteroid surface are metallic ores and water ice. The extraction processes are discussed below.

Metallic Ore

Metals or metal-rich minerals are extracted by the astrobots (see Section 3.3) running along the asteroid surface. These use a robotic arm to mine material on the asteroid surface. This arm is capable of using multiple attachable tools which can be swapped as per the current situation. These tools include:

1. A jackhammer to break up larger deposits such as chunks of metals and minerals.
2. An auger to extract loose minerals and material broken up by the jackhammer. When mining ice, liquid nitrogen is passed through channels located inside the blade to avoid sublimation.
3. An excavator scoop to clear away regolith in order to uncover deposits.
4. A sensor suite that can scan for deposits and analyse the composition of the local area.
5. Construction tools for building surface infrastructure.

Once the surface infrastructure has been constructed, mining is carried out in the following steps:

1. First, the asteroid must be stabilized. It is possible that a rubble pile asteroid or an asteroid with large internal voids could collapse or spin itself apart during mining operations. The TRAIL binds the asteroid together while any internal voids are filled with waste rock from the metal processors onboard Erebor.
2. Next, the available resources (on the surface as well as underground) are thoroughly documented. For subsurface prospection, probes are drilled into the surface to analyse the composition.
3. Once a large deposit has been located, a SHADE unit is built around it and the ore extracted. For subsurface deposits, a shaft is dug from the surface. Excavated regolith is stored on the asteroid itself in the regions with a lower concentration of resources.
4. Once mining is completed, the asteroid is rebuilt using compacted regolith to prevent possible fragmentation in the future. If the asteroid poses a risk to Earth, Erebor diverts it to a safer orbit before it departs.

Ice Mining

Water (H_2O) is the source of the hydrogen fuel for the Nuclear Thermal rockets on Erebor, the RATHAs and several other spacecraft. Ice is mined autonomously using Astrobots (refer to Section 3.3) rather than by sublimation (which can result in some water being lost). The Astrobots move along the TRAIL on the surface of the asteroid and use an auger cooled with liquid nitrogen to extract ice without melting it. At distances from the Sun less than 3 AU (the 'frost line'), ice sublimates when exposed to direct sunlight. Hence, ice is mined only inside the SHADE. As the SHADE is partially airtight, any ice unintentionally sublimated does not immediately escape to space and is reclaimed by the compressor fans.

Mined ice is stored underground in insulated containers. These containers are transported to Erebor using the VASP drones (refer to Section 4.1.3).

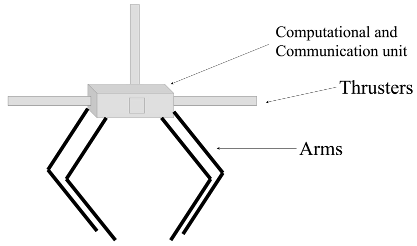


Figure 4.1: VASP Drone (not to scale)

4.1.3 Material Transportation

Once the ore has been mined, it must then be transported to Erebor for processing.

Ore Containers

Ore is stored in the storage unit on the astrobot. This is a sealed (to prevent material from flying out under the low gravity of an asteroid), detachable container with dimensions of (lbh) 7.5 m $\times$ 2 m $\times$ 2 m (for a volume of 30 m^3). As rock typically has a density of 2860 Kg/m^3, each container can hold 85.8 tons of material but possibly more if chunks of metal are mined. These containers are loaded onto the VASP drones for transport to Erebor from the asteroid surface.

VASP Drones

The VASP drones (Vehicle for Asteroid Surface Payload) are used to transfer payload between the asteroid surface and Erebor. The drones consist of thrusters mounted on extended pylons (to increase the torque and improve attitude control), a central chassis (containing the avionics, communication equipment and propellant) and four payload manipulators (or 'arms') which assist in carrying payload. They are largely autonomous, except for the landing and docking (with Erebor) phases which are overseen by operators.

The payload manipulators are used to carry containers, astrobots and other unwieldy cargo. The drones can carry upto 1000 tons as asteroids have negligible gravity (in the order of a few micro gs), hence upto 10 containers (bundled together) can be carried at once. Cryogenic fuel is used due to its efficiency and because production facilities already exist aboard Erebor. Due to the low gravity, the drones have enough fuel for a round trip (to and from the asteroid) and hence no refueling is needed on the asteroid.

4.1.4 Ore Processing

Metals processing onboard Erebor takes place in several steps:

1. Mined material is crushed into smaller particles and minerals, ice and metal chunks are concentrated from the regolith.
2. The extra regolith is then compacted and returned to the surface of the asteroid for storage.
3. The metals are extracted using techniques such as electrolysis, reduction or vapor phase refining.
4. The extracted metals are sent to the refining units in order to increase their purity.
5. After purification, metals are either formed into ingots or sheets, either for export or for the 3D printing unit.

Concentration

The raw material from the asteroid does not have a high enough concentration of resources for direct extraction and the ore must first be concentrated. This is done using physical methods such as centrifugation, sublimation of volatile material and magnetic separation.

Sublimation Crushing the ore can cause volatile material to heat up above its freezing point and sublimate. Hence the extraction of volatile resources such as water ice and ammonia is the first process carried out. Water ice is stable in a vacuum in the temperature range of 170K to 200K[PZ04]. If heated above this temperature in a vacuum, the ice sublimates and the vapor can then be easily collected. This process is carried out in a heated centrifuge to ensure that vapors separate from the regolith and accumulate towards the center (due to convection currents). The vapors are condensed by running the piping along Erebor's exterior (which is in permanent shadow, due to the TPS). The obtained water may have contaminants such as ammonia and amino acids, especially if it is from a C-type asteroid. They can be separated using a combination of precipitation using acids and further distillation under reduced pressure, if required.

Crushing, Centrifugation, Magnetic Separation Once volatiles have been separated, the regolith is crushed mechanically into smaller pieces of uniform size. This streamlines processing as well as increases the surface area of materials. The crushed mixture is then rapidly rotated in a centrifuge to sort the particles based on their density. This is done to separate any metal and ore particles from the crushed rock and sand, as well as to differentiate the different ores. Electromagnets in the walls of the centrifuge further separate particles of ferromagnetic materials such as Iron, Cobalt and Nickel.

Metal Processing

The next step in the process is the extraction of crude metal from the concentrated ore. The ores obtained can be broadly classified into two main types[NC08]:

1. Metals in the elemental (or native) form, for example, various iron-nickel alloys such as Kamacite ($\alpha-$ (Fe, Ni), contains 4%−7.5% Nickel by weight)[Las+19], Taenite ($\gamma-$ (Fe, Ni), contains 27%−65% nickel by weight), copper and other metals such as Cobalt, Gold, Platinum, Iridium and Rhodium.
2. Metals contained in compounds, mostly silicates and oxides.
   (a) Silicate ores are abundant in S-type asteroids. Important silicates include:
      i. Pyroxene (XYZ_2O_6, where X: Ca, Na, Fe^{2+}, Mg or Zn; Y: Mg, Fe^{2+}/Fe^{3+}, Al or Cr and Z is a combination of Al and Si)
      ii. Olivine ($(Mg, Fe)_2SiO_4$)
      iii. Feldspars ($(K, Na, Ca)(Si, Al)_4O_8$)
      iv. Fayalite (Fe_2SiO_4)
      v. Enstatite ($MgSiO_3$)
   (b) Important oxide ores are:
      i. Chromite ($FeCr_2O_4$)
      ii. Ilmenite ($FeTiO_3$)
      iii. Magnetite (Fe_3O_4)
      iv. Perovskite ($CaTiO_4$)

Once the composition of the asteroid is ascertained, metals are extracted using an appropriate process. Iron, nickel, titanium and zirconium are extracted using gaseous phase reactions, silicates and oxides are reduced electrolytically while native metals are directly refined to produce pure metal.

Gaseous Phase Refining The impure sample is treated with reagent to produce a metal complex or compound in the gaseous phase. The gas is isolated and the metal is reobtained in the pure form. The two gaseous phase processes carried out onboard Erebor are namely the Mond process for refining iron and nickel, and the Kroll process for refining titanium and zirconium.

Mond Process The Mond process[Rob98] uses carbon monoxide (CO) to extract and purify iron and nickel. The carbon monoxide reacts with iron and nickel in an impure sample to form volatile metal carbonyls (namely Iron pentacarbonyl ($Fe(CO)_5$) and Nickel tetracarbonyl ($Ni(CO)_4$)). The gaseous carbonyls are separated from the impure sample and then decomposed upon heating to yield highly pure metal. Nickel and iron react with carbon monoxide as follows:

$$Ni(s) + 4\,CO(g) \longrightarrow Ni(CO)_4(g) \tag{4.1}$$
$$Fe(s) + 5\,CO(g) \longrightarrow Fe(CO)_5(g) \tag{4.2}$$

These reactions can occur at as low a temperature as 60°C but optimal rate has been found to be at around 130 °C. Iron reacts at a slower pace than nickel and also at higher temperatures. Hence, iron and nickel are separated from the iron-nickel ore by varying the temperature of the reaction. Further separation is possible as $Fe(CO)_5$ and $Ni(CO)_4$ are weakly bonded and separate upon distillation.
Decomposition occurs at 180°C, yielding solid metal of 99.8% purity. The carbon monoxide is reobtained and reused.

$$Ni(CO)_4(g) \longrightarrow Ni(s) + 4\,CO(g) \tag{4.3}$$
$$Fe(CO)_5(g) \longrightarrow Fe(s) + 5\,CO(g) \tag{4.4}$$

Kroll Process The Kroll process is a vapor phase process for the extraction of titanium and zirconium. $TiCl_4$ or $ZrCl_4$ are reduced using molten magnesium to produce titanium or zirconium with a purity of 99.5%−99.7%. Initially, $TiCl_4$ is produced from the ores rutile (TiO_2) or ilmenite ($FeTiO_3$, more common in asteroids) by heating with carbon and chlorine gas at 1073 to 1173 K:

$$2\,FeTiO_3(s) + 6\,C(s) + 7\,Cl_2(g) \longrightarrow 2\,TiCl_4(g) + 2\,FeCl_3(g) + 6\,CO(g) \tag{4.5}$$

Pure carbon is valuable in space and hence is reclaimed by reducing the carbon monoxide with liquid magnesium. This process is feasible under a temperature of 2000°C. The magnesium oxide is converted to magnesium chloride as it is a common product in several other processes and hence can be processed on a large scale.

$$CO(g) + MgO(l) \longrightarrow C(s) + MgO(s) \tag{4.6}$$
$$MgO(aq) + H_2O(l) \longrightarrow Mg(OH)_2(s) \tag{4.7}$$
$$Mg(OH)_2(s) + HCl(aq) \longrightarrow MgCl_2(aq) + H_2O(l) \tag{4.8}$$

The $TiCl_4(g)$ and $FeCl_3(g)$ are separated from each other and other volatile impurities via fractional distillation. Molten magnesium is then used to reduce the metal chlorides to pure metal at 1073 to 1173 K in an Argon atmosphere.

$$TiCl_4(g) + 2\,Mg(l) \longrightarrow Ti(s) + 2\,MgCl_2(g) \tag{4.9}$$
$$2\,FeCl_3(g) + 3\,Mg(l) \longrightarrow Fe(s) + 3\,MgCl_2(g) \tag{4.10}$$

The pure titanium is deposited as sponge metal and heated to 1273 K to remove the remaining magnesium and magnesium chloride. The sponge metal is recast into ingots by heating them in an electric arc furnace. The magnesium chloride is electrolysed in the molten state to reclaim magnesium metal. As magnesium is a powerful reducing agent ($Mg^{2+}(aq) + 2\,e^- \longrightarrow Mg(s)$) and has a standard electrode potential of −2.38V at 25°C, it is used as a common reducing agent in almost all of the processes aboard Erebor. Hence, the electrolysis of molten

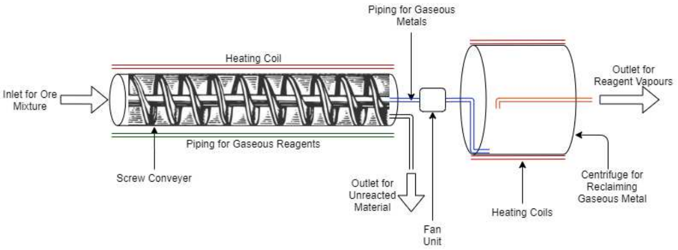


Figure 4.2: Apparatus for gaseous phase processes

magnesium chloride is carried out on a large scale.

$$MgCl_2(l) \longrightarrow Mg(s) + Cl_2(g) \tag{4.11}$$

Apparatus for Gaseous Phase Processes Gaseous phase refining is carried out in both microgravity as well as partial gravity. The various gaseous phase processes are carried out in separate units, but the basic design is the same. The apparatus as shown in Figure 4.2 consists of a screw conveyor fitted in a tube and a cylindrical centrifuge. Gaseous metal compounds are prepared from the concentrated ore as it travels along the screw conveyor. The deposition phase then takes place inside the centrifuge, as the handling of gases is simplified in the partial gravity environment. A more detailed step-by-step flow is given below:

1. The concentrated ore is mixed with the required solid reactants (for example, ilmenite is mixed with pure carbon in the Kroll Process) and loaded onto the screw conveyor using a robotic arm.
2. Once on the screw conveyor, the gaseous reagent (carbon monoxide in the Mond process and chlorine in the Kroll process) is passed through the ore. Heating coils on the exterior provide the required temperature for the reaction.
3. The gaseous metal compounds are drawn through pipes running inside the shaft of the screw conveyor by powerful fans and directed into the centrifuge. The unreacted ore is collected on the other end of the conveyor and is disposed of.
4. In the centrifuge, the gaseous metal compounds react with reducing agents and are deposited in the pure form. Heating coils in the walls provide the heat required for the reaction. Deposition takes place on small pellets of the pure metal, allowing the location to be controlled.
5. Once the concentration of the deposited metal is satisfactory or the reducing agent (for example, liquid magnesium in the Kroll process) has been depleted, the centrifuge is stopped. The pure metal is removed, new nucleation pellets are loaded and the reducing agent (if required) is replenished.

Electrolysis

Electrolysis is a common industrial process with several applications. As energy is supplied externally, almost all metals can be reduced, regardless of the reduction potential. No chemical reducing agent is required, further reducing the complexity associated with the process.
Some disadvantages are that it is extremely energy intensive. Also, metal salts have to be electrolysed in the molten state (as the movement of charged particles is required) and handling fluids in microgravity is impractical. Thus, electrolysis must be performed in a centrifuge which drastically increases the mass and footprint of each unit.
Many processes which are carried out using electrolysis on Earth such as the reduction of alumina (Al_2O_3) to produce aluminium (the Hall-Heroult process) are not performed aboard Erebor. They are instead carried out using reduction with magnesium which reduces the number of processes. Electrolytic reduction is required to reclaim magnesium (the standard reducing agent in several processes), but it is more efficient to electrolytically reduce only magnesium on a large scale versus several metals (each requiring a separate unit) on a small scale.
The main processes carried out using electrolysis are the electrolytic reduction of silicates, the reclamation of magnesium metal from magnesium oxide and chloride as well as the alkaline water electrolysis for the production of hydrogen.

Electrolysis of Silicates Iron and magnesium silicates (such as olivine (Fe_2SiO_4/Mg_2SiO_4), commonly found in S-type asteroids) are electrolysed in their molten state to produce pure metal[Col92]. This is carried out in a centrifuge to simplify handling liquids in microgravity (as is used for the electrolysis of water, see Section 3.2.1).
As silicates are extremely corrosive at high temperatures, the materials for the electrodes must be carefully selected. Platinum is used as the anode, but it cannot be used at the anode as a platinum-iron alloy (with a melting point below the operational temperature of the electrolytic unit) can get formed. Thus, the anode is constructed out of an iron-silicon alloy (with a similar composition as the product). As the anode is maintained in thermodynamic equilibrium with the silicate melt, no undesired reactions take place. The following reactions take place at the electrodes. At the anode:

$$Fe^{2+} + 2\,e^- \rightleftharpoons Fe^0 \tag{4.12}$$

$$Si^{4+} + 4\,e^- \rightleftharpoons Si^0 \tag{4.13}$$

At the cathode:

$$4\,(SiO^-) \rightleftharpoons 2\,(Si{-}O{-}Si) + O_2 + 4\,e^- \tag{4.14}$$

$$Fe^{2+} \rightleftharpoons Fe^{3+} + e^- \tag{4.15}$$

(This is an undesired reaction which takes place in melts with a high iron concentration.)
The above reactions are carried out at 1250°C−1400°C. The end product formed is an iron-silicon alloy which is further purified using electrolytic refining. Overall, 47 MJ is consumed to produce 1 Kg of O_2 and 1.4 Kg of Fe.

Reclamation of Magnesium Magnesium metal is an important reducing agent in several industrial processes (see Section 4.1.4). It is recovered from $MgCl_2$ and MgO by the electrolysis of molten $MgCl_2$. Electrolysis must be carried out in the molten state for the following reasons:

1. The reduction of magnesium is not possible in an aqueous medium as it is outcompeted at the cathode by the reduction of water.

$$2\,H_2O(l) \longrightarrow 2\,OH^-(aq) + H_2(g)$$
$$E^0 = -0.83V \text{ at } 25°C \tag{4.16}$$

2. Solid magnesium salts cannot be electrolysed as the lattice forces do not permit the movement of ions and hence the flow of current is not possible.

As MgO has a much higher melting point (2800°C) than $MgCl_2$ (712°C), it is more energy efficient to reduce molten $MgCl_2$ versus molten MgO. Hence, any MgO is first converted to $MgCl_2$:

$$MgO(aq) + H_2O(l) \longrightarrow Mg(OH)_2(s) \tag{4.17}$$

Magnesium hydroxide is sparingly soluble in water (0.009 gm/L at 18°C) and forms a white precipitate in a basic medium. The powder is collected and reacted with aqueous HCl in a separate vessel to produce magnesium chloride. Magnesium chloride is highly soluble in water (72.7 gm/100 ml at 100°C and 54.6 gm/100 ml at 20°C). However, as solubility is proportional to temperature, it is precipitated from a saturated solution upon cooling (as with most ionic compounds).

$$\mathrm{Mg(OH)_2(s) + 2\,HCl(aq) \longrightarrow MgCl_2(aq) + 2\,H_2O\,(l)} \tag{4.18}$$

Electrolytic reduction is carried out in a centrifuge (similar to the gaseous phase processes, see Section 4.1.4). This eliminates the need to handle molten metal in microgravity while also allowing gaseous chlorine (formed at the anode) to separate easily. Here, the $MgCl_2$ crystals are first heated to their melting point (712°C) and then an electric potential of 2.534 V is applied across the molten salt $MgCl_2$ decomposes at 2.534 V when electrolysed with an inert graphite electrode, (Yating Yuan et al [Yua+16]). Platinum is used as the cathode as it is chemically inert and can withstand the temperature inside the centrifuge without melting (platinum has a melting point of 1768.4°C). The reaction which takes place is as follows:

$$\mathrm{MgCl_2(l) \longrightarrow Mg\,(s) + Cl_2(g)} \tag{4.19}$$

$$\text{At the anode : } \mathrm{2\,Cl^- \longrightarrow Cl_2(g) + 2\,e^-} \tag{4.20}$$

$$\text{At the cathode : } \mathrm{Mg^{2+} + 2\,e^- \longrightarrow Mg\,(s)} \tag{4.21}$$

Pure magnesium metal is deposited on the cathode. It is collected by removing the cathode and heating it at 700°C, melting away the magnesium (melting point: 651°C). The chlorine gas liberated at the anode bubbles out of the molten salt and accumulates at the center of the centrifuge. It is collected using fans and reused in the preparation of hydrochloric acid.

$$\mathrm{Cl_2(g) + H_2(g) \longrightarrow 2\,HCl\,(g)} \tag{4.22}$$

($\Delta H = -92.3$ KJ/mol of HCl produced, which is highly exothermic.)

Hydrogen Production Water obtained from the asteroid is electrolysed to produce hydrogen propellant. Alkaline water electrolysis (using 25%−30% KOH as the electrolyte) is the selected process owing to its high efficiency of upto 80% and hydrogen of 99% purity. Due to inefficiencies in the system, there is a gradual loss of KOH making it one of the few consumables on Erebor which must be resupplied periodically. The reaction is conducted with at cell potential of 1.8V.

$$\begin{aligned}\text{Anode : } & \mathrm{2\,OH^-(aq) \longrightarrow O_2(g) + 2\,H^+(aq) + 2\,e^-} \\ & E^0 = 1.23\text{V (Theoretical)}\end{aligned} \tag{4.23}$$

$$\begin{aligned}\text{Cathode : } & \mathrm{2\,H_2O\,(l) + 2\,e^- \longrightarrow 2\,OH^-(aq) + H_2(g)} \\ & E^0 = 0\text{V (Reference reaction)}\end{aligned} \tag{4.24}$$

$$\text{Overall : } \mathrm{2\,H_2O\,(l) \longrightarrow 2\,H_2(g) + O_2(g)} \tag{4.25}$$

The oxygen is not required in nearly the same quantities as hydrogen. Some of the oxygen is used to maintain atmospheric levels in the pressurized segments, however the vast majority is vented overboard. This vented oxygen plays a vital role in Erebors thermal control system as it is first run through a heat exchanger in the nuclear reactor and thus can carry away any excess thermal energy. Electrolysis is carried out in a pair of large cylinders with a radius of 10 m and a length of 20 m (for a total volume of 6283.18 m^3or about 6000 $m^3$of usable volume). Each cylinder rotates at 1 rad/s providing an acceleration of 10 m/s^2 along the circumference. The gaseous products rise to the center of the rotating cylinder where they are collected.

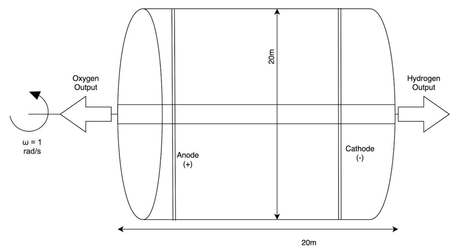


Figure 4.3: Centrifuge used for electrolysis of water

Scale of Operations Erebor is designed around the ability to relocate from one asteroid to another and hence must be able to refuel the main hydrogen tank within a reasonable timeframe. It has been decided that the rate of hydrogen production is such that the main tank can be refilled completely within 2000 days. It should be noted that a completely full tank or 7 Km/s of delta-V is almost never required. As the delta-V required is reduced, the fuel required goes down exponentially.
Erebor has a total fuel capacity of 17,500,000 tons of hydrogen gas and 1/9th of the mass of water is hydrogen, 157.5 million tons of water must be processed in order to refuel completely. This means that 78,750 tons of water ice has to be transported to Erebor per day, or 4000 tons per hour (assuming 20 hours of operations per day). As the VASP drones have a capacity of 1000 tons, this amounts to four trips per hour.

Reduction

Metals are present in compounds in the form of positively charged species (cations). In order to obtain them in the metallic form (that is, in the neutral state), these compounds must be reduced with the help of an appropriate reducing agent.
The suitability of a given reducing agent for reducing another species at a particular temperature is determined using the Elingham diagram, which is the plot of the change in the standard Gibbs free energy (ΔG) of the oxidation half reaction of a species versus temperature. The net ΔG of a full redox reaction is found by subtracting the ΔG of the half reaction of the species getting reduced (inverting the reaction from oxidation to reduction) from the ΔG of the oxidation half reaction. Chemical reactions are feasible in the direction of decreasing Gibbs free energy, thus, if the line representing a particular reaction is lower than the line representing another reaction, it means that the former is able to reduce the latter.
As is evident from the Elingham diagram, magnesium is a powerful reducing agent and can reduce almost all other metallic ions. Magnesium is already used in the Kroll process for the production of titanium (see Section 4.1.4) and thus it makes sense to use it as a general purpose reducing agent to streamline operations. Apart from magnesium, hydrogen is also used as a reducing agent, albeit on a smaller scale.

Reduction using Magnesium Magnesium is used as the reducing agent in the majority of processes carried out aboard Erebor. Magnesium is extremely versatile, as it is a powerful reducing agent (evident from the Elingham diagram) and can also reduce both metal oxide and chlorides. The reactions taking place are as follows:

$$\mathrm{Mg \longrightarrow Mg^{2+} + 2\,e^-} \tag{4.26}$$

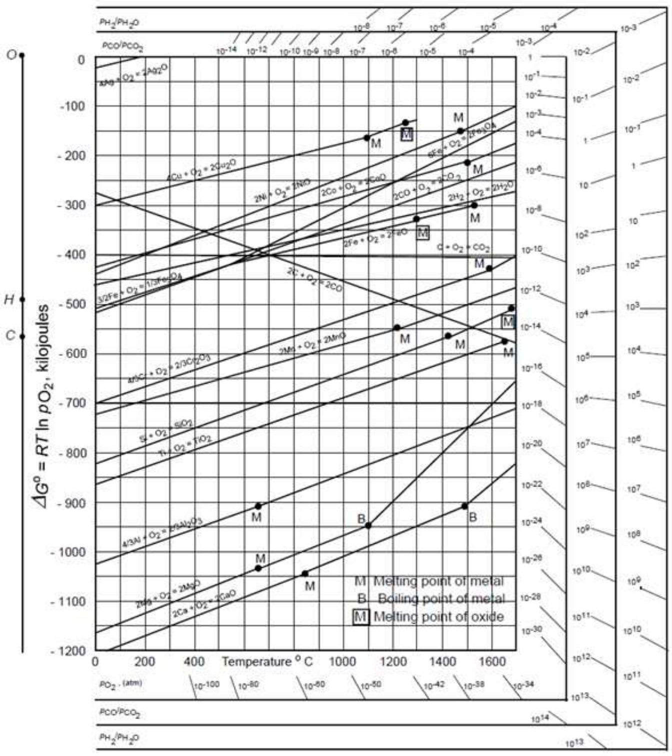


Figure 4.4: Elingham diagram[1]

(Oxidation of magnesium)

$$MO/MCl_2 + 2\,e^- \longrightarrow M + 2\,Cl-/O_2{}^- \tag{4.27}$$

Where M is any metal except for Li, Na, K or Ca. Hence, the overall reaction can be written as:

$$MO + Mg \longrightarrow M + MgO \tag{4.28}$$
$$MCl_2 + Mg \longrightarrow M + MgCl_2 \tag{4.29}$$

The process is carried out under reduced pressure and at 1000°C so that the MgO and $MgCl_2$ sublimate away (similar to the Kroll process, see Section 4.1.4), leaving behind pure metal. Thus, further refining is not required in most cases. The magnesium oxide/chloride vapors are collected and electrolysed to reclaim magnesium metal, ensuring that the process is sustainable (refer to Section 4.1.4 for more details).
Reduction using magnesium is used in a myriad of processes such as the extraction of metal from TiO_2 (rutile), Al_2O_3 (alumina), Fe_2O_3 (haematite), Fe_3O_4 (magnetite) as well as in the Kroll process and the reclamation of carbon from CO.
Magnesium has the following advantages as a reducing agent:

1. Magnesium has a standard reduction potential of -2.38 V (in aqueous medium at 25°C) and is the strongest reducing agent apart from Li, K, Ca and Na (which are extracted via electrolysis rather than reduction). Thus, it can be used as the reducing agent in almost all industrial processes (such as the production of C (from CO), Al, Fe and Ti).
2. Separate electrolytic reduction units for different metals (which adds mass and complexity) are not required as only magnesium must be electrolytically reduced.
3. As Mg is less electropositive than Li, Na, K or Ca, it has a lower reduction potential and hence can be electrolytically reduced using less energy.
4. Magnesium is divalent (one atom provides two electrons) and hence less is required as compared to monovalent alkali metals such as Li, Na or K (each metal atom provides one electron).
5. As evident from the Elingham diagram (see Figure 4.4), reduction using magnesium is possible at low temperatures (as compared to carbon, commonly used on Earth) which increases the energy efficiency.
6. Magnesium is already used in the Kroll process. By also using it as a general purpose reducing agent, common electrolytic reduction facilities can be used and the efficiency of the process increases due to economies of scale.

Reduction using Hydrogen Hydrogen is also used as a reducing agent. In fact, hydrogen is used as a reference to measure the standard reduction potential of a reaction, hence the electrode potential is 0 V at 25°C in an aqueous solution.

$$2\,H^+(aq) + 2\,e^- \longrightarrow H_2(g)$$
$$E^0 = 0V \text{ (Reference reaction)} \tag{4.30}$$

Hydrogen can be used to reduce ilmenite ($FeTiO_3$) to produce iron, titanium dioxide (TiO_2, further reduced using magnesium) and water (electrolysed to reclaim hydrogen), as proposed by Lawrence A. Taylor et al [Tay+93]. The following reaction is performed at 1000°C:

$$FeTiO_3(s) + H_2(g) \longrightarrow Fe(s) + TiO_2(s) + H_2O(g) \tag{4.31}$$

Even though pure titanium can be directly obtained from ilmenite via the Kroll process, hydrogen reduction is carried out (albeit on a small scale) because having an alternate process is always advantageous.

Refining

In many cases, the metals obtained are not of a suitable purity for export and further refining is required. For example, gold, silver, platinum, iridium, cobalt, copper, aluminium and other trace metals are present in their native state in asteroids (especially M-type asteroids) but they either are mixed with impurities or of too low a concentration for export to be viable. Many industrial processes carried out aboard Erebor (such as the reduction of silicates) do not produce a completely pure product and require further purification, while the Mond process, Kroll process, and reduction using magnesium produce products of sufficient purity and further refining is not necessary.
There are two processes available for refining aboard Erebor, namely the Zone refining process (for silicon, gallium, germanium and indium) and electrolytic refining (for gold, silver, platinum, aluminium, copper and other trace metals).

Zone Refining Zone refining relies on the increased solubility of impurities in liquid metal and can be used to purify silicon, gallium, germanium and indium. A ring-shaped induction coil is used to liquefy one end of a metal ingot. The coil is then translated along the ingot, with the molten 'zone' moving along with it. As impurities are more soluble in the molten metal than in solid crystals, they follow the molten zone and are concentrated at the other end of the ingot. This process is repeated multiple times to produce extremely pure metal (for example, germanium with as little as one part impurity per ten billion parts germanium).

Electrolytic Refining Electrolytic refining is used to purify all other metals, including (but not limited to) cobalt, copper, gold, silver, platinum, aluminium, iridium and other trace metals. As the metal produced is extremely pure and no chemical

[1] Image credit: D.R. Gaskell, Introduction to Metallurgical Thermodynamics[Gas81]

[2] Image credit: Zone Refining, Toppr: `https://www.toppr.com/ask/question/zone-refining-is-a-method-to-obtain-2/`

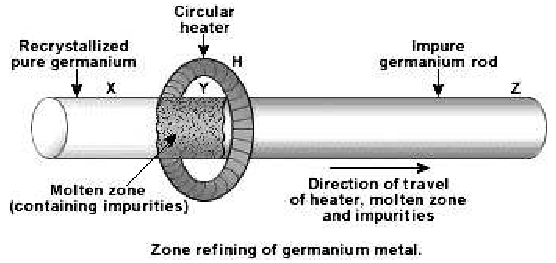


Figure 4.5: Ultrapure metal obtained using the Zone process.[2]

reagents are required, rendering this method extremely suitable for Erebor.

The sample of impure metal is used as the anode and a small sample of the pure metal is used as the cathode. The electrodes are immersed in an acidified solution of the metal salt (usually metal sulphides or chlorides of the concerned metal), which acts as the electrolyte. Upon passing current, the impure metal in the anode is oxidised to produce cations which dissolve in the electrolyte while the impurities form a precipitate known as anode mud. At the cathode, cations from the electrolyte are reduced and are deposited on the cathode, producing a mass of pure metal.

The anode mud contains traces of gold, silver, iridium and other platinum group metals. These are extracted from the anode mud by treating it with appropriate reagents such as aqua regia (a 3:1 solution of concentrated HNO_3 and HCl which is capable of dissolving gold and platinum).

Electrolytic refining is carried out in a centrifuge (see Figure 4.3 for a similar unit) for two main reasons:

1. In microgravity, the electrolyte (like most liquids) tends to form a sphere due to its surface tension. This is impractical for electrolysis and hence some acceleration is desired.
2. The anode mud is extremely valuable and must be collected. In the presence of some acceleration, it precipitates along the rim of the cylinder which aids in collection.

4.2 Manufacturing

Limited manufacturing onboard Erebor is carried out as the primary purpose of Erebor is resource extraction and bulk export. The manufacturing facility primarily exists to produce replacement components in case of part failures or new tooling for various applications as and when the need arises.[DA+] Manufacturing is predominantly carried out through 3D printing. Additive manufacturing has already been demonstrated in a microgravity environment, for example with the Additive Manufacturing Facility (AMF) developed by Made in Space Inc and operational aboard the ISS since 2016. The AMF is compatible with over 30 polymers and the Made in Space Recycler (flown in 2019) has been demonstrated to be capable of handling recycled materials such as plastics to produce high quality printer feedstock. Several technologies for the additive manufacture of metallic objects are under development including the VULCAN by Made in Space as well as Stargate by Relativity Space. It is expected that by the time Erebor is constructed the technology is mature enough to be employed at a suitable scale.

Chapter 5: Epilogue

5.1 Demographics

5.1.1 By Age

The population of Erebor is 7500. This includes all demographics, not just the working population. Onboard Erebor, the male to female ratio is 1. The maximum number of children per couple is kept at 2. This helps to prevent overpopulation while also keeping the population of Erebor stable. Immigration from Earth is only permitted in order to replace someone who has left Erebor. As Erebor is largely industrial in nature and may operate far away from Earth, there are no facilities on board to cater to tourists.

Age Group	Population Size	Comment
0-15	1,500	Children. Not in the workforce.
15-30	1,500	Adolescents and young adults. Some are pursuing higher education while others enter the workforce. This is the age when people have children.
30-45	1,500	In the workforce.
45-60	1,500	In the workforce.
60-75	1,500	Most are retired. Some may pursue less physically intensive careers such as education, governance, etc.

Table 5.1: Erebor population by age

There is a good reason to maintain the senior citizens age group: Erebor is a home, and recent research shows that grandparents contribute to children's well-being [MS14]. In addition, senior citizens form a vital part of any population due to their greater life experience.

5.1.2 By Occupation

Erebor's occupation demographics (after complete construction) is shown in Table 5.2.

Occupation	No.	Comment
Robot Monitoring	200	Ensure that robots are functioning correctly, managing robot pathways, fixing glitches and software errors remotely.
Mineralogists	100	Asteroid surface analysis, assessing potential targets, etc.
Piloting	100	Piloting the asteroid hoppers remotely, RATHAs, and Erebor itself.
Computer Scientists	100	Managing DIMAAG, communications, onboard computers, data storage, internet and intranet.
Astrophysicists	100	Planning Erebor maneuvers, monitoring solar storms, guidance and navigation, etc.
Robot Maintenance	200	Fixing hardware issues, upgrading robots at the robot site and fixing mechanical breakdowns.
Reactor Maintenance	200	Monitor and repair the nuclear reactor using Reactor Bots.
Industrial Engineers	100	Managing, repairing, and retooling industries onboard Erebor.
Specialised Maintenance	300	Perform those functions which robots cannot, including spacewalks, some asteroid surface operations, etc.
Metallurgists	600	Design and improve industrial processes related to metal ores and extraction.
Botanists	300	Manage agriculture, aeroponics, develop new plant varieties (GM) and ensure crop health.
Education	100	Specified in Section 5.2.1.
Governance	100	Democracy. 40 legislative, 40 executive, 20 judiciary.
Healthcare	100	Specified in Section 5.2.2.
Logistics	400	Managing supplies, material movement, loading and unloading RATHAs and goods trains where robots cannot.
Miscellaneous	1500	Manual labor, plumbing, etc.

