The "Tesla" Orbital Space Settlement

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The paper presents conceptual research undertaken as an independent student project on certain parameters of an orbital space settlement (called Tesla), with emphasis on its structure and parking orbit. The Tesla is proposed to orbit the M-type Near Earth Apollo asteroid 1950 DA and provide abode to 2500 residents. With a delta-v requirement of 6.8 km/sec, the asteroid is one of the most accessible metallic asteroids. The primary objective of Tesla is to supplement mining activities on the asteroid. The concept of Net Present Value (NPV) is briefly introduced to assess the economic feasibility of selection and mining of the target asteroid. The Tesla is proposed to have a terminator orbit about 1950 DA which is self-stabilizing through solar radiation pressure. The structure is a rotating truncated (half cut) torus, with a central co-axial non-rotating cylinder. The torus rotating about the main axis at 1.5 rpm ensures 1g pseudo-gravity to its residents. The torus provides area for habitation and agriculture while the cylinder (at 0g) supplements recreational and industrial activities. The major and minor radiuses of the torus are 397m and 77m respectively while the height and radius of the cylinder are 500m and 150m respectively. Electricity is supplied using solar power satellites and solar panels on the cylinder. Radiation shielding and micrometeoroid protection is provided with the use of asteroid regolith and industrial slag. Wobble and Nutation control of the rotating structure is provided by active mass dampers. Thermal control is provided using multiple radiators on the exterior of the cylinder.

I. Introduction

Space exploration has come a long way in the last century. The seeds of which were sown by Konstantin Tsiolkovsky, with his ideas on rocketry, and space stations. Much has been done since then, with the pioneering work of Dr. Gerard O'Neill[1] on orbital space settlements. Although present day technology allows the concept of building settlements in space, the high investments and lack of cheap resources prevent space settlements from being a modern day reality. A successful space settlement endeavor requires huge initial investments and easy availability of materials. The prerequisite for any space settlement, apart from providing comfortable life support systems, is to overcome the dependence on Earth and rather utilize the bountiful resources available in space. The feasibility and success (both commercial and technical) of an orbital settlement largely depends on its design and location. Some of the likely locations being advocated in recent years are on Moon, Mars, LEO (low Earth orbit), and Earth-Moon Lagrange points etc. The author strongly asserts that although the above mentioned locations are feasible, it is the Near Earth Asteroids (NEA) that offer greater promise in future. The analysis shown in the paper had been done mainly to see how ideas from different literature sources might be brought together to illustrate the feasibility of a hypothetical space settlement in support of mining operations on an NEA. NEAs are likely to bear high content of platinum group metals (PGMs). All common classes of meteorites contain higher concentration of PGMs than the richest ore bodies in Earth's crust[2]. On Earth, the best mines contain 4-6 ppb (parts per billion), whereas based on meteorite content, 30-60 ppb is guessed in many asteroids, possibly much higher[3].Spectroscopic studies suggest that a wide range of resources are present in asteroids and comets, including nickel-iron metal, silicate minerals, semiconductor, water, and trapped or frozen gases including carbon dioxide and ammonia[4]. The products obtained can not only provide construction materials for an orbital space settlement but also provide profits from the sale of both raw and processed materials. In fact; exploitation of such minerals would be a possible environmentally friendly remedy for impending terrestrial shortages of such resources.

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Asteroid spectral type	**Inferred Mineralogy**	**Product**
C, D, P	Clay, organics, ice at depth	Volatiles: H_2O, CO_2, CH_4
B, G, F	Clay, silicate, limestone, Nickel-Iron metal	Volatiles: Nickel-Iron metal
Q, S, M	Silicates, Nickel-Iron metal	Metal, Silicates, Platinum group metals

Table 1: Matrix of spectral type, inferred mineralogy, and potential products

In comparison to the Moon and Mars, most NEAs require lower cost. A smaller mission is required to retrieve asteroid material, since there is very little fuel spent on landing and launching from an asteroid's micro-gravity as compared to the Moon and Mars.Furthermore, in space, the parameter which measures the difficulty of delivering mass from one orbit to another is not distance, but the required velocity change, delta-v (also denoted Δv), needed to perform this transfer. There are a number of known asteroids more accessible than the Moon and Mars in terms of delta-v from the LEO[4].In comparison to the resources available on asteroids, the Moon's surface is volatile-poor and metal- poor. In the future, the rising cost of resource acquisition on Earth will surpass the falling cost of acquiring equivalent or substitute materials in space. This is likely to provide the economic catalyst for large-scale acquisition and utilization of space resources. In fact, given favorable technical developments and target asteroid conditions, we may soon be able to obtain some resources in space at lower costs than we can mine and process them on Earth.

Although the value of NEA resources runs in billions of dollars, at current market prices, a big disadvantage of is that they are "temporary assignment" missions since they can be reached economically at only certain times in their orbit. For example, a given asteroid may be economically attractive in terms of delta-v for several months which recurs at seven year intervals. One may advocate the construction of a surface base on an NEA and argue on the advantage of an orbiting habitat. However, there are a number of difficulties for habitation owing to the micro gravity on the asteroid's surface. A settlement in an NEA orbit can practically mine and process the materials almost 365 days a year. The proximity of the settlement to the asteroid will minimize the launch costs and maximize the mass returned to the market thereby ensuring greater returns. The extracted materials can easily be processed on the orbiting settlement, thereby substantially reducing the time delay from commitment of capital to the mining project until the sale of the product. Apart from processing extracted materials, the settlement can also:

- Manufacture mining related machinery, and custom built robots.
- Lease out work space and equipment to mining companies.
- Provide abode to the mining crew.
- Provide space for orbital hotels and low-g recreation thereby generating revenues from the tourism industry.
- The settlement can support research and exploration activities for the NEAs since as of now, less than 10% of the NEA population has been compositionally characterized; even sizes of NEAs are poorly constrained. So even for radar determined diameters (which are one of the best) the uncertainties are as high as 30-40%.
- With more than 1000 known potentially hazardous NEAs, the settlement can serve as an asteroid tracking observatory, this can also facilitate technical analysis of potential asteroids that show commercial and economic promise in the near future.

There is a growing need of an "industrial powerhouse" in space in order to efficiently harness the bountiful resources on the NEAs. Further sections in the paper analyze the orbital location and the structural design of such a space settlement, which the author has named Tesla mentioned in honor of the late inventor Nikola Tesla.

II. Selection of the target NEA

Development and operation of in-orbit infrastructure for Tesla will require large masses of materials for construction, shielding and propellants for orbit-change maneuvers. All these requirements directly depend on Tesla's orbital location. The actual feasibility of a prospective orbital location for Tesla would therefore largely depend on the target asteroid. MJ Sonter[5] in 1997 calculated that the proper figure of merit used to assess financial feasibility of proposed projects is the Net Present Value (NPV). Sonter claimed that NPV is the appropriate measure for the feasibility of a proposed terrestrial mining venture, and thus should be applied towards the feasibility of a hypothetical asteroid mining venture.NPV calculates the present value of receipts of money to be received n years in the future, taking into account the foregone interest that the invested money could have been earning. The goal is to have a project with a large positive NPV. Projects with negative NPV should not be considered.NPV in the asteroid mining case depends on:

- The cost to launch and conduct the mining mission,
- The mass returned and what you can sell it for.
- The time it takes to accomplish the mission.

Net Present Value of a Receipt R obtained in year N is = $R\,(1 + I)^{-N} - C$, Where I is the market interest rate paid on investments and C is the capital spent on the project. The Net Present Value (or more accurately, the expectation NPV) depends on and is a function of: the delta-v required to reach the asteroid, and the exhaust velocity of the propulsion system; the time duration from launch to product delivery; the value of the product once developed; and the market interest rate. Once sufficient infrastructure is established in orbit, Tesla will be able to manufacture the extracted materials onboard; this material can be delivered into Earth orbit (which will be our market initially).

The primary aim is to harvest asteroid resources for Tesla's construction, and supply resources to the market i.e. Earth orbit. But as a long term goal, Tesla can even emerge as a market in itself, processing, supplying and selling the commodities for deeper scientific and economic space ventures like Mars, even the asteroid belt. About half of the NEAs are believed to be C-type, with most of the remainder S-type, and a small percentage M-type[6]. Based on their orbital characteristics, the NEAs are classified as:

- **Apollo**: Asteroids whose orbits cross Earth's orbit but spend most of their time outside Earth orbit .They have high eccentricity, low-inclination orbits and demand Hohmann transfers for both outbound and inbound trajectories, because of their relatively high delta-v requirement[16].
- **Atens**: Asteroids whose orbits cross Earth's orbit. Unlike Apollos, Atens spend most of their time inside Earth orbit. They demand a Hohmann transfer to rendezvous with the target asteroid at its perihelion[16].
- **Amors:** Asteroids whose orbits approach but do not cross Earth orbit, and whose orbits are further from the Sun than Earth's orbit. Many have orbits which reside entirely between Earth and Mars. Such close, low eccentricity, low inclination NEAs, may be favorable for continuous low-thrust spiral, non-Hohmann returns[16].

Apollos, Amors and Atens can be generally ranked in desirability according to their delta-v for access and return, according to the out and back transit time, and their composition i.e. products offered. The desired products initially would be water (for propulsion) and nickel-iron for sale as construction material for settlement. It must be noted that no single target NEA is expected to have everything required. For our case, the preference would be C-type and M-type asteroids, having confirmed carbonaceous and metallic character respectively.

Name	**Spectral type**	**Eccentricity**	**Delta –v (km/sec)**	**Diameter (km)**	**Semi-major axis(AU)**	**Orbital classification**
1950 DA	M	0.507	6.8	~1.8	1.699	Apollo
1986 DA	M	0.586	7.1	~2.3	2.811	Amor
1999JU3	C	0.190	4.6	~0.92	1.190	Apollo
1996FG3 (binary system)	C	0.350	6.6	~0.43	1.054	Apollo

Table 2: Some prospective NEA targets with their data[8]

As seen from the Net Present value parameters, the target asteroid should allow a large positive NPV in order, to be commercially feasible. In our case, the asteroid with the least delta-v, low eccentricity, inclination and having the highest average solar flux will be the most desired. Reliably estimating costs and profitability is beyond the scope of this study. However, it can be safely assumed that the main target for any long term commercial space venture will be a metallic asteroid since it offers maximum profit potential. At present, there are 2 M-type NEAs having confirmed metallic composition, 1950 DA[9], 1986 DA[10].

