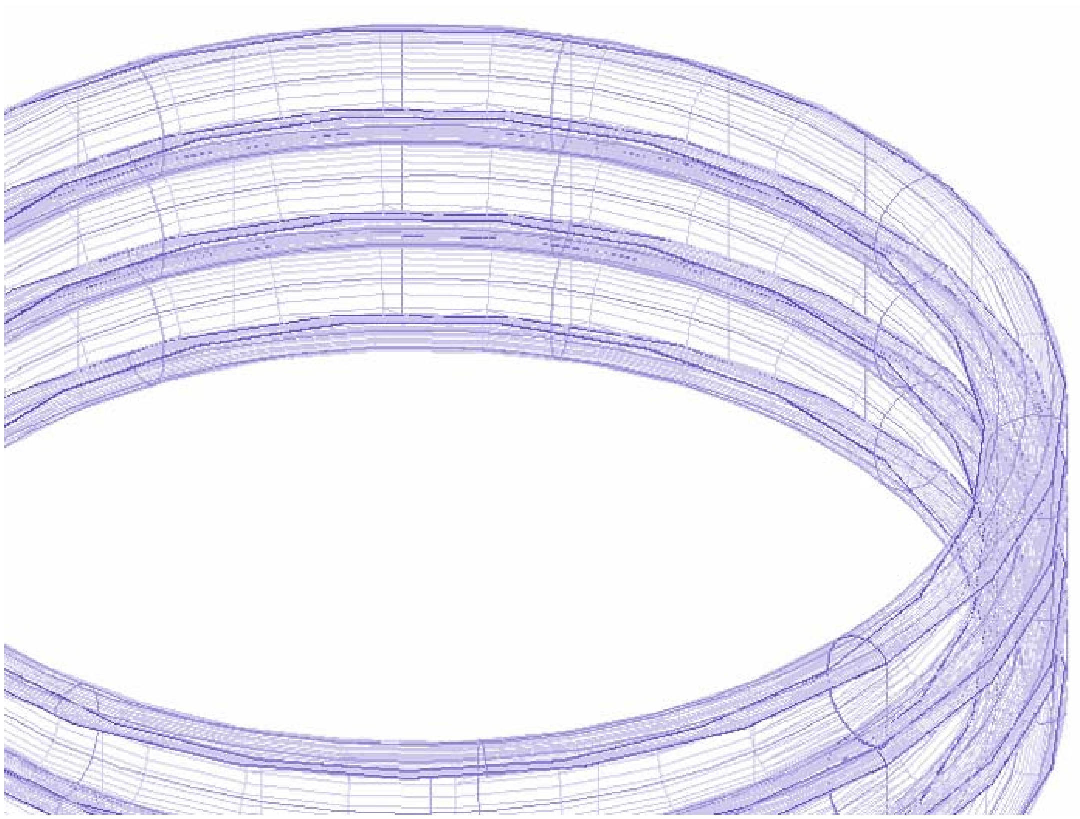
# VADEMECUM

## 'Go With Me'

**2006 Submission to the**
**Student Space Settlement Contest**

**NASA Ames Research Center**

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# Acronyms

| | |
|---|---|
| C | Centigrade |
| dW | Dry Mass |
| EVA | Extra-vehicular activities |
| fW | Fresh Mass |
| G | Gravitational constant |
| g | Gram / Unit of acceleration due to gravity |
| GEO | Geosynchronous Orbit |
| HEO | High Earth Orbit |
| ICRP | International Commission on Radiological Protection |
| IPO | Initial Public Offering |
| ISS | International Space Station |
| kg | Kilogram |
| kW | Kilowatt |
| kPa | Kilopascal |
| L | Liter |
| LEO | Low Earth Orbit |
| LIBOR | London Interbank Offered Rate |
| m | Meter |
| MAP | Microwave Anisotropy Probes |
| Mb | Millibar |
| MW | Megawatt |
| NASA | National Aeronautics and Space Administration |
| NEA | Near Earth Asteroid |
| NEO | Near Earth Object |
| NGST | Next Generation Space Telescope |
| PESTO | Photosynthesis Experiment Systems Testing and Operations |
| R & D | Research and Development |
| rpm | Rotations per minute |
| SCR | Solar Cosmic Rays |
| SISCA | Sasakawa International Center for Space Architecture |
| SOHO | Solar and Heliospheric Observatory |
| SPE | Solar Particle Events |
| Sv | Unit of dose equivalent for radiation |
| UN | United Nations |
| UV | Ultra Violet |

# *Acknowledgements*

*A few people were key in helping me prepare this paper. Foremost, I would like to thank Dr. John Menner for his mentoring, guidance and advice throughout the preparation stage. I would also like to thank Mr. Parry, my physics teacher for reviewing and commenting on the paper and helping me refine some of the ideas and concepts; Dr. Karin Kneissl, Professor of International Relations at the Diplomatic Academy of Vienna, Austria for helping me map out the international conventions that could be used to govern space; and Mario Kozma for his insights and advice on financing options for Vademecum.*

*My special thanks also go to Professor Ali Eskandarian, Associate Dean of the College of Professional Studies at George Washington University, Washington, D.C., and Professor Yahya Rahmat-Samii, Electrical engineering chair at UCLA, for reviewing and commenting on the paper.*

*There are also members of my family that I would like to thank: My father, uncle and aunt for continuously boosting my interest in space; my grand-mother, Alfred and Amira for putting up with me when I worked rather than spent time with them during the last 2 summer holidays, Maryam Samii for her help with the paper's layout, and my mother for editing and assisting me with the background research.*

*Preparing this paper has been the most enriching experience I have ever had. Not only was it the single most rewarding educational process I have been through, but it has also been fascinating because of all the people I met during my research. I have referred to them above and could not have even considered participating in this contest had it not been for their support. I am extremely grateful to them all.*

*“Anything one man can imagine, other men can make real.”*
Jules Verne

## 1. Introduction

Why the name Vademecum? In Latin, Vademecum literally means "go with me". I chose this name because I see this project as an adventure, a challenge, the future. I am calling on those who wish to join me in this adventure to come along so we can put our energies and minds together to realize this project, this dream.

Like this paper, my life has been an adventure so far. I am 16 years old, and was born in Washington, D.C.. I spent the first few years of my life in Vienna, Austria. My family and I then moved to the Washington, D.C. area until I was 11. We then moved to Paris, France and are now based in Brussels, Belgium.

The bulk of the paper was written over the last 2 summer holidays. Some of it was completed in the course of the 2 academic years (2004-2005 & 2005-2006). I relied exclusively on the internet, books and individual interviews for my research. My knowledge of mathematics and physics, chemistry and biology is limited to what I have learned at school and what I acquired through this research. I have not had the benefit of extensive support from a teacher or any expert and this paper is therefore my own work based on the research mentioned above. Rather than focusing on the theory, my attempt has been to focus on ideas and concepts which I found interesting and promising and on which I would like to build as I learn more about these subjects at school and college.

The paper is meant to address the following 6 basic questions:

Why do we need a space station?
What should it be like? (design, structure, capacity, gravity, habitat)
How do we build it, finance it, and organize it?
Where should it be located?
When do we get it done? (timeline)
What risks will we be facing? (risks during and after construction)

I have thus organized the paper around the above questions.

## 2. Why do we need a space station?

There are many reasons why we should look beyond Earth and establish new roots elsewhere in the galaxy. Besides Man’s natural instinct to explore, to lean, to build for future generations there are other important reasons for looking beyond Earth. Among the most important are the following:

Ensuring the survival of our species : The primary reason to "look elsewhere" and extend our life on Earth to other worlds is survival of the human race. The atomic bomb, diseases, being hit by an asteroid, natural disasters, etc. are all factors which could result in our extinction. Having humans elsewhere gives our race a chance to survive these very real risks.

Economic: Besides the economic incentives generated by the abundant natural resources available in space, there is a whole lot of knowledge and technology that will be generated through Man's encounter with new worlds. This will have enormous economic value to governments and entrepreneurs alike. There is therefore a considerable economic incentive to explore beyond Earth.

Environmental: By moving away from Earth, we would reduce straining Earth's environment and allowing it to live longer. We may even learn how to preserve it better through research in outer space.

Tourism and Entertainment: Outer space provides a commercially interesting option to entertain people and distract them from their immediate surroundings.

To me, the most important of these reasons is the survival of the human race and the need to ensure "prosperity for our posterity". Although a single colony in space may appear unsafe, it is certain that when several such habitats are developed in space, they would together create a safe environment and would contribute substantially to human survivability. In short, the establishment of such a colony would be an act of self-replication. It would be meant to create a "back-up system" for our race.

# 3 .What should Vademecum be like?

## 3.1 Design Options

In developing the design criteria for Vademecum, I kept three main premises in mind, which helped guide the choices I made, and helped determine Vademecum's final design and configuration. These premises are:

- ***The population's safety above all else*** -- The choices I will make will be primarily guided by the safety and security of those who will live on the station.

- ***The population's well-being on the station*** -- Whatever the final shape of the station, its size and its fabric, a pre-eminent premise will be for life on the station to be as similar to that on Earth as possible.

- ***The decision to start small, expand gradually*** -- For economic and safety reasons, **<u>I opted for developing a small gradually expandable colony (starting with 5000 people, with a maximum capacity of 10,000), rather than building a more costly, larger one from the start</u>**.

Based on the above considerations, I developed the following design criteria:

| **Quantifiable Criteria** | |
|---|---|
| Gravity | 1g |
| Rotation | ≈ 1 rpm |
| Exposure to Radiation (skin dose) | 3.00 Sv |
| Temperature | $20 \pm 5^{\circ}C$ |
| Humidity | $65 \pm 8\%$ |
| Air Pressure | 1000 mb |
| Hours of Light/24 h | ≈ 14 h |
| Composition of the Atmosphere | |
| of which oxygen | 20% |
| of which nitrogen | 78% |
| of which other gases | 2% |
| Population Year 1 after construction | 5,000 |
| of which Men | 50% |
| of which Women | 50% |
| Maximum Population | 10,000 |
| Total Projected Area per person[1] | $68m^2$ |
| of which residential | $12m^2$ |
| of which work/business | $12m^2$ |
| of which public/recreational | $24m^2$ |
| of which agricultural | $20m^2$ |
| Total Volume Area per person[1] | $1750m^3$ |
| of which non-agricultural land | $825m^3$ |
| of which agricultural land | $915m^3$ |
| Minimum food supply/person/day | 3,1 kg |
| Minimum water supply/person/day[1] | 20 L |
| Minimum energy supply/person/day[1] | 1 kW |

**Table 1 - Vademecum's overall quantifiable design criteria**

[1] These minimum requirements are as per NASA Ames/Stanford 1975 Summer Study, http://lifesci3.arc.nasa.gov/SpaceSettlement/designer/sphere.html

| Non-Quantifiable Criteria |
|---|
| Maximum efficiency in the use of space |
| Maximum economic/financial efficiency |
| Minimum mass |
| Minimum pollution/waste |
| Materials to be non-flammable |
| Maximum natural sunlight |
| Maximum lines of vision (sideways and overhead) |
| Maximum security from within/outside |
| As close to living on Earth as possible |
| Preferably expandable for future generations |

**Table 2 - Vademecum's overall non-quantifiable design criteria**

**The structure of Vademecum:** This was a very difficult choice. I spent a lot of time looking at various options and analyzing them. In particular, I looked at the traditional shapes of the sphere, the cylinder, the dumbbell and the torus, and started from the premise of a 1g and an rpm of about 1. With these parameters in mind, I derived the surface area and the volume. Below is a summary of my analysis on these 4 options which provides the basic design and characteristics of each option:

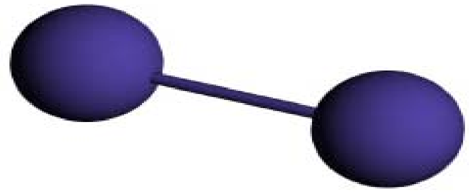
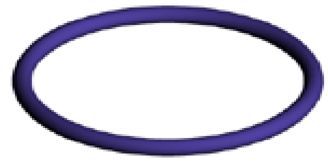
| | Sphere[2] | Cylinder | Dumbbell[3] | Torus[4] |
|---|---|---|---|---|
| Picture (to scale) |  |  |  |  |
| Gravity | 1g | 1g | 1g | 1g |
| Rotation Rate | 1.0566 r.p.m. | 0.9962 r.p.m. | 0.9702 r.p.m. | 1.0374 r.p.m. |
| Surface Area | 8,042km² | 4,775km² | 3,079km² | 2,130km² |
| Volume | 2,144,661km³ | 301,593km³ | 359,189km³ | 69,220km³ |
| Livable Area | 1,787km² | 754km² | 1,539km² | 1,065km² |
| Population (max) | 26,282 | 11,088 | 22,638 | 15,661 |

**Figure 1 - Comparative Design Options for Vademecum**

[2] This shape has gravity fluctuations. The 1G referred to in the table is only true for a particular point in the structure. Other parts will be approximately at 1G. The livable area was assumed to be 2/9$^{th}$s of the total surface area, mainly round "the equator" of the sphere.

[3,4] These shapes have gravity fluctuations. The 1G referred to in the table is only true for a particular point in the structure. Other parts will be approximately at 1G. The livable area was assumed to be half of the total surface area.

- **the Sphere:** It is a very attractive option since it emulates the shape of our Earth, but we would live within it rather than on its outer surface. Our Sun would be at its core, we would have a wonderful feeling of openness and space. The sphere's outer surface would be covered with solar panels to collect a significant amount of energy for consumption by the station. This option was proposed by Dr. Freeman Dyson[5] and studied at length by others. Although it provides an enormous volume, a surface area and gathers vast amounts of energy, it is not optimal. By using pseudo-gravity by means of rotation, 1g would only be obtained at the sphere's equator. Therefore, despite its enormous volume, the sphere's livable area could be relatively small. Also, its enormous mass would require huge amounts of materials, with serious cost implications, transport difficulties. Altogether, this option is too risky for both financial and logistical reasons and is not an optimal solution for a first attempt to build a human colony in space[6].

- **the Cylinder**: This option also offers interesting features. It is expandable (one can elongate the cylinder and enlarge the living space), it sustains 1g everywhere with no variations in gravity levels, it is relatively easy to build (combination of rings layered next to each other to form a cylindrical shape), presents a strong and sturdy structure. If some of its surface is covered with glass, it lets in sufficient amounts of natural light. But compared to the Torus, it demands a larger atmospheric volume. Therefore, although the cylinder is a very good option, it is not the optimal one.

- **the Dumbbell**: This option offers a livable area that is comparable to that of the Sphere, while using far less volume. It is certainly an improvement over the Sphere, though it brings with it some disadvantages: It is not expandable, and transport between the two mini-spheres is rather difficult (people stand in opposite directions in each of the mini-spheres, i.e., they stand on an East-West axis on one and on the West-East axis on the other).

- **the Torus:** Most research shows that the Torus is the most efficient shape for this type of station. As the numbers in the above comparative table show, the Torus provides the best livable area compared to its size. It lets in sufficient amounts of sunlight, provides a relatively open vista for its inhabitants, it could be built with modular structures and assembled in space. It is also expandable in the sense that several toruses may be stacked to create extra space for the population, with light flowing through its center.

Recognizing that the torus presents the most attractive characteristics, I tried to investigate the torus further, in order to determine whether any variation of the torus

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[5] Proposal presented in 1959, when Professor Dyson was at Cambridge University, UK and Cornell, US. He is currently the President of The Space Studies Institute.

[6] http://www.nada.kth.se/~asa/dysonFAQ.html

could offer an even more optimal structure for Vademecum. I therefore examined three other shapes, based on the toroidal structure. My aim was to improve on the characteristics of the torus by looking for the optimal combination of habitable area (i.e., more living space) and relatively less atmospheric volume. Below is a review of the three additional shapes I considered:

- The first was a **Toroidal Ellipsoid**. I soon realized that while the ellipsoid provides more living space thanks to the larger curvature on its outer pole, it also requires more atmospheric volume to maintain a normal pressure (see pictures below). In other words, both its inner and outer curvatures generate more space, and while we may gain more living space, we will use up larger volumes of air. In addition, the outer curvature would face problems of gravity (the curve is too deep and there would be too much of a difference in gravity between the deepest point of the curve and the other areas, especially since the overall radius of the structure is relatively small).

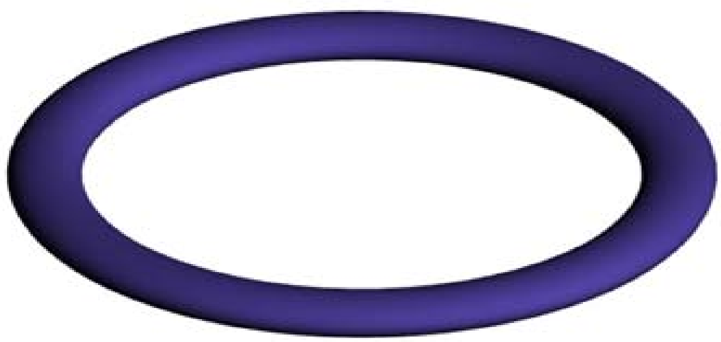


**Figure 2 - Vademecum as a Toroidal Ellipsoid**

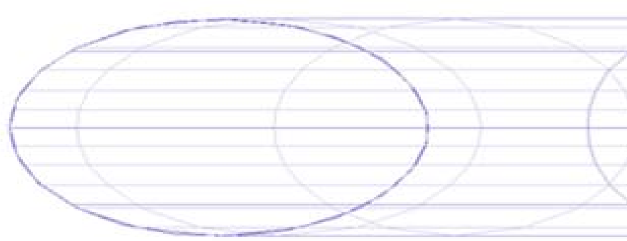


**Figure 3 - Toroidal Ellipsoid Option – Cross Section view**

- I then resorted to a combination of two ellipses – I will refer to this option as a **Combo** -- as shown in the picture below. The first half which is the deeper half represents the area where people will live; the other half is the "air" space, for the atmosphere. This shape offers advantages, which appear to be particularly interesting: it increases living space while reducing the atmospheric volume. The curvature of the outer edge should be calculated based on the structure's overall radius, to avoid important variations in gravity. This is particularly interesting for larger stations, with larger radii because the variations in gravity in the outer edge would be smaller.

**Figure 4 - Vademecum as a combination of 2 ellipses, or "combo" option**

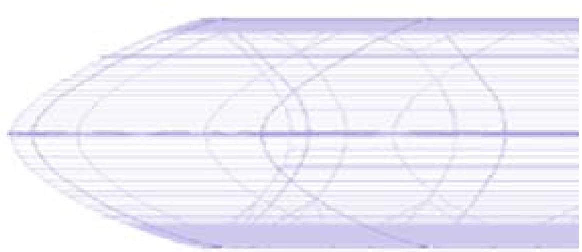


**Figure 5 - Combo Option – Cross Section view**

* The third torus-based shape I evaluated was an ellipse with a flat outer pole (see picture below). I will refer to it as the "**truncated ellipsoid**". This shape offers all the advantages of the torus and its flat outer pole provides constant and stable gravity for the inhabitants. This shape is particularly interesting for smaller structures with smaller radii because of the absence of gravity variations.