Table 5.2: Erebor population by occupation

5.2 Miscellaneous Issues

5.2.1 Education

Around 300 teachers are in the education sector. Of these, 200 are in the schools and the remaining 100 are in colleges. The subjects taught are:

1. Science (Physics, Chemistry, Biology, Astronomy)
2. Earth Studies (if teenagers wish to relocate back to Earth, they may do so after the age of 18)
3. Languages (English, Sanskrit, Mandarin, German)
4. Arts (Dance, Drama, Music, Visual)
5. Physical Education (schools can use sporting complexes and parks at certain times)
6. Computer Science (C/C++, Lisp, Python)

5.2.2 Healthcare and Hospitals

Hospitals are located in the GHARs, and there are healthcare units located in the MIU in case of emergencies. Doctors and nurses are available 24/7 in case of serious emergencies. Besides this, all citizens have monthly health check ups and must exercise or play a sport to ensure a healthy populace.

The special risks in space are: DNA damage, muscle atrophy, loss in bone density, and elongation of the spine. These occur due to radiation exposure and long durations in zero gravity, hence, most of the population does not face these risks. However, citizens who work near the reactor or in the MIU may suffer from these maladies. These citizens are required to go for weekly health checkups and keep a tab on time spent exposed to radiation and zero gravity.

5.2.3 Selection

The first 7,500 people to colonise Erebor are selected based on applications. Their qualifications and proficiency are the primary consideration, along with age, marital status, family, and psychological testing. Prior citizenship, nationality, sex, religion, etc. are not factors considered for this formation. As soon as the first 7,500 are selected, they are granted Erebor citizenship. Erebor is a settlement, and hence people are expected to move here with their families. Anybody born on Erebor is granted Erebor citizenship by birth. If anybody residing on Earth or any other colony would like to shift to Erebor, there must first be a vacancy in the population.

5.2.4 Computers

Hardware

Few users require access to the resources of DIMAAG, and it is primarily reserved for those doing scientific research and calculations related to Erebor's movement. It is administered by a group of computer engineers, who are the only people with `sudo` access to DIMAAG. For security purposes, DIMAAG remains isolated from the central Erebor network.
All citizens are provided with personal computers. Although it is incredibly difficult to predict how computing needs will evolve over the next 25 years, we estimate that 16GB of RAM, a four-core CPU at around 3GHz, and a 1TB SSD should be sufficient. However, this is subject to change.
Erebor has other computers as well, for external communication and server management, which are managed by the computer engineering team.

Software

Operating Systems DIMAAG runs a UNIX-like system without a GUI, and as such, isn't very different from the current POSIX specification, with the exception that home folders are encrypted. A good candidate for such a system is SE-Linux, which has an excellent set of access-control policies useful for critical systems. SSH is generally used to access DIMAAG via a private network.
Personal computers are free to run whichever OS the owner prefers, although Debian and Arch-based Linux distributions are strongly encouraged, due to ease of maintenance and high stability.

Personal Communication Erebor has its own social network: Khuzdul (namesake: Tolkein's Dwarvish language). It is required that all messages are encrypted on the sending device, and decrypted at the receiver: true end-to-end encryption is employed. RSA-2048 is preferred for important messages, though the faster symmetric key AES is also used once key exchange is completed via RSA. For fun, we've written a sample program in Python that can RSA-encrypt and decrypt files of arbitrary length, located in Appendix C.

Text Editors Although people are free to use any text editor, they are strongly encouraged to use `vi` and `emacs`. It has been proposed that the results of a novice trying to exit the former be used in place of RSA's psuedorandom number generator, though this possibility remains unexplored at the time of writing. Moreover, the hospitals are considering the creation of a special wing for pinky injuries and dizziness from viewing Emacs Lisp's nested parentheses.

5.3 Conclusion

5.3.1 Life on Erebor

Reproduced below is a few diary entries of an Erebor resident, Alexander Jackson, who is a college student in GHAR A.

Wed 10/04/2047: 1618 hours GAST
It's time to choose a career, I guess. I feel a bit like Barry from that ancient Seinfeld film, *The Bee Movie*: the fear of specialization and the moment of the choice is frightening.
I just stepped out of my last ever Verilog class: I'm now trained in aerospace, electronics, and computer engineering, with a fair amount of focus on robotics, but somehow, I don't feel ready to choose. I love what I do...but should I even remain on Erebor, or go back to Earth to see what home's really like?

> **Editor's note:** Erebor's students learn multiple branches of engineering in the short span of five years, though each is a separate degree on Earth. In most Earth systems, there's a three-year gap at minimum between learning to add and learning the foundations of algebra: not a very useful utilization of time. Instead, Erebor's system is modelled after the Hungarian gymnasium system of the early 20th century that produced von Neumann. Students showing proficiency at certain subjects are fast-tracked into a system where they interact with college professors early-on, doing research in fields ranging from political science to mathematics. The gymnasium phase is eight years long, by the end of which nearly 90% of students have found something they're good at. The wide variety of subjects means the alumni are polymaths: useful to Erebor and easing unemployment.

My thoughts ground to an abrupt halt when I saw Vanessa pass by, talking to her friend.
"So, we graduate on Friday, finally! Aren't you hyped?" she said, the excitement visible on her face.
"Yeah, finally!" her friend grinned.
They walked out of earshot. Maybe I should tell her how I feel. I've postponed it for five years now, and college is over. Maybe on Friday. I boarded the bus. Where was I? Yes, what to do after college.
My parents own the most popular late-night restaurant of GHAR A, and are generally popular, well-connected people. By a lucky chance, they were selected to come on Erebor twenty years ago as construction workers, and their age is now showing in the wrinkles on their faces. I'm the first in the family to get a STEM college degree: my parents can't really help with career choice.
We live right above our restaurant, *Les Amis*. Dad was behind the bar as usual.
"How was college?"
"Fine."
"Something's on your mind. Talk to me, Alex. What's wrong?"
I didn't want to tell him that after five years of college, I had no idea what to do with my life, but I decided to be honest.
"I don't know what to do with my life. I don't think I can choose something in Erebor I want to do for the rest of my life. I feel empty and restless, and like a waste of resources."
Dad shook his head.
"Come on back."
We went into the garage, where he had opened up the milkshake mixer, and sat down, cleaning the drive belt.
"Have you ever been to the NATASHA? The MIU? Have you ever been on an EVA?"
I laughed, confident that he was joking.
"Come on Dad, they're off limits. Practically nobody can go there."
"I built them with my own hands. Nothing's truly off limits: this is our home. Today is Wednesday, and Mr. Lex Commitman is going to come for his quiet dinner as usual. I'll ask him if he'll take you."
"Okay, but how will this help me figure out what I want to do?"
Dad smiled. "You'll see."

Thu 11/04/2047: 0534 hours GAST
I just got home. Where to begin?
At around 9:00 PM, Mr. Commitman came in for dinner. As usual, I was helping clean up used tables.
"Mr. Commitman, the usual?" asked Dad.
"Yes, that sounds good," Mr. Commitman said.
"By the way, I needed some help, if you have time," Dad said, then leaned in and spoke to Mr. Commitman for a couple of

minutes, then waved to me. I walked over.
"Hi, Alex. Have a seat. Eaten dinner yet?" asked Mr. Commitman.
"No, sir, not yet."
"Call me Lex. C'mon Bob, give me some time with the kid," said Lex with a twinkle in his eye.
Dad grinned and went to another table.
"So, I hear you're in college and have no idea what to do with your life. Why do you think you feel this way?"
"Lex, I'm not sure. I think it's because I've been living on Erebor my whole life, maybe I don't see the *why* of existence. I'm not sure what I want to do, I'm not sure that I want to do anything. Maybe I'm burnt out?"
"Hmm, at your age, you know, I felt much the same way about settling down into a nine-to-five job and not understanding much about life at all."
"What did you do?"
"I'll show you. Let's go," he said, waving goodbye to Dad and walking me out of the door.
"When I was in my final year at MIT, I had no idea what to do. The economic effects COVID-19 pandemic were still felt worldwide, and good jobs were hard to come by. Few people had the luxury of choosing what they wanted to do. The planet was an incredibly polluted place, despite – or perhaps because of – politicians making plans to mitigate pollution and the economic crisis. One of my options was going and working in a rich, high-end place like Silicon Valley, ignoring what was happening to the world and building chips. There was only one place I knew doing something really exciting: building this station, Erebor."
We'd reached the train station block, and we took and elevator to the top, and stepped into the 2130 *Rosalind Franklin Express*. Although it was my first time here, these trains felt like home: they were remarkably like the ones we use for transport within the GHAR, albeit with more handles and larger belts.
"So you went to work for Erebor?"
"It wasn't that simple. Getting a position was so incredibly competitive that I failed the interview process the first two times. Finally, after two years of working at MIT as an assistant professor, I got an engineering position working on the NATASHA's spoke transport system. Speaking of which, let's go."
I hadn't realised it, but I felt like I was getting lighter and lighter. Of course: the train was at zero relative velocity with the NATASHA, and we were now floating. I felt strangely helpless. Lex used the handles to move out of the train and into one of the waiting elevator pods, and I followed his example.
"Lex, you designed this?"
"Yup. These go all the way up to the Logistics Hub, where the observation deck is. Anyway, as I was saying, that's how I ended up coming here. And you know something? It gave me purpose, because I knew that through my work, I was indirectly helping the billions of people on Earth."
"Yes, but..."
"I know you're still confused. But wait...here comes the Hub."
The elevator stopped, revealing a large train-like rail, on which a large transport robot was running. We hopped on.
"This is the central railway: it goes all the way through the MIU in a pressurized tube, and is transparent where it can be," Lex explained. There were a lot of other people on board: all from GHAR B.
I looked out excitedly – everything we'd studied in our classes about how Erebor works, I was going to see. Our field trips went at best till the Logistics Hub. There were an incredible number of processes going on, most automated. Other than processing of minerals, there were large plants being carefully sorted by size and type then sliced by machines and further processed: much like a factory.
The train stopped at a station.
"Look," Lex pointed through a window.
There was a large window, through which the NATASHA was visible, surrounding the slow-rotating GHARs: almost eerie. Behind it, the large hydrogen tank and the darkness of space. Truly beautiful, silent, and eerie.
"This is probably the coolest bit about Erebor, Alex. The fact that NATASHA does most of the radiation shielding keeps our mass low enough to move around, and having the GHARs rotate in opposite directions cancels all forces and torques along the axis. It's also the reason Erebor succeeded where others failed: the resources devoted to humans' survival are low, focusing our efforts on the MIU and asteroids."
We eventually reached the end of the MIU, and turned back, as I saw the other side of the MIU: robot maintenance, 3D printers, and electrolytic processes. The whole MIU seemed to be a paradigm of efficiency: and nearly entirely automated. No wonder dad chose to start a restaurant rather than work in the MIU: they didn't need him!
Lex and I reached the elevator pods again, and went in.
"Now comes the funnest part of our little tour. Let's check out the NATASHA."
We stepped out at the station, but instead of proceeding toward either of the GHARs, we proceeded further down in another elevator, eventually reaching the NATASHA's top floor. It was quiet, and the air damp. As far as the eye could see, there were rows and rows of plants, inside their aeroponic modules. The smell was something I hadn't really smelled before: moist and...green.
"This is the inside of the NATASHA. Let's walk. So what exactly is bothering you?"
"Well, Lex, the thing is, all this is beautiful. I love it, it's incredibly intricate and beautiful. I still feel like something's missing in life...is there something wrong with me?"
Lex sighed.
"Back when we were building Erebor, I had questions about the mental health of the kids growing up here. It's safe to say that never, in human history, has a child grown up completely isolated from Earth: I mean, none of you have ever seen soil, or the sky, or real animals.
"I don't think there's anything wrong with you. You're a bright young man. Maybe there's a lot to be found out about raising kids away from Earth. It's not easy, and all of us are learning how to do it.
"At the same time, what you're feeling isn't only because you grew up on Erebor, and I strongly encourage you not to think of that as the cause. *Nobody* has any clue what life is all about. Nobody knows why we're here, nobody knows what our purpose is. Not me, not anyone, and that's all right. What you should draw your attention to is finding a purpose for *yourself*.
Pick anything. I picked transport systems. Look around you, explore. Find something you can do forever without getting bored or tired, something that deeply interests you and drives you to create new things and keeps you happy. Some people say finding a passion is hard: I disagree. I have multiple passions. You can find one easily: look around you. Think back to what you know and what you've learnt: what you're a natural at. You know, I – watch out! That's an Agbot – step aside!"
I jumped aside, and a largish robot passed beside me, went a few meters ahead, and stopped. It carefully scanned the plant under question, stood and appeared to think for a moment, then sprayed some fluids onto the roots and moved on. I suddenly became aware of multiple Agbots moving around, their sound

had been obliterated up till now by the conversation. It was eerie and yet had a certain beauty about it: a robotic gardener, keeping us alive.
Lex looked sideways at me.
"You liked the Agbot, didn't you?"
"Yeah – I don't know. It's really cool. I studied robotics but skipped studying biology because it's so boring, so I don't really understand what it's doing."
"That's probably why Agbots aren't *nearly* as good as we want them to be: people in robotics don't know biology, and biologists don't know how to build a good robot!"
"Hmm..."
Lex smiled. We walked around the NATASHA for a bit, then Lex dropped me home. I'm going to sleep now, but before I do: I think I found my passion! The NATASHA is the forest of Erebor, and the Agbots the animals. I'm going to apply for a job working on Agbot engineering: hopefully learning some biology along the way. In any case, even if it turns out that I don't like it: at least I'll have learnt something new and contributed something useful.

Sun 7/1/2074: 0847 hours GAST
Today, we leave for Earth. Vanessa, and our daughter, Emma, who's now 21 (and much in the same position I was at her age), and I have collectively decided that we need to visit the place we came from. Erebor has a ten year long exchange program with Earth residents, and our RATHA is at 1100 hours.
I'm writing in this diary after years, so if someone is reading this: I'm now heading the Agbot division, and I'll continue to work remotely from Earth. I was able to come up with some innovations that greatly reduced the amount of human intervention required when Agbots sensed issues with a plant: primarily by leveraging years of Earth's knowledge of growing crops, and our own experiments in aeroponics.
Lex went on to become a Senator on Erebor's first democratic government after we broke even, focusing on economics and working on mental health issues. He created a few zero-gravity zones in the Logistics Hub's extra space, with sports like Quidditch and air football. He comes to Dad's restaurant sometimes, and always has pieces of advice for me.
It all worked out well in the end. Dad tells me that he knew I'd fall in love with *something* while seeing the whole of Erebor with Lex. Maybe Emma will find her calling on Earth.
Here's to going back home.

5.3.2 Future Prospects

It's difficult to predict how human systems and societies behave and evolve. However, we imagine that living on Erebor will be both fulfilling and thrilling. This paper doesn't attempt to lay in stone precisely what Erebor will be like: in particular, we expect that the citizens of Erebor will solve the problems they encounter, and grow, as all humans do. We hope citizens will remain connected to Earth, as such, Erebor's servers will have a large number of movies and music from back home. People will have space to socialise: the population is large enough to allow significant choice for friendships and relationships, and the layout of the GHARs facilitate this: from having restaurants and parks to train stations where human contact is a must.
All in all, it is expected that citizens will have good mental and physical health, and Erebor will be home to a thriving, resourceful population of problem-solvers.

There are several studies regarding asteroid mining assigning a monetary value in the billions but these figures are largely theoretical. A significant fraction of this value is tied up in platinum group and other valuable elements which are scarce on Earth. Due to the limited supply of these resources on the Earth's crust, these command high prices in present-day markets. Eventually as mining and export operations from Erebor scale up, the supply increases leading to a steep reduction in the prices. This is compensated however by a large increase in demand, ensuring continued profitability. The increase in availability catalyzes the development of previously unforeseen applications and technologies resulting in an improvement in the quality of life on Earth significantly.
While high-value but low-volume platinum group resources are a vital export, bulk goods such as iron, aluminium, nickel, copper and titanium are vastly more important due to their value for the colonization of space. As humanity spreads out into the cosmos, and the construction of large structures such as O'Neill cylinders, Stanford torii and other planetary bases on various celestial bodies, the demand for theses resources in space increases dramatically. These resources can either be sourced in-situ, transported from the Earth or exported from Erebor. The Earth can be completely ruled out due to the destructive nature of mining and the prohibitively expensive nature of transportation to space. The in-situ production of resources is also not practical in many cases. On many planetary bodies, the concentration of resources is too low for practical purposes. In addition, refining metals is extremely energy intensive and the equipment involved is bulky and expensive. Resources extracted from planetary surfaces must be transported out of that celestial body's gravity well, necessitating fuel and specialised hardware which raises the cost and decreases the volume. In contrast, exporting metals from Erebor using the ALBATROSS uses virtually zero propellant.
Erebor also can supply resources to the Earth which is advantageous as asteroid mining causes zero environmental damage. No biodiversity is lost, no deforestation is required, no pollutants enter the atmosphere/hydrosphere, no people have to be displaced and the atmospheric carbon footprint is zero. Hence, by eliminating the disastrous environmental consequences of resource production, Erebor (and other Erebor-class colonies) increases the resources available to humanity while also eliminating the ecological cost completely.
In the long run, asteroid mining can fundamentally transform our species. Once the Erebor has repaid the cost of construction and steady state production volumes are achieved, all excess production is directed to the construction of future Erebor-class colonies (Lothlorien, The Shire, etc). Eventually, the total output exceeds the demand even when accounting for space settlement. At this point, work on megaprojects such as a Dyson swarm can be initiated. By increasing the energy production by multiple orders of magnitude, our civilization can rise on the Kardashev scale (which measures the advancement of a civilization using the total energy consumption as the primary metric) from the present day 0.73 to possibly even a type 2 civilization. Ultimately, a post-scarcity civilization is achieved and Erebor's primary objective, the elevation of humanity, can be achieved. Erebor is not an end in itself but a means to the human race eventually colonizing the Solar System.

5.3.3 Afterword

It is our hope that you enjoyed reading about Erebor as much as we enjoyed writing about it. From the first rough sketch of the NATASHA to watching the final document compile, it's been a journey where we learnt a lot, but more importantly, expressed and gave solid form to our countless ideas and discussions.
Thank you for being a part of our journey, and thank you for taking the time to read *Erebor*.

Appendix A: Gallery

A.1 Structure

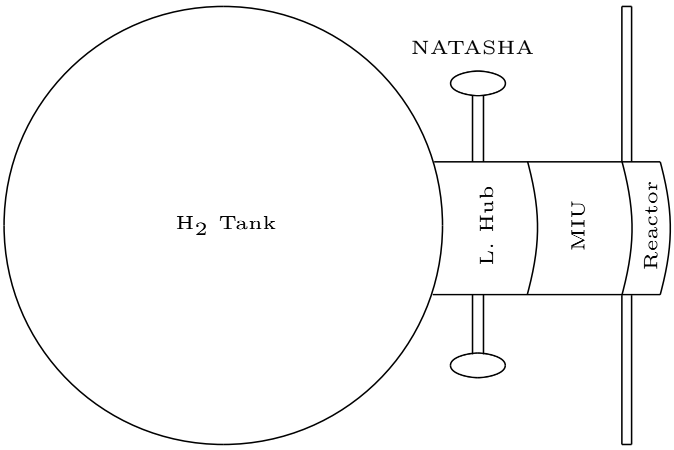


Figure A.1: Erebor Cross Section

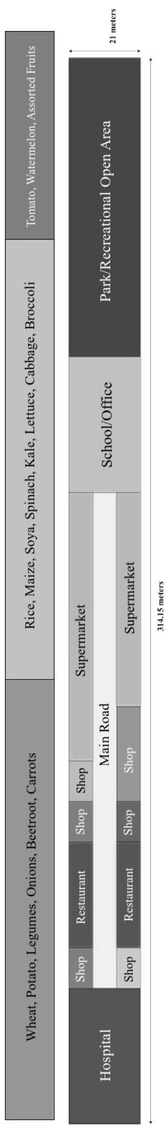


Figure A.2: NATASHA and GHAR sections, top view

Figure A.3: GHAR park cross section

A.2 Support Systems

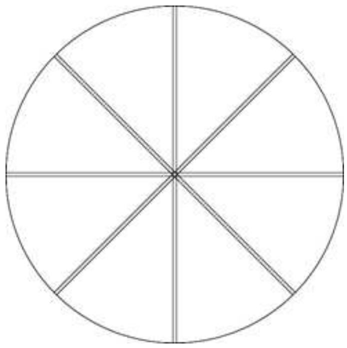


Figure A.4: Division of the reactor block into 8 subsections. Each bulkhead is armoured and can withstand an explosion.

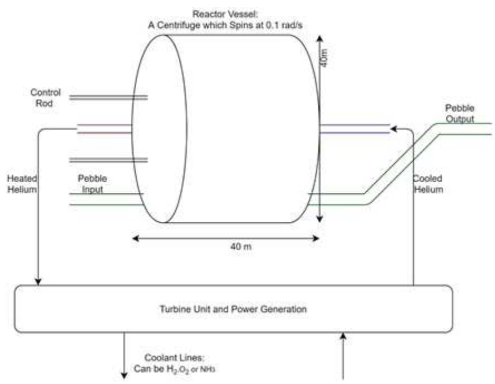


Figure A.5: An interior schematic of the inside of each reactor unit. The pebble inspection and processing unit is not shown.

A.3 3-D CAD

The following are 3-D views of Erebor. Note that the hydrogen tank is not to scale to aid viewing. All other parts are to scale. The Logistics Hub, MIU, and reactor are slightly separated to illustrate their respective lengths.

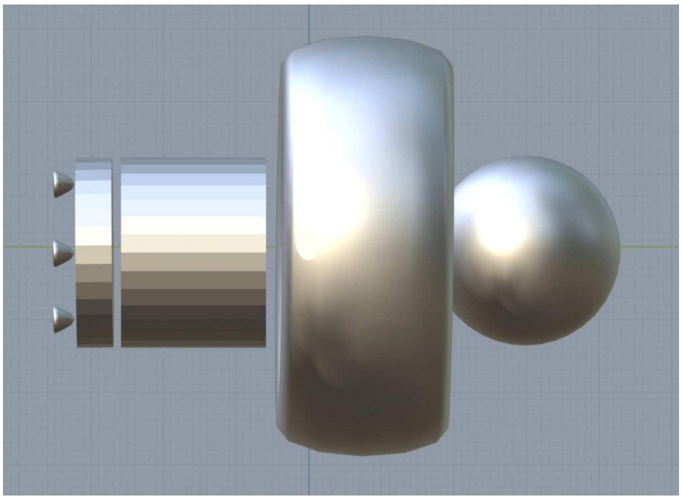


Figure A.6: 3-D: Side view

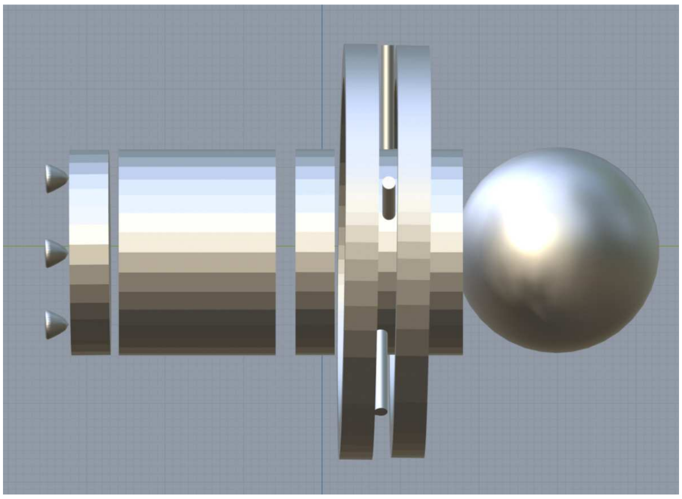


Figure A.7: 3-D: Side view without NATASHA

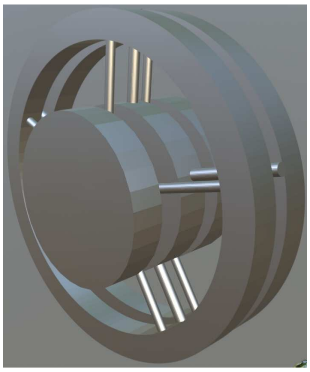


Figure A.8: 3-D: GHARs and Logistics Hub

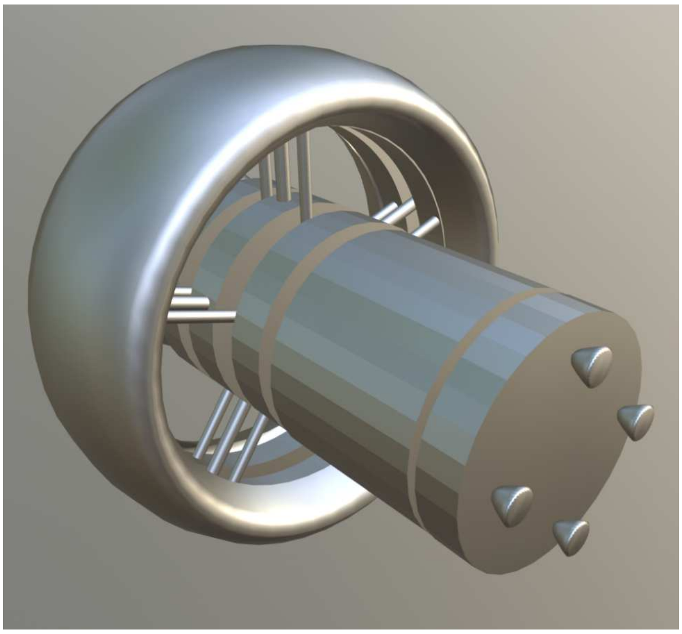


Figure A.9: 3-D: Perspective view

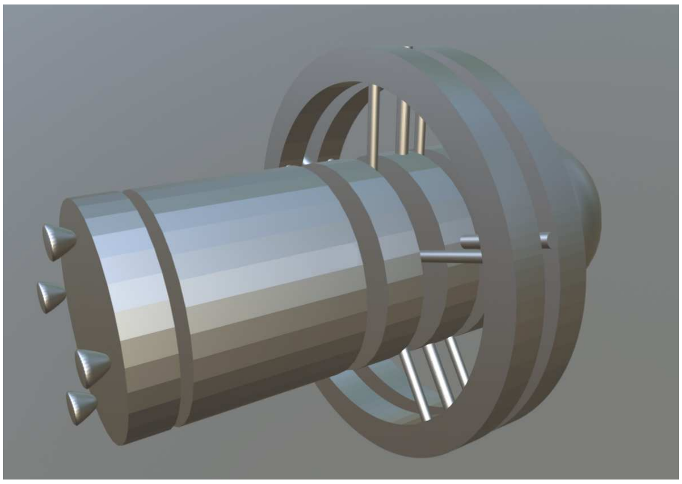


Figure A.10: 3-D: Perspective view without NATASHA

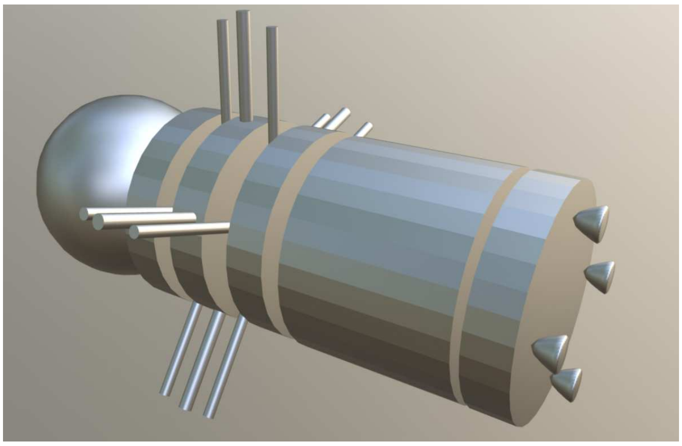


Figure A.11: 3-D: Perspective view without GHARs

Appendix B: Derivations and Calculations

B.1 Tension in rotating ring

We consider the simplest case of a uniform rotating ring, with uniform tension, and negligible thickness. We model our torii to be rings, since torii actually bear greater tensions at smaller radii due to their circular cross-section (1.5 times, to be precise). Modelling torii as a ring helps account for these previous conditions (uniformity) not holding true.

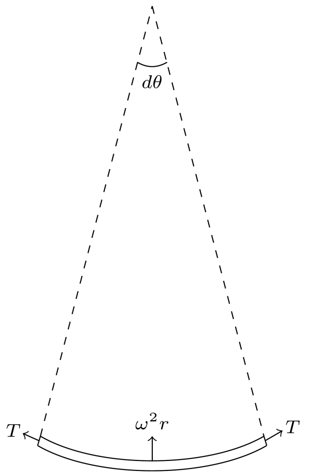


Figure B.1: Free body diagram of rotating ring

From the free body diagram, it is obvious that:

$$2T\sin\frac{\mathrm{d}\theta}{2} = \frac{\mathrm{d}m(v^2)}{R} \tag{B.1}$$

For small values of θ, $\sin\theta = \theta$. Thus,

$$2T\frac{\mathrm{d}\theta}{2} = \mathrm{d}m\left(\frac{v^2}{R}\right) \tag{B.2}$$

$$T\int_0^{2\pi}\mathrm{d}\theta = \frac{v^2}{R}\int_0^{M}\mathrm{d}m \tag{B.3}$$

$$T = \frac{Mv^2}{2\pi R} \tag{B.4}$$

B.2 Tsiolkovsky rocket equation

Consider a rocket (including propellant), whose free-body diagram is given in Figure B.2.

According to Newton's Second Law, the sum of external forces is equal to the change in momentum.

$$\sum F = \lim_{\Delta t\to 0}\frac{P_f - P_i}{\Delta t} \tag{B.5}$$

The expressions for the initial and final momenta are:

$$P_i = (m+\Delta m)V \tag{B.6}$$
$$P_f = m(V+\Delta V) + \Delta m V_e \tag{B.7}$$

Where V is the initial velocity ($t=0$), $m+\Delta m$ is the initial mass ($t=0$), $V+\Delta V$ is the final velocity ($t=\Delta t$), m is the

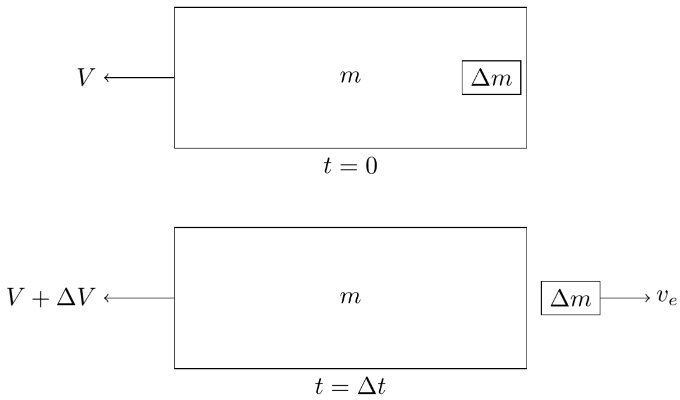


Figure B.2: Free body diagram of rocket

final mass ($t=\Delta t$), and V_e is the velocity of the exhaust. If the exhaust velocity is v_e, $V_e = V - v_e$. Then,

$$P_f - P_i = m\Delta V - v_e\Delta m \tag{B.8}$$

Substituting this value back in B.5:

$$\sum F = m\frac{\mathrm{d}V}{\mathrm{d}t} + v_e\frac{\mathrm{d}m}{\mathrm{d}t} \tag{B.9}$$

(Since $dm = -\Delta m$.) As there are no external forces, $\sum F = 0$:

$$m\frac{\mathrm{d}V}{\mathrm{d}t} = -v_e\frac{\mathrm{d}m}{\mathrm{d}t} \tag{B.10}$$

$$\int_V^{V+\Delta V}\mathrm{dV} = -v_e\int_{m_0}^{m_f}\frac{1}{m}\mathrm{d}m \tag{B.11}$$

$$\Delta V = v_e\ln\frac{m_0}{m_f} \tag{B.12}$$

B.3 Elliptical Orbits

We prove the following two facts:

1. The time period of an elliptical orbit is:

$$T^2 = \frac{4\pi^2a^3}{GM}$$

2. The total energy of a planet in an elliptical orbit is:

$$E_t = -\frac{GMm}{2a}$$

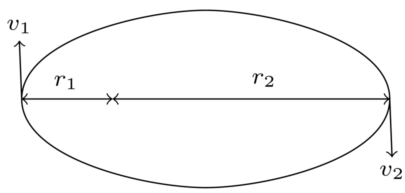


Figure B.3: An elliptical orbit

From the figure,

$$mv_1r_1 = mv_2r_2 = L \tag{B.13}$$

$$\frac{1}{2}mv_1^2 - \frac{GMm}{r_1} = \frac{1}{2}mv_2^2 - \frac{GMm}{r_2} = E \tag{B.14}$$

Rearranging,

$$\frac{1}{2}\left(v_1^2 - v_2^2\right) = G\left(\frac{1}{r_1} - \frac{1}{r_2}\right)M \tag{B.15}$$

From B.13,

$$\frac{L^2}{2m^2}\left(\frac{1}{r_1^2} - \frac{1}{r_2^2}\right) = \frac{L^2}{2m^2}\left(\frac{1}{r_1} + \frac{1}{r_2}\right)\left(\frac{1}{r_1} - \frac{1}{r_2}\right)$$

$$= G\left(\frac{1}{r_1} - \frac{1}{r_2}\right)M \tag{B.16}$$

Or,

$$\frac{L^2}{2m^2} = G\left(\frac{1}{r_1} + \frac{1}{r_2}\right)M \tag{B.17}$$

Since the area of an ellipse is given by πab, where a and b are the semi-major and semi-minor axes respectively,

$$T^2 = \frac{(\pi ab)^2 \times 4m^2}{L^2} = 2\frac{(\pi ab)^2}{GM}\left(\frac{1}{r_1} + \frac{1}{r_2}\right) \tag{B.18}$$

Recall that the semi-major axis a is the arithmetic mean of r_1 and r_2, and the semi-minor axis b is their geometric mean, giving us:

$$\left(\frac{1}{r_1} + \frac{1}{r_2}\right) = \frac{r_1 + r_2}{r_1 r_2} = \frac{2a}{b^2}$$

Substituting this value in B.18:

$$T^2 = \frac{4\pi^2 a^3}{GM} \tag{B.19}$$

To find the total energy,

$$\frac{1}{2}mv_1^2 - \frac{GMm}{r_1} + \frac{1}{2}mv_2^2 - \frac{GMm}{r_2} = 2E \tag{B.20}$$

Substitute $v_1 = L/mr_1$, $v_2 = L/mr_2$:

$$\frac{L^2}{2m}\left(\frac{1}{r_1^2} + \frac{1}{r_2^2}\right) - GMm\left(\frac{1}{r_1} + \frac{1}{r_2}\right) = 2E \tag{B.21}$$

By rearrangement,

$$E_t = -\frac{GMm}{2a} \tag{B.22}$$

B.4 Energies in Asteroid Orbit

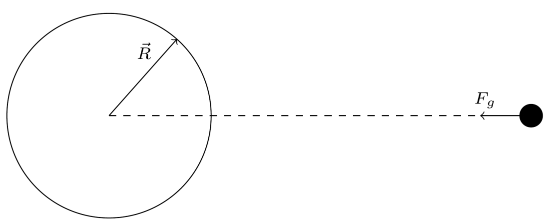


Figure B.4: Object near (approximately spherical) asteroid

(It is assumed that at distance ∞, the gravitational force is zero.)
From B.4,

$$F_g = G\frac{Mm}{x^2} \tag{B.23}$$

At infinity, $E = 0$ (work done by gravity).
At the object, $E = 0 = U + W$ (potential energy),
$\implies U = -W$.

$$W = \int_{\infty}^{R} \vec{F_g} \cdot \mathrm{d}\vec{x} = \int_{\infty}^{R} \left(G\frac{Mm}{x^2}\right) \mathrm{d}x \cdot \cos\pi \tag{B.24}$$

$$= -\int_{\infty}^{R} \left(G\frac{Mm}{x^2}\right) \mathrm{d}x = GMm \int_{R}^{\infty} \left(\frac{1}{x^2}\right) \mathrm{d}x \tag{B.25}$$

$$= \frac{GMm}{R} \tag{B.26}$$

$$\therefore U = -\frac{GMm}{R} \tag{B.27}$$

To calculate the potential energy of an object in circular orbit around an asteroid:

$$E_t = \mathrm{PE} + \mathrm{KE} \tag{B.28}$$

We know,

$$\mathrm{PE} = -\frac{GMm}{R} \tag{B.29}$$

For kinetic energy, first equate centripetal and gravitational force.

$$\frac{mv^2}{R} = G\frac{Mm}{R^2} \tag{B.30}$$

$$\frac{mv^2}{2} = G\frac{Mm}{2R} \tag{B.31}$$

Since $\frac{1}{2}mv^2$ is the expression for kinetic energy, we can substitute this value back in B.28:

$$E_t = \frac{-GMm}{R} + \frac{GMm}{2R} \tag{B.32}$$

$$= -G\frac{Mm}{2R} \tag{B.33}$$

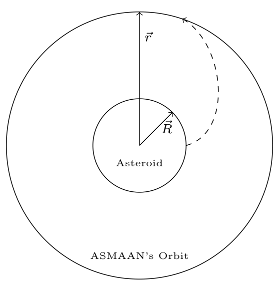


Figure B.5: Energy delta calculation

Change in energy is given by:

$$E_f - E_i = -G\frac{Mm}{2r} - \left(-G\frac{Mm}{R}\right) \tag{B.34}$$

$$= GMm\left(\frac{1}{R} - \frac{1}{2r}\right) \tag{B.35}$$

B.5 Power of a rocket engine

The kinetic energy of the rocket is given by:

$$\frac{1}{2}mv_e^2$$

The power is then given by:

$$P = \frac{1}{2}mav_e = \frac{1}{2}Fv_e \tag{B.36}$$

Where a is the acceleration and F is the thrust.

B.6 Radiation Pressure for an Ideal Reflector

Despite having zero mass, photons have momentum (predicted by Einstein, verified by Compton), given by:

$$p = \frac{h}{\lambda} \tag{B.37}$$

where p is the momentum, h is Planck's constant, $6.626 \times 10^{-34}\,\mathrm{J \cdot s}$, and λ is the wavelength of the photon.
Manipulating B.37:

$$p = \frac{hc}{c\lambda} = \frac{h\nu}{c}$$

ν is the frequency and c is the speed of light.

$$\therefore p = \frac{E}{c}$$

by Planck's radiation law $E = h\nu$.
A force can be written as $\vec{P} \cdot \vec{A}$ or simply PA for an area perpendicular to the force. Similarly the energy incident on the surface can be expressed as IA (Intensity × Area for a surface perpendicular to the incident radiation), the previous equation can be rewritten as

$$PA = \frac{E}{c} = \frac{AI}{c} \implies P = \frac{I}{c} \tag{B.38}$$

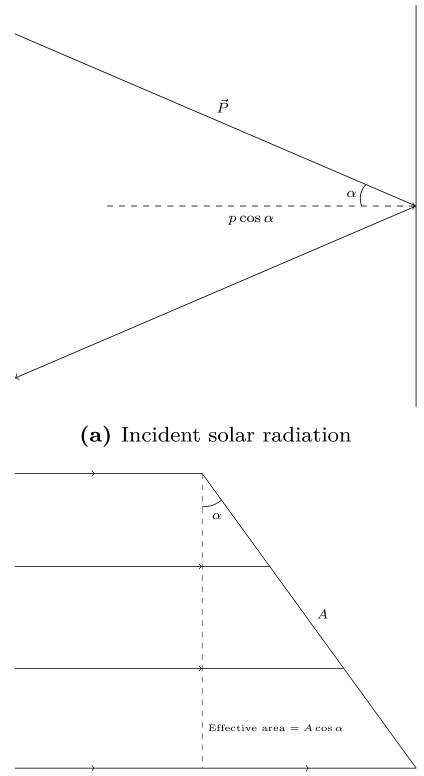
for a surface perpendicular to the incident light.
However, for an ideal reflector, the impulse imparted per photon is doubled, as its momentum changes from $\frac{E}{c}\hat{\boldsymbol{\imath}}$ to $-\frac{E}{c}\hat{\boldsymbol{\imath}}$. That is,

$$\underbrace{\Delta p = -\frac{2E}{c}\hat{\boldsymbol{\imath}},}_{\text{photon}} \quad \underbrace{\Delta p = +\frac{2E}{c}\hat{\boldsymbol{\imath}}}_{\text{surface}} \tag{B.39}$$

Hence, the pressure experienced by a perpendicular ideal reflector is $P = 2I/c$.
Further, the intensity of solar radiation at a distance of 1 AU from the Sun is given by the solar constant $G_{sc} = 1.361$ kW/m^{2}at a distance of 1 AU from the Sun. As solar radiation diminishes by the inverse square law,

$$I = \frac{G_{sc}}{R^2} \qquad \therefore P = \frac{2G_{sc}}{R^2} \tag{B.40}$$

for a perpendicular surface. However, at an angle of α to the



(a) Incident solar radiation

(b) Non-perpendicular collision

Figure B.6: Non-perpendicular solar radiation pressure

perpendicular two factors come into play:

1. The effective area (i.e. the area on which solar radiation is incident) is reduced by a factor of $\cos\alpha$.
2. The momentum transferred per collision is only $\cos\alpha$ times the value of a perpendicular collision, as only the component of the momentum along the normal can be considered.

Thus, for a surface inclined at an angle of α to perpendicular:

$$p = \left(2\frac{G_{sc}}{cR^2}\right)\underbrace{(\cos\alpha)}_{(1)}\underbrace{(\cos\alpha)}_{(2)} \tag{B.41}$$

$$= \frac{2G_{sc}}{cR^2}\cos^2\alpha \tag{B.42}$$

B.7 How many struts do we use?

Maximum tensile strength of Zylon®: 5.8 GPa
Each strut may not bear more than 75% of its maximum tensile strength: 4.35 GPa
Cross sectional area of each strut: 1 mm^2
Effective mass of NATASHA and GHARs: 1010 tons
Maximum acceleration of Erebor: 0.24 mm/s^2
The effective tension is $T = 242,400$ N
The struts are positioned such that they make an angle of 60° with the hull, when under tension. Hence, only the component of the tension parallel to the acceleration (i.e. $\cos 60° = 0.5$) can be considered. Hence, the total tension borne across all the struts is $T\sec 60°$ or $2T = 484,800$ N
The required cross sectional area hence is 1.115×10^{-4} m^2.
Hence, the required number of struts is 112. We use 125 struts in case of damage during operation.

Appendix C: Erebor Communication System

This section has the source code of a single module of a possible Erebor-wide personal communications network, which encrypts input files of arbitrary length using the RSA asymmetric key algorithm[RSA78], and has a basic interactive command line interface.

C.1 Requirements and Dependancies

Python 3.6, Pandas, Progress.

```
$ pip install pandas progress
```

On some Linux systems, you may have to

```
$ sudo apt install python3-pip
$ pip3 install pandas progress
```

This program is written to be platform independent, using Python implementations everywhere rather than (possibly simpler) alternatives like command line calls. It's been tested on a machine running Linux Mint 19.3 (XFCE 64-bit), macOS Sierra and in two Microsoft Windows virtual machines (7 and 10), and behaves as expected.

C.2 Installation

The source code for this project is available on GitHub. You should either download it from `https://github.com/nebhrajani-a/rsa-py` or clone it into a new directory.

```
$ git clone --depth 1 https://github.com/nebhrajani-a/rsa-py
```

C.3 Executing

To use the program, `cd` to `python-rsa/src` and execute

```
$ python main.py
```

Note: If you use Windows, Python may be aliased to `py` instead. Make sure `python` runs Python 3 and not Python 2. On some Linux systems Python 3 needs to be called using `python3`.

C.4 Source Code

C.4.1 prime_generator.py

```
import first_primes as fp
import secrets

def gen_random(l):
    '''Generate a random number l bits long.'''
    randgenerator = secrets.SystemRandom()
    return randgenerator.randrange(2**(l-1)+1, 2**l - 1)

def low_level_checker(l):
    '''Check that the random number isn't divisible by the
        ↪ first few primes.'''
    while True:
        x = gen_random(l)
        for divisor in fp.first_primes:
            if x % divisor == 0 and divisor**2 <= x:
                break
        else: return x

def miller_rabin_checker(mrc):
    '''Run 40 iterations of the Miller-Rabin Primality Test
        ↪ .'''
    randgenerator = secrets.SystemRandom()
    max_divisions_by_two = 0
    y = mrc-1
    while y % 2 == 0:
        y >>= 1
        max_divisions_by_two += 1
    assert(2**max_divisions_by_two * y == mrc-1)
    def trial_composite(round_tester):
        if pow(round_tester, y, mrc) == 1:
            return False
        for i in range(max_divisions_by_two):
            if pow(round_tester, 2**i * y, mrc) == mrc-1:
                return False
        return True
    number_of_rabin_trials = 40
    for i in range(number_of_rabin_trials):
        round_tester = randgenerator.randrange(2, mrc)
        if trial_composite(round_tester):
            return False
    return True

def driver(l):
    while True:
        prime_candidate = low_level_checker(l)
        if not miller_rabin_checker(prime_candidate):
            continue
        else:
            return prime_candidate
```

C.4.2 math_functions.py

```
import sys
sys.setrecursionlimit(10**6)
from math import ceil

def poweroftwocheck(n):
    if (n == 0):
        return False
    while (n != 1):
        if (n % 2 != 0):
            return False
        n = n // 2
    return True

def gcd(a,b):
    if a == 0:
        return b
    return gcd(b % a, a)
def lcm(a,b):
    return (a*b) // gcd(a,b)

def eea(a, b):
    '''Extended Euclidean algorithm'''
    if a == 0:
        return (b, 0, 1)
    else:
        g, y, x = eea(b % a, a)
        return (g, x - (b // a) * y, y)

def modinv(a, m):
    '''Find modular multiplicative inverse using EEA'''
    g, x, y = eea(a, m)
    if g != 1:
        raise Exception('Modular inverse does not exist.')
    else:
        return x % m
def cra(c, p, q, d_p, d_q, q_inv):
    '''Chinese Remainder Algorithm'''
    m_1 = pow(c, d_p, p)
    m_2 = pow(c, d_q, q)
    if m_1 >= m_2:
        h = q_inv*(m_1-m_2) % p
    else:
        h = q_inv*((m_1 + (ceil(q/p))*p) - m_2) % p
    return pow((m_2 + h*q), 1, p*q)
```

C.4.3 rsa_primitive.py

```
import prime_generator as pg
import math_functions as mf

def get_bits():
    print("Generating keys (one-time procedure).")
```

```
    while True:
        try:
            bits = int(input("Key length (bits)?\n> "))
            if bits >= 128 and mf.poweroftwocheck(bits):
                print("Key length okay...generating keys.")
                return bits
            else:
                print("ERR: Key length must be a power of two
                    ↪  and greater than or equal to 128.")
        except (TypeError, ValueError):
            print("ERR: Enter a valid key length.")

def gen_keys(bits):
    p = pg.driver(bits//2)
    q = pg.driver(bits//2)
    n = p*q
    lambda_ = mf.lcm((p-1), (q-1))
    e = 65537
    d = mf.modinv(e, lambda_)
    d_p = d % (p-1)
    d_q = d % (q-1)
    q_inv = mf.modinv(q, p)
    return [p, q, n, e, d_p, d_q, q_inv, bits]

def enc(m, e, n):
    c = pow(m, e, n)
    return c

def dec(c, p, q, d_p, d_q, q_inv):
    m = mf.cra(c, p, q, d_p, d_q, q_inv)
    return m
```

C.4.4 data_conversion_primitives.py

```
def nochunk_PT2OS(text):
    return [ord(i) for i in text]

def PT2OS(text, l):
    ret = [ord(i) for i in text]
    l_2 = len(ret)
    if l_2 < l:
        newline = [10]
        spaces = [0] * (l - l_2 -1)
        ret.extend(newline)
        ret.extend(spaces)
    return ret

def OS2PT(stream):
    return ''.join(chr(i) for i in stream)

def OS2IP(X):
    l = len(X)
    i = 1
    sum_ = 0
    for X_i in X:
        sum_ = X_i*(256**(l-i)) + sum_
        i += 1
    return sum_

def I2OSP(x, l):
    if x >= 256**l:
        raise ValueError("Int too large.")
    i = 0
    X = []
    while i != (l-1):
        r = x % 256
        X.append(r)
        x = x // 256
        i += 1
    X.append(x)
    return X[::-1]
def read_in_chunks(file_object, chunk_size):
    '''Lazy function (generator) to read a file piece by
        ↪ piece.'''
    while True:
        data = file_object.read(chunk_size)
        if not data:
            break
        yield data

def kill_nulls(filename):
    f = open(filename, 'r')
    lines = f.readlines()
    f.close()
    lines.pop()
    f = open(filename, 'w')
    for line in lines:
        f.write(line)
    f.close()
    f = open(filename, 'r')
    string = f.read()
    f.close()
    string = string[:-1]
    f = open(filename, 'w')
    f.write(string)
    f.close()
```

C.4.5 interaction_functions.py

```
import usr_data as ud
import data_conversion_primitives as dcp
from getpass import getpass
import os.path

def login_or_signup():
    while True:
        try:
            state = int(input("[1] Create account\n[2] Sign
                ↪ in\n> "))
            if state not in (1, 2):
                print("ERR: Enter a valid choice.")
            else:
                return state
        except (TypeError, ValueError):
            print("ERR: Enter a valid choice.")

def signup_core():
    while True:
        try:
            user = str(input("Enter a username:\n> "))
            if ud.search_column('username', user):
                print("Username taken, try another.")
            else:
                break
        except (TypeError, ValueError):
            print("Enter a valid username.")
    while True:
        try:
            passphrase_a = getpass(prompt = "Passphrase: ")
            passphrase_b = getpass(prompt = "Repeat
                ↪ passphrase: ")
            if passphrase_a == passphrase_b:
                passphrase_a = dcp.OS2IP(dcp.nochunk_PT2OS(
                    ↪ passphrase_a))
                passphrase_a = pow(passphrase_a, 65537,
                    ↪ 206013970136021274755909796996044923643)
                    ↪
                break
            else:
                print("Passphrases do not match. Try again.")
        except (ValueError, TypeError):
            print("Enter a valid passphrase.")
    return [user, passphrase_a]

def signup_pqned(data, pqned):
    data.extend(pqned)
    ud.add_data(data)

def login():
    while True:
        try:
            user = str(input("Enter your username:\n> "))
            if ud.search_column('username', user):
                break
            else:
                print("Username doesn't exist.")
        except (TypeError, ValueError):
            print("Enter a valid username.")
```

```
    while True:
        try:
            passphrase = getpass(prompt = "Passphrase: ")
            passphrase = dcp.OS2IP(dcp.nochunk_PT2OS(
                 ↪ passphrase))
            passphrase = pow(passphrase, 65537,
                 ↪ 206013970136021274755909796996044923643)
            if passphrase == ud.get_field(user, 'password'):
                break
            else:
                print("Incorrect passphrase. Try again.")
        except (TypeError, ValueError):
            print("Enter a valid passphrase.")
    return user

def get_operation():
    while True:
        try:
            location = int(input("\n[1] File\n[2] String\n[3]
                 ↪  Add path\n[4] Delete account\n[5] Exit\n
                 ↪ > "))
            if location not in (1, 2, 3, 4, 5):
                print("ERR: Enter a valid choice.")
            else:
                return location
        except (TypeError, ValueError):
            print("ERR: Enter a valid choice.")


def get_input_file():
    while True:
        filename = str(input("Input file?\n> "))
        try:
            with open(filename):
                return filename
        except FileNotFoundError:
            print("Incorrect file or path.")

def get_output_file():
    filename = str(input("Output file?\n> "))
    return filename
def encrpyt_or_decrypt():
    while True:
        try:
            state = int(input("[1] Encrypt file\n[2] Decrypt
                 ↪ file\n> "))
            if state not in (1, 2):
                print("ERR: Enter a valid choice.")
            else:
                return state
        except (TypeError, ValueError):
            print("ERR: Enter a valid choice.")


def get_encrypt_list(user):
    bits = ud.get_field(user, 'bits')
    e = ud.get_field(user, 'e')
    n = ud.get_field(user, 'n')
    return [bits, e, n]
def get_decrypt_list(user):
    bits = ud.get_field(user, 'bits')
    p = ud.get_field(user, 'p')
    q = ud.get_field(user, 'q')
    d_p = ud.get_field(user, 'd_p')
    d_q = ud.get_field(user, 'd_q')
    q_inv = ud.get_field(user, 'q_inv')
    return [bits, p, q, d_p, d_q, q_inv]
def del_user():
    user = login()
    ud.drop_row(user)

def get_reciever():
    while True:
        try:
            user = str(input("Enter recipient username:\n> ")
                 ↪ )
            if ud.search_column('username', user):
                break
            else:
                print("Username doesn't exist.")
        except (TypeError, ValueError):
            print("Enter a valid username.")
    return user

def get_path():
    while True:
        path = str(input("Path?\n> "))
        if os.path.isdir(path):
            return path
        else:
            print("Not a valid path.")
```

C.4.6 usr_data.py

```
import pandas as pd
from os import path

def save_table(usr_data):
    usr_data.to_pickle("usr_data.pkl")

def read_table():
    return pd.read_pickle("usr_data.pkl")
if not path.exists("usr_data.pkl"):
    usr_data = pd.DataFrame(columns = ['username', 'password
         ↪ ', 'p', 'q', 'n', 'e', 'd_p', 'd_q', 'q_inv', '
         ↪ bits'])
    usr_data.loc[0] = ['root', 0, 0, 0, 0, 0, 0, 0, 0, 0]
    save_table(usr_data)



def add_data(data):
    usr_data = read_table()
    usr_data.loc[usr_data.index.max() + 1, :] = data
    save_table(usr_data)

def search_column(column, value):
    usr_data = read_table()
    result = (usr_data[usr_data[column] == value])
    if result.empty:
        return False
    else:
        return True
def get_field(key, column):
    usr_data = read_table()
    x = usr_data.username[usr_data.username.str.contains
         ↪ ('|'.join(key.split(' ')))]
    index = x.index[0]
    return usr_data.loc[index][column]
def get_index(key, column):
    usr_data = read_table()
    x = usr_data.username[usr_data.username.str.contains
         ↪ ('|'.join(key.split(' ')))]
    index = x.index[0]
    return index

def drop_row(key):
    usr_data = read_table()
    index_ = get_index(key, 'user')
    usr_data.drop(index=index_, inplace = True)
    save_table(usr_data)
```

C.4.7 main.py

```
import rsa_primitive as rsa
import math_functions as mf
import data_conversion_primitives as dcp
import interaction_functions as intfunc
from progress.bar import IncrementalBar
import sys


state = intfunc.login_or_signup()
if state == 1:
    data = intfunc.signup_core()
    bits = rsa.get_bits()
    pqned = rsa.gen_keys(bits)
    print("Keys successfully generated.")
    intfunc.signup_pqned(data, pqned)
```

```
user = intfunc.login()

while True:
    operation = intfunc.get_operation()
    if operation == 1:
        enc_or_dec = intfunc.encrpyt_or_decrypt()
        if enc_or_dec == 1:
            recpt = intfunc.get_reciever()
            input_file = intfunc.get_input_file()
            output_file = intfunc.get_output_file()
            enc_data = intfunc.get_encrypt_list(recpt)
            bits = enc_data[0]
            e = enc_data[1]
            n = enc_data[2]
            chunk_size = (bits//8) - 1
            open(output_file, 'w+').close()
            list_of_chunks = []
            fobj = open(input_file, 'r')
            l = sum(1 for _ in (dcp.read_in_chunks(fobj,
                 ↪ chunk_size)))
            with open(input_file) as fin:
                print("All okay.")
                for data in IncrementalBar('Encrypting...',
                     ↪ max=l).iter(dcp.read_in_chunks(fin,
                     ↪ chunk_size)):
                    data = dcp.PT2OS(data, chunk_size)
                    data = dcp.OS2IP(data)
                    data = rsa.enc(data, e, n)
                    list_of_chunks.append(int(data))
            with open(output_file, 'a') as fout:
                print(list_of_chunks, end='', file=fout)
            print("Encrypted. Output written to", fout.name)

        else:
            input_file = intfunc.get_input_file()
            output_file = intfunc.get_output_file()
            dec_data = intfunc.get_decrypt_list(user)
            bits = dec_data[0]
            p = dec_data[1]
            q = dec_data[2]
            d_p = dec_data[3]
            d_q = dec_data[4]
            q_inv = dec_data[5]
            chunk_size = (bits//8) - 1
            open(output_file, 'w+').close()
            with open(input_file) as fin:
                list_of_chunks = fin.read()
            list_of_chunks = list_of_chunks.strip('][').split
                 ↪ (', ')
            print("All okay.")
            f = open(output_file, 'a')
            bar = IncrementalBar('Decrypting...', max=len(
                 ↪ list_of_chunks))
            for data in list_of_chunks:
                data = rsa.dec(int(data), p, q, d_p, d_q,
                     ↪ q_inv)
                data = dcp.I2OSP(data, chunk_size)
                data = dcp.OS2PT(data)
                print(data, end='', file=f)
                bar.next()
            f.close()
            dcp.kill_nulls(output_file)
            bar.finish()
            print("Decrypted. Output written to", f.name)

    elif operation == 2:
        enc_data = intfunc.get_encrypt_list(user)
        bits = enc_data[0]
        e = enc_data[1]
        n = enc_data[2]
        chunk_size = (bits//8) - 1
        dec_data = intfunc.get_decrypt_list(user)
        bits = dec_data[0]
        p = dec_data[1]
        q = dec_data[2]
        d_p = dec_data[3]
        d_q = dec_data[4]
        q_inv = dec_data[5]

        m = str(input("Enter a string: "))
        m = dcp.PT2OS(m, chunk_size)
        m = dcp.OS2IP(m)

        c = rsa.enc(m, e, n)
        print("Encrypted string is:", m)
        m = rsa.dec(c, p, q, d_p, d_q, q_inv)

        m = dcp.I2OSP(m, chunk_size)
        m = dcp.OS2PT(m)
        print("Decrypted string is:", m)

    elif operation == 3:
        path = intfunc.get_path()
        sys.path.append(path)
        print(sys.path[-1], "successfully appended to sys.
             ↪ path.")


    elif operation == 4:
        while True:
            try:
                sure = str(input("[ACCOUNT DELETION]: Proceed
                     ↪ ? Irreversible. (y or n): "))
                if sure not in ('y', 'n'):
                    print("[ACCOUNT DELETION]: Please answer
                         ↪ y or n.")
                else:
                    if sure == "y":
                        intfunc.del_user()
                        print("All okay. Account successfully
                             ↪ deleted.")
                        exit()
                    else:
                        break
            except (TypeError, ValueError):
                print("[ACCOUNT DELETION]: Please answer y or
                     ↪  n.")

    else:
        exit()
```

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