Asteroid	**Volume (m^3)**	**Surface density (kg/m^3)**	**Average solar flux**	**Pt content (kg)**	**Pd content (kg)**	**Au content (kg)**
1950 DA	$\sim 0.8\times10^9$	5×10^3	0.50	8.09×10^7	4.04×10^7	1.98×10^7
1986 DA	$\sim 4\times10^9$	5×10^3	0.15	4.04×10^8	2.02×10^8	9.92×10^7

Table 3: Quantifiable data on metallic NEAs[11]

It has been estimated that the asteroid 1950DA has reserves comparable to the Bushveld complex in South Africa, and in fact the PGM concentrations is thought to be even higher[11]. Moreover, there are good launch opportunities to 1950 DA throughout much of this century[11] .Being the most accessible NEA with rich reserves of Nickel-Iron and platinum group metals, 1950 DA is the best known target. The revenue earned from processing and selling of Nickel-Iron and Platinum group metals (PGEs) can be used to repay the initial cost for Tesla's construction. Table 4 below shows the current costs of the metals present on a metallic asteroid. In the future, the rising cost of resource acquisition on Earth will surpass the falling cost of acquiring equivalent or substitute materials in space[37]. This is likely to provide the economic catalyst for large-scale acquisition and utilization of space resources[37].

Metal	**Price(in $ per kg) as of 2009**
Platinum	48000
Palladium	14000
Iridium	14000
Rhodium	80000
Ruthenium	6400
Gold	35000

Table 4: Cost of metals expected to be present on an M-type asteroid[7]

VI. Mining facilities on the asteroid

Apart from focusing on how to accommodate humans in a new environment, it is also important to focus on resource recovery and mining equipment requirements on the asteroid. Various studies have been conducted on resource recovery and equipment requirements for asteroid mining[34, 35, 36; 37].Table 5 gives a basic overview on the various mining and processing techniques that can be employed on different asteroids.

Asteroid type	**Mining**	**Processing**
Ice mixtures	blast, heat, distill	phase separation
Friable rock	blast, rip	phase separation, mechanical, chemical, magnetic
Hard rock	blast, disc cutters	mechanical, chemical, magnetic
Metallic Ni-Fe(massive)	concurrent with processing	smelting, carbonyl methods

Hard rock metallic Ni-Fe	blast, heat	rip mechanical, chemical, magnetic; smelting

Table 5: Various mining and processing techniques for different asteroids[36]

The operations for mining the asteroid can be primarily divided into 2 facilities: Mining infrastructure on the asteroid and the processing facilities on board Tesla. For a metallic asteroid like 1950 DA, it has been shown that the surface layers are expected to be brittle in shadow, but more ductile in sunlight[36]. The low gravity of a small asteroid would present a challenge for the crew attempting to set up the mining infrastructure on the asteroid surface. This challenge can be mitigated by the use of circumferential ropes[36]. Specific asteroid miner systems[35, 37] for Ni-Fe and PGM extraction can be used for harvesting these materials. These miners will analyze, excavate and acquire the regolith for metals. These acquired materials will then be sent to the processing plant on Tesla where they can be processed and refined using techniques like carbonyl processing for PGM.

III. Orbit dynamics about 1950DA

Apart from the asteroid's gravity, the primary forces that act on Tesla are solar tide and solar radiation pressure. Without the necessary orbital maneuvers, the solar tide and radiation pressure perturbations may strip the settlement out of orbit about an asteroid. According to DJ Scheeres[12], the solar tide has a relatively small effect as compared to other forces and must be considered once precise orbit determination has been done. Solar radiation pressure (SRP) is important when orbiting small and intermediate sized asteroids, or at large distances from the asteroid. The best solution available for stable orbits around small asteroids like 1950 DA in the presence of SRP is a terminator orbit, which by definition is near-perpendicular to the current sun direction. Hence Tesla may have a sun synchronous terminator orbit[13] around the asteroid namely because the orbit is self-stabilising through SRP. It nominally requires minimal maintenance and may not require correction manoeuvres for weeks/months.

One important condition for terminator orbit is that it should lie outside of ~1.5×D Resonance radii of the asteroid. Moreover, ion thrusters may be deployed on Tesla that can be used for orbit correction and prevent orbit destabilization also since the SRP may not be able to stabilize Tesla at the aphelion.

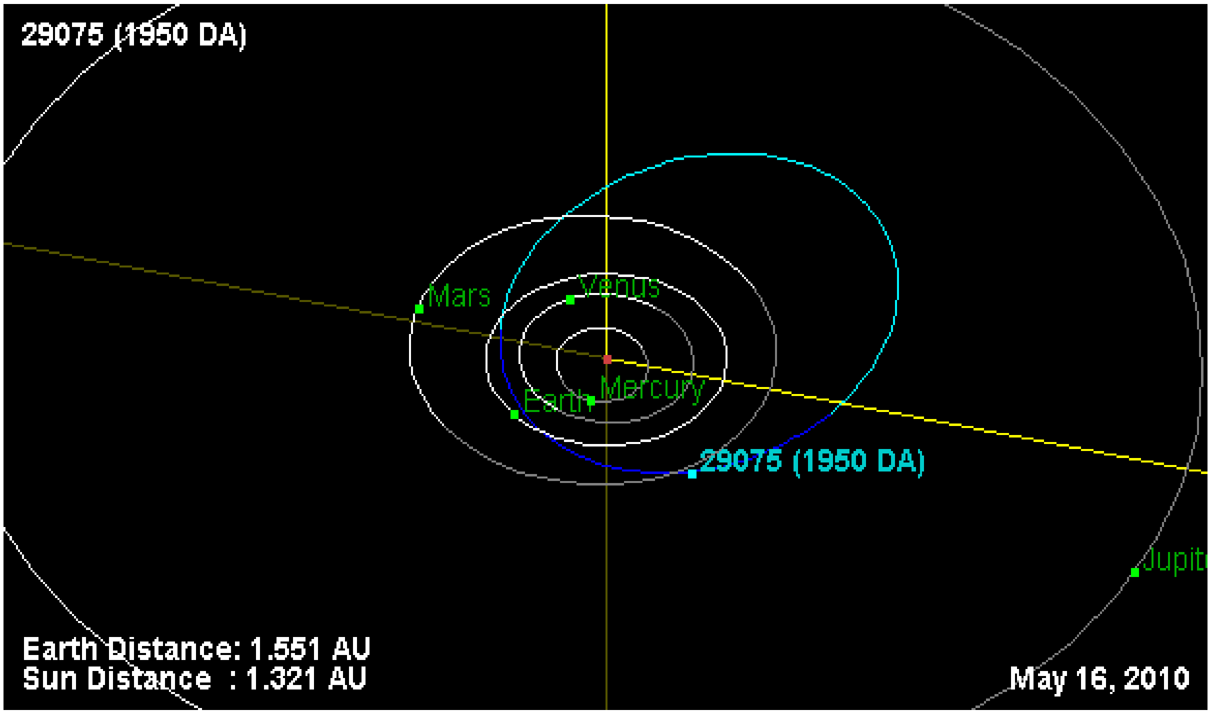


Fig.1: Orbit of asteroid 1950DA[29]

IV. Structure and Design

The prerequisites for any space settlement design are:

- Excellent life support systems i.e. water, pseudo-gravity, power, atmosphere, agriculture, recreation etc.
- Adequate radiation and debris protection.
- Safety considerations like isolation of industrial activities from habitation.
- Rotational stability, wobble control.
- Cost effectiveness.
- Commercial and technical feasibility.

The NASA summer studies[14] produced three feasible settlement designs capable of producing artificial gravity through rotation namely, Cylinder, Bernal sphere and Stanford torus, which have been discussed below:

a. Bernal Sphere

Advantages	Disadvantages
• Best structural shape for containing pressure providing a strong base for entire colony. • Least amount of surface area with the greatest volume/best protection, shielding.	• Hardest to construct • Unequal distribution of artificial gravity

b. Cylinder

Advantages	Disadvantages
• Balanced surface area and volume. • Provides equal gravity to all the down surfaces except end caps. • Provides room for future expansion.	• Not efficient at containing pressure • Big radius due to its huge distribution of land based area.

c. Stanford torus

Advantages	Disadvantages
• Assures maximum habitable area per ton of nitrogen. • Balanced symmetrical structure, suitable for a good life support system. • Permits possibility of incremental construction and agriculture as an integral part of the living area.[14]	• Requires a huge shielding to accomplish purpose. • Largest surface area with least volume, inefficient in maintaining construction costs

From the above mentioned data it turns out that the torus is best suited for habitation. For the best life support systems, it is also necessary for the design to allow minimal gravity variation in the habitation region. This can be done by introducing some modification in the torus design. If the outer semicircle is removed from the cross section of the torus, it would generate a truncated (half cut) toroidal design. This design (with double shell outer walls) offers constant and stable gravity to the inhabitants i.e. ($\Delta g=0$)[15] and might reduce the mass of the structure and atmosphere compared to a full torus. However, the structural analysis remains to be done and the design is still speculative.

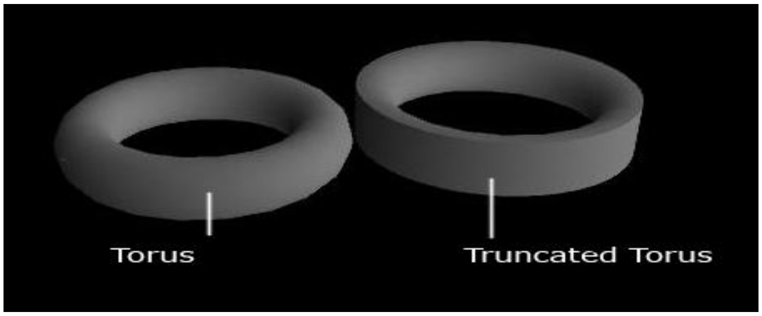
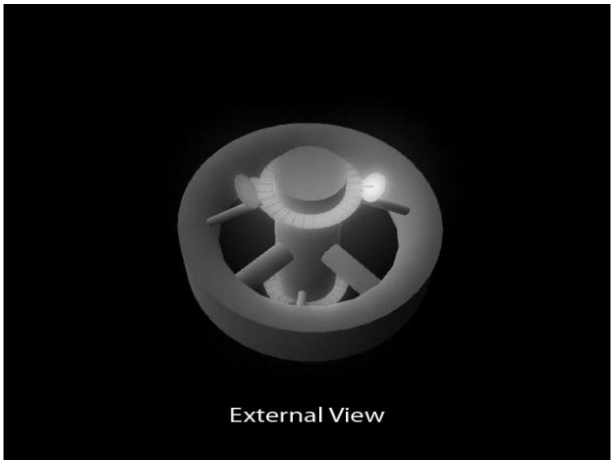


Fig.2: Shape of a normal and truncated (half cut) type torus

Although we require 1g for habitation, the requirement of micro gravity modules in our structure cannot be ignored. Most of the industrial activities would require a micro gravity environment since moving large masses of nickel-iron feedstock and slag on and off of a rapidly-rotating structure would be energetically intensive and a major control problem. Hence, it is proposed to have a micro gravity facility that can efficiently cater to the industrial requirements of the settlement, apart from providing space for recreation and research. It is important to consider the construction methods of the Tesla settlement around the asteroid. Due to the availability of ample resources on 1950 DA, it is proposed that the major portion of the structure be in-situ derived from local resources, while some crucial structural elements can be prefabricated. During the initial construction of Tesla, it will also be important to set up mining bases on the asteroid; where in the crew can operate the various activities. The settlement can be constructed using the advanced technology of tailored force fields[**39**].

A. External configuration

When choosing the dimensions of the structure, several factors have to be taken into consideration like generation of artificial gravity, as well as the necessary space to support Tesla's inhabitants and industrial activities. The dimensions of the truncated torus depend on the population of inhabitants. As per the NASA summer study[**14**], the total area required per person is 155 m^2. Hence a total of 387500 m^2 would be required for a population of 2500 residents. The design description and challenges that need attention have been discussed below:



1. *Design description*

The essential form of the Tesla space settlement consists of a half-cut (truncated) torus rotating about its principal axis. Four spokes or conduits join the torus to a central non rotating cylinder. Further, four inclined tubes connect the rotating structure to the cylinder acting mainly as support and strengthening piers. The torus and the cylinder are built with double shell outer walls (discussed further in truncated design challenge).The central cylinder is connected by electromagnetic bearings to a second concentric outer cylindrical hull, which is connected by the spokes to the truncated torus.The torus provides area for habitation and agricultural facilities for a total population of

2500 inhabitants. The central cylinder provides essential micro gravity facilities for research, recreation as well as industrial activities. Apart from a few modules in the central cylinder, the entire settlement is pressurized. Unpressurized areas in the cylinder can be used for storage and research that requires perfect vacuum. There are 2 docking ports located at the two ends of the central cylinder. Having the docking areas located at the center allows vessels to arrive and depart with minimal maneuvering. A total of 4 concave mirrors are positioned on the central cylinder to reflect sunlight into the living areas of the tours. Furthermore, thermal radiators are positioned on the cylinder mainly to dissipate excess heat from the settlement. Figure 2 below describes various exterior views of the settlement.

2. *Design challenges*

Truncated design: Although the truncated design offers constant and stable gravity, one major design constraint is the atmosphere imposed tensile stresses which can cause bending[23].The habitat's internal pressure creates both longitudinal and transverse pressurization loads on the habitat wall. In addition to the longitudinal pressure loads, the habitat also sees longitudinal loads due to centripetal acceleration and the ion thrusters used for stabilization. Stiffness against bending would require beams and joists unlike a balloon thin skin used in a circular cross section torus.A possible solution would be to build all structural elements of Tesla (the torus, the spokes and the cylinder) with double-shell outer walls. The distance of the cavity between inner and outer shell would depend on the dimensions of each element. The two shells can be stiffened by a structural framework. The cavity between this framework can be filled with asteroid regolith for radiation and micrometeoroid shielding and a layer of foam glass for thermal protection. Quantitative analysis is recommended in order to prove that the high mass impact of the double shell outer walls will be less than the structural and atmospheric mass reduced through the truncated design.

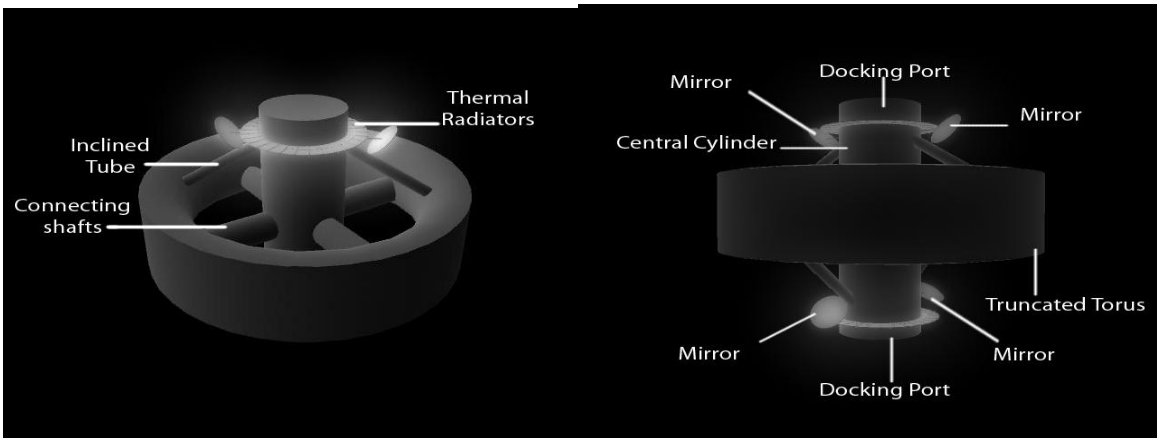


Fig.3: Various Views of the Tesla Space Settlement design

Artificial gravity: Artificial gravity is extremely crucial for long term sustenance of habitation in space, the absence of which may cause severe issues like cardio vascular changes and bone damage[17] .Hence it is necessary to simulate earth gravity to ensure the long term survival of the inhabitants. Since the settlement is rotated; centrifugal force, normal to the floor can provide the required magnitude of artificial gravity. Although people have proposed lower acceleration levels such as 0.8g etc., the minimum pseudo-gravity required to preserve human health remains unknown. The maximum radius of the torus can be determined by the optimum pseudo gravity level (1g) and the maximum rotation rate consistent with the reaction of human body. A rotation rate of about 1.5 rpm is proposed, which is well within the range of human tolerance. This gives the major radius of the torus to be approximately 397m.The minor radius of the torus can be calculated from the required area, which comes out as approximately 83m.The values of the required pseudo-gravity and the rotation rate have been tested in the SpinCalc[40], an artificial gravity calculator designed by Theodore Hall that assists in finding a set of parameter values that confirm to all comfort boundaries. The values of major radius of the torus and tangential velocity are found to be in the comfort zone. No adverse effects arising from the Coriolis forces are expected since the rotation rate is less than 3 rpm. The non-rotating cylinder would require sufficiently large area for the mining and processing industries besides catering to the recreational and research needs. Approximate dimensions with diameter and height as 300m and 500m respectively are proposed for the cylinder based on the summer study's estimation for the total industrial and recreational area.

Sunlight: In order to harness maximum advantage of solar energy, it is proposed to have 4 concave mirrors positioned on the central cylinder, which may direct the sunlight to the torus apart from providing day night cycles on Tesla.

Electricity: Approximately 60 kW of energy per person[18] will be required onboard Tesla, 50 kW for agriculture and 10 kW for other purposes. For a population of 2500 residents, this implies a total power of 150 MW. Solar power satellites beaming energy wirelessly onto body mounted rectennas on the torus and cylinder may be used for producing the required power. These satellites may be kept in a fixed orientation relative to the sun to ensure constant power supply. Moreover, solar panels may also be deployed on the exterior of the cylinder to further supplement the power requirement.

Radiation and Micro meteorite shielding: Substantial radiation shielding will be required for the settlement, in order to protect the inhabitants from the harmful cosmic rays along with secondary radiation and solar flare events. In absence of any shielding, radiation may cause serious health effects, apart from genetic mutations. It has been proposed that a shielding of approximately. 60 to 70 cm of regolith (or 22 cm of water) could be sufficient for radiation protection[38].Dense regolith could be filled into the structural cavity between the double shell outer walls during construction in order to provide sufficient radiation and micrometeorite protection. Additionally small "Solar Flare Shelters" could be a part of the living quarters to protect the inhabitants just for time of solar eruptions.Moreover, the slag (containing silicates etc.) produced after processing of mined ores can also prove to be an efficient shielding material.

Wobble and Nutation control: Although the rotating structure would be rotationally stable, it will tend to wobble as people move around the settlement[18] and since the living area is unlikely to have equal distribution of mass. Another challenge is of nutation[20] which is the irregular motion in the axis of rotation of a large symmetric rotating object. One method to counter these issues is to ensure equal distribution of mass in the living area, but this method would be impractical on a large scale. Another better alternative may be the use of active mass dampers[21] to stabilize violent motion against harmonic vibration. Nutation and wobble sensors connected to a control propulsion system may be used to correct the slightest tendency of the structure to wobble.

Thermal control: Considering the rotation movement of the settlement it is easy to imagine that the position of a certain point of the truncated torus towards the Sun is permanently changing. Therefore we can assume the temperatures of the different parts of the torus suffer constant variation depending on their position towards the Sun. The temperature of a certain surface will naturally tend to rise when facing the Sun and will tend to drop as soon as it begins to face the opposite direction. Some dilation and contraction phenomena can also be expected to occur during a complete rotation of the torus. Therefore it is proposed that the inner circumference of the torus be provided with a thermal shield, along with a foam glass layer between the double shells of the torus. Multiple thermal radiators can be placed on the exterior of the cylinder in order to reduce the thermal stress and dissipate the heat generated by the electric power systems.

B. Interior configuration

To design a long-duration habitat, it's important to consider the full gamut of human experience of the environment. Long-term viability depends on much more than just the structural efficiency. A space habitat isn't just a machine; it's a life experience. To be viable, it needs to keep the inhabitants satisfied with their condition. The qualitative criterion for internal habitation design has been mentioned below[14]:

- Long line of sight.
- Large overhead clearance.
- Green belts.
- Availability of conventional consumables.
- Natural light.
- Private space.

- Capability of physically isolating segments of the habitat from each other.
- External views of large natural objects.

The challenges and their proposed solutions are mentioned below:

1. *Interior land allocation*

The interior area of Tesla may be sub-divided into living area and zero g modules.

Living area: It is proposed that the living area be divided into several modules catering to both the residential and agricultural needs of Tesla. It has been found that the interior design of a space habitat should have flexibility. Such flexibility can include the use of movable partitions, removable wall covers, projectible designs, etc[42]. Visual variety can be introduced through the judicious use of different architectures, texture or color[42]. The modules can have different architectural themes that will improve the outlook of the habitat and attract the inhabitants. The residential area may for example, have Roman, Indian, Greek and Chinese architecture all very rich and unique in different ways. The ancient Indian architectural text of 'Vastu Shastra'[22]may be used to regulate planning and design specifics of town planning. The stipulations are said to be governed by ancient empirical knowledge of the human body and its relation to the cosmos. Following these stipulations, it is said, ensures overall human well-being. The construction of these interior modules may be facilitated through the automated technique of Contour Crafting[27]. Contour Crafting (CC) is a recent layered fabrication technology that has a great potential in automated construction of whole structures as well as sub-components. Using this process, a single house or a colony of houses, each with possibly a different design, may be automatically constructed in a single run.

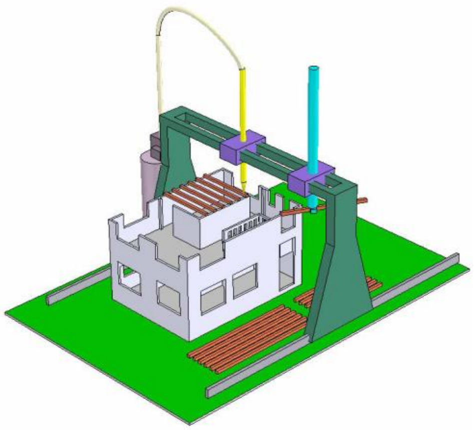


Figure 4.Construction of conventional buildings using CC

Zero-g modules: The zero-g modules will be instrumental in providing the inhabitants with adequate recreational facilities. The modules may also cater for astronaut crew training intending to travel on long missions like Mars, asteroid belt etc. The mining and processing industry can hugely benefit from the zero-g environment, with expectations of higher performance levels in micro gravity specially in terms of processing of high performance eutectics and semi conductors[26]. The cylinder has a command/control/communication module responsible for terrain mapping of the asteroid and communicating with the mining based equipment. The cylinder will also include Ni-Fe and PGM processing plants, storage unit for fuel such as LH2/LOX and a manufacturing module for mining based machinery. It will be necessary to ensure maximum isolation of the industrial area from the recreational modules with facilities of evacuation and sealing in case of any accident.

2. *Atmosphere*

Creating an atmosphere is extremely important but at the same time quite difficult too. In the structural design of a habitat, the total atmospheric pressure is one of the most significant loads with structural mass varying linearly with the internal pressures[23]**.**An optimum atmospheric pressure of 50 kPa has been suggested for a stay time >80 years in a space habitat[23]. It has been observed that the lowest pressure will result when the atmosphere contains pure oxygen at a partial pressure similar to the Earth sea level i.e. 25.3 kPa. High oxygen, reduced pressure atmosphere would afford several advantages to space habitat design[28]. These include a reduced structural weight of the habitat and less storage of gas cylinders. The environments in space suits during EVAs (Extra Vehicular Activity) is high oxygen (100%), low pressure (4.3psia). So, operating the space habitat nearer to EVA conditions reduces the amount of time the astronauts must pre-breathe before a spacewalk[28].

However, to reduce the risk of fire danger, the pressure may be increased to 50 kPa by adding nitrogen. The habitat pressure of 50 kPa can be considered optimum as it lies between the hypoxia limit and the Normoxia limit (sea level) [28].

3. Agriculture

Agriculture on board Tesla may be facilitated using vertical farming systems[24, 31] operating under controlled atmosphere, lighting conditions etc. for efficient crop growth.Vertical farming is envisioned as a sustainable, urban, indoor, multi-storey agricultural system that could supplement or replace conventional farms. The vertical farm, a theoretical construct created by Prof. Dickson Despommier[30] is imagined as a food production centre turning out crops, fish, poultry, and eggs. Since the multi storied vertical towers reduce the area required for food production therefore the extra area may be used for creating parks, lakes and biotechnology research.

Fig 4. Vertical farming system.[31]

4. Recreation

The provision of proper recreational facilities on-board Tesla would be instrumental in maintaining the morale and long-term health of the station's inhabitants. Accordingly a generous amount of space for recreational uses would be required. Recreational space may be divided into three categories: sporting facilities, parks/open space and low gravity areas. Perhaps the biggest advantage of living in Tesla would be of low g recreation. The non-rotating cylinder may have separate modules for low g recreation like orbital hotels, micro-g swimming pools as proposed by Heppenheimer[25].

5. Transportation

The living area with a sufficiently small circumference may not need a transport system like electric cars, trains etc. Walking and cycles may be encouraged to ensure healthier life standards for people. The transportation in the cylinder may be facilitated through elevators.

VI. Conclusions

Although the paper works out some of the problems associated with the proposed habitat design facility, much of it is speculative and many of the assumptions have not been validated. Much is left to be done in order to accomplish a well integrated conceptual space settlement design. It is truly believed that ensuring the survival and growth of our civilization, requires us to move beyond the realms of our home, Earth and go towards the far reaches of outer space.

Acknowledgement

The Tesla space settlement design is mentioned in honour of late Nikola Tesla. Nikola Tesla (10 July 1856– 7 January 1943) was an inventor and a mechanical and electrical engineer. Tesla's patents and theoretical work formed the basis of modern alternating current power (AC) systems, including the polyphase power systems and the AC motor.

References

1. G. K. O'Neil, "The High Frontier: Human Colonies in Space", Space Studies Institute Press, Princeton, NJ, 1976, 1977, 1982, 1989.
2. Lewis, J.S, "Mining the Sky: Untold Riches from the Asteroids, Comets, and Planets", Addison-Wesley Publishing Co., 1996.
3. Blair, B.R., "The role of Near-Earth Asteroids in Long-Term Platinum Supply", Space Resources Roundtable II (Colorado School of Mines), Golden, Colorado, 2000.
4. MJ Sonter, "Near Earth Objects as Resources for Space Industrialization" .Solar System Development Journal, volume 1, page 1 -31, 2001.
5. MJ Sonter, "The Technical and Economic Feasibility of Mining the Near-Earth Asteroids", Presented at 49th International Astronautical Federation Congress, Sept 28 - Oct 2, 1998, Melbourne, Australia.
6. Lewis, J.S, "Resources of the Asteroids", Journal of the British Interplanetary Society, Vol. 50, 1997, pp. 51-58.
7. www.platinum.matthey.com
8. http://echo.jpl.nasa.gov/~lance/delta_v/delta_v.rendezvous.html.
9. M.W Busch et al, "Physical modeling of Near-Earth Asteroid (29075) 1950 DA", Icarus 190 (2007), pp. 608–612.
10. S.J Ostro .et al, "1986 DA: Radar Evidence for a Metallic Composition", Science 252 (1991), pp. 1399-1404.
11. M.W Busch, "Feasibility of asteroid mining", Society of economic geologists newsletter, April, 2006.
12. DJ Scheeres, "Satellite dynamics about asteroids", AAS 94-112.
13. D.J. Scheeres, "Close Proximity Operations Small Bodies: Orbiting, Hovering and Hopping appeared in: Mitigation of hazardous Comets and Asteroids", edited by M.Belton et al., Cambridge, University Press, 2004.
14. Johnson, R. and Holbrow, "Space Settlements: A Design Study," C.Tech. Rep. SP-413, NASA, 1975.
15. www.nss.org/settlement/nasa/Contest/Results/2006/Vademecum.pdf by A. Bridi.
16. Shane Ross, "Near-Asteroid Mining" , Caltech 107-81, Dec. 2001
17. Theodore Hall, "Artificial gravity and the architecture of orbital habitats", Journal of the British Interplanetary Society.VOL. 52 No. 7/8 pp. 290-300 JULY/AUGUST 1999.
18. Al Globus, Ankur Bajoria, Nitin Arora, Joe Straut, "The Kalpana One Orbital Space Settlement Revised".
19. Andrew J. Piekutowski, Kevin L. Poormona, Eric L. Christiansen, Bruce A. Davis, "Performance of Whipple Shields at Impact Velocities above 9 km/s".
20. Marcel J. Sidi, "Spacecraft Dynamics and Control": A Practical Engineering Approach.
21. Reinhorn, T. T. Soong, R. Helgeson, M.Riley, H. Cao and J. Chu, "Analysis, Design, and Implementation of an active mass Damper", University at Buffalo.

22. www.123eng.com/projects/vastu%20shastra.pdf

23. Edward Bock et al., “Effect of Environmental Parameters on Habitat Structural Weight and Cost.” - Space resources and settlements, technical papers derived from the 1977 Summer Study at NASA Ames Research Centre, Moffett Field, California. NASA SP-428.

24. Mark Fischetti, “Growing vertical”, Scientific American Earth 3.0, 2008.

25. Heppenheimer, T. A., “Colonies in Space”, Warner Books, 1977.

26. Brij K. Dhindaw, “Materials science research in microgravity –Current status and an experimental case study”, Current science, 344 VOL. 79, NO. 3, 10 Aug 2000.

27. Behrokh Khoshnevis et al, “Mega-scale fabrication by Contour Crafting”, International Journal of Industrial and Systems Engineering, Vol. 1, No. 3, 2006.

28. Lange, K.E., Perka, A.T., Duffield, B.E., and Jeng, F.F., “Bounding the Spacecraft Atmosphere Design Space for Future Exploration Missions”, 2005, NASA/CR-2005–213689.

29. http://neo.jpl.nasa.gov/1950da/orbit.html

30. Dickson Despommier and Eric Ellingsen, “The Vertical Farm: The sky-scraper as vehicle for a sustainable urban agriculture” CTBUH 8th World Congress 2008.

31. http://www.verticalfarm.com/designs.html

32. Grandl et al, “Commercial asteroid resource development and utilization”, IAA-95-IAA.13 .03 46th International Astronautical Congress, 1995 Oslo, Norway.

33. Haym Benaroya, Thomas C. Taylor “Developing a Space Colony from a Commercial Asteroid Mining Company Town”, Living in Space, published by Aerospace Technology Working Group.

34. L.S. Gertsch, R.E. Gertsch, “Mine planning for asteroid ore bodies”, Space Resources Roundtable II, Denver, CO, Abstract 7030, November 2000.

35. Ken Erickson, “Optimal Architecture for an Asteroid Mining Mission: Equipment Details and Integration”. AIAA Space 2006.

36. Ian Garrick-Bethell, Christopher E. Carr, “Working and walking on small asteroids with circumferential ropes”, Acta Astronautica 61 (2007) 1130 – 1135.

37. Gerlach, C. L., “Profitably Exploiting Near-Earth Object Resources,” Proceedings of the 2005 International Space Development Conference, National Space Society, Washington DC, 2005.

38. J.von Puttkamer, “Der Mensch im Weltraum”, Frankfurt 1987, ISBN 3-524-69068-8.

39. Narayanan Komerath et al. “System Design of Large Space Structures Using Tailored Force Fields” AIAA Space-2006.

40. Theodore Hall., http://www.artificial-gravity.com/sw/SpinCalc/SpinCalc.htm

41. http://en.wikipedia.org/wiki/Vertical_farming.

42. Connors, M. M.; Harrison, A. A.; Akins, F. R., “Living Aloft: Human Requirements for Extended Spaceflight”, NASA SP-483.