

Shielded Dumbbell L5 Settlement

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Abstract

We present a two-sphere dumbbell configuration of a rotating settlement at Earth-Moon L5. The two-sphere configuration is chosen to minimize the radiation shielding mass which dominates the mass budget. The settlement has max 20 mSv/year radiation conditions and 1 g artificial gravity. If made for 200 people, it weighs 89000 tonnes and provides 60 m² of floorspace per person. The radiation shield is made of asteroid rock, augmented by a water layer with 2 % of the mass for neutron moderation, and a thin boron-10 layer for capturing the thermalized neutrons. We analyze the propulsion options for moving the material from asteroids to L5. The FFC Cambridge process can be used to extract oxygen from asteroid regolith. The oxygen is then used as Electric Propulsion propellant. One can also find a water-bearing asteroid and use water for the same purpose. If one wants to avoid propellant extraction, one can use a fleet of electric sails. The settlers fund their project by producing and selling new settlements by zero-delay teleoperation in the nearby robotic factory which they own. The economic case looks promising if LEO launch costs drop below ~ \$300/kg.

Keywords: L5 space settlement, radiation shielding

1. Introduction

To live permanently in space, a human being needs air, food, radiation shielding, earthlike gravity, and a sufficient number of fellow settlers and living space. All requirements can be satisfied in rotating free-space habitats made of asteroid or lunar materials as proposed by Gerard O'Neill in his pioneering works [1, 2]. Such unplanetary living is attractive because it offers a way to avoid common natural hazards such as hurricanes, volcanism, earthquakes and wildfires. It is also attractive from the longer term population and economic growth points of view. There is so much material in the asteroid belt ($2.4 \cdot 10^{21}$ kg) that if made into settlements, it allows several orders of magnitude growth in the human population.

One could build an orbital settlement in equatorial low Earth orbit (ELEO) with much lower mass than elsewhere, because in ELEO the Earth's magnetic field protects rather well against cosmic rays and solar protons [3]. However, in LEO there is the risk of orbital

debris. For example, recently the insurance company Assure Space stopped offering collision risk coverage policies in LEO [4]. There is also the issue of having to perform a targeted reentry when done with the facility. Letting it fall freely would be a public safety issue for people living near the equator.

To avoid these issues, in this paper we consider a settlement at the Earth-Moon Lagrange L5 (or L4) point. The L5 point offers Apollo-like short traveltime from Earth, so that the transfer vehicle does not need much radiation shielding.¹ Satellite orbits around ~ 8–10 Earth radii are also an alternative, but they have somewhat larger delta-v for bringing asteroid material than L5. The Moon makes most orbits in ~ 15–150 Earth radii unstable in the long run. L5 is an exception. Distant translunar orbits would also be possible, but they exhibit longer traveltimes from Earth. Longer manned trips increase the mass of the transfer vehicle through the radiation shielding and the life support system.

The structure of the paper is as follows. First we consider radiation shielding. Then we establish that be-

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¹We write "L5 point" for brevity. In reality the orbit wanders around the L5 or L4 point with large amplitude [5].

cause radiation shielding dominates the mass, an optimal entry-level configuration is a dumbbell comprising two spheres. We point out that only the radiation shielding mass needs to be sourced from asteroids in the first phase. We analyze a number of propulsion options for moving the material and do costing analysis. We close the paper by discussion and summary.

2. Radiation shielding

Galactic cosmic rays (GCRs) have higher energies than solar energetic particles. For good radiation protection, the GCR flux must be significantly suppressed, and this requires several tonnes of mass per square meter. At such shielding thicknesses the solar energetic particles are suppressed almost entirely so they can be ignored in the analysis.

Globus and Strout [6] used the OLTARIS tool to simulate the GCR equivalent radiation doses (millisievert rates) behind various thicknesses of different materials (Globus and Strout [6], Table 2). They recommend 20 mSv/year as the equivalent dose level during the solar minimum (of 2010) when the galactic radiation is at maximum, a value which we also adopt here.

Here we also use the OLTARIS tool. The tool supports two geometries: a slab and a sphere. In the slab geometry, the dose between two adjacent infinite plates is predicted, where each plate has the given shielding thickness. In the sphere geometry, the program predicts the dose at the center of a solid sphere whose radius is equal to the given shielding thickness. The dose predicted using the slab geometry is smaller (typically about two times smaller) than that using the sphere geometry, because in the slab geometry, many of the cosmic rays enter obliquely to the shield and so move a longer distance within the shield. For a hollow sphere, in the limit where the inner radius is much larger than the shell thickness, the dose at the inner wall approaches asymptotically the slab geometry prediction. The dose at the centerpoint of a hollow sphere does not depend on the sphere's inner radius, so it can be calculated by assuming zero inner radius. Thus for a hollow sphere, the dose at the center is larger than the dose near the walls. The reason is that center-reaching cosmic rays pass through the shell perpendicularly regardless of their arrival direction, whereas near the wall typical rays must pass through the shell obliquely, experiencing more attenuation.

For radiation shields, Z-grading is in general useful, that is, using high-Z materials as the outer layer and progressively lower Z materials as one goes inwards. We want the bulk of the shield to be asteroid regolith. We

also need structural material, which we assume to be steel, which is iron to a good approximation. We put the steel as the outermost layer since iron's mean atomic mass is larger than that of regolith. Inside the regolith we put a layer of water whose mass is 2 % of the mass of the regolith and water combined. It is the intention that this amount of water can be obtained from the asteroid regolith by heating it. If not, the water can be brought from Earth. The dry regolith layer is modeled by OLTARIS' lunar regolith option.

Part of the equivalent dose consists of neutrons spallated from the regolith by cosmic rays. The water layer moderates these neutrons. As the innermost layer we add a thin 1 kg/m² layer of boron-10. (If one wants to avoid isotope separation, one can use 5 kg/m² of natural boron which is 20 % B-10 and 80 % B-11.) This isotope absorbs neutrons efficiently, especially thermal neutrons. The water moderates the neutrons to be absorbed by the boron.

Table 1 defines the layers of our wall. This shield was designed to limit radiation to 20 mSv/year equivalent dose at the center of the sphere during worst case, i.e., solar minimum. The equivalent doses were computed for "Female Adult Voxel" phantom [7].

Table 1: 20 mSv/year shield using 2 % of water.

Material, thickness	kg/m ²	Role
Iron, 2.3 cm	180	Structural wall
Dry regolith, 3.34 m	8683	Shield
Water, 17.7 cm	177	Neutron moderator
Boron-10, 0.4 mm	1	Neutron absorber
Total, 3.5 m	9041	

For the solar maximum (of 2001) conditions, the equivalent dose is 25 % smaller (14.87 mSv/year). For solar minimum, a slab geometry calculation shows that near the inner wall the equivalent dose is 50 % smaller (9.97 mSv/year) than at the center. During solar maximum the inner wall equivalent dose drops to 7.53 mSv/year.

Globus and Strout [6] also require that the absorbed dose for pregnant women be less than 6.6 mGy/year, or 5 mGy per pregnancy. In our case this condition is satisfied since the absorbed dose at the center of the sphere during solar minimum is 4.0 mGy/year.

3. Mass-optimal geometry

A sphere has the minimal surface area per volume and is thus the best geometry for minimizing shielding mass. To include artificial gravity, we need two spheres

rotating about each other in a dumbbell configuration (Fig. 1a). We select a baseline rotation rate of 2 rpm (revolutions per minute), which is probably a conservative choice regarding avoidance of motion sickness [9]. With 1 g artificial gravity, 2 rpm corresponds to rotation radius of $R = 230$ m. The main structural element is the truss that connects the spheres. It carries the centrifugal load of the heavy spheres. It also acts as the shaft of an elevator that provides access from the living spheres to a central docking port. There are two docking ports for redundancy, upward and downward in Fig. 1. The docking ports are essential because they are the way to enter and exit the settlement. To ease the docking of the connecting spacecraft, the docking ports are located on the axis of rotation.

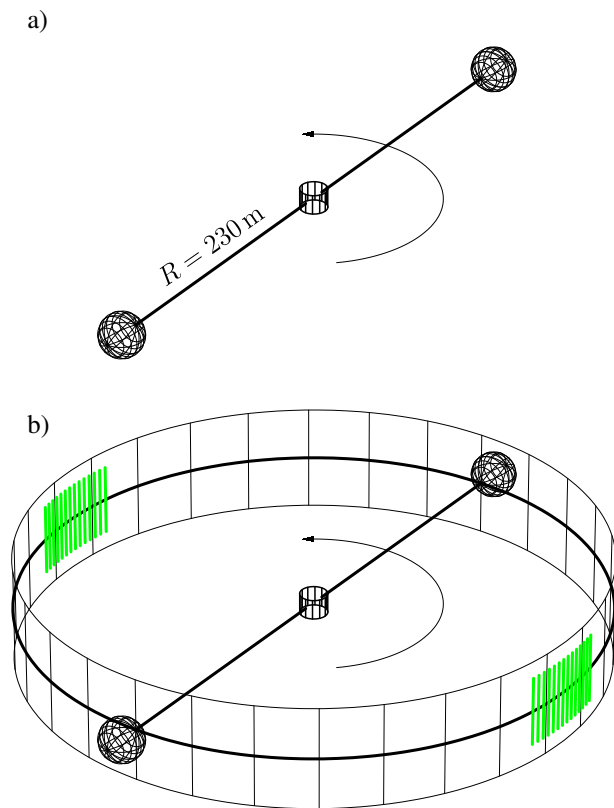


Figure 1: (a) Dumbbell settlement with elevator shaft and central docking ports, (b) with ringroad, cylindrical solar panels and greenhouse areas indicated (green).

To move from one sphere to the other, one can use the elevators, but then one experiences temporary weightlessness in the central region, which is an inconvenience. To eliminate this problem and to provide redundancy in routing, we add a pressurized ring-shaped tube that hosts a road. The ringroad is at constant radial

distance from the rotation axis so its user does not need to move uphill or downhill in artificial gravity.

To produce food as part of the closed ecosystem, we add artificially illuminated greenhouses (Fig. 1). The greenhouses rest on the cylinder on which solar panels are mounted. The greenhouses are served by the ringroad and we place them 90° off the heavy living spheres to make the azimuthal mass distribution more uniform. We assume that food production needs 16 kW of electrical energy per person, so 3.2 MW total for population of 200. This corresponds to 2500 kcal per day per person of food plus 30% margin, and 1% efficiency in converting greenhouse electrical energy into edible energy of the crops. Most of the energy is dissipated inside the greenhouses and radiated into space from their roofs. To keep the heat transfer passive and thus reliable, the radiator must be cooler than the greenhouse. At radiator temperature of $+4$ C, the emitted thermal power per area is 300 W/m^2 at emissivity of 0.9. Thus to dissipate 3.2 MW of power one needs 10560 m^2 of greenhouse roofs. The greenhouses are stacked in as many layers as is needed to yield the wanted amount of radiated cooling power per roof area. The green areas in Fig. 1b show the greenhoused areas. Pressure containment of the greenhouses also contributes to structural mass. The mass is proportional to greenhouse total volume. To calculate the volume, we assume 50 W/m^3 of volumetric power dissipation and 1 bar greenhouse pressure.

Agriculture is performed robotically because the greenhouses are outside of the thick radiation shields. We make an assumption that agriculture works despite GCR. To what extent this is true depends on many factors, one of which is plant lifetime. Plants that grow rapidly from seeds are less likely to have problems due to radiation-induced mutations than long-lived trees, for example. More research is needed on this point.

We place the greenhouses so that they can be served by the ringroads. The ringroads are used not only by people, but also by wheeled robots that move crops to the living spheres and human wastes back to the greenhouses. The indicated area of the cylindrical solar panel in Fig. 1b is larger (by factor of 2) than what is needed to produce 3.2 MW, because the settlement needs power also for other purposes than food production. The spin axis is perpendicular to the ecliptic plan so that the solar panels are all the time optimally illuminated. The power system is a rather small fraction of the total mass, which is dominated by radiation shielding mass (97%) and structural mass (2.6%).

Figure 2 shows a cross-sectional view of the spheres.

The inhabitants live in the centrifugally produced ar-

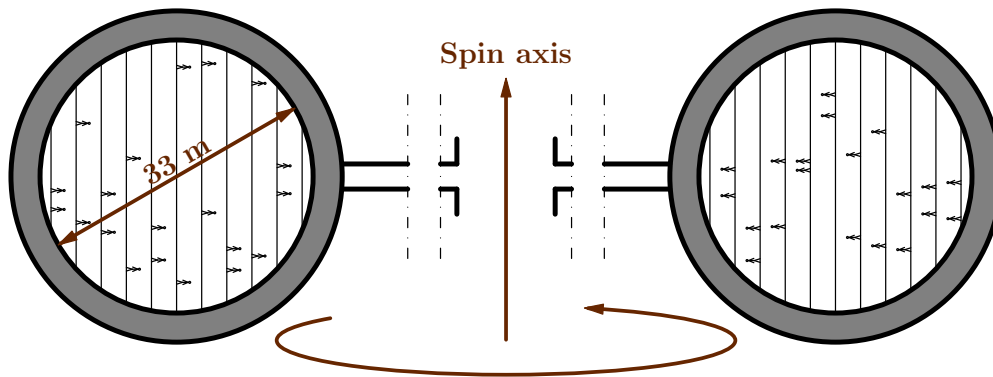


Figure 2: Cross-sectional view.

tificial gravity, with their heads towards the axis of rotation. Each sphere has inner diameter of 33 m. In this section we give the baseline values of the parameters and motivate them later. With effective room height of 3 m it contains ten floor levels and provides 6000 m² of floorspace area for its 100 inhabitants so that each person has 60 m² of living area. For example, it can be 25 m² of private area per person, 32 m² of public and working areas including corridors, and 3 m² (5 %) taken by walls. Tables 2 and 3 list the main parameters of the 200 person settlement.

Table 2: Parameters of 200 person settlement.

Population	200
Floorspace per person	60 m ²
Sphere inner diameter	33 m
Rotation radius	230 m
Steel tension	800 MPa (30 % of limit)
Radshield mass per area	9.04145 t/m ²
Radshield density	2.6 g/cm ³
Radshield thickness	3.5 m

For relatively small settlements such as 200 inhabitants, the density of the regolith affects the mass: the denser the shield, the less of it is needed because the sphere's radius is not that much larger than the shield thickness. Bulk densities of asteroids vary in rather wide range. Asteroid Eros is stony and with bulk density of 2.67 g/cm³ [10]. Smaller stony asteroids are less compressed by gravity and they can have lower densities; for example Itokawa has 1.95 g/cm³. The minerals themselves would allow even higher densities. The most abundant minerals are SiO₂ whose density is 2.65 g/cm³ and MgO which is 3.6 g/cm³. Iron-rich minerals are often even denser. We use the value 2.6 g/cm³ which is a bit less than Eros' bulk density. Reaching this den-

sity requires the fragmented rock to be compressed by vibrating, pressing or melting.

Table 3: Power and mass budgets of 200 person settlement.

	Total	Fraction	Per person
Power	3.2 MW		16 kW
Radshield	86423 t	96.9 %	432 t
Structural	2270 t	2.55 %	11.35 t
Other	493 t	0.55 %	2.47 t
Total	89186 t	100 %	446.0 t

The mass efficiency of radiation shielding increases if the population is increased, because the spheres become larger. When making the spheres larger, however, the difference in artificial gravity between the top and the bottom increases, unless one also increases the rotation radius. When scaling up we require that the maximum gravity is not more than 10 % larger than the average, and the minimum is not more than 10 % smaller.

Increasing the rotation radius increases the structural mass fraction, because the sphere-supporting trusses become longer. We propose that the structural mass is piano wire steel. This material is 99 % of iron, and iron is abundant on asteroids. In the first phase the structural material is brought from Earth, but in later stages it can be sourced from asteroids. We also set a requirement that the structural fraction does not increase beyond 17 %, because the majority of stony asteroids have more iron than this limit. Nothing prevents an even larger iron fraction, but the only drawback is that then one may have to start abandoning some of the asteroid material as waste. When the rotation radius is increased to 1.6 km, the 17 % limit is reached. If one wants to further increase the population without increasing the max/min gravity difference beyond $\pm 10\%$, one can add more spheres. Configurations of up to ~ 30 spheres are

still more mass efficient than an uninterrupted torus.

Figure 3 shows the rotation radius, mass per person, structural mass (steel) per person and the number of spheres as a function of population. For each population, the mass-optimal configuration was found automatically. The rotation radius is the constant 230 m up to 600 people, after which it grows in order to avoid more than $\pm 10\%$ difference in gravity between sphere top and bottom. The mass per person is inversely proportional to sphere radius, so that it is proportional to power $-1/3$ of the sphere volume and population. For small spheres, the dependence is slightly steeper because the radiation shield thickness is not negligible in comparison to sphere radius in this regime. For most of the population range, the structural mass per person is almost constant. This is because two competing effects nearly cancel each other. A larger rotational radius makes the truss longer, but it also enables larger spheres which yields less radiation shielding mass per person and therefore smaller carried load for the truss, per person. For population less than 600, the rotation radius is constant because we do not allow faster than 2 rpm rotation rate.

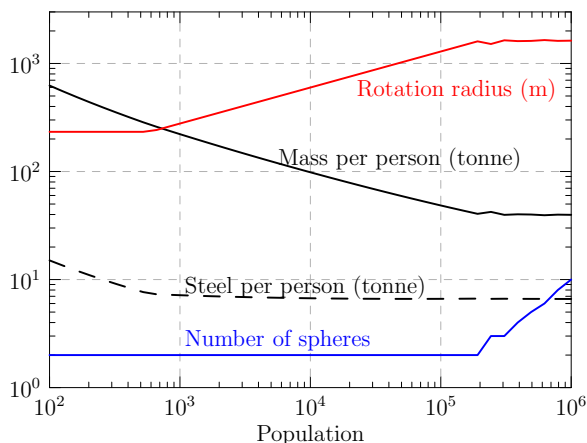


Figure 3: Scaling as function of population.

With the employed parameters, two is the optimal number of spheres up to population of $2 \cdot 10^5$.

Table 4 summarizes the employed requirements.

Table 4: Employed limitations.

Parameter	Value	Motivation
Rotation rate	≤ 2 rpm	No dizziness
Difference in gravity	$\leq \pm 10\%$	Life convenience
Structural fraction	$\leq 17\%$	No wasted asteroid material

4. Material sourcing

Most of the material is asteroid rock or regolith used for radiation shielding. This fraction is 97 % in the baseline case of 200 people. Thus one can already reach asteroid mass ratio of 30 [= 97/(100 - 97)] by bringing only rock from the asteroids.

Most of the rest is structural material and most of it is used for the two trusses that support the living spheres. Tensile strength is the most important mechanical property required; compressive strength is less important. We recommend to use piano wire steel, which is 99 % iron. The tensile strength is 2.6-3 GPa and the production process stems from the 19th century so it is not high-tech. If the structural material is sourced from asteroids, the mass ratio increases to 170 in the baseline case of 200 people (Tables 2 and 3). Sourcing structural material from asteroids requires strict quality control because the structural parts are life-critical.

To increase the mass ratio further, one could import water and carbon from asteroids as raw materials for growing the biomass that circulates between plants and people.

5. Propulsive transfer of materials

Most of the mass (97 % for a 200-person dwelling) is radiation shielding, for which there are no structural or other requirements so that it can be any unprocessed or processed asteroid rock. Thus the main challenge is propulsion: how to transfer material from asteroids or the Moon to the L5 orbit. Here we briefly analyze some of the potential methods.

5.1. Lunar material

Lunar material could be lifted by an electromagnetic mass driver as envisioned by O'Neill [11]. The mass driver would be a large investment. The electrical energy of the shot must be stored in large capacitor banks, which is a major cost item. The fixed shooting direction tends to reduce the flexibility regarding target orbit. The centralized nature of the facility is a potential reliability concern.

Lunar material could also be lifted by a sling [12, 13], which would be much lighter infrastructure than the electromagnetic mass driver and it avoids the use of capacitor banks. However, because the Moon rotates while the plane of the rotating sling stays inertially fixed, the sling crashes to the surface after some time, unless prevented by propulsion or other means. The time to crashing depends on the parameters, but is typically inconveniently short.

To lift lunar material, it is often proposed to make LH₂/LOX propellant from the water ice that exists in the polar lunar regions. However, the estimated H₂O resource is only a few times 10¹¹ kg [14]. This amount is not sufficient for long-term use. For example, a settlement with 10⁶ people corresponds to mass of 3.5 · 10⁴ kg per person (Fig. 3), i.e. total mass of 3.5 · 10¹⁰ kg, which is already ~ 10 % of the total lunar water resource².

5.2. Asteroid material transferred by O₂ electric propulsion

As shown recently [15], the so-called FFC Cambridge electrolytic process can be used to separate earthly, lunar or asteroid rock into oxygen gas and a solid residue comprising metals and silicon. The oxygen can be used as Electric Propulsion propellant [16]. The O₂ Electric Propulsion technology is currently under development in the context of Air-Breathing Electric Propulsion [16], which is enabling technology for very low orbiting satellites that are naturally immune to orbital debris and do not generate new debris.

The FFC Cambridge process requires calcium chloride electrolyte. The electrolyte can be recycled, but the initial amount must be brought from Earth. Chlorine is a rather rare element on asteroids. In the proof of concept experiment of Lomax et al. [15], 1.6 kg of CaCl₂ was used to process 30 grams of lunar regolith simulant. According to the newest results [17], ~ 75 % of the total oxygen was extracted after 16 hours in the reactor. Thus, during one year, 545 batches can be processed, altogether processing 16.4 kg of regolith and liberating 4.3 kg of O₂, if the total oxygen content of the rock is 35 %. Thus for one year, the mass ratio (O₂ : CaCl₂) is (4.3 : 1.6) = (2.7 : 1). Because the process demonstration was intended only as a proof of concept and was not optimized, it is likely that the amount of electrolyte and/or the throughput time can be improved, maybe significantly.

5.2.1. Delta-v from asteroids

To estimate the delta-v from a given asteroid to L5, we compute the optimal Hohmann transfer delta-v from the asteroid to circular zero inclination 1 au heliocentric orbit, consisting of two or three impulsive burns, whichever strategy gives the smallest delta-v. The burns set the aphelion, the perihelion and the inclination. In reality, since we are considering low-thrust Electric Propulsion, the burns are not impulsive and therefore

²The chemical propellant mass is of the same order of magnitude as the payload mass in the lunar case.

they are not optimal. On the other hand, in reality one could make use of lunar flyby maneuver to kill up to 1.6 km/s of of the incoming hyperbolic excess speed. Because the effects work in opposite directions regarding the needed delta-v, we think that the impulsive Hohmann transfer delta-v gives a useful approximate measure of the low-thrust delta-v.

Figure 4 shows the cumulative mass in known asteroids sorted by the delta-v computed as just explained. The masses in Fig. 4 are based on the tabulated absolute magnitudes in JPL Small Body Database by assuming albedo of 0.15, density of 2 g/cm³, and spherical shape. The cumulative mass jumps at certain large and well accessible asteroids, some of which are marked in Fig. 4. To build the first settlement, we need 78000 tonnes of asteroid rock, which is only little larger than the estimated mass of asteroid 2000 SG 344, which in one source has been estimated as 7.1 × 10⁷ kg [18]. To be conservative, however, we shall assume the use of asteroid Apophis whose mass is 3 orders of magnitude larger. Apophis is also one of the potentially hazardous asteroids, so reducing its mass is not harmful from the planetary defense perspective.

The delta-v from Apophis is 3.37 km/s. For the transfer spacecraft using O₂ electric propulsion, we assume the parameters listed in Table 5.

Table 5: Parameters of the electric propulsion transfer spacecraft.

Delta-v	3.37 km/s
Specific impulse	2500 s
Efficiency	0.4
Traveltime	1.5 years
Acceleration when thrusting	0.12 mm/s ²
Fraction of thrusting arcs	60 %
Power/mass of power system and thruster	100 W/kg
Tank mass versus tank content (LOX)	0.01
→ Propellant mass versus rock mass	0.15
→ Dry mass versus rock mass	0.043
→ Mass ratio	23

The assumed specific impulse of 2500 s is on the high end of Hall thrusters and low end of gridded ion engines [19]. The assumed efficiency of 40 % is somewhat lower than the efficiency of state of the art xenon Hall thrusters which are typically above 50 %. We motivate the assumption by the fact that O₂ is less optimal propellant than xenon.

The power per mass ratio of 100 W/kg is typical to contemporary solar panel power systems. The thruster is typically quite lightweight in comparison. We assume a passively cooled LOX tank. The tank walls can be thin

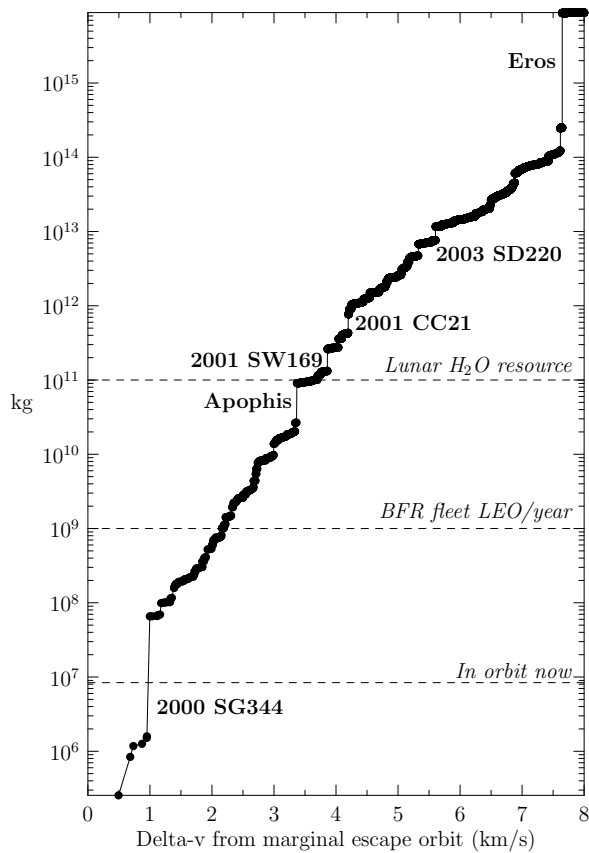


Figure 4: Cumulative mass of known asteroids as a function of delta-v.

since the pressure is low and the tank does not have to withstand launch vibrations or impulsive accelerations. We obtain the result that 13 % of the initial rock must be turned into oxygen, so that the ratio (propellant : rock) becomes (0.15 : 1). The 13 % corresponds to only about one third of the total oxygen content of typical asteroid rock.

Thus, the ratio of payload to dry mass of the transfer spacecraft is 23. If the spacecraft is used for multiple trips (1.5 year transfer followed by shorter triptime for going back to the asteroid), the effective mass ratio is increased.

5.3. H_2O electric propulsion

A drawback of the FFC Cambridge process is that the $CaCl_2$ electrolyte must be imported from Earth. Instead of extracting O_2 from rock, one can use a (C-type) water-rich asteroid, extract water by heating, and use the H_2O for Electric Propulsion. For Electric Propulsion thrusters, O_2 and H_2O are rather similar. Both are light molecules and when in hot and ionized state, they are chemically active.

The amount of water in the material is likely to be less than what is needed for propulsion, unless the specific impulse is chosen to be particularly high or the asteroid is particularly wet. Thus one must probably be prepared for mining and drying more material than one transports. To handle the waste material in the most sustainable way, one can create an artificial asteroid of the abandoned material and set it to orbit the parent asteroid. Then the dried-up material is not wasted permanently, but it remains most easily accessible to those future miners who prefer water-independent transportation techniques such as FFC Cambridge.

Water is easier to store than O_2 because it is storable as a room temperature liquid.

5.4. Hydrogen reduction of oxides

The Swedish-Finnish steelmaking company SSAB intends to replace traditional carbon reducing agent in steelmaking by hydrogen, thus enabling CO_2 -free production of steel. Hydrogen gas reacts with iron oxides to form reduced iron and water. The water is electrolysed to extract the oxygen. The hydrogen is injected back into the reactor.

Ordinarily, hydrogen reduction is applicable only to iron oxides. Turning the hydrogen to atomic or ionized form might also allow reduction of other oxides [20]. This is relevant for asteroids because most of the oxygen is bound in silicon and magnesium oxides.

The benefit relative to FFC Cambridge is that there is no need to import process chemicals from Earth. Hydrogen is needed, but it can be circulated, and the initial amount can be obtained from the water that exists in most asteroids to some extent.

5.5. Electric sail

The solar wind electric sail (E-sail, [21, 22]) is a propellantless propulsion method, based on the momentum flux of the solar wind. The E-sail consists of long and thin metallic tethers that are kept in high positive potential by an onboard high voltage source and electron gun that pumps out negative charge from the system. The maximum thrust of an E-sail depends on materials and other parameters, but is roughly of the order of ~ 1 newton [22]. With acceleration of 0.1 mm/s^2 as in Table 5, the single transfer spacecraft can thus move 10 tonnes of material. To build a 200 person settlement weighing 78000 tonnes (Table 2), one needs $\sim 10^5$ trips. Thus one needs a large fleet of E-sail spacecraft.

The E-sails are tens of kilometers in diameter. Thus, traffic congestion at the asteroid and at the settlement construction site become issues. The problem can be

avoided by moving the materials first by traditional spacecraft which rendezvous with E-sails once there is enough free space around. This increases the complexity to some extent, but the scheme remains efficient since the majority of the delta-v comes from the propellantless E-sail.

A fully autonomous optical navigation system is preferred. Otherwise operations and radio communication costs can become high, because the fleet is large. An autonomous optical navigation system was in principle demonstrated already in Deep Space 1 in 1998.

The E-sail tethers are made of multiple wires to be tolerant of the natural micrometeoroid flux. However, centimeter-sized particles can break all the subwires of a tether at once. Debris possibly generated by the asteroid mining is thus potentially dangerous for the E-sails. Making rendezvous with the E-sails far enough from the asteroid also mitigates this problem.

5.6. Comparison of methods

Table 6 summarizes the benefits of the four propulsion options for moving asteroid materials.

Table 6: Comparison of propulsion options for moving asteroid materials (Section 5).

	O ₂ EP	H ₂ O EP	H ₂ reduct.	E-sail
Any asteroid	+		(+)	+
No waste	+			+
No cryogenic tank		+		+
No Earth-imports		+	+	+
Easily dockable	+	+	+	
No large fleet	+	+	+	

5.7. Space manufacturing to increase the mass ratio

The Dutch-Luxembourgian company Maana Electric (<http://www.maanaelectric.com>) is developing a self-contained automatic factory, built in a standard-sized shipping container that takes in desert sand robotically and produces finished solar panel arrays, installing them in the surrounding desert. The company targets not only Earth, but also the solar system. If this technology proves to be practical, one could use it to produce solar panels for the transfer vehicle from the mined asteroid regolith, thus reducing the mass that must be brought from Earth. Structural parts of the transfer vehicle may be possible to 3-D print from the metal-rich residue of the FFC Cambridge process.

Making parts of the transfer vehicle from asteroid materials is simpler than making parts of the settlement,

because the transfer vehicles are unmanned and redundant. Thus a failure of one of them is not catastrophic. However, if strict quality checking standards are imposed, then it becomes feasible to also make structural parts of the settlement from asteroid materials. Our baseline structural material is piano wire steel. Piano wire steel is 99 % iron, which is abundant on asteroids. Other structural materials such as magnesium alloys or basalt or silica fibers can also be considered.

6. Costing of 200 person settlement

Table 7 gives the masses and launch costs of the 200-person settlement. We assume FFC Cambridge (subsection 5.2) and that the asteroid surface miners and the O₂ extraction factory together can weigh up to 3000 tonnes. The contribution of surface miners is likely negligible in comparison with the factory. In subsection 5.2 we found that at the current unoptimized prototype level of the FFC Cambridge process, one unit of Earth-imported CaCl₂ electrolyte produces 2.7 units of O₂ per year. From Table 5, transportation of one mass unit of asteroid rock needs 0.15 mass units of O₂ propellant. Thus, transportation of one mass unit of asteroid rock needs $0.15/(5 \times 2.7) = 0.011$ units of Earth-imported CaCl₂, if the production period is taken to be 5 years. Thus, transportation of 96576 tonnes of rock needs 1062 tonnes of CaCl₂, which is 35 % of the 3000 tonnes allowed for the O₂ factory. Recall that this is based on the presently existing unoptimized FFC Cambridge process of Lomax et al. [17].

Table 7: Mass and launch cost budget for 200-person settlement, assuming O₂ propellant extraction but no other space manufacturing.

	Total	Per pers.	Source
Asteroid rock	86423 t	432 t	Table 3
Transfer s/c dry	3716 t	19 t	Table 5
Miner & O ₂ ex.	3000 t	15 t	See text
Steel	2270 t	11.4 t	Table 3
Other	493 t	2.47 t	Table 3
Earth to L5	9479 t	47.4 t	Sum
Earth to LEO	28437 t	142 t	3× L5
Launch/F9	\$85B	\$426M	\$3k/kg
Launch/Starship goal	\$853M	\$4.26M	\$30/kg

In Table 7 we assumed – conservatively – that chemical propulsion is used to push the payloads from LEO to L5 so that the mass originally launched to LEO is 3 times larger than the mass that ends up in L5. Falcon 9 costs \$3000/kg to LEO in the default partially reusable mode. The fully reusable Starship rocket might be as

much as 100 times more cost-effective (\$30/kg). Adopting that, the launch cost per settler becomes \$4.2M.

Predicting the eventual per-kilogram cost of Starship or its competitor is challenging at the moment. One recent statement of SpaceX speculated with only \$2M cost per launch, i.e. \$13/kg [23]. To cover the uncertainty, in the Discussion part we shall also consider an intermediate price case of \$300/kg.

If the launch is e.g. 20 % of the total cost (the other being designing and building the settlement and the asteroid mining chain for obtaining the radshield rock), each settler needs an initial capital of $5 \times 4.2M = \$21M$. Settlers can earn their investment back and more, since once living at L5, they can teleoperate the nearby robotic settlement production factory complex in zero-delay mode. Thus the first group of settlers earns money by producing new settlements. They do it more efficiently than from ground because they avoid the 2.6 second free-space communication delay in teleoperation.

As was remarked above in subsection 5.7, solar panels and structural parts (including tanks) of the Electric Propulsion transfer spacecraft could be made from asteroid resources. Structural parts of the O₂ factory could also be made of asteroid-derived steel. Once proper quality control processes are in place, structural parts of the settlement can also be made of asteroid-derived piano wire steel. In Table 8 we show an example where space manufacturing has cut the net Earth-imported mass to 20 % of the original.

Table 8: Same as Table 7 but with space manufacturing.

	Total	Per pers.	Source
Mining & transfer	6716 t	33.6 t	Table 7
Steel	2270 t	11.4 t	Table 7
M&T effective	1343 t	6.7 t	0.2 ×
Steel effective	454 t	2.3 t	0.2 ×
Other	493 t	2.5 t	Table 7
Earth to L5	2290 t	11.5 t	Sum
Earth to LEO	6870 t	34.4 t	3 × L5
Launch/F9	\$20.6B	\$103M	\$3k/kg
Launch/Starship goal	\$206M	\$1M	\$30/kg

That is, under the stated assumptions space manufacturing reduces launch costs by a factor of 4.2.

7. Discussion and summary

Radiation shielding dominates the mass of beyond-LEO settlements. The assumed 9 t/m² shield provides max 20 mSv/year equivalent dose environment. If the

shield is made thinner, the effective dose would increase rapidly.

For large settlements where the shield thickness is negligible in comparison with the sphere radius, the mass density of the radshield does not matter. But for 200-person settlements it does play a role. We assumed density of 2.6 g/cm³ which is the same as the bulk density of larger asteroids such as Eros. Reaching this density probably requires some technical effort, for example making bricks out of it by pressing, sintering or melting [24].

It is advantageous to separate the water and to put it in its own layer, inward of the regolith. In this way, the hydrogen of the water moderates the spallated neutrons so that they can be captured by a thin layer of boron or other neutron absorber. A 2 % water content is sufficient for moderating the neutrons. Water is also intrinsically a better shield material than rock, so it is better if more is available. To be conservative, in the calculations we assumed only 2 %.

For moving the materials from asteroids there are several propulsion options. Extracting O₂ from rock by FFC Cambridge and using it for Electric Propulsion is a possible method. A drawback is the necessity to import the CaCl₂ electrolyte from Earth. Finding a water-rich asteroid and using H₂O as Electric Propulsion propellant is one of the other alternatives. The E-sail is also one option. It needs no propellant extraction, but requires a large fleet size.

Tables 7 and 8 show the launch cost per person without and with space manufacturing, and with present (Falcon 9) and future (Starship) launch vehicles. Introduction of space manufacturing (under certain assumptions) reduces launch costs by a factor of 4.2, and replacing Falcon 9 by the Starship cost goal of \$30/kg reduces them by a factor of 100 (Table 9):

Table 9: Launch costs per settler with various launch prices and with or without space manufacturing.

LEO cost	Space manufact.	Per person
\$3000/kg (Falcon 9)	No	\$426M
\$3000/kg (Falcon 9)	Yes	\$103M
\$300/kg	No	\$42.6M
\$300/kg	Yes	\$10.3M
\$30/kg (Starship goal)	No	\$4.26M
\$30/kg (Starship goal)	Yes	\$1M

If Starship reaches \$30/kg, the first 200-person settlement could probably be built without space manufacturing. Each settler might need initial capital of ~ \$21M,

20% of which is the launch. Such initial capital sounds realistic for 200 settlers. The money is used to build and launch the parts of the settlement as well as the asteroid mining infrastructure needed to make its radiation shields. Once the settlers have moved in, they can earn back the money by selling new settlements produced by their robotic mining and manufacturing infrastructure, which they are now in the position to use more smoothly by delayless teleoperation.

In Table 9 we also list the LEO launch price intermediate case of \$300/kg, which is 10 times smaller than Falcon 9, but 10 times higher than the Starship goal. Because Starship launches 150 tonnes per launch, \$300/kg corresponds to each Starship launch costing \$45M, which is about the same as the present Falcon 9 launch cost in its default partially reusable configuration (\$50M). Given that Starship is fully reusable, its launch should cost less than that of Falcon 9, because the fuel cost is only ~ \$2M per launch. In the \$300/kg case, the launch cost per settler is \$10.3M if space manufacturing is used. Such figure sounds realistic for 200 settlers. If space manufacturing is not used, then the launch cost is \$42.6M per settler. This initial cost level is also probably feasible for 200 settlers, provided that there is a credible roadmap for lowering costs in the future by implementation of space manufacturing and/or by lowering launch costs.

We summarize our main findings:

1. The radiation shield against GCRs dominates the mass (97% in the case of 200 person settlement). It can be asteroid rock.
2. A sphere is the optimal shape for radiation shielding. Hence the two-sphere dumbbell configuration is best.
3. As structural material we recommend piano wire steel.
4. Several propulsion options to transport rock from asteroid to L5 are viable.
5. To cut costs by space manufacturing, one can make solar panels and structural parts of the transfer vehicles and the settlement from asteroid materials.
6. The economic case looks promising if LEO launch cost is \$300/kg or below.
7. The settlers make money by constructing more settlements by teleoperating a nearby robotic factory with negligible communication delay.

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References

- [1] O'Neill, G.K., The colonization of space, *Physics Today* 27, 9, 32–40 (1974). <https://space.nss.org/the-colonization-of-space-gerard-k-o-neill-physics-today-1974/>
- [2] O'Neill, G.K., *The high frontier*, New York (1977).
- [3] Globus, A., S. Covey and D. Faber, Space settlement: an easier way, *NSS Space Settlement J.* (2017). <https://space.nss.org/media/NSS-JOURNAL-Space-Settlement-An-Easier-Way.pdf>
- [4] "Assure Space won't cover collision risk in low Earth orbit", *Space News*, March 11 (2020). <https://spacenews.com/assure-space-leaves-leo/>
- [5] Hou, X.Y., X. Xin, D.J. Scheeres and J. Wang, Stable motions around triangular libration points in the real Earth–Moon system, *Monthly Notices of the Royal Astronomical Society*, 454, 4, 4172–4181 (2015). <https://academic.oup.com/mnras/article/454/4/4172/997896>
- [6] Globus, A., and J. Strout, Orbital space settlement radiation shielding, *NSS Space Settlement J.* (2017). <https://space.nss.org/media/NSS-JOURNAL-Space-Settlement-Radiation-Shielding.pdf>
- [7] Kramer, R., H.J. Khoury, J.W. Vieira, E.C.M. Loureiro, V.J.M. Lima, F.R.A. Lima and G. Hoff, All about FAX: A Female Adult voXel phantom for Monte Carlo calculation in radiation protection dosimetry, *Phys. Med. Biol.* 49, 23, 5203–5216 (2004).
- [8] Hassler, D.M., et al., Mars' surface radiation environment measured with the Mars Science Laboratory's Curiosity rover, *Science*, 343, 6169, 1244797 (2014).
- [9] Globus, A. and T. Hall, Space settlement population rotation tolerance, *NSS Space Settlement J.* (2017). <https://space.nss.org/media/NSS-JOURNAL-Space-Settlement-Population-Rotation-Tolerance.pdf>
- [10] Yeomans, D.K., et al., Radio science results during the NEAR-Shoemaker spacecraft rendezvous with Eros, *Science*, 289, 5487, 2085–2088 (2000).
- [11] O'Neill, G.K. and H.H. Kolm, High-acceleration mass drivers, *Acta Astronaut.*, 7, 11, 1229–1238 (1980).
- [12] Baker, D. and R. Zubrin, Lunar and Mars mission architecture utilizing tether-launched LLOX, *AIAA 90–2109, AIAA/SAE/ASME/ASEE 26th Joint Propulsion Conference*, July 16–18, 1990, Orlando, Florida.
- [13] Landis, G.A., Analysis of a lunar sling launcher, *J. British Interplanetary Soc.*, 58, 9/10, 294–297 (2005).
- [14] Eke, V.R., L.F.A. Teodoro and R.C. Elphic, The spatial distribution of polar hydrogen deposits on the Moon, *Icarus*, 200, 12–18 (2009).
- [15] Lomax, B.A., M. Conti, N. Khan, N.S. Bennett, A.Y. Ganin and M.D. Symes, Proving the viability of an electrochemical process for the simultaneous extraction of oxygen and production of metal alloys from lunar regolith, *Planet. Space Sci.*, 180, 104748 (2020).
- [16] Andreussi, T., E. Ferrato, V. Giannetti, A. Piragino, G. Cifali, M. Andrenucci and C.A. Paissoni, Development status and way forward of SITAEL's air-breathing electric propulsion, *AIAA Propulsion and Energy 2019 Forum*, 19–22 August 2019, Indianapolis, USA, AIAA 2019–3995, doi:10.2514/6.2019-3995.

- [17] Lomax, B.A., M. Conti, N. Khan, A. Ganin and M. Symes, The Metalysis-FFC process for the efficient extraction of oxygen on the lunar surface, Presentation given in ESA Space Resources Workshop, Luxembourg, October 10–11, 2019.
- [18] <https://web.archive.org/web/20041024225737/http://neo.jpl.nasa.gov/risk/2000sg344.html>
- [19] Goebel, D.M. and I. Katz, Fundamentals of electric propulsion: ion and Hall thrusters, Wiley (2008). https://descanso.jpl.nasa.gov/SciTechBook/st_series1_chapter.html
- [20] Sabat, K.C., P. Rajput, R.K. Paramguru, B. Bhoi and B.K. Mishra, Reduction of oxide minerals by hydrogen plasma: an overview, Plasma Chem. Plasma Process., 34, 1–23 (2014).
- [21] Janhunen, P., Electric sail for spacecraft propulsion, J. Prop. Power, 20, 763–764 (2004).
- [22] Janhunen, P., P.K. Toivanen, J. Polkko, S. Merikallio, P. Salminen, E. Hægström, H. Seppänen, R. Kurppa, J. Ukkonen, S. Kiprich, G. Thornell, H. Kratz, L. Richter, O. Krömer, R. Rosta, M. Noorma, J. Envall, S. Lätt, G. Mengali, A.A. Quarta, H. Koivisto, O. Tarvainen, T. Kalvas, J. Kauppinen, A. Nuottajärvi and A. Obraztsov, Electric solar wind sail: Toward test missions, Rev. Sci. Instrum., 81, 111301 (2010).
- [23] <https://techcrunch.com/2019/11/06/elon-musk-says-spacexs-starship-could-fly-for-as-little-as-2-million-per-launch/>
- [24] Soilleux, R.J., Orbital civil engineering: waste silicates reformed into radiation-shielded pressure hulls, J. British Interplanetary Soc., 72, 244–252 (2019).