**Figure 6 - Vademecum as a truncated ellipsoid**

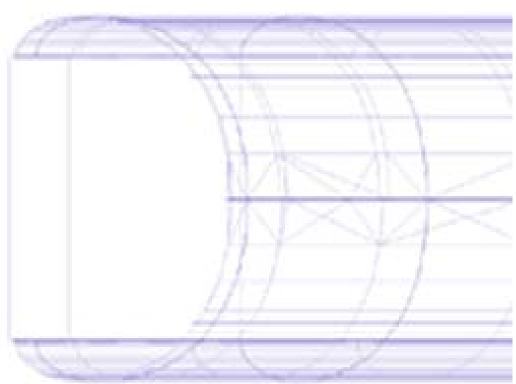


**Figure 7 - Truncated Ellipsoid - Cross Section view**

A summary of the three toroidal-based shapes is provided below:

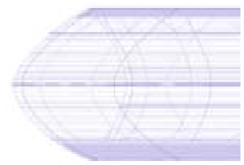
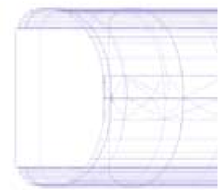
| | Ellipsoid | Combo | Truncated Ellipsoid |
|---|---|---|---|
| Picture |  |  |  |
| Gravity | 1g | 1g | 1g |
| Δg [7] | 0.055 | 0.04 | 0[8] |
| Surface Area | 2,479 km² | 2,137 km² | 1,411 km² |
| Volume | 90,011 km³ | 65,732 km³ | 61,586 km³ |
| Livable Area | 1,239 km² | 1,239 km² | 784 km² |
| Population (max) | 18,228 | 18,228 | 11,531 |

**Table 3 - Comparative Toroidal Design Options for Vademecum**

If we were to build a larger structure with a larger radius, I would have opted for the “combo” structure since it would provide a better ratio of living space to atmospheric volume with limited fluctuations in gravity in its outer edge. But since we have decided to start small (about 5,000 people) and grow incrementally (to 10,000 people), and we have also decided to start with a small less costly structure, I opt for the truncated ellipse option. Its flat outer edge will avoid any issues with gravitational fluctuation and it would still have all the advantages of a basic toroidal shape.

I would now like to introduce five additional design considerations:

1. **Maximizing Natural Sunlight through windows.** The importance of regular and adequate natural sunlight for the health of human life (for instance for bone development, effectiveness of muscles, glandular activity, healthy blood structure, psyche and morale, etc.), and for living organisms and plants is well known. Since artificial light does not produce a complete spectrum of light, we need to ensure the supply of sufficient amounts of natural sunlight to Vademecum’s population. In addition, we need to make sure that natural sunlight is supplemented with sufficient artificial light to provide extra light for plants and humans for illumination. I propose to make available 14 hours of light (combining natural and artificial light) to ensure the well-being of plants and a 10

[7] Ratio indicating gravity variations in the livable area.

[8] The truncated ellipsoid is the only option which provides no variation in gravity in any part of the livable area.

hour night to allow for the plants' anabolic activities to take place. To let the natural light into the station, I plan to have large glass windows placed on the inner curvature of the station, looking out towards the center of the truncated ellipse. The glass will be transparent but will have partial shielding against UV radiations.

2. **Maximizing Energy Supply through a twin set of curved mirrors**: In order to take maximum advantage of the sunlight and solar energy, we plan to use a twin set of curved mirrors above and beneath the station. The mirrors would serve 2 main purposes: i) amplify sunlight to the station to generate more solar energy, optimize the use of sunlight for the well-being of people and plants; and ii) to provide a day-night effect if the station is located in constant sunlight, so as to create more of an Earth-like environment. The mirrors will have the following characteristics:

    - They will be connected to the central body of the station by 2 bars made of hard composite plastic materials (similar to those used by Boeing and Airbus on the wings of their new aircrafts);
    - The bars could be extended/shortened to increase/reduce the impact area of sunlight;
    - Thanks to sensors, the mirrors would tilt as needed to take maximum advantage of sunlight and/or to direct sunlight to specific portions of the station; and
    - The mirrors will be curved to widen the illumination area of the mirrors.

3. **Capturing the Sun's rays to generate energy:** The whole area between the inner part of the toroidal structure and the micro-gravity center will be covered with solar panels to capture and convert solar energy into power. For Vademecum, the total surface area to be covered with solar panels represents 1,539,380 $m^2$. The actual amount of power generated through the panels is assessed under section Power Generation, Storage and Distribution.

4. **Building a micro-gravity research center:** To improve the colony's research activities, we plan to build a micro-gravity center at the core of the station. The center would be connected to the main colony through tunnels (similar to those used in Charles de Gaulle Airport in Paris to connect the main terminal with the various terminals of the airport). The center's main purpose would be to conduct research under micro-gravity conditions which are propitious for research activities that are very difficult to replicate on Earth. Such research could generate income for the colony. Some space could also be leased to research companies to offset some of Vademecum's running costs. The center will have a cylindrical shape and rotate with the main station. It would benefit from micro-gravity conditions thanks to its small radius. It will be expandable in its length (i.e. the cylinder could get longer if needed). Its outer surface could also be covered with solar panels to generate a maximum amount of energy.

5. **Expanding Vademecum:** When Vademecum reaches its maximum population capacity at about 10,000, it could be expanded through extra structures, layered on top/beneath the original ring as shown in the picture below. It is estimated that if 3 rings are piled up, they could still allow for sufficient sunlight to go through the station. It is therefore estimated that 3 rings could be stacked over time, for a maximum overall population of about 30,000 people on Vademecum. Below are drawings of the expanded Vademecum.

With the above considerations in mind, Vademecum will be designed as per the drawings below, including the micro-gravity unit at the center of the station, the solar panels laid on the inner surface area, the twin mirrors, and the glass ceilings in the inner curvature of the station (referred to in the picture below as "window"). It will have an outer diameter of 1,600m, and a habitable area of about 785,000 km². If considering 68m² of total projected area per person, we will be able to accommodate a maximum of 11,500 people, i.e., 15% over our planned capacity limit of 10,000. When standing up on the main station, the inhabitants will have a glass ceiling about 100 m above their foot level, which should give enough of a space feeling. Thanks to the glass, they will be able to see through the station and have an upward vista of about 1600m. The sideway vista is about 775m.

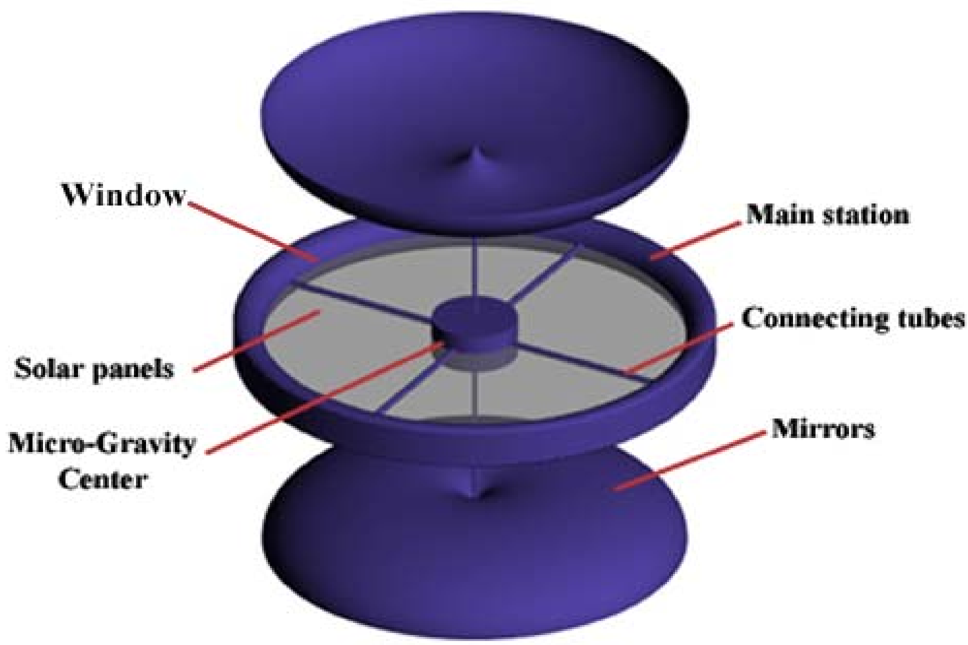



**Figure 8 - Vademecum with micro-gravity center, twin mirrors and solar panels – Side view**

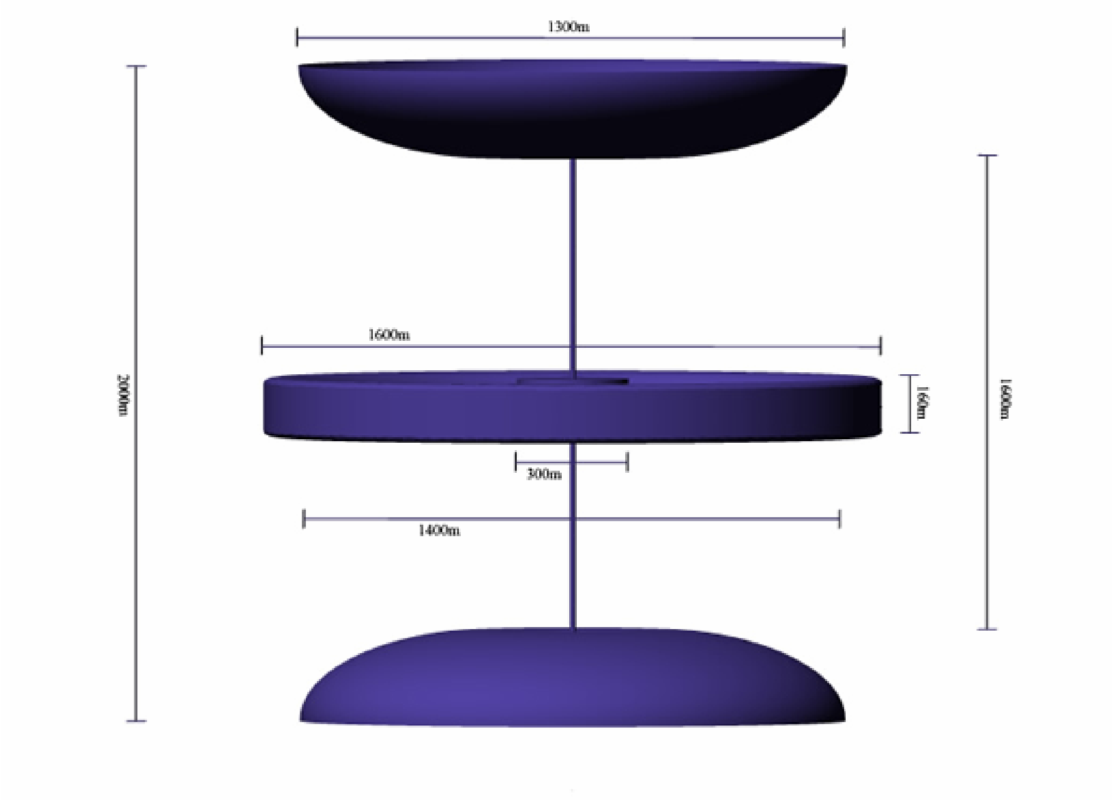



**Figure 9 - Vademecum with micro-gravity center, twin mirrors– Cross Section**

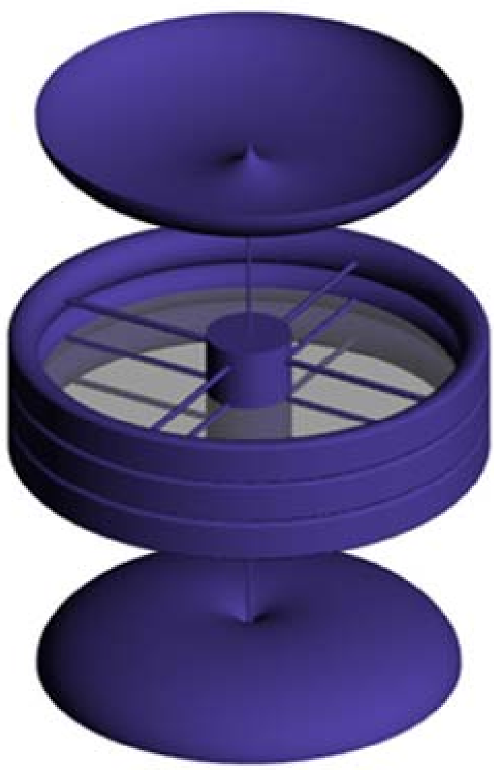


**Figure 10 - Expanded Vademecum with micro-gravity center, twin mirrors and solar panels**

**Figure 11 - Expanded Vademecum with twin mirrors– Cross Section**

## 3.2 Vademecum’s Life Support System

For Vademecum’s population to live safely and comfortably, it requires adequate food, potable water, good hygiene, breathable air, waste disposal, medical care, and safety from known risks. In short, it needs a stabilized and optimal life-support system that would be based on a combination of physical, biological and regenerative processes that are well integrated, i.e., where the various life-support functions are well-harmonized and coordinated. Many space agencies have come up with options for advanced life support systems in space, but these are designed for long duration human spaceflight, not space colonization. I have based my research quite extensively on the systems that are currently used and those are being tested for future use.

I propose to establish 7 separate but inter-related life-support systems in Vademecum relating to air, biomass, food production and storage, thermal management, waste management, water management; and power generation, storage and distribution.

### 3.2.1 Air System[9]

Air supply is obviously one of the most critical life-support functions. The station’s air (composition and pressure) will be the same as that on Earth. It will be generated mainly

[9] Anthony Hanford, Lockheed Martin Space Operations, Aug 2004 for NASA;
Advanced Life Support Baseline Values and Assumptions Document & Research Needs for Regenerative Life Support Systems, Chapter I-2, 1977 Ames Summer Study on Space Settlements, NASA
www.science.howstuffworks.com/space-channel.htm

through an initial limited supply of "imported gases" from Earth, supplemented overtime by air created through photosynthesis. As in a submarine, there are 3 things that must happen in order to make the air breathable on the station:

- Oxygen has to be replenished as it is consumed;
- Excess carbon dioxide must be removed from the air; and
- The moisture created by humans and plants must be regulated.

These functions will be fulfilled by Vademecum's air system. As stated earlier, an initial quantity of breathable air will have to be "imported" from Earth either in pressurized tanks (with cautionary measures to avoid fire hazards as occurred with a similar device on Mir in 1997)[10]. Oxygen will be either released continuously by a computerized system that senses the percentage of oxygen in the air, or it will be released in batches periodically through the day. This preliminary "imported" quantity of breathable air will have to be supplemented by new air created through photosynthesis over time. Recent experiments (Photosynthesis Experiment Systems Testing and Operations, PESTO) conducted by NASA on the ISS indicate that we will be able to use plants to recycle air (Under PESTO, wheat plants were able to produce and clean air through photosynthesis)[11].

Carbon dioxide can be removed from the air chemically with soda lime (sodium hydroxide and calcium hydroxide) using devices called scrubbers. The carbon dioxide is trapped in the soda lime by a chemical reaction and removed from the air. Other gases such as carbon monoxide, which are generated by the equipment on the station, can be removed by burners. Finally, filters are used to remove particulates, dirt and dust from the air.

The moisture will be removed through a dehumidifier or chemically. This prevents it from condensing on the walls and equipment in the station.

In developing parameters for Vademecum's atmosphere, I paid particular attention to the composition of air and air pressure issues. I have used numbers provided by various studies (referred to in footnotes) to present a reasonable air composition structure, although humans and plants have different air structure and pressure preferences (for example, plants prefer lower pressure of carbon dioxide than humans). For purposes of comfort, simplicity and risk of contamination, I suggest using the same air across the whole station, except in the plant chambers where the air composition and pressure may be adjusted to fit the specific needs of certain plants and vegetables.

The air would be stored and distributed through an air system which would control air quality control (including recycling of gases), and detect/suppress fire.

[10] http://www.popsci.com/popsci/aviationspace/dde95b4a1db84010vgnvcm1000004eecbccdrcrd.html
[11] NASA spaceport newsletter, Sept 19, 2003 "Plant experiment helps provide air and water on ISS".

As far as air pressure is concerned, I opted for being as close to that at sea-level pressure because it is the condition under which people can live safely for extended periods of time. The air pressure limit has therefore been set at about 1000 millibars (mb) On Earth, at sea level, values range between 970 mb and 1040 mb. Lower air pressures require higher percentage of oxygen, which increases the risk of fire on the station.

### 3.2.2 Vademecum's Biomass System[12]

Very closely linked to Vademecum's air system is the biomass system which is meant to regenerate air and water, and to produce, store and provide raw agricultural products to the food system. There is extensive ongoing research on the ISS with regard to biomass creation and its air and water regenerative actions. For example, as stated earlier (section 3.2.1), the PESTO study has shown that wheat plants were able to produce and clean air through photosynthesis. Although the research has not yet been fully conclusive in this regard, it has been estimated by NASA that if more than 25% of the food (by dry mass) is produced locally; all the required water can be regenerated by the same process. If 50% of the food (by dry mass) is produced on site, all the required air can be regenerated by the same process. We plan to produce the totality of Vademecum's biomass needs onsite and have therefore allocated approximately 30% of the station's livable area to agriculture. Our biomass system should therefore be more than fully regenerative in terms water and air.

Regenerative life support requires a different crop production process in space. It is suggested that rather than planting in soil, we would grow crops in nutrient-enriched water through a method called hydroponics (from the Greek hydros, water, and panos, labor).[13] The technology which was first researched in England in 1699 by John Woodward has evolved considerably over the years, especially over the last 20 years. It the special circumstances of space, hydroponic technology presents 4 main advantages over traditional agriculture:

- It provides a controlled environment for plant growth;
- Most plants produce more in less time and sometimes of higher quality;
- There is a reduced risk of soil-born diseases; and
- The technology is water-efficient (uses considerably less water)

Hydroponics will be primarily used to produce crops which rank high in energy, nutritional content and taste[14]. It is recognized by nutritionists that fresh food (those

[12] Anthony Hanford, Lockheed Martin Space Operations, Aug 2004 for NASA – Advanced Life Support Baseline Values and Assumptions Document; Drysdale A, (2001) The Boeing Company, Kennedy Space Center, FL .
[13] http://en.wikipedia.org/wiki/hydroponic
[14] www.rso.cornell.edu/scitech/archive/97sum/plants.html

derived from original sources such as plants and vegetables) provide the best nutrition for people. Plants will be the basis of the station's food, air and water self-sufficiency and the only way of Vademecum's survival overtime. It is suggested that plant growth will be organized in plant chambers using artificial light. Plant growth rates depend on the type of plant and its growth conditions. The table below provides growth rates in terms of grams of biomass per square meter and per day. The dray mass (dW), fresh mass (fw) and water content for both edible and inedible biomass are also provided. The harvest index represents the ratio of edible to total biomass.

| | | | Edible Biomass | | | Inedible Biomass | | |
|---|---|---|---|---|---|---|---|---|
| **Crop** | **Mature plant height m** | **Harvest Index** | **Dry Basis g/m2/day** | **Fresh Basis g/m2/day** | **Fresh Basis Water Content %** | **Dry Basis g/m2/day** | **Fresh Basis g/m2/day** | **Fresh Basis Water Content %** |
| **Cabbage** | 0.35 | 90 | 6.06 | 75.78 | 92 | 0.67 | 6.74 | 90 |
| **Carrot** | 0.25 | 60 | 8.98 | 74.83 | 88 | 5.99 | 59.87 | 90 |
| **Celery** | 0.25 | 90 | 10.33 | 103.27 | 90 | 3.77 | 37.69 | 90 |
| **Dry Bean** | 0.50 | 40 | 10.00 | 11.11 | 10 | 15.00 | 150.00 | 90 |
| **Lettuce** | 0.25 | 90 | 6.57 | 131.35 | 95 | 0.73 | 7.30 | 90 |
| **Onion** | 0.25 | 80 | 9.00 | 81.82 | 89 | 2.25 | 22.50 | 90 |
| **Pea** | 0.50 | 40 | 10.73 | 12.20 | 12 | 16.10 | 161.00 | 90 |
| **Peanut** | 0.65 | 25 | 5.63 | 5.96 | 5.6 | 16.88 | 168.75 | 90 |
| **Pepper** | 0.40 | 45 | 10.43 | 148.94 | 93 | 12.74 | 127.43 | 90 |
| **Radish** | 0.20 | 50 | 5.50 | 91.67 | 94 | 5.50 | 55.00 | 90 |
| **Rice** | 0.80 | 30 | 9.07 | 10.30 | 12 | 21.16 | 211.58 | 90 |
| **Soybean** | 0.55 | 40 | 4.54 | 5.04 | 10 | 6.80 | 68.04 | 90 |
| **Spinach** | 0.25 | 90 | 6.57 | 72.97 | 91 | 0.73 | 7.30 | 90 |
| **Tomato** | 0.40 | 45 | 10.43 | 173.76 | 94 | 12.74 | 127.43 | 90 |
| **Wheat** | 0.50 | 40 | 20.00 | 22.73 | 12 | 30.00 | 300.00 | 90 |

**Table 4 - Overall Physical Properties of Crops at Maturity**[15]

It must be noted however that plant productivity varies from one cycle to the next, even under controlled environments like a plant chamber, so the values mentioned above should be considered as typical, not standard.

As regards the conditions within the plant chambers, we will use a lower pressure CO2 (0.120 kPa for plants vs. humans at 1.0 kPa) and relatively higher humidity rates (about 75%). Also the temperatures are likely to vary from one chamber to the other as some plants (e.g., potatoes, wheat) grow better at relatively lower temperatures. The specific

[15] Data from Ball, Butault, Nehring (2001) US Agriculture, 1960-69: A Multilateral Comparison of Total Factor Productivity" Technical Bulletin # 1895, US Department of Agriculture;
Wheeler (2001) National Aeronautics and Space Administration, JF Kennedy Space Center, FL; and Anthony Hanford, Lockheed Martin Space Operations, Aug 2004 for NASA – Advanced Life Support Baseline Values and Assumptions Document

criteria to optimize the growth of each plant-type are being studied primarily at the Biomass Production Chamber at the Kennedy Space Center. Those criteria will be used in determining the exact environment to be created for each plant/plant chamber.

**Animal Agriculture:** Given the complex nature of livestock rearing especially in an intricate space environment, it is suggested to limit food production to plant and vegetables and refrain from developing a livestock component in Vademecum. Livestock rearing would impose very complex health requirements which would be very difficult to address initially. It would also require more land area, a specific waste management program, atmospheric recycling, etc. Its main benefit would be the nutritional value generated by meat and dairy consumption (proteins, calcium, other minerals), but such nutrients can be supplied through other means. It is suggested however, that once the various life-support systems are in place and they are stabilized, we could initiate an aquatic animal agriculture program and even allow familiar pets such as cats and dogs on Vademecum. Aquatic animals on Vademecum would not only contribute to the nutritional well-being of the population, but they would also contribute to the food-production cycle on Vademecum. Useless plant wastes could be recycled into proteins and fishmeal and the remains would be recycled back to plant nutrients and carbon dioxide. As far as familiar pets are concerned, once it is ascertained that they would not pose a safety hazard to the population, they could be allowed as home pets, just like on Earth.

### 3.2.3 Food Production System

Humans living in space must have an adequate diet. Their food intake and quality will have a tremendous impact on their physical as well as psychological well-being, and allow them to maintain long-term health and their work capacity. The inhabitants' food requirements will be composed of fresh agricultural produce (edible biomass, see above) and processed foods such as pasta (pasta has already been produced with wheat flour and cowpea meal, which contains an amino acid balance like that of an animal protein). The volume of food intake will depend on the amount of physical work they perform and on the conditions under which they live (esp. gravity and the Coriolis force[16] which has impacts body temperature and mass, and atmospheric composition). But for purposes of simplification, we will assume an average food intake per person of about 3000 cal/day. This should consist of water, carbohydrates, sugars, fats, proteins, minerals and vitamins. Given the importance of an adequate diet, it is suggested that regular re-evaluations of diets be undertaken.

[16] Coriolis Force is a force that acts on any moving object in an independent rotating system. It can have an effect on people aboard the moving object. The faster the movement, the larger the Coriolis force.

### 3.2.4 Thermal System[17]

Outer space is an extremely cold environment, and temperatures are likely to vary substantially from one part of the station to the other, mainly as a result of heat generated through the machines and equipment on the station. Vademecum's thermal system will therefore be designed to address the population's comfort as far as the temperature of the station is concerned and maintenance of the equipment within its thermal limits. The thermal system will transfer heat from the areas of the station which have higher temperatures to those that where it is colder. Such heat transfers can be done in several ways:

- Through passive methods which can usually handle smaller heat loads and require little maintenance. This is achieved through the use of adequate insulation materials, surface coatings, paints which aim at reducing heat loss thought the walls of the station (just like home insulation); electrical heaters for heating specific areas of the station; and heat pipes which uses liquid ammonia in a pipe to transfer heat from a warm area to a cold area. The ammonia evaporates at the warm end of the pipe, travels to the cold end and condenses, giving up heat. The liquid then travels back to the warm end along the walls of the pipe via capillary action.

- Through active methods which are more complex and require regular maintenance. This is achieved through conduction, convection or radiation. **Conduction** refers to the transfer of heat within matter by diffusion, for instance through metal plates that collect heat by direct contact with equipment. **Convection** refers to the transfer of heat whereby matter acquires heat by close molecular interaction, and then bulk motion of that matter carries both the matter and the thermal energy away from its location of origin. For instance, heat may diffuse from hotter metal to an adjacent cooler moving fluid, and then the bulk motion of the moving fluid carries the heat away from its origin. **Radiation** refers to an exchange of heat between two surfaces without any intervening matter. Specifically, heat transfers from one surface to another surface that it can "see" simply by virtue of a temperature difference between the two surfaces. In a perfect vacuum, which is approximated in free space, no intervening matter is present to convey heat from one surface to another by either conduction or convection, yet heat does transfer from a hotter surface to a cooler surface via electromagnetic waves in a mechanism called radiation. Warm spacecraft reject their thermal loads from relatively hot surfaces to relatively cold space by radiant heat transfer. While radiation also describes the mechanism by which other forms

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[17] Research Needs for Regenerative Life Support Systems, Chapter I-2, 1977 Ames Summer Study on Space Settlements, NASA;
www.science.howstuffworks.com
Article from Los Angeles Times, 12/1/2002:Los Angeles' Toilet-to-Tap Fear Factor;
D.J. Waldie, and Anthony Hanford, Lockheed Martin Space Operations, Aug 2004 for NASA – Advanced Life Support Baseline Values and Assumptions Document

of energy, such as solar particles and x-rays, pass though a vacuum, thermal radiations merely transfers heat and has no additional mutational effect on biological creatures exposed to it.

Typical technology and equipment needs for the thermal system include heat exchangers, cold plates, pumps, fans, valves, working fluids, fluid lines, radiators, phase change devices, etc.

### 3.2.5 Waste Management System

Usually, wastes are considered materials which are no longer useful and can therefore be disposed of. However, given the special nature of life in space and the need to recycle and re-use a maximum amount of materials, the solid and liquid wastes will be processed, along with human wastes (the recycling of gaseous wastes will be handled by the air system). This process will constitute Vademecum's waste management system.

The main objective of the waste management system is to process waste materials before they build up to toxic levels and to convert them into different kinds of useful inputs. The processes to be used could be physiochemical including techniques such as water reclamation technology for contaminated water, dehydration processes to obtain dry waste (as used in the Skylab and Space Shuttle programs), oxidation methods which either combine solid and liquid waste oxidation or convert solid waste into sterile ash. There are also regeneration techniques which use microorganisms either by themselves or in combination (generally aquatic animals).

In deciding on our waste management concept, there are a few important elements to retain:

- The waste management method should efficiently convert the various wastes into useful inputs for other elements of the station, i.e., we should maximize the efficiency of the system by selectively recovering what can be recovered for re-use on the settlement; and

- We should pay close attention to the trace elements that remain. Despite the decades of scientific research on water quality, it has been difficult to reduce the risk of traces of remaining contaminants to zero. There is a danger that such trace elements may become concentrated to toxic levels. It is therefore important not only to establish levels of tolerability and toxicity for all living components on the station, but also to put in place very stringent methods for monitoring and controlling all phases of waste collection and treatment on the station. (also see Risks section)

### 3.2.6 Water Management System[18]

As in the case of air, a certain quantity of water will have to be ‘imported’ from Earth initially. At a later stage, plants are expected to generate extra water to meet the population’s personal, agricultural and other needs.

Water is one of the substances that will have to be saved very rigorously on Vademecum (the daily consumption in space should initially not exceed 20 liters/day/person)[19]. Water will also have to be recycled very strictly in space. A water recovery and management subsystem will collect, recycle and distribute water from various sources including the sink, the shower, urine, spacesuits, wastewater, heating/cooling systems, the station’s fuel cells cooling system. Moisture exhaled by the population will also be recycled and saved. The recovery and management system will consist of various condensers, filters, and purifiers which will bring the wastewater’s quality back to acceptable levels for drinking.

### 3.2.7 Energy Generation, Storage and Distribution System

Solar energy is abundant in orbit. It is also reliable and easy to use. It is already commonly used to power satellites. But given issues with solar power’s economic efficiency, its use is not as widespread as it could/should be on Earth. However solar energy presents the only feasible way to draw a secure and continued source of energy for space use. Given the high oil prices, massive research[20] is now being conducted in alternative renewable energies, particularly in solar energy, with a view to making current solar cells cheaper and more efficient.

The research is also being focused on special applications of solar energy, such as in space. In particular, materials such as gallium arsenide which have many diodes[21] in series have demonstrated that they can absorb electromagnetic spectrum very efficiently. The Triple junction solar cell (3 diodes layered, with each absorbing a different light spectrum) has achieved an efficiency of 35%[22], although they are very expensive. There are also experiments being conducted with non-silicon panels using quantum hetero-structures (carbon nano-tubes referred to as quantum dots) embedded in special plastics.

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[18] http://science.howstuffworks.com/space-channel.htm
Anthony Hanford, Lockheed Martin Space Operations, Aug 2004 for NASA – Advanced Life Support Baseline Values and Assumptions Document; Drysdale A, (2001) The Boeing Company, Kennedy Space Center, FL .

[19] As per "Space Settlements-A Design Study" by NASA publications, http://www.belmont.k12.ca.us/ralston/programs/itech/SpaceSettlement/designer/sphere.html

[20] Among others at the US Department of Energy, Berkeley Lab, at the University of California at Berkeley, University of Toronto, and companies such as NanoPower Research Laboratories.

[21] Component that restricts the direction of movement of charge carriers

[22] A solar module's energy efficiency is the ratio of the maximum output electrical power divided by the input light power under "standard" test conditions.

These are not as efficient as the silicon panels but they are far less expensive. While conventional solar cells only generate electricity from the visible light spectrum, experimental cells have been made that use the infrared spectrum mainly by varying the size of the quantum dots. These panels are also likely to achieve about 30% efficiency. Other technologies using cadmium telluride and copper indium gallium selenide, and nano-particulate titanium dioxide (Graetzel photo-electrochemical cells) are also being tested and generally target about 30% efficiency using optics to concentrate the incident light.

Despite extensive and promising research, for our purposes on Vademecum, I have based my estimates on the more conservative approach of using currently available technology instead of relying on any of the above options. We would cover the full surface area of 1,539,380 m² at the center of the station with solar panels. Considering that the "standard" solar radiation is 1000 watts/ m² on Earth and that an important proportion of it is lost in the conversion, and that only 12% is recovered, i.e., an efficiency rate of 12% or an output of 120 Watts/ m², we could obtain 185 MW of power generated through solar cells[23].

Vademecum's needs are estimated at 1kW/person/day, or 10MW for Vademecum's total population each day. By producing 185 MW/day, the above system will easily meet the station's power needs and will allow a substantial amount of energy to be stored for back-up. Storage can be envisaged as follows:

- Nickel-Hydrogen (Ni-$H_2$) batteries[24]. These batteries are charged during periods of exposure to the Sun (insolation) and discharged when the station is in the shadow. They have been designed specifically for use in LEO and tested on the ISS over several years. The tests have exceeded the ISS's requirements and the batteries are now commonly used on the ISS.

- An alternative and possibly more efficient storage technology is that of the Flywheel[25]. It is a simple device for storing energy, and could provide significant advantages over battery technologies since it can store energy more efficiently than chemical batteries. NASA is in the final stages of its research and testing program in this area. The program aims to achieve a 5-fold increase in storage capacity over existing batteries and a two-fold increase in battery life for LEO applications. This technology will require less hardware (save mass); it will

23 In reality we are likely to achieve a far better efficiency for two reasons: i) by the time the construction takes place, this fast-advancing technology would have achieved better yields mainly through the use of nano-technology; and ii) because in a space situation, the strength of the solar rays will not be mitigated by the Earth's atmosphere, we are likely to achieve far greater yields than currently assumed.

24 American Institute of Aeronautics and Astronautics, Fred Cohen (Boeing) Penni Dalton (NASA Glenn Research Center: "Update on ISS Nickel-Hydrogen Battery on-orbit performance".

25 NASA Glenn Research Center, Power and Propulsion Office: "Aerospace Flywheel Development Overview"

provide higher efficiency in storage (save power); and it will have a longer life (15 years as compared to about 7 for the Ni-$H_2$ batteries).

In terms of power distribution, like a power grid on Earth, the solar cells will generate primary power – approximately 160 volts of electricity. The primary power will be converted by a secondary transformer to provide a regulated 124-volt current to be used by the station's equipment and population. The primary power will also be used to charge the Ni-$H_2$ batteries[26].

## 3.3 Gravity[27]

To lead a life similar to that on Earth, humans need gravity. Humans could suffer a series of harmful and serious consequences if exposed to zero-gravity for extended periods of time. A listing of the impact of living without gravity is provided in Annex I. Gravity on Earth is natural. In space, in the absence of sufficient gravity, we must create gravity through artificial means. There are several ways to create artificial gravity on Vademecum:

- **Linear Acceleration:** The settlement could accelerate continuously in a straight line so as to achieve 1g. Though this method could be advantageous for interstellar travel, it does not serve Vademecum's purpose and the needed propulsion would be too expensive.

- **Mass:** Artificial gravity may be achieved by installing an ultra-high density core in the center of Vademecum, generating its own gravitational field. Technically, this is not really artificial gravity, but gravity itself. The drawback of this method is that it requires an extremely large mass to produce minute amounts of gravity and is therefore uneconomical.

- **Tidal Forces:** In this method, gravity is obtained by placing two bodies above each other (one could be a settlement, the other could be another settlement or just a mass) and connecting them by a tether. This method could be worth considering for a small object as a satellite, but it is not optimal for larger objects such as a space settlement.

[26] www.science.howstuffworks.com
[27] Theodore W. Hall, Architecture and Planning Research Laboratory, University of Michigan, Ann Arbor "The Architecture of Artificial Gravity: Mathematical Musings on Designing for Life and Motion in a Centripetally Accelerated Environment"
Theodore Hall, "Space Manufacturing 9, The High frontier, Accession Development and Utilization", Conference at Princeton, Sept 1993
Theodore Hall, Chinese University, Hong Kong, "Space Manufacturing 10, Pathways to the Frontier", May 1995
"Research Needs for Regenerative Life Support Systems, Chapter I-1", 1977 Ames Summer Study on Space Settlements, NASA
http://en.wikipedia.org/artificial_gravity

- **Magnetism:** Gravity could be achieved through diamagnetism, but would require magnets with incredibly powerful magnetic fields. Considering current technology, this method would generate enough artificial gravity to levitate at most a frog. This method would be much too impractical and expensive for Vademecum; and

- **Rotation:** In this case, everything inside the station will be forced toward the outside by centrifugal force. This method's side-effects are: i) Coriolis forces which would cause dizziness, nausea, and disorientation; ii) gravity gradients which would imply different gravity rates (for instance between one's head and feet) in a small radius station and seriously impair movement– this risk does not apply to Vademecum as the radius is sufficiently large to avoid it.

From the above analysis and for the specific purposes of Vademecum, it seems most reasonable to use rotation as the mechanism to create 1g from artificial gravity. However, artificial gravity, whether produced through rotation or otherwise affects the human body in a number of sensitive and sometimes adverse ways. Some of the disturbances that life in this environment can have on humans include:

- **Disturbances relating to changes in the human motor system:** Moving through artificial gravity is like going up or down the stairs. Going up is different from going down. Seeing where you are going allows you to make the appropriate adjustments and movements. Similarly, moving through artificial gravity requires the person to make adequate motor decisions. Moving west is different from moving east. The impact of the coriolis force and multiple rotations does not occur until after the movement has occurred so people will have to learn to coordinate their movements in ways they are not accustomed to on Earth.

- **Disturbances relating to changes in the human vestibular system:** The vestibular system, or balance system, is the sensory system that provides input to our movement and orientation in space. It is situated in the inner ear and contains three canals which are function in a push-pull system (one stops when the other is active) in such a way as it allows us to sense the directions of rotation. In space, when people or objects move within a rotating environment, they undergo extra acceleration which distorts their gravitational environment. As a result, they don't perceive things in their surrounding in the same way as they would on Earth, and their vestibular system therefore gets distorted. People will have to gradually adapt to new ways of moving in space and a new type of architecture will help them better orient themselves in such environments.

As a result of these disturbances, the sheer fact of hanging, falling and otherwise moving themselves and their objects around the station will create deviations that are likely to disturb them considerably. The station will therefore require new architectural thinking[28]. So far, architects who have designed the interior of rotating space stations and space colonies have attempted to transplant Earth architecture to the space settlements. But their illustrations do not reflect the dynamic nature of artificial gravity. Artificial gravity calls for a re-examination of the basic architectural concepts used in design so far. Through the analysis provided below, I would like to substantiate my point.

To start with, the definitions of direction will have to be redefined for Vademecum's inhabitants since north and south will not have the same significance as on Earth. North pole, south pole will not be clear locations, etc. If one were to describe the direction of motion within an artificial gravity environment using simple every day terms:

| | | |
|---|---|---|
| Up | would signify | Radially toward the center |
| Down | | Radially away from the center |
| East | | Tangentially with the rotation |
| West | | Tangentially against the rotation |
| North | | Ninety degrees left of East |
| South | | Ninety degrees right of East |

By the same token, artificial gravity will make certain habitual movements totally unfamiliar to us in space. Take the example of a ball that one would drop. The table below takes us through a step by step comparison of holding and dropping a ball under natural and artificial gravity:

| **Natural Gravity** | **Artificial Gravity** |
|---|---|
| The ball's weight is perceived through resistance to gravity. | The ball's weight is perceived through resistance to inertia |
| | |
| Holding the ball prevents it from accelerating. | Holding the ball causes it to accelerate centripetally. |
| | |
| Releasing the ball allows it to accelerate. | Releasing the ball allows it to stop accelerating. |
| | |
| The ball accelerates toward the floor. | The floor accelerates toward the ball. |

**Table 5 - Comparison of Natural and Artificial Gravity**

What specifically happens when an object is in motion relative to a rotating environment is explained mathematically in Annex 2

[28] The Architecture of Artificial Gravity: Mathematical Musings on Designing for Life and Motion in a Centripetally Accelerated Environment, Thoedore W. Hall, University of Michigan, 1991

**Finding Comfort in Artificial Gravity**: Much research[29] has been done over the past years to find the suitable comfort zone for artificial gravity. This research has indicated that "earth-normal" gravity is obtainable, provided a number of elements work together effectively. These are that the station's radius, the centripetal acceleration[30], the angular velocity[31] and the tangential velocity[32] work together to create feelings as close as humans feel on Earth as they move around their environments.

Why are these elements so important?

- The radius is important because the centripetal acceleration - the nominal artificial gravity - is directly proportional to it. Therefore, when the radius is too small, the population will experience a head-to-foot "gravity gradient" (i.e., a difference between gravity levels at their head and their feet) which will make them feel very uncomfortable. It is therefore important to ensure that the radius is big enough to avoid this problem. Our radius on Vademecum is 800m. We will see below how it plays with the other elements to be considered.

- The angular velocity is important because if it is not small enough, the cross-coupling of one's normal movements (for instance turning your head one way or the other) coupled with the rotation of the habitat will lead to dizziness and motion sickness. It is therefore important for the angular velocity to be low enough. In our case, it is at around 1 rpm.

- The reason why tangential velocity is important is because when people or objects move within a rotating habitat, they are subjected to Coriolis and centripetal accelerations that distort the gravity. In such situations, the ratio of Coriolis acceleration to centripetal acceleration is twice the ratio of the relative velocity to the station's tangential velocity. To avoid problems of dizziness and unease, one should minimize this ratio by maximizing the habitat's tangential velocity. In the case of Vademecum, the tangential velocity represents roughly 88m/s and is suitable for humans.

- The centripetal acceleration is important because without it, we would be in weightlessness. It needs to provide adequate floor traction to be comfortable to humans, and generally this is achieved at 1g which is what we have on Vademecum.

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[29] http://hyperphysics.phy-astr.gsu.edu, http://physics.bu.edu/~duffy/py105/Rotationalkin.html,, http://www.artificial-gravity.com/sw/SpinCalc/SpinCalc.htm

[30] The centripetal force (from Latin *centrum* "center" and *petere* "tend towards") is the force that is cause by the acceleration of an object that moves in a circular path towards the center of the circle.

[31] The angular velocity is the rate of change of angular displacement of an object rotating around an axis. It describes the rate at which an object's orientation changes with respect to time.

[32] The tangential velocity is the linear velocity of a point on a rotating rigid object at a distance from the axis of rotation.

To conclude on this point, the main message I wish to convey is that it will be counterproductive to try to emulate Earth architecture on Vademecum. A new type of architecture will have to be developed that takes into account the issues raised above. For instance, it is suggested to use different curves in architecture to allow the station's inhabitants to adjust their movements. The curve would indicate the magnitude and direction of the gravitational distortion. Because the shape of the curve will be independent of the rate or gravity level, it could be built in the architecture, like in the shape of walls, doors, windows, etc. Since research in this area is still rather preliminary, more work needs to be done before a firm proposal can be made. For Vademecum, I suggest to build "model" structures and test them before large-scale construction is initiated.

## 3.4 Noise Management[33]

When living in a closed habitat, the issue of noise propagation and vibration will be quite important. There is extensive experience in noise management especially through submarine technology where the use of special acoustic materials which avoid echoes and isolate sources of vibration is quite common. Another practical way of mitigating noise propagation is to physically separate the more noise "industrial" areas of the station from the residential ones.

# 4. How do we build the Space Station?

We will obviously need an enormous amount of materials. Materials needed for the constructions of the station can be extracted from three main sources.

From Earth itself

One option is to carry all basic and essential materials from Earth, not just those that cannot be found easily in space, but also those that can. This is probably not the cheapest option, but it offers a number of advantages: safety in the choice of materials and products; no need to exploit, extract, process the materials in space, faster implementation of the project since you can bring ready-to-assemble products, greater possibilities for testing materials and assembly on Earth. The main drawback of this option is the enormous transportation costs associated with shipping large volumes of materials from Earth to space.

In this scenario, Vademecum would be made of light composite inflatable materials packed tightly in canisters which would combine the packaging and mass efficiencies of an inflatable structure with the advantages of a hard protective structure for safe shipment. The elements would be inflated and assembled in space (more details on the inflatable

[33] Research Needs for Regenerative Life Support Systems, Chapter I-2, 1977 Ames Summer Study on Space Settlements, NASA

structure provided under Implementation Plan)[34]. Other items that would need to be shipped are plants and seeds (biomass), gases (in liquid and gaseous state, including nitrogen which is not readily available outside Earth), vehicles, robots, and much more. In short, there should be everything to allow the colony to get started. Elements that can then be reproduced/grown on the settlement would be developed in situ overtime.

From the Moon[35]

An important part of our materials' needs could be met by the resources available on the Moon. The useful materials present on the moon are Aluminum, Magnesium, Oxygen, Iron, Silicon, and Calcium (see table below), though it has little hydrogen, carbon, or nitrogen.

The metals could be used for construction, and oxygen could be processed for respiration and creating an atmosphere on Vademecum. The reason oxygen-bonded materials are easily found on the Moon is because they are light weight and over time, they rise up to the lunar surface.

Materials available on the Moon include[36]:

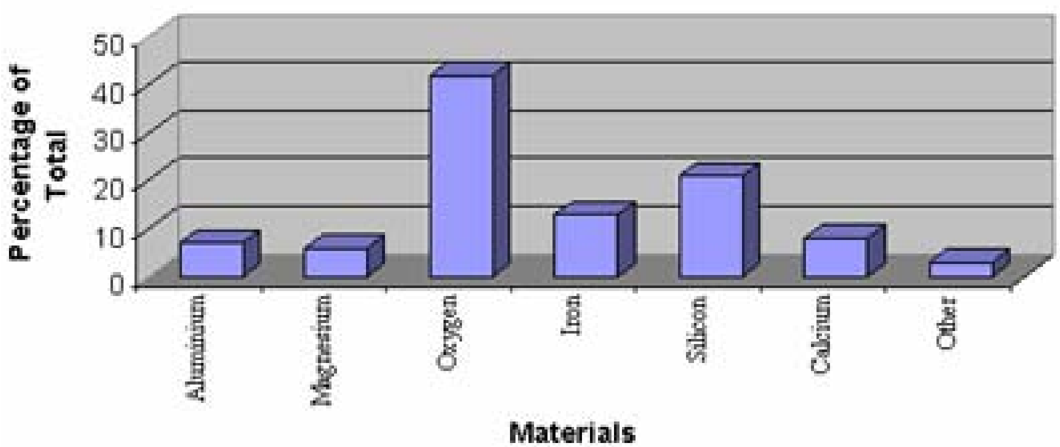


**Table 6 - Main Lunar Resources**

To become useful, these materials will need to be mined then processed. The Moon's surface is very powdery, due to millions of years of micrometeorite impacts and no active geology. This powder can be fairly easily mined without the need of heavy Earth machinery as the Moon has 1/6 the gravity of the Earth.

[34] http://science.howstuffworks.com, http://www.techbriefs.com/spinoff/spinoff1999/ard6.htm, http://www.nasatech.com/TSP2/register_form.php

[35] Entering Space by Robert Zubrin

[36] http://www.ssi.org/body_slideshow.html

This allows cheap mining and mineral processing. Because of the lack of weather on the moon, the lunar base will survive for much longer than it could on Earth. Lunar dust is the only constraint for structures built on the Moon, as it is extremely abrasive. However basalt is highly resistant to abrasion and this is an ideal material for lunar construction. Oxygen on the Moon is abundant as it bonds easily to so many things. It is lightweight so it rises to the lunar surface forming the upper crust. There are several ways to obtain pure oxygen. Oxygen can be found in mineral ilmenite, which can be found to be 10% concentrations in the lunar regolith (i.e. lunar soil). The reaction is the following:

$FeTiO_3+H_2—Fe+TiO_2+H_2O$

The water produced is then electrolyzed to produce hydrogen (which is recycled back into the reactor) and oxygen. This reaction is very endothermic (meaning they need energy input) so they must be done at very high temperatures (above 1000C).This process has been experimented by researchers working at Carbotek in Houston, Texas.
Another way to obtain pure oxygen is through carbothermal reduction. This process works with a larger variety of lunar rocks, including the very common silicates. The reaction is the following:

$MgSiO_4+CH_4—MgO+Si+CO+2H_2O$

The water obtained is then electrolyzed to produce oxygen while the carbon monoxide and hydrogen from the electrolysis are combined to remake the methane.

$CO+3H_2—CH_4+H_2O$

The first reaction of this process is also very endothermic but the last reaction is exothermic (meaning it produces energy) and occurs rapidly at 400 C. The carbon and hydrogen reagents are extremely rare on the Moon, so the systems must be designed for very efficient recycling

From Asteroids[37]

Many useful materials can also be extracted from asteroids where gravitational forces are much less, there is no atmosphere, and there is no biosphere to damage.
Those asteroids which pass near Earth or NEAs are particularly attractive since they are within reach. The materials can be useful for a variety or purposes which include building and sustaining Vademecum, to resource exploitation for commercial purposes. NEOs contain substantial amounts of metals, oxygen, hydrogen and carbon. NEOs also contain some nitrogen, but not necessarily enough to avoid major supplies from Earth.

The table below categorizes the volatiles and metals found on asteroids by their use. The elements shown in the table are based on analysis of meteorites on Earth who are believed to come from asteroids and from spectral studies.

[37] Near-Asteroid Mining, Shane Ross, Caltech 107-81, Dec. 2001

Volatiles (hydrogen, methane, water) could be used to produce rocket propellant needed for transport. Rare-Earth metals could be used to manufacture structural materials (nickel-iron grains can be used to make metal sheets and beams), and silicon and germanium could be used to make solar photovoltaic panels. Platinum and platinum-group metals and gold are also available on asteroids.

| **VOLATILES** | |
|---|---|
| **Primary Use** | **Molecules** |
| Life Support | $H_2O$, $N_2$, $O_2$ |
| Propellant | $H_2$, $O_2$, $CH_4$, $CH_3OH$ |
| Agriculture | $CO_2$, $NH_4OH$, $NH_3$ |
| Oxidizer | $H_2O_2$ |
| Refrigerant | $SO_2$ |
| Metallurgy | CO, $H_2$, Ni $(CO)_4$, Fe $(CO)_5$, $H_2SO_4$, $SO_3$ |
| **METALS & SEMICONDUCTORS** | |
| **Primary Use** | **Element** |
| Construction | Fe, Ni |
| Precious Metals | Au, Pt, Pd, Os, Ir, Rh, Ru, Re, Ge |
| Semiconductors | Si, Al, P, Ga, Ge, Cd, Cu, As, Se, In, Sb, Te |

**Table 7 - Materials from Asteroids**

New research in astronomy has in fact identified a large number of new NEAs over the last few years. About 1500 NEAs are now known to us from about 30 some 15 years ago. Of these, about 500 are estimated to have a diameter of 1km or more. More –about 200 – new asteroids are being discovered each year.

Asteroid geology has also advanced quite dramatically over the years and it is estimated that about 50% of NEAs may be volatiles, containing clays, hydrated salts, and hydrocarbons.

In terms of their composition, they can be classified in three categories:

- C-type (carbonaceous): very high content of carbonaceous material, water-bearing;
- S-Type (stony): high content of rocky material such as silicates, sulphides and metals; and
- M-type (metallic): demonstrating high radar reflectivity of metals.

The NEAs are either predominantly carbonaceous (C-type), or M-type or S-type, though about 50% of the larger kilometer-wide NEAs are predominantly C-type (carbon and water-rich). The table below shows the mineralogical, chemical and physical properties of asteroids based on four different meteorites. Since meteorites vary very much in their composition, the numbers provided below are just samples drawn from specific data[38].

Current knowledge on carbonaceous asteroids is based on chemical analysis conducted on meteorites which are believed to have come from parent bodies known as "carbonaceous chondrites". They are named after tiny pieces of rock called "chondrules" that are found in them. They are divided into 5 sub-categories:

- C1-type which contain about 10% water in clay mineral matrix, hydrocarbons and organic compounds, sulfur, iron sulfide and water soluble sulfate forms, nitrogen, magnetite, etc.

- C2-type which contain little magnetite, less water, carbon and sulfur, and about 10%v soluble sodium and magnesium salts; and

- C3, C4 and C5 types which are poor in water, carbon and other volatiles, but have other similarities to C1 and C2 carbonaceous chondrites.

The table below provides a mineral comparison of asteroids and the Moon, and demonstrates that there is far greater opportunity to find useful materials on asteroids than on the lunar surface. There is a relatively high prevalence of metals in stony meteorites. Iron meteorites or M-Type asteroids are even more metal-rich (about 99% metal). C-type asteroids and carbonaceous meteorites contain about 5%-20% water. In contrast, the lunar surface has no native water but its hydrogen, if converted into water would optimally generate a maximum of 0.045% of water on the lunar surface. Contrary to what was believed until recently, the Moon is relatively poor in resources as compared to asteroids.

[38] O'Leary et al. Retrieval of Asteroidal Materials, Space Resources and Settlements, NASA SP-428

|  | Mineral | C2-type | C1-type | S-type | M-type | Lunar Regolith |
|---|---|---|---|---|---|---|
| **Free Metals** | Fe | 10.7% | 0.1% | 6-19% | 88% | 0.1% |
|  | Ni | 1.4% | -- | 1-2% | 10% | -- |
|  | Co | 0.11% | -- | 0.1% | .5% | -- |
| **Volatiles** | C | 1.4% | 1.9-3% | 3% | -- | 0.014% |
|  | $H_2O$ | 5.7% | 12% | 0.15% | -- | 0.045% |
|  | S | 1.3% | 2% | 1.5% | -- | 0.12% |
| **Mineral Oxides** | FeO | 15.4% | 22% | 10% | -- | 15.8% |
|  | $SiO_2$ | 33.8% | 28% | 38% | -- | 42.5% |
|  | MgO | 23.8% | 20% | 24% | -- | 8.2% |
|  | $Al_2O_3$ | 2.4% | 2.1% | 2.1% | -- | 13.8% |
|  | $Na_2O$ | 0.55% | 0.3% | 0.9% | -- | 0.44% |
|  | $K_2O$ | 0.04% | 0.04% | 0.1% | -- | 0.15% |
|  | $P_2O_5$ | 0.28% | 0.23% | 0.28% | -- | 0.12% |
|  | CaO | -- | -- | -- | -- | 12.1% |
|  | $TiO_2$ | -- | -- | -- | -- | 7.7% |
| **Physical** | Density (g/cm3) | 3.3 | 2.0-2.8 | 3.5-3.8 | 7.0-7.8 | 1.5-1.9 |

**Table 8 - Comparative table of minerals to be derived from Asteroids and the Moon**

If possible, I would have opted for extracting materials from space, mainly from Asteroids since they appear to be extremely rich in valuable materials. However, out of concern for safety and to reduce risks associated with construction in space, I would prefer to ship all materials from Earth. As technology advances and Vademecum's population grows, we could consider building future settlements with materials extracted and processed in space. But for the time being, my preference is to choose the safer route of carrying all materials and equipment needed to get started from Earth, regardless of shipping costs. Had I decided to build Vademecum with materials from Asteroids, I would have taken a totally different approach. Such alternative approach has been elaborated upon in Annex 3.

## 5. Where should Vademecum be located? [39]

This is an important decision, because we do not want Vademecum to be too far from Earth (for comfort and safety, as well as for materials); nor too far from the Moon (for resources); and a place which would give us sunlight, somewhere which won't be chaotic, where it will be stable and safe to live.

In studying the suitable location for Vademecum, I came to realize that location has been a frequent point of contention between space colonization advocates. Mars, the Moon,

[39] http://www.physics.montana.edu/faculty/cornish/lagrange.pdf, www.wikipedia.org, 1975 NASA Summer study

Mercury, Venus, Europa have all been promoted and studied as possible sites for life away from Earth. So have gas giants (floating cities), asteroids and orbit.

Compared to other locations, orbit has substantial advantages and one major, but solvable, disadvantage. Orbits close to Earth can be reached within hours; whereas the Moon is days away and Mars is much further. There is plenty of continuous solar power in the Earth's orbit, whereas on planets, access to sunlight is limited to the day/night cycle. Weightlessness makes construction of large colonies considerably easier than in a gravity environment (astronauts have been able to move multi-ton satellites by hand). Finally, it is far easier to obtain a desired level of gravity by rotating an orbital colony.

The main disadvantage of orbital colonies is lack of materials, but this problem is solvable because materials can be "imported" from elsewhere.

One can decide to be on several orbits. If interested in the proximity to Earth, it is best to consider the Earth's orbit and identify a suitable location within it. These options could include any given location near Earth such as in Low Earth Orbit (LEO), the closest possible area to Earth, within 200-1200km above Earth's surface. LEO is located between the Earth's atmosphere and the Van Allen Radiation belt, with a low angle of inclination. Atmospheric and gravity drag associated with launch typically add 1500-2000 m/s to the delta-V required to reach normal LEO orbital velocity of 7800 m/s. An object in LEO is expected to move slightly overtime as a result of the drag, which means that it would have to be pulled back every once in a while to its original location.

LEO is located below the Intermediate Circular Orbit (ICO)[40] and way below the Geostationary Orbit. Orbits lower than LEO are not stable and are likely to perish due to substantial atmospheric drag. Higher orbits are exposed to intense radiation and charge accumulation. So far, most manned spacecrafts have been in LEO (including all Space Shuttle mission, except sub-orbital test flights such as Project Mercury and Project Apollo which went beyond LEO). Likewise, many satellites are also placed in LEO since it requires far less energy to place them in LEO and the satellite needs less powerful transmitters to transfer data. As a result, LEO is becoming quite congested, not least with space debris. The US Space Command has estimated that more than 8000 objects larger than 10cm are currently in LEO[41].

Otherwise, we could also consider establishing Vademecum on some known locations which offer specific advantages in that they are particularly stable. These are known as the Lagrangian points, which are the five positions in space where a small object with no other forces acting on it (i.e., a space settlement) can be stationary with respect to two larger objects (i.e., the Earth and the Moon). These points are similar to geosynchronous

[40] ICO also referred to as Medium Earth Orbit or MEO is the area between the atltitudes of Low Earth Orbit (1200km) and geosynchronous orbit (36000km) away from the Earth's surface. Many satellites are installed at ICO.

[41] www.wikipedia.org

orbits[42] because they allow an object to be in a static position rather than an orbit where its relative position changes continuously.

The Lagrangian points can be identified on several locations in the solar system: In the Sun-Jupiter system, there are several thousand asteroids, collectively referred to as the Trojan Asteroids and are in orbits around the Sun-Jupiter L4 and L5 points. Other bodies can be found in the Sun-Saturn, Sun-Mars, and other systems yet. For the purposes of this project, two options would have been realistic:

i) The first was a Lagrangian point at equal distances between the ***Earth*** and the ***Moon***; and
ii) The second was at a same Lagrangian point at equal distances between the ***Earth*** and the ***Sun***.

From within these two options, the Earth-Moon location offers very clear advantages for the following reasons:

- The proximity to Earth is important not just for safety reasons, but also for proximity to raw materials and to facilitate transportation of people and materials,
- It will give us a chance to create an Earth-like day/night cycle;
- It will reduce our exposure to radiations; and
- There are also important psychological reasons associated with visualizing Earth and the Moon.

These 5 locations referred to as L1, L2, L3, L4 and L5, are named Lagrangian points in honor of the French-Italian mathematician Joseph Lagrange, who discovered them in 1772 while he was studying the restricted 3-body problem. What was “restrictive” in his analysis was the capacity of a 3 body structure to co-exist, when one of the 3 bodies is much smaller in mass than the other two.

Lagrange’s finding was a departure from the hitherto Newtonian principle that the gravitational interactions between different numbers of bodies in a system would result in the bodies orbiting chaotically until there is a collision, or a body is thrown out of the system to achieve balance. However, Lagrange reformulated this theory by creating a new system of calculations and identifying areas where a third body could remain stationary.

[42] A geosynchronous orbit is a geocentric orbit that has the same orbital period as the sidereal rotation period of the Earth. It has a semi-major axis of 42,164 km.

The five Lagrangian points are defined and determined as in the table below:

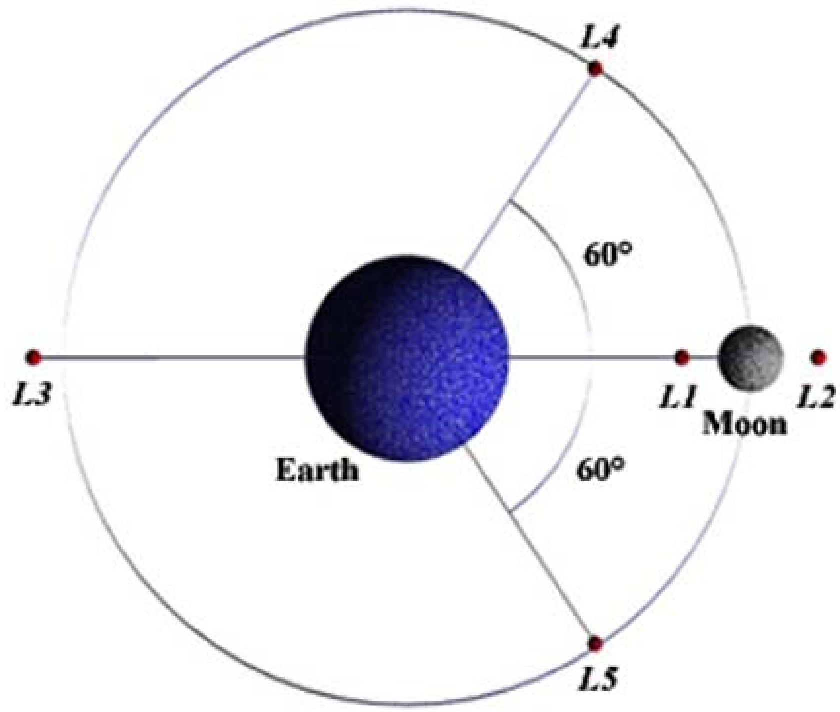


**Figure 12 - The five Lagrangian points in a two-body system (e.g., the Earth and the Moon)**

L1 is located in between two large masses M1 and M2. When an object which orbits one of the large masses (e.g. the Moon) more closely than the other (e.g., the Earth), it would normally have a shorter orbital period than the Earth. However, this ignores the effect of the Earth's own gravitational pull. If the object is directly between the Earth and Moon, then the effect of the Earth's gravity is to weaken the force pulling the object toward the Moon, and therefore increase the orbital period of the object. The closer to Earth the object is, the greater this effect becomes. At L1, the orbital period of the object becomes exactly equal to the Earth's orbital period. For example, the Sun-Earth L1 point is often used to make observations of the Sun. In fact, a Solar and Heliospehric Observatory (SOHO) is already stationed at the Sun-Earth L1. The Earth-Moon L1 allows easy access to lunar and Earth orbits and is ideal for a half-way manned space station to transport cargo and people to the Moon and back.

L2 is located on the line defined by the 2 large masses, beyond the smaller of the two. For instance, on the side of the Moon away from the Earth, the orbital period of an object would normally be greater than that of the Moon. The extra pull of the Moon's gravity decreases the orbital period of the object, and at L2, the orbital period becomes equal to the Moon's. Sun-Earth L2 is a good spot for space-based observatories (The Wilkinson

Microwave Anisotropy is already located at the Sun-Earth L2). Earth-Moon L2 would be good for a communications satellite covering the Moon's far side.

L3 is also located on the line defined by the two large masses, beyond the larger one of the two. The Earth-Moon L3 lies on the opposite side of the Earth, where the combined pull of the Moon and Earth causes the object to orbit with the same period as the Earth. The Sun-Earth L3 has been commonly used to place a "counter-Earth" in science fiction and comic books.

L4 and L5 are located at the third point of an equilateral triangle with the base of the line defined by the 2 masses. The point is ahead of, or behind, the smaller mass in its orbit around the larger mass. This is why L4 and L5 are often referred to as the triangular Lagrange points. For instance, the Earth-Moon L4 and L5 points lie 60 degrees ahead or behind the Moon in its orbit around the Earth.

In terms of stability, the first three Lagrangian points are technically stable only in the plane perpendicular to the line between the two bodies. Outside those points, L1, L2 and L3 are nominally unstable. In contrast, the L4 and L5 points are stable and in equilibrium, provided the ratio of masses $M1/M2$ is $> 24.96$ in the Sun-Earth and Earth-Moon systems. Therefore, both L4 and L5 appear to be the more stable points to locate a station on orbit[43].

From the above analysis, it appears that the best and most stable location for Vademecum would be the L4 or L5 Lagrangian point. However, since we plan to ship practically all supplies and initial requirements of Vademecum from Earth, transportation becomes a crucial factor in our choice of locating Vademecum. Given exorbitant propulsion fuel costs, the further Vademecum lies, the more costly the project will become. As a result, I finally opted to locating Vademecum at Low Earth Orbit (LEO), at some 200 Km from Earth. This would substantially cut transport cost and time. It will also be safer for the inhabitants since they will be far closer to Earth. I hope that with technological advancement, I will be able to ship Vademecum further out into space at a later date. But for the time being, for purposes of economy and safety, I prefer to base it at LEO.

# 6. Implementation Plan

The project will be implemented in 6 stages, as follows:

Preparation on Earth;
Shipping materials from Earth to Low Earth Orbit (LEO);
Assembling Vademecum at LEO;

[43] The process of identifying the Lagrange points involves equations which calculate motion while the 3 bodies maintain a constant level of separation. The equations are presented in Annex 4.

Spinning it to create artificial gravity;
Installing and Testing the Life Support System; and
Inhabiting Vademecum.

## 6.1 Preparing the Project on Earth

Substantial preparation will be required on Earth to maximize the smooth and successful implementation of the project and to minimize risks. This will help us conduct research, analyze, study risks, experiment and test, and prepare the project adequately in all its many dimensions. This stage will include several tracks, most of which can be conducted in parallel. The main steps include:

**Research Strategy:** A fundamental component of the project preparation stage will be to conduct research and tests to mitigate any risk of defects and malfunction and to optimize the use of materials to the extent possible. Research will be required in the following key areas: options for the construction and assembly of the station, research into the best transportation module to allow more efficiency (more space/less weight), robotics and controlled tele-operation, trained machine intelligence tests; testing the different materials and how they may interact with one another in space, test for the inner architecture given special artificial gravity conditions. Though far easier, the integration and adaptation of solar cell technology to the equipment and machinery on Vademecum should also be tested. Tests will also be needed to ensure adequate life support systems: waste management using bacteria, integrating various regenerative systems (biologic physiochemical), etc. The above is only a limited review of all the areas where further research and testing will be required.

**Fund-raising Strategy**: The project has to be documented and "sold" to potential financiers, with money raised from governments, individuals, corporations, and the stock-market. It is only through massive support that such an ambitious and expensive project could see the light of day. For this project to be successful and for its funding to be secured, it will have to be communicated and explained very broadly and clearly to a large number of people across the world. A simple but sophisticated communication effort will have to be developed, to share the ultimate objective of this operation: this project is for people – people should be at the heart of it, as they are its basis.

**Legal Issues**: As much as inhabiting space will require technology and funding, it will also require a legal basis. Clear international rules have to be set up before humans can inhabit space and use its resources. Otherwise, there may be problems in the long-run. When European countries colonized Africa and other parts of the world in the 1800's, they exploited these countries' natural resources as though it were their own. Centuries later, problems still exist between the colonizers and the colonized. I therefore believe that there needs to be a general agreement on this type of venture among as many countries as possible. This is especially important because of the vast economic and financial returns that space exploration and exploitation could generate. I suggest that in parallel to progress in science and technology, there needs to be legal work and political consensus-building around how such a project should be implemented (also see under Vademecum's Governance System).

## 6.2 Shipping materials from Earth

Today, the weight of a space shuttle at launch is approximately 95% fuel. More efficient alternatives have been and continue to be sought, but so far no viable alternative energy has been able to create the thrust necessary to move a sizeable ship much beyond Earth's orbit.
Identifying such an energy source which would allow us to go further and more easily is indeed a key challenge for the scientific community. The most realistic approach for Vademecum is to use the most commonly used means and energy source that is used currently, i.e., a space cargo ship to transport maximum volume of tightly packed materials, and people. Therefore, we would transport the materials including Vademecum's shell and its contents from Earth to LEO by using solid fuel propulsion. Though expensive and environmentally damaging, it is the only possible source of energy for the Earth-LEO route.

In manufacturing the station on Earth, we will plan to make the actual assembly and building process as easy as possible, minimizing human extra-vehicular activities (EVA) and reducing the number of steps and processes, as well as the time involved in the construction.

## 6.3 Building Vademecum in low orbit

Vademecum will be a light inflatable structure. The idea of using inflatable materials in space is certainly not new and was experimented as early as the 1960's by the Russians. The concept was abandoned for a long time and it is recently resurfacing and is being tested for use on the International Space Station through a project referred to as "TransHab". I think the use of an inflatable structure is very well suited to meet Vademecum's needs, particularly since we plan to ship the bulk of Vademecum's initial material needs from Earth and it is therefore important to consider light yet sturdy materials. Using this type of structure would help facilitate project execution, provide a lot of room at lower cost, thus minimizing the risks to Vademecum's population.

As stated earlier, the structure I have in mind for Vademecum is that of a truncated-ellipse. The structure will be built with a shell made of composite materials with a thickness of 1.5m, and a weight of about 7g/cm³. The shell will be composed of 7 layers of materials. A description of the various layers is provided below[44]:

1. The outermost layer is meant to be very resilient, and serves primarily a function of shield against radiation and U-V protection. It is made of Hydrogenated Fullerene Reinforced Polyethylene and is UV-cured through the use of resins (for

[44] http://www.estec.esa.nl/structures/images/infworkshop2002.pdf

more on the composition and functions of this material, please ref. Risks-Radiation section)

2. The second layer is meant to provide thermal protection and is made of glass fiber cloth that resists abrasion by the charged particles in the Earth's ionosphere and serves as a thermal blanket to Vademecum. The material offers excellent structural performance and flexibility.

3. It consists of fibrous reinforcement that is impregnated with a thermoset polymer resin. The resin is chemically hardened through exposure to heat. The material is typically encased on both sides by a thin polymeric film that acts as a pressure barrier. This material has been extensively used in spacecraft components with success. The third layer is a critical part of the station's shell. It is referred to as the restraint layer and it is composed of interwoven Kevlar (poly-paraphenylene terephthalamide), an aramid-fiber material which has a very high strength-to-weight ratio and great impact resistance. Kevlar derives its strength from inter-molecular hydrogen-bonds and aromatic stacking interactions between aromatic groups in neighboring strands (see below). It consists of relatively rigid molecules, which form a planar sheet-like structure which results in high mechanical strength and a remarkable heat resistance. Because it is highly unsaturated, i.e., the ratio of carbon to hydrogen atoms is quite high, it has a low flammability. The interwoven nature of the material allows it to distribute tremendous weight evenly and efficiently around the structure, much in the same way as the reeds in a round basket are woven to spread the weight and give the basket strength. When inflated, these woven straps form a system that is capable of withstanding up to 4 atmospheres of pressure differential between interior and exterior.

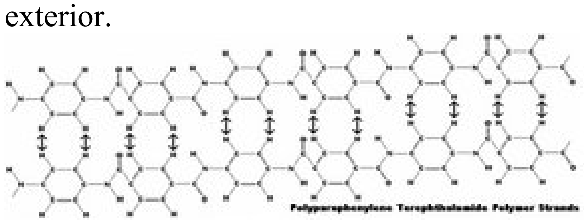

**Figure 13 - Strands of inter-molecular hydrogen bonds and aromatic groups** [45]

4. The fourth layer is primarily meant to shield the station from micro-meteorites which are often encountered in space and travel at velocities of 7km/sec. It will be composed of a shield of impact-resistant layers separated by open-cell foam. The foam is made of two-part polyurethane mixed with polystyrene or polyurethane that foams when exposed to vacuum. It is meant to "rigidize" the structure by coating the space between layers of materials and is also an aid in the inflation process of the structure. It is particularly strong when it is combined with composite laminate materials.

[45] www.wikipedia.org/kevlar

5. The fifth acts as a frame for the station. It is composed of modular structures that will be assembled to create an inner skeleton. These are meant to maintain the Vademecum's shape and avoid any deformation caused by internal (pressure) or external (micro-meteorites or debris) causes. The modules will be particularly reinforced around the edges of the truncated ellipse, which are the main pressure points of the structure. The modular elements will be made with new composite materials (e.g., "Glare" currently used in the new aircrafts)[46]. They are made of aluminum-glass-fiber laminates and are lighter and have better corrosion and impact resistance than conventional aluminum alloys used so far. It can also be repaired rather easily, using conventional aluminum repair techniques.

6. Identical to the fourth layer, the sixth one is also meant to be a shield of impact-resistant material, separated by foam.

7. The final and innermost layer is composed of four sub-layers of glass-fabric reinforced rubber bladders. It will be in direct contact with the inner atmosphere of the station and will provide gas tightness.

Based on the above data and considering Vademecum's entire surface area (1,410,804 $m^2$), the weight of the various layers ($7g/cm^3$) and that the structure will be 1.5m thick, the overall weight of the shell will be about 1500 tons. This assumes that the 'windows' are of the same density as these layers, i.e. $7g/cm^3$.

As stated earlier, Vademecum will arrive at LEO in pre-fabricated state, ready to be assembled and inflated. The assembly will be made by inflating the structure with inert gases (using compressed air in liquid form shipped from Earth) and mounting the various parts using tele-operated and automatic space robotics to minimize human labor and reduce the risk of exposure to radiation.

## 6.4 Spinning it to create artificial gravity

Although this step seems simple, it is very crucial and must be done with a lot of care. The technique we will use to spin Vademecum will be done as shown in the diagram.

46 www.boeing .com/commercial/777family

**Figure 14 - Creating artificial gravity**

The diagram shows that 2 forces, each attached to Vademecum by ropes of equal lengths along the circumference of the settlement will move at equal and opposite velocities to create a circular movement around the center of the station.

In order not to damage Vademecum, the velocity must be gradually increasing from a low initial velocity, i.e., it should have a low angular acceleration.

## 6.5 Installing and Testing the life support system

Being the final step before allowing a relatively large population of humans to settle the colony, all the seven life support systems as well as their back-ups must be installed and thoroughly pre-tested. This portion of the implementation is one of the most labor intensive parts of the project.

## 6.6 Inhabiting Vademecum

The final stage will consist of taking a first population of 5000 people to the station gradually through a series of consecutive trips.

People will be taken to the station either directly from Earth or via LEO using solid fuel propulsion vehicles as their means of transportation. As stated earlier, we are targeting an initial population of 5,000 to reach the station's final capacity of about 10,000 people overtime. Once additional stations are added onto Vademecum, it would reach 20,000 and ultimately 30,000 people (with 3 linked stations in total).

It is suggested that we split the initial population evenly between male and female, consider a minimum "entry age" of 5 and a maximum of 55, with the bulk of the population being between 25-35 years old. The minimum age of 5 is determined as a threshold for a child to be physically strong enough to take the trip and adapt to his/her new environment. The maximum age of 55 is set as a limit so that each person entering the station has at least an estimated 10-15 years of productive life to contribute.

The initial entrants will be screened carefully for their health and physical/mental wellbeing. In terms of the entrants' qualifications, we will select a variety of skills, yet keep in mind the integrity of family structures of those willing to migrate (e.g., a technician's wife/husband may not be professionally qualified but should not be excluded for this purpose).

## 7. Transportation:

Transportation is a key logistical aspect of the project. There are 3 transportation routes to keep in mind:

- ***Earth-LEO route:***

  In main transportation route of this project is obviously the Earth – LEO route since we have decided to transport practically everything from Earth. As a result, many back-and-forth trips will have to be arranged to allow for the transportation of equipment, machines, and people. Although most of the initial flights would be unmanned, people will be flown in gradually as the assembly becomes more complex and requires human intervention.

  In the absence of other environmentally friendly options, we will use the solid-fuel propulsion vehicles to serve the Earth-LEO route.

  As per the figure below, we will use what is referred to as the "Hohmann transfer orbit"[47] to move the space vehicle from one orbit to the other using the lowest possible delta-v for the specific transfer. For instance, a Hohmann transfer orbit will take a vehicle from LEO to the Geosynchronous orbit (GEO)[48] in just over 5 hours, from LEO to the Moon in about 5 days, from Earth to Mars in about 260 days.

[47] It was named after Walter Hohmann, the German scientist who wrote about it in 1925.
[48] A geosynchronous orbit is a geocentric orbit that has the same orbital period as the sidereal rotation period of the Earth.

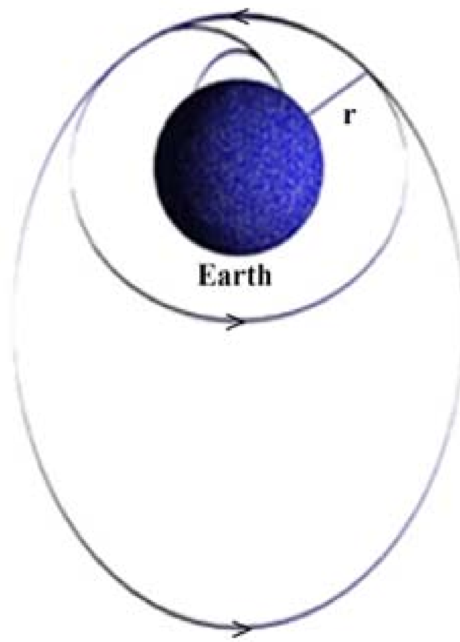


**Figure 15 - Escape Velocity**

- ***Transportation within the station:***

Transportation within the station will be provided through a circular tramway-type transport mechanism riding around the circumference of the station;

- ***Transportation to and from the micro-gravity center:***

Transportation to and from the micro-gravity center will be achieved through an elevator-type mechanism.

As stated earlier, I would hope that once technology advances and Vademecum has proven its safe survival at LEO, it could be moved further out in space. Currently, the technology which I find most interesting to consider for such a purpose is the use of solar sails. I am elaborating further on this option in Annex 5.

## 8. Risks

Throughout every decision made about Vademecum, my primary premise has been the safety and comfort of Vademecum's residents. Therefore, every decision has, in itself been based on mitigating as many potential risks as possible. The choice of the structure (truncated torus) may not have been the best in terms of the ratios, but it provided the safest choice to avoid any risk of gravity differential which would affect the population's well-being; the location at L4/L5 on the Lagrangian point would have provided more stability, but being at LEO close to Earth is not just cheaper, but also safer in terms of the time it takes to get help and assistance from Earth; the choice for the relatively small size of the settlement is not just a decision based on economic grounds to reduce costs, but also to expose as few people as possible initially to the risk of anything going wrong. All these choices were therefore made to minimize risking the residents' safety and maximizing their comfort. Nonetheless, other risks remain which will be evaluated below:

## 8.1 Radiation

Radiation can be lethal to humans in the space environment. Exposure to radiation will have genetic and developmental effects; it will result in the production of tumors, and affect the vascular and central nervous systems. It is therefore essential to reduce Vademecum's exposure to radiation by adequately shielding the station. Below, I will introduce the various types of radiation and present options for shielding the station.

There are two kinds of radiation, electromagnetic (non-ionizing) radiation and ionizing radiation[49].

1) Ionizing radiation is composed of high energy particles and photons, and can be further categorized into:

- Van Allen Belts which consist of 2 radiation belts composed of electrons and ions trapped in the earth's magnetic field. They are shaped like a donut ring around the earth and are spread unequally within the magnetosphere. The two belts are located at altitudes of 300km – 1200km and above 10,000km. Extended stays within each of these belts can be fatal.

- Solar Particle Events (SPE) and Solar Cosmic Rays (SCR) occur as solar flares and solar winds respectively. Solar flare activity corresponds to an 11-year solar cycle and results from storms in the sun's magnetosphere. It reaches a maximum during the periods before and after sunspot maximum. Most events last about an hour. Massive, highly lethal occurrences are relatively rare, but last hours or even days. Solar wind is a plasma that is given off from the sun as a proton-electron gas. The winds contribute to the Van Allen Belts.

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[49] http://paperairplane.mit.edu/16.423J/Space/SBE/eva/EVA/space_env.htm, http://web.mit.edu/12.000/www/finalpresentation/environment/radgrav.html and Sasakawa International Center for Space Architecture, SICSA Vol. 2, no.3: July-Sept 1989

- Galactic Cosmic Rays (GCR) have the highest energy of the 3 types of ionizing radiation. They consist of protons, alpha-particles and heavy nuclei. These rays travel from distant stars in galaxies towards earth from all directions. This type of radiation does not penetrate the low earth orbit but people's transit (for example to the Moon or Mars) would be affected by it.

Generally, ionizing radiations pose a serious threat to people traveling in space. Their effects include headaches, dizziness, abnormal taste and smell, nausea, diarrhea, decreased blood pressure, decreased white blood cells, irritability and insomnia. Later effects can include vision problems, cancer, fertility problems, and abnormal development.

An atom is ionized when one or more electrons are stripped away (e.g., from a collision with a speeding proton). Injury occurs when high energy protons, cosmic rays, x-rays, or gamma rays penetrate and split apart cell molecules. This can kill or damage the cell. In addition, particles passing through spacecraft walls can ionize atoms within those walls, creating another hazard, called secondary radiation.

Heavy cosmic ray particles such as the nuclei of carbon, oxygen and iron atoms do the most damage because they carry greater positive electrical charges than protons, causing more ionization within the cells. A single heavy cosmic ray particle can kill a cell. Protons, however, do the most overall damage because there are so many of them. They comprise the substance of most cosmic rays.

2) Non-Ionizing radiations pose a relatively smaller threat. Possible effects include memory loss, vision problems, although tests results are inconclusive and contradictory. Generally, the effects of non-ionizing radiation in space are harmless.

The table below shows the international limits for annual dose limits for terrestrial workers and this is compared with the annual dose limits proposed for humans in space.

| Type of Measurement | Terrestrial Nuclear Worker (Sv/year) | Astronaut/Cosmonaut (Sv/year) |
|---|---|---|
| Skin Dose | 0.50 | 3.00 |
| Eye Dose | 0.15 | 2.00 |
| Blood Forming Organ | 0.02 | 0.50 |

**Table 9 - Absorbed Dose Limits and Recommendations by the International Commission on Radiological Protection.**[50]

[50] Annals of ICRP

To shield against radiation, traditionally aluminum was the most commonly used material. However, current research is proving that fabrics may be even more effective than metals. A material called Hydrogenated Fullerene Reinforced Polyethylene is particularly interesting because of its high hydrogen content and low molecular weight. However, it has a relatively low thermal stability. But combined with hydrogenated fullerenes, it achieves excellent shielding. The fabric is layered (200-300 layers) and molded in the shape of a brick. The air is removed through a pump and "cooked" in a special oven (an autoclave) up to 93C and put under a pressure of 690 kPa. The combination of heat and pressure bonds the materials together to create a highly resistant material.

Despite the resistance of this material, one should look into ways of reducing the human body's sensitivity to radiation. So besides research on the material itself to come up with an even more resistant, lighter material, one should make efforts on the medical front to limit the effect of radiation on people in space and see how to reduce the damage on cells and tissues (eyes, brain and internal organs)[51].

## 8.2 Health Hazards and Contamination[52]

Microbes can develop very easily in Vademecum's air and water through human contamination, agriculture, the water supply system, waste products and other materials in the habitat. In addition to known and common microbes, new ones can form especially given the very different environment on the station, and they can spread unexpectedly and rapidly. This important health risk can be partially controlled by the conventional techniques of quarantine, screening and immunization. However, some carriers are likely to be so difficult to identify that keeping them out of the habitat would be close to impossible. This risk is exacerbated by the fact that it is impossible to bring "fresh outside air" to clean the atmosphere. The emphasis should therefore be on prevention and monitoring of biologically damaging and toxic materials and stringent environmental monitoring. An additional preventive measure could include separating the environmental control of different segments of the station to enable each segment to be isolated in case of emergency.

## 8.3 Fire

Again in this case, the emphasis should be on prevention. Although many of the conventional fire protection techniques used on Earth can be replicated on Vademecum, even a small fire could have a far more devastating impact on the station than on Earth. It could threaten the structure of the station as well as its habitat, air pressure and air quality. Material selection will therefore be of utmost importance. Similarly, rapid

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51 http://www.nasa.gov/vision/space/travelinginspace/radiation_shielding.html

52 Research Needs for Regenerative Life Support Systems, Chapter I-2, 1977 Ames Summer Study on Space Settlements, NASA

automatic fire control systems and fire detection will be essential to maximize the station's safety.

## 8.4 Other

A failure in the regenerative life support system could be fatal to Vademecum' population. To minimize this important risk, it is essential that besides extensive research and testing of the life support equipment and processes, a back-up system be put in place in case the system fails.

# 9. How to organize Vademecum -- The Station's Governance System[53]

Like everything else in this project, there are also many ways of "designing" a governance structure for Vademecum. Prior to examining options for Vademecum's governance, we would like to present the broader perspective, i.e., possible governance options for space as a whole. This is particularly important because we will be using resources from space and that the population of Vademecum and other such settlements will have to live together peacefully in space. Therefore, they should determine a basic set of common rules which they would follow.

The UN General Assembly adopted a Treaty called "Principles Governing the Activities of States in the Exploration and Use of Outer Space including the Moon and other Celestial Bodies" in January 1967 which itself was based on 2 prior resolutions dating back to October and December 1963 (resolutions # 1962-18, 1884-18). The Treaty which has been ratified by only a limited number of countries, calls for international cooperation around the peaceful exploration and use of outer space.

This Treaty – though a good basis for further legal work on outer space—is very general and has not been ratified by enough states to create a solid foundation for regulating outer space exploration and use.

The Geneva Convention of the High Seas (1958) and its subsequent amendments last of which in 1980, has been used extensively in international jurisdiction. It can perhaps serve as a better tool and starting point for any legal foundation for space. It distinguishes between "territorial" waters, i.e., waters which belong to each state, from "international" waters, which are also referred to as the "high seas". In our case, territorial water can be compared to a specific volume or space around each colony which would fall under the exclusive control of that colony as regards its economy, defense, management, government, etc. Beyond this "territorial" area, a common set of principles

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[53]Text based on an interview conducted by the author with Dr. Karin Kneissl, Professor of International Law, University of Vienna, Austria, summer of 2004, website of the United Nations (www.un.org), http://www.un.org/law/ilc/texts/hseas.htm,

need to be defined to regulate the use of space. Here again, we can use the example of the Geneva Convention which among others, covers in great detail the:

- freedom of navigation;
- freedom of fishing (which in our case can be referred to as the freedom to use space materials);
- freedom to lay submarine cables and pipes (i.e., law governing communications between settlements, earth, etc); and
- freedom to fly over high seas (i.e., a law to regulate transportation in space).

However, since all the settlements and colonies in space are not likely to be "owned" by states (i.e., a settlement could also be owned by a private corporation / individuals), we will need a more flexible, yet complex set of rules to allow for such diversity. We propose the following elements to design a basic set of rules for the exploration and use of "high space":

- We propose the creation of a Space Council composed of representatives of each settlement/colony;

- Voting rights should be determined not just on the basis of economic power and demography, but also on the basis of a colony's special characteristics (too small, too prone to natural disasters, i.e., meteorites, radiation, etc…). In other words a mixture of diverse criteria will determine the weight of each colony's vote.

- We propose a flexible voting structure whereby colonies which contribute to the well-being of the whole community gain "points" in the form of higher voting rights. This is meant to create a positive system of incentives to ensure peaceful coexistence. However, there are limits to the number of "points" gained by any given colony to avoid situations of monopoly and to guarantee oligopoly.

- Similarly, in addition to incentives for positive behavior, there should be sanctions for negative behavior and abuse. We suggest that in the same way that a colony can gain points, it can also loose some. For more serious or repeated breaches, the right to use space resources would be withdrawn.

- It is also important to note that while regulation is important and necessary, one should not over-regulate because it is difficult to anticipate technological progress.

- The concept of "Terra Nullius" (land that doesn't belong to anyone), used by European colonizers of Africa in the $18^{th}$ and $19^{th}$ centuries should be avoided because of its invading/conquering connotations. The spirit and purpose of space settlement should be clearly against conquering and invading space and in favor of long-term settlement, cohabitation and collective use and exploitation of resources.

## 9.1 Vademecum’s Principles and Code of Ethics

Although our community will be rather small (though it will start with only 10,000 people, it could expand to about 30,000) and would therefore not require a heavy structure or rules, it is suggested to set out a few simple principles to govern the community and constitute the foundations of our society away from Earth. These include:

- A strict adherence to environmental sustainability. We will use materials that are recyclable; we will use low or no-waste energy sources;

- Our society will be based on values, such as the respect for others and nature in general, since it is the basis of our existence, freedom of opinion, freedom of expression, fairness and rule of law.

- Though very small, our community will be governed by a democratic mini-executive, and small judiciary and legislative branches, similar to a provincial or municipal government;

- When our community will be established, a ‘’code of ethics’’ will be written and voted on by referendum; it will become the ‘’constitution’’ of our community;

- An executive and the legislature will be voted for a given period of time determined by the constitution and a judicial system will be put in place accordingly;

- Our society will be secular, i.e., religion will have no place in government and will be a private matter for each citizen;

- We will make known our neutrality and our adherence to peaceful coexistence with others; and

- People, goods[54], services, capital will able to flow freely in and out of our community.

To join this community, one has to agree to adhere to these principles. One needs to produce a clean criminal record from one’s country on Earth, a satisfactory medical report and pledge of allegiance to the principles of this community. Given the high risks to the community and to the settlement as a whole, there will be severe consequences for those who would threaten the settlement.

[54] All goods, with the exception of weapons and drugs.

# 10. Vademecum's Financing and Implementation Timeline[55]

To estimate the eventual cost of this project, I looked at the projected total cost of the International Space Station. By its completion in 2010, the ISS would have cost about $100 billion. High technology in the space frontier is certainly not cheap. However, it is not all that expensive either. Considering that the 100 billion figure is shared between all the participants of the ISS (US, Russia, Canada, Japan, and 17 European countries including Belgium, Denmark, France, Germany, Italy, the Netherlands, Norway, Spain, Sweden, Switzerland and others)[56] over a period of about 30 years, for the vast knowledge and the potential it has created, this is a fair price.

By the end of its projected lifetime, the ISS would have completed 44 spaceflights; its assembly would have taken about 2000 man-hours and would involve over 100 separate components. It will have a life span of 10 years and when completed, it will house up to 7 people, with a living space equivalent to the cabin size of two 747 jets.

Besides the ISS, I looked at several projects such as the Biosphere 2 (cost $200 million, about 5 years to build), the ITER project[57] (estimated to cost $10 billion over 30 years), but none of these comes close to what a project of the scale of Vademecum could cost. I think the construction of a city like Dubai in the United Arab Emirates[58], is perhaps closer to Vademecum in that it is based on a concept and a vision of creating an ambitious entity practically from scratch. Like Dubai, Vademecum needs massive upstart funding which should be sustained for a very long time before it starts generating income. Like Dubai, Vademecum is unique: no other city has been built with the same rationale and the same motivation. Although Dubai is over 5 times bigger than Vademecum (4000km²) and has 10 times its population (1.1 million people), it comes closer to Vademecum than do other space projects.

Whatever the best comparison for Vademecum is, one fact is clear: Vademecum will cost a lot of money. Although I find it very difficult to come up with a precise cost estimate, I believe it will is likely to be the most expensive project humans have ever

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[55] Text based on an interview conducted by the author with Mario Kozma, Investment Banker, Brussels, Belgium

[56] The financing share of the European countries member of the European Space Agency (ESA) has been about 8 billion Euros, or about $10 billion. The ESA estimates that over a 30-year period, the cost to Europeans has been about 1 Euro per person/year:, i.e., less than the price of a cup of coffee in most European cities. (ref. www.esa.int/esaHS/ESAQHA0VMOC_iss_0.html)

[57] ITER (literally meaning "the way" in Latin) is an international magnetic confinement experiment, planned to be built in France and designed to show the scientific and technological feasibility of a full-scale fusion power reactor. (www.wikipedia.org)

[58] Dubai is the second largest of the 7 Emirates which form the United Arab Emirates, or UAE, located in the Persian Gulf. Unlike the other emirates, Dubai has managed very successfully to diversify its economy in such a way that it relies on oil revenues for only 6% of its income. The rest is generated through port services, banking & finance, tourism, media services, etc.

mounted, and could cost several hundred billion dollars before it starts generating income (possibly $200 billion over and above the $100 billion spent on the ISS).

Below, is a summary of some of the key elements of a timeline as compared to the 6 implementation stages described earlier in the paper:

- I estimate the project to be completed and be built in about 20 years and to become profitable within 25 years. The 6 implementation stages of the project have been broken down as per the table below. In short,
    - preparations on Earth (including the R&D stage) are estimated to take 10 years;
    - shipping materials prior to the station's assembly at LEO would take about 5 years;
    - five years have been earmarked to assemble the station shell, its life support system and interior; and
    - another 5 years to inhabit it and make it profitable.

An estimated ratio of costs for each implementation stage has also been provided below:

| Implementation Stages | Duration | Estimated Share of Costs |
|---|---|---|
| 1) Preparations on Earth | Year 1-10 | 35% |
| 2) Shipping Materials to LEO | Year 10-15 | 15% |
| 3) Assembling Vademecum | Year 15-18 | 35% |
| 4) Create Artificial Gravity | | |
| 5) Installing Life Support System | Year 18-20 | 15% |
| 6) Inhabiting Vademecum | | |

**Table 10: Vademecum's Implementation Timeline and Costs**

- Needless to say that I consider this timeline very hypothetical. In reality, it is very difficult to judge how long such a complex multifaceted project will take. Things change rapidly in the world and if the right incentives are there, the project could be implemented somewhat faster. Otherwise, if the political/commercial incentives are not there, it could drag on for 30-40 years.

- Incentives could be based on economic and/or health motivations: To illustrate this point , if developing "emerging" countries maintain their economic growth at their current high levels (7% economic growth in developing countries in 2004 compared to 3% in rich countries)[59], they'll need massive amounts of raw materials, metals, and energy. This will result in an increase in the price of raw materials and energy, and create a situation where it will make economic sense to go get more materials in space. This should help accelerate the drive to expand

[59] The World Bank, Global Economic Prospects 2005

space exploration, with a primary commercial objective of material exploitation. Incentives could also be driven by pandemics: if the occurrence of new diseases (e.g., avian flu, SARS, Ebola, etc.) there will be an incentive to move elsewhere to guarantee the survival of the human race. So be it for commercial, health or purely survival reasons, the timeline for a project such as this one could change very dramatically depending on the situation and the motivation that drives it.

- Another factor that is likely to accelerate space research and exploration is that by the sheer fact that more countries become interested in space (China, India, Brazil now have their own space programs), R&D on space will mushroom in all parts of the world and a result, we are likely to achieve far more technological progress in a relatively shorter period of time.

Given the above factors that blur our capacity to be precise about the timeline for the project, let us assume the following facts: 6 implementation stages, 25 years to achieve profit, and massive funding needs in the order of several hundred billion dollars. I propose 4 sequential financing stages over the 20-year implementation period which link to the 6 implementation stages of the project as follows:

| **Implementation Stages** | **Financing Stages** | **Financing Structure** | **Duration** |
|---|---|---|---|
| 1) Preparations on Earth | 1) 100% government grant financing | Develop Fundraising Strategy | Year 1-10 |
| 2) Shipping Materials to LEO | 2) Bond Issuance, with at least 80% government guarantee | Develop Business Plan to present to potential private financiers | Year 10-15 |
| 3)Assembling Vademecum | 3) Sell shares to venture capitalists. Target: 40% government, 60% venture capital | Establish Management Company, with joint public-private ownership | Year 15-18 |
| 4) Create Artificial Gravity | | | |
| 5) Installing Life Support System | 4) IPO[60] | Vademecum becomes 100% private owned | Year 18-20 |
| 6) Inhabiting Vademecum | | | |

**Table 11: Vademecum's 4 financing stages**

A more detailed description of the 4 financing stages is provided below:

***Stage 1:*** For this stage of the project which consists of basic project preparation on Earth including conducting background R&D, it is expected that financing will be provided entirely by governments. Although some private firms may become interested in investing in space research (e.g., Bigelow, a Las Vegas start up company that initiated the TransHab project and other similar expandable space modules for space tourism, etc.), it is expected that the majority of the funding in the R&D stage will be provided by government grants. As I already mentioned above, as more and more emerging countries become interested in space exploration, it is likely that an increasing number of

[60] IPO stands for Initial Public Offering. This refers to the time when a company is put on the stock market so individuals/companies can start buying/selling its shares publicly.

governments get involved in supporting space research. It is therefore important to coordinate the various tracks/areas of research to avoid duplication and overlap and encourage complementarities between various projects.

***Stage 2:*** An important share of the project's cost will be incurred in stage 2 (Shipping materials from Earth to LEO), and more generally for transportation expenses (current launch costs vary from $2,000-$14,000 per pound for operational vehicles). I have estimated the cost of stage 2 to represent about 35% of total costs. I propose to finance these costs by issuing bonds that would have an important government backing (at least 80%). Yields for this type of high-risk bonds should be in the order of LIBOR[61] + 3% to be attractive. In parallel to raising money for this stage from the bond market, it is important to prepare Vademecum's business plan so as to prepare the ground for the third stage of financing arrangements.

***Stage 3:*** At this point, we should be starting to assemble Vademecum in orbit. Therefore, the prospects of starting to inhabit it and initiate material exploitation is nearing and it is time to approach a group of venture capitalists to finance the next financing stage of the project. At this point, it is essential to incorporate a management company for Vademecum with a joint private-public ownership structure. Given the relatively high financing risks remaining, only a few high-powered, high-risk/high-return venture capitalists would be able and interested in supporting this project. We will target them all (groups such as Carlyle[62] which are capable of investing tens of billions in relatively high-risk projects in high-risk regions of the world) and plan on raising up to 60% of the capital requirements of this stage through such financiers. The rest will remain in government hands.

***Stage 4:*** By year 18, we should be installing Vademecum's life support system. At this point, the prospects of important revenue generation are less than 10 years away and it is the propitious time to start the final stage of Vademecum's financing, i.e., the IPO stage. Vademecum's shares will be floated on the stock market and massive amounts of money can be generated from the public at large and from across the world for the remainder of the project.

Whereas large amounts of money will be needed over an extended period of time to support the implementation of Vademecum, we will have to develop a number of income generating activities which would, in time help off-set some of the station's running costs, and eventually turn it into a profitable money-making venture. Some of the potentially

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[61] LIBOR is a daily reference rate based on the interest rates at which banks offer to lend to other banks in the London wholesale interbank money market. It is used commonly as an international reference point for interest rates.

[62] The Carlyle Group is a Washington, D.C. based global private equity investment firm with more than $30 billion of equity capital in 2005. This large pool of money belongs to just 800 individuals from all over the world. The firm employs more than 300 investment professionals in 14 countries with multiple offices in North America, Europe and Asia. Carlyle focuses on leveraged buyouts, venture capital, real estate and high-yield investments.

income-generating activities include space tourism, renting space for research under micro-gravity conditions, doing and selling our own research to companies/governments, exploiting and marketing space/asteroid resources; possibly selling excess solar energy supplies to Earth. Several of these income generating ventures could be initiated in parallel so as to start generating income for Vademecum about 5 years after the project has been completed and the station has been inhabited.

As the saying goes, time is money, and without money, one cannot go very far. For such a complex and expensive project, the design of a sophisticated financing plan along the lines outlined above will be absolutely key. In the absence of almost unlimited amounts of money made available in time for the various stages of the project, there will be serious slippages, and public confidence in our project will falter. I therefore would like emphasize the absolutely crucial nature of this aspect of the project which could "make or break" the realization of this dream.

## 11. Conclusion:

In this paper, my attempt has been to come up with a realistic project, based on the premise that it should build on existing research and technology. In terms of methodology, I have presented ideas and options, and taken the reader through the analysis that lead me to decide on the final options for Vademecum.

To a large extent, my starting premise has been the ISS. I have referred to it numerous times in the paper, though my objective has been to create a bigger settlement (far beyond the 7 person capacity of the ISS), one that is permanent and has a life well beyond the relatively short lifespan of the ISS, one in which the inhabitants will enjoy Earth-like comfort (e.g., walk their dogs in the settlement's green zones), and one which will be able to ensure its own financial sustainability and autonomy.

Through the research, I came to realize that at this point, the obstacles for building a station in space are no longer technical or financial. I don't want to simplify the technical challenges, but with time and more research, it is very clear to me that we can solve the technical problems. The financial challenges are certainly mighty, no doubt, but just looking around us it is clear that when the will and the incentive is there to raise money, there can be plenty of it.

Once a strong incentive exists for humans to move over to space, they just will. The incentive could be economic (need for materials and resources) or could be linked to our security (environmental, health, defense). Happily or not, the day will come where we will feel compelled to move for any of the above reasons. Then, I hope that the massive research being conducted by space agencies, universities, research institutes, companies, etc. all around the world will be advanced enough to allow for a low-risk high-return first wave of space migration.

I can close where I started, with Jules Verne's quote: "Anything one man can imagine, other men can make real." Vademecum, LEDA, TEMIS, one of these projects will see the light of day sometime, I am sure.

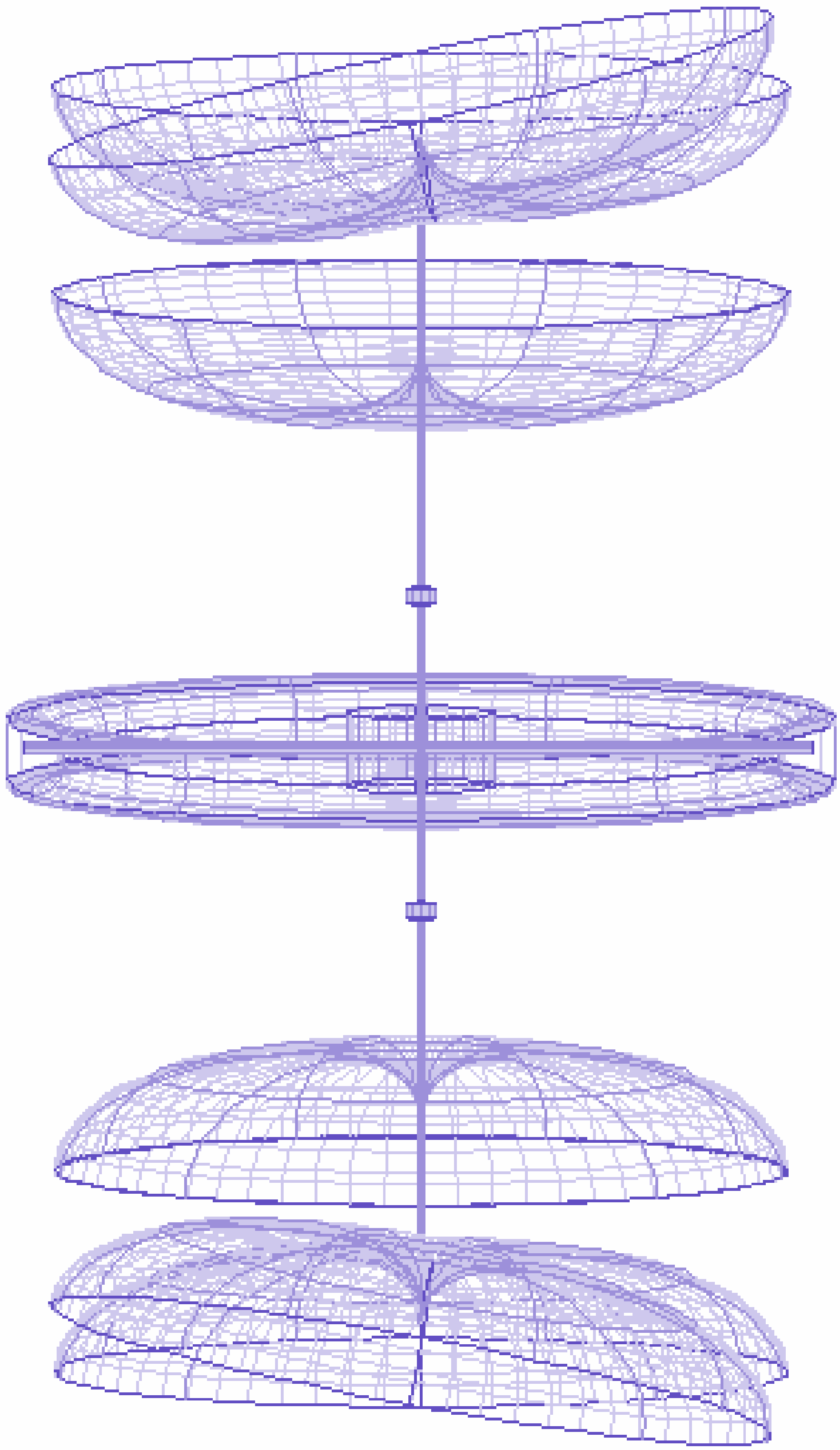

**Figure 16 - Vademecum with flexible mirrors (moving up/down and tilting sideways to maximize exposure to sunshine)**

## Annex 1

## The impact of living in a 0g environment on humans[63]

Exposure to 0g, i.e., to an environment of constant weightlessness is not well tolerated by humans, especially if people travel back-and-forth in different gravity areas and if such travels are frequent and within short time-spans. Long-term exposure to such circumstances has a series of consequences on humans. A brief listing of such impacts is provided below:

**fluid redistribution:** Bodily fluids shift from the lower extremities toward the head.

**fluid loss:** The brain interprets the increase of fluid in the head as an increase in total fluid volume. As a result, the rate of excretion of various fluids changes and among others, this results in the reduction of blood volume.

**electrolyte imbalances:** Changes in fluid distribution lead to imbalances in potassium and sodium and processes needed to maintain the environment necessary for cells to function properly.

**cardiovascular changes:** An increase of fluid in the thoracic area leads initially to increases in left ventricular volume and cardiac output.

**red blood cell loss:** Blood samples taken before and after American and Soviet flights have indicated a loss of as much as 0.5 liters of red blood cells.

**muscle damage:** Muscles atrophy and loss of tissue from lack of use.

**bone damage:** Bone tissue is deposited where needed and resorbed where not needed. Diet and exercise have been only partially effective in reducing the damage.

**hypercalcaemia:** Fluid loss and bone demineralization conspire to increase the concentration of calcium in the blood, with a consequent increase in the risk of developing kidney stones.

**immune system changes and interference with medical procedures:** The above changes affects the body's immune system and fluid redistribution affects the way drugs are taken up by the body, with important consequences for space pharmacology.

**vertigo and spatial disorientation:** As explained in detail in the above section, spatial disorientation can occur in artificial gravity. Similar feelings occur in weightlessness where one can experience arbitrary and unexpected changes in the sense of verticality.

**space adaptation syndrome:** About half of all astronauts and cosmonauts have been afflicted. Symptoms include nausea, vomiting, anorexia, headache, malaise, drowsiness, lethargy, pallor and sweating. The sickness usually subsides in 1-3 days.

**loss of exercise capacity:** This may be due to decreased motivation as well as physiological changes.

**degraded sense of smell and taste:** The increase of fluids in the head causes stuffiness similar to a head cold. Foods take on an aura of sameness and there is a craving for spices and strong flavorings such as peppers and mustard.

**weight loss:** Fluid loss, lack of exercise and diminished appetite result in weight loss.

**flatulence:** Digestive gas cannot "rise" toward the mouth and is more likely to pass through the other end of the digestive tract.

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[63] This annex extracted from www.wikipedia.org/wiki/Human_adaptation_to_space

**facial distortion:** The face becomes puffy and expressions become difficult to read, especially when viewed sideways or upside down. Voice pitch and tone are affected and speech becomes more nasal.

**changes in posture and stature:** The neutral body posture approaches the fetal position. The spine tends to lengthen.

**changes in coordination:** Earth-normal coordination unconsciously compensates for self-weight. In weightlessness, the muscular effort required to reach for and grab an object is reduced. Hence, there is a tendency to reach too far to grasp an object.

# Annex 2

## Living in Artificial Gravity: What happens when an object is in motion relative to its environment[64]

*"Note: The following nomenclature has been used in the calculations below.*
dots above indicate derivatives with respect to time:

| | |
|---|---|
| $X,Y,Z$ | Global inertial coordinates. |
| $x,y,z$ | Local environment coordinates. |
| $\mathbf{i},\mathbf{j},\mathbf{k}$ | Basis vectors. |
| $\mathbf{\Omega}$ | Angular velocity of $x,y,z$ relative to $X,Y,Z$. |
| $\mathbf{\omega}$ | Angular velocity of object relative to $X,Y,Z$. |
| $\mathbf{\lambda}$ | Angular velocity of object relative to $x,y,z$. |
| $\mathbf{R}, \dot{\mathbf{R}}, \ddot{\mathbf{R}}$ | Position, velocity, acceleration relative to $X,Y,Z$. |
| $\mathbf{r}, \dot{\mathbf{r}}, \ddot{\mathbf{r}}$ | Position, velocity, acceleration relative to $x,y,z$.( |
| $R,V,A$ | Magnitudes of $\mathbf{R}, \dot{\mathbf{R}}, \ddot{\mathbf{R}}$. |
| $r,v,a$ | Magnitudes of $\mathbf{r}, \dot{\mathbf{r}}, \ddot{\mathbf{r}}$. |
| $\mathbf{H}$ | Angular momentum. |
| $I$ | Moment of inertia. |
| $\mathbf{M}$ | Moment. |
| $g,g'$ | Magnitudes of natural and artificial gravity. |
| $t$ | Elapsed time. |
| $l,h$ | Arc distance and height relative to observer. |
| $r_f, r_h$ | Floor radius, height radius ($r_h = r_f - h$). |
| $r_c$ | Radius to midpoint of chord. |
| $s$ | Linear distance. |
| $\theta_1,\theta_2$ | Position angles in equations (5) and (6). |
| $\alpha$ | Velocity angle in equation (6). |
| $q$ | Quantity defined in equation (14). |
| $c$ | Arbitrary constant of integration. |

For a moving object in a rotating environment, the total acceleration in inertial space is:

$$\ddot{R} = -\Omega^2 r + 2\Omega \times \dot{r} + \ddot{r} \qquad (1)$$

The above considers that angular velocity is constant, and that the station's center of rotation is not accelerated.

[ $-\Omega^2 r$ ] represents centripetal acceleration associated with the angular velocity
[ $2\Omega \times \dot{r}$ ] represents the Coriolis acceleration associated with the relative velocity of the station

[64] This annex copied from "The Architecture of Artificial Gravity: Mathematical Musings on Designing for Life and Motion in a Centripetally Accelerated Environment, Thoedore W. Hall, University of Michigan, 1991".

[ $\ddot{r}$ ] represents the relative acceleration of the object

For circular motion at constant speed around the circumference of a rotating cylinder, the formula may be written:

$$r \perp \Omega\ , \quad \dot{r} \perp \Omega\ , \quad \dot{r} \perp r$$

$$\lambda = \frac{r \times r}{r^2}$$

$$\dot{r} = \lambda \times r$$

$$\ddot{R} = -\Omega^2 r + 2\Omega \times \dot{r} - \lambda^2 r \qquad (2a)$$
$$= -(\Omega + \lambda)^2\, r \qquad (2b)$$

In the design of rotating artificial gravity environments, only the first term in equation (2a) [ $-\Omega^2 r$ ] represents "design gravity". The others represent gravitational distortions that result from the motion of people and objects within the environment. The goal is to design the environment such that the first term alone yields some preferred acceleration while simultaneously minimizing the others. Equation (2a) suggests three strategies:

Restrict the direction of local motion to be parallel to the axis of rotation. In this case the second and third terms of equation (2a) vanish. Unfortunately, eccentric motion parallel to the axis tends to destabilize the rotation, causing the axis to wobble and invalidating the initial assumption of constant angular velocity.
Minimize the speed of local motion. This seems to imply some type of behavior modification, whether through individual experience and aversion to motion sickness, deliberate training, or some type of mechanical restraint.
Minimize the angular velocity of the environment. For a given centripetal acceleration, minimizing the angular velocity requires maximizing the radius, as dictated by the first term of equation (2a). The net effect is to minimize the other terms.

Equations (1) and (2) describe linear accelerations. Of equal importance are angular accelerations and changes in momentum. The momentum required to produce a change in angular momentum is:

$$M = \dot{H}_{XYZ}$$
$$= \dot{H}_{XYZ} + \Omega \times H$$

In the above, the second part of the equation [ $\Omega \times H$ ] is not expected. As with Coriolis acceleration, the unexpected term is a cross product of angular velocity of the station.

Experiments suggest that illusions of body and visual field angular motions are approximately proportional to the cross product of the angular velocities of the station. The disturbances caused by velocity and artificial gravity can be minimized through the following 3 strategies:

--Restrict the orientation of local rotation to be parallel to the rotation of the station.
--Minimize the angular velocity of the local rotation.
--Minimize the angular velocity of the environment.

On Earth, a plum bob at rest hangs vertically and the cord aligns with the gravitational force. If the cord is cut, the weight falls vertically down. In artificial gravity, a plumb bob at rest hangs radially away from the center and the cord aligns with the centripetal force. If the cord is cut, the weight does not fall radially as one might expect, but tangentially, perpendicular to the gravitational force. In other words, to an observer within the artificial gravity environment, the trajectory of the falling weight would not appear straight.

From an inertial point of view, the station will appear to be rotating in a set direct trajectory. From a rotating point of view, the station will appear motionless and the trajectory will appear as an involute curve. The figure below shows the inertial view. The next figure shows the trajectory as the person/spectator would see it. The dotted lines show the ball's inertial trajectory.

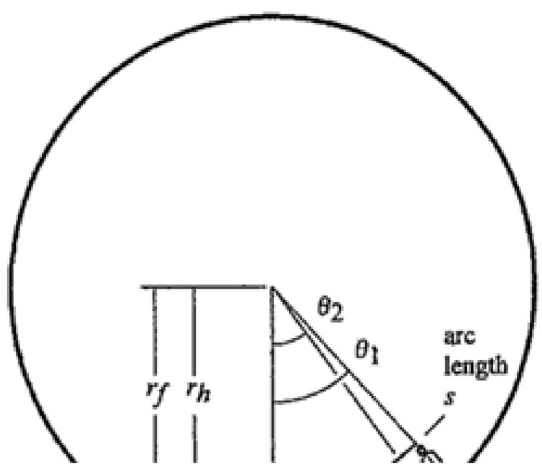


**Figure 17 Inertial view of dropped ball**

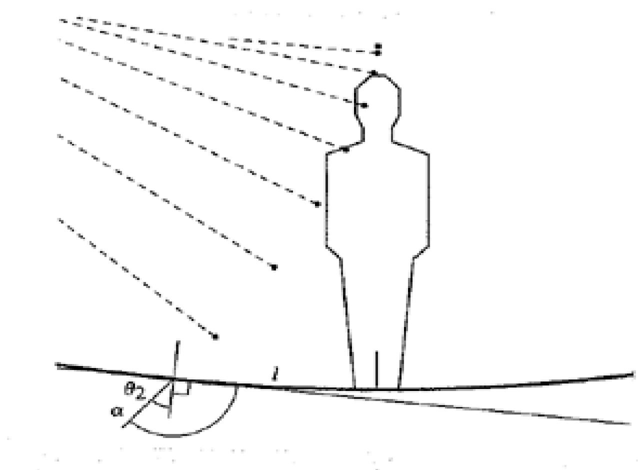


**Figure 18: Rotating view of dropped ball**

If the ball is dropped, it will change direction and fall somewhat west of its initial position. The deflection is dictated by the geometry (radius of the floor & height of the ball). The fall is therefore independent of the rotation rate. The radial position of the ball and the tangential distance it travels before it hits the floor are:

$$r_h = r_f - h$$

$$s = \sqrt{r_f^2 - r_h^2}$$

The ball's trajectory is a straight line subtending the angle of:

$$\theta_2 = \arctan\left(\frac{s}{r_h}\right)$$

The ball's deflection as measured along the floor is then:

$$\begin{aligned} l &= r_f\left(\theta_2 - \theta_1\right) \\ &= r_f\left(\arctan\left(\frac{s}{r_h}\right) - \frac{s}{r_h}\right) \end{aligned}$$

Where positive is east and negative is west. The deflection is always to the west because:

$$\forall\ x\ >\ 0:\ \arctan(x)\ <\ x$$

The velocity, speed and direction angle of the falling ball relative to the rotating floor at the point of impact are:

$$\dot{r} = \Omega r_h(\cos(-\theta_2)i + \sin(-\theta_2)j) - \Omega r_f i$$
$$= -\Omega \frac{s}{r_f}\left(s\ i + r_h\ j\right)$$

$$v = \Omega s$$

$$\alpha = -\frac{\pi}{2} - \theta_2$$
$$= -\frac{\pi}{2} - \arctan\left(\frac{s}{r_h}\right)$$

The speed v is directly proportional to the tangential distance of the fall.

The time it takes from the point of release to the point of impact is:

$$t = \frac{s}{\Omega r_h}$$

The figure below shows the relationship between floor radius and trajectory deflection for a ball dropped from a height of 2m. With a floor radius of 1000m, the deflection is a 2m drop is still more than 8cm.

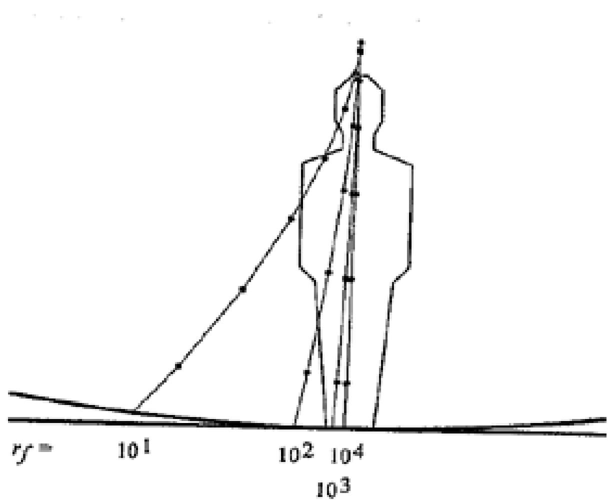


**Figure 19: Dropped a ball in artificial gravity: relationship of floor radius to trajectory deflection**

Obviously, if the ball were forcefully thrown, its behavior would be even more bizarre, especially if were thrown up and against the direction of rotation."

# Annex 3

## Another option for building Vademecum: drawing materials from Asteroids[65]

"It is indeed a very appealing option to draw materials from Asteroids for Vademecum's construction. Had it not been for the risks involved, it is certainly the option I would have chosen. Under such a scenario, I would have proposed to implement the project as follows:

- establishing a presence at LEO where the extracted materials from asteroids will be transported. LEO will be our storage and assembly facility; LEO can be manned to assemble, fix, test materials before dispatch to L5; and

- establishing a presence at HEO where the raw materials will be processed using the more solar energy. I suggest going to HEO because it will provide with abundant solar energy and longer exposure to sunlight – in other words, a more efficient processing of materials to build Vademecum's construction modules. HEO will therefore be our manufacturing plant. However, it is suggested to avoid or at least minimize the presence of workers at HEO given the risk of exposure to radiation. The work at HEO will therefore be largely done by tele-operated robots

The preparation stage will imply transporting the mining extraction material to the asteroid and anchoring it to the surface or sub-surface with bonded matrices. This may be difficult if the asteroid is made of unconsolidated material, in which case the anchoring will have to be made over a wider area. One can tie the spacecraft to the NEA by passing a rope around the entire asteroid, or drive-in pitons or fire in harpoons, screw in large screw-plates, etc. One must also take measures to contain the extracted asteroids.

The actual extraction is a considerable challenge. As stated earlier, there are already many known NEAs. It is estimated that there are at least 1000 NEAs with a diameter over 1km and that those with diameters above 100m may number at least 100,000. So there is an abundance of NEAs to draw materials from. There will be several factors which will determine how difficult the task will be: accessibility; astrodynamical considerations; trajectories; how to return to Earth's orbit; and those aspects related to the actual mining, extraction and production of the needed materials. We will study these various considerations below:

In space, the parameter which will measure the difficulty of obtaining mass from one orbit to the other is not the distance, but rather the required velocity change, or delta-v needed to perform the transfer. The table below provides some velocity increments

[65]This annex extracted from Ross Shayne, Near-Earth Asteroid Mining, CalTech Dec2001

needed for various transfers and demonstrates that it is generally far easier to go from LEO to anywhere else than from the Earth surface to LEO or other destinations.

| Transfer | Delta-V (km/s) |
|---|---|
| Earth surface to LEO | 8.5 |
| Earth surface to escape velocity | 11.2 |
| Earth surface to GEO | 11.8 |
| LEO to escape velocity | 3.2 |
| LEO to GEO | 3.5 |
| LEO to HEO[66] | 2.5 |
| LEO to Moon landing | 6.3 |
| LEO to Near Earth Asteroid[67] | 4.0 |
| Lunar surface to LEO | 2.4 |
| NEA to Earth transfer orbit | 1.0 |
| Phobos/Deimos[68] to LEO | 8.0 |

**Table 12: Velocities for various transfers**

It also appears from earlier research that 10% of NEAs are more accessible in terms of delta-v than the Moon and that it is far easier to return from them to Earth than from the Moon. It has been estimated[69] that about 90 known NEAs (6% of the known total) are more accessible than the Moon, i.e., that they have a minimum outbound delta-v from LEO of less than 6 km/s. Many more (about 200) have delta-v's of about 6.5 km/s.

Once we are at the Asteroid and the mining ear is well anchored into the surface, the mining process can start. The method will depend on the nature of the material which is being extracted. Recovering regolith is different from recovering solid metal, different again if the ores are in ice and volatiles. Loose material can be shoveled whereas hard material will have to be broken, disaggregated. It may require drilling or blasting. But generally, the following methods can be used:

loose regolith - - - scraper
competent silicate matrix - - drill and blast or cut
silicates and ices or hydrocarbons - vaporization
silicates and metal - - - cut or crush
extensive metal - - - cut

[66] Highly Eccentric Earth Orbit
[67] 4.0km/s is the minimum for known NEAs; 200 known NEAs are under 6.5km/s.
[68] Phobos and Deimos are asteroid-like moons of Mars
[69] Sonter, MJ, Near Earth Objects as Resources for Space Industrialization – Solar System Development Journal 1 (1) -31, 2001.

On Earth, most mining is done underground. It may be reasonable to use similar techniques on Asteroids because it makes containment of materials far easier; it also provides for richer materials since the surface may be depleted of the desired materials, and the resulting empty volume may itself be useful for storage."

# Annex 4

## Equations to calculate the location of the Lagrangian Points[70]

"$M_1$ and $M_2$ are two masses $\vec{r}_1$ and $\vec{r}_2$ are the respective positions of the two masses. The total force exerted on a third mass m at position $\vec{r}$ will be:

$$\vec{F} = -\frac{GM_1 m}{[\vec{r}-\vec{r}_1]^3}(\vec{r}-\vec{r}_1) - \frac{GM_2 m}{[\vec{r}-\vec{r}_2]^3}(\vec{r}-\vec{r}_2)$$

$\vec{r}_1$ and $\vec{r}_2$ are functions of time while $M_1$ and $M_2$ are orbiting each other.
If one solves the problem for M1 and M2, one may insert the orbital solution for $\vec{r}_1$ (t)and $\vec{r}_2$ (t) and find a solution to the equation of motion which maintain the relative positions of the 3 bodies fixed :

$$\vec{F}(t) = m\frac{d^2\vec{r}(t)}{dt^2}$$

These "stationary" solutions are the Lagrange points. To find these points is to consider a co-rotating frame of reference where the 2 largest masses hold fixed positions. This new frame of reference originates at the center of the mass and has an angular frequency Ω provided by Kepler's law:

$$\Omega^2 R^3 = G(M_1 + M_2)$$

R = distance between the two masses

There is a disadvantage in using a non-inertial frame of reference since we have to add a series of pseudo-forces to the equation of motion. The effective force in a frame rotating with angular velocity $\vec{\Omega}$ is related to the inertial force $\vec{F}$ according to the transformation

$$\vec{F}_\Omega = \vec{F} - 2m\left(\vec{\Omega}\times\frac{d\vec{r}}{dt}\right) - m\vec{\Omega}\times\left(\vec{\Omega}\times\vec{r}\right)$$

Now we have to correct for the Coriolis force as well as the centrifugal force. To get the generalized potential, we can use:

[70] This annex copied from http://www.physics.montana.edu/faculty/cornish/lagrange.pdf

$$U_\Omega = U - \vec{v}\times\left(\vec{\Omega}\times\vec{r}\right)+\frac{1}{2}\left(\vec{\Omega}\times\vec{r}\right)\times\left(\vec{\Omega}\times\vec{r}\right)$$

And for the generalized gradient:

$$\vec{F}_\Omega = -\nabla_{\vec{r}} U_\Omega + \frac{d}{dt}\left(\nabla_{\vec{v}} U_\Omega\right)$$

Although the positions of equilibrium points are not affected by the velocity dependent terms in the effective potential, they are important in assessing the dynamic stability of motion about the equilibrium points.

In the figure below, a plot of $U_\Omega$ with $\vec{v}$ = 0, M1 = 10, M2 = 1 and R = 10. The extreme of the generalized potential are labeled L1 –L5.

Insert figure on p.3

By choosing a set of Cartesian coordinates originating from the center of mass with the z axis aligned with the angular velocity, we have:

$$\vec{\Omega} = \Omega\hat{k}$$
$$\vec{r} = x(t)\hat{i} + y(t)\hat{j}$$
$$\vec{r}_1 = -\alpha R\hat{i}$$
$$\vec{r}_2 = \beta R\hat{i}$$

Where

$$\alpha = \frac{M_2}{M_1+M_2},\ \ \beta = \frac{M_1}{M_1+M_2}$$

To find the static equilibrium points we set the velocity at $\vec{v} = d\vec{r}/dt$ to zero and seek solutions to the equation $\vec{F}_\Omega = \vec{0}$ where

$$\vec{F}_\Omega = \Omega^2\left(x - \frac{\beta\left(x+\alpha R\right)R^3}{\left(\left(x+\alpha R\right)^2+y^2\right)^{3/2}} - \frac{\alpha\left(x-\beta R\right)R^3}{\left(\left(x-\beta R\right)^2+y^2\right)^{3/2}}\right)\hat{i}$$
$$\Omega^2\left(x - \frac{\beta y R^3}{\left(\left(x+\alpha R\right)^2+y^2\right)^{3/2}} - \frac{\alpha y R^3}{\left(\left(x-\beta R\right)^2+y^2\right)^{3/2}}\right)\hat{j}$$

Mass m is equal to unity without loss of generality. To find the equilibrium points with a brute-force approach, the magnitude of each force component should be set to zero, and we should then solve the coupled, fourteenth order equations for x and y. If one considers the problem from a physical angle, one could use the symmetries of the system to take us to the answer.

Since the system is reflection-symmetric about the x-axis, the y component of the force must vanish along this line. Setting y = 0 and $x = R(u + \beta)$ (u is meant to measure the distance from $M_2$ in units of R), the condition for the force to vanish along the x-axis reduces the chance of finding solutions to the three fifth-order equations

$$u^2\left((1-s_1)+3u+3u^2+u^3\right)=\alpha\left(s_0+2s_0u+(1+s_0-s_1)u^2+2u^3+u^4\right)$$

where,

$s_0 = sign(u)$
$s_1 = sign(u+1)$
The three cases have $(s_0, s_1)$ = (-1,1), (1,1), (-1,-1), whereas the case (1, -1) cannot occur.

In each of the three cases, there is one real root to the quintic equation, giving us the positions of the first 3 Lagrange points. Closed-form solutions to equation (10) are not possible to find for general values of $\alpha$, so instead we are seeking approximate solutions valid in the limit $\alpha \ll 1$. To the lowest order in $\alpha$, we find the first 3 Lagrange points to be positioned at:

$$L1: \quad \left(R\left[1-\left(\frac{\alpha}{3}\right)^{1/3}\right],0\right),$$

$$L2: \quad \left(R\left[1+\left(\frac{\alpha}{3}\right)^{1/3}\right],0\right),$$

$$L3: \quad \left(-R\left[1+\frac{5}{12}\alpha\right],0\right).$$

For the Earth-Sun system $\alpha \approx 3\times10^{-6}$, $R = 1AU \approx 1.5\times10^{8}\,km$

L1 lies on the line defined by the two large masses $M_1$ and $M_2$ and between them. L2 lies on the line defined by the two large masses, beyond the smaller of the two. Sun-Earth L2 is a good spot for space-based observatories. Because an object around L2 will maintain the same orientation with respect to the Sun and Earth, shielding and calibration are much simpler. L3 lies on the line defined by the two large masses, beyond the larger of the two.

To identify the location of the other two points, we need to balance the centrifugal force, which acts in a direction radially outward from the center of mass, with the gravitational force exerted by the two masses. Clearly, force balance in the direction perpendicular to centrifugal force will only involve gravitational forces. This suggests that the force should go into directions parallel and perpendicular to $\vec{r}$. The projection vectors are $x\hat{i}+y\hat{j}$ and $y\hat{i}-x\hat{j}$. The perpendicular projection yields

$$F_{\Omega}^{\perp}=\alpha\beta y\Omega^2R^3\left(\frac{1}{\left((x-R\beta)^2+y^2\right)^{3/2}}-\frac{1}{\left((x+R\alpha)^2+y^2\right)^{3/2}}\right)$$

Setting $F_{\Omega}^{\perp}=0$ and $y\neq 0$ tells us that the equilibrium points must be equidistant from the two masses. Using this, the parallel projection would read:

$$F_{\Omega}^{\parallel}=\Omega^2\frac{x^2+y^2}{R}\left(\frac{1}{R^3}-\frac{1}{\left((x-R\beta)^2+y^2\right)^{3/2}}\right)$$

Demanding that the parallel component of the force vanish leads to the condition that the equilibrium points are at a distance R from each mass. In other words, L4 is situated at the vertex of an equilateral triangle, with the two masses forming the other two vertices. L5 is obtained by a mirror reflection of L4 about the x-axis. Explicitly, L4 and L5 have the following coordinates:

$$L4:\quad \left(\frac{R}{2}\left(\frac{M_1-M_2}{M_1+M_2}\right),\frac{\sqrt{3}}{2}R\right),$$
$$L5:\quad \left(\frac{R}{2}\left(\frac{M_1-M_2}{M_1+M_2}\right),-\frac{\sqrt{3}}{2}R\right).$$

The L4 and L5 points thus lie at the third point of an equilateral triangle with the base of the line defined by the two masses, such that the point is ahead of, or behind, the smaller mass in its orbit around the larger mass.

After having determined the equilibrium points within the restricted three-body system, we need to determine whether these points are stable enough to host Vademecum. One way to do this is to look at the shape of the effective potential to determine whether the equilibrium points occur at hills, valleys or saddles. However, this method fails when we have a velocity dependent potential. What can be done instead is to perform a linear stability analysis about each Lagrange point. This entails linearizing the equation of motion about each equilibrium solution and solving for small departures from equilibrium as follows:

$$x = x_i + \delta x, \quad v_x = \delta v_x,$$
$$x = y_i + \delta y, \quad v_y = \delta v_y,$$

$(x_i, y_i)$ is the position of the i-th Lagrange point, the linearized equations of motion become

$$\frac{d}{dt}\begin{pmatrix} \delta x \\ \delta y \\ \delta v_x \\ \delta v_y \end{pmatrix} = \begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ \frac{d^2U_\Omega}{dx^2} & \frac{d^2U_\Omega}{dxdy} & 0 & 2\Omega \\ \frac{d^2U_\Omega}{dydx} & \frac{d^2U_\Omega}{dy^2} & -2\Omega & 0 \end{pmatrix}\begin{pmatrix} \delta x \\ \delta y \\ \delta v_x \\ \delta v_y \end{pmatrix}$$

The second derivatives of $U_\Omega$ are evaluated at $\vec{r} = (x_i, y_i)$.

The stability of L1 and L2 of the Earth-Sun system is important. For example, the solar observatory SOHO is currently parked at L1, and NASA plans to send Microwave Anisotropy Probes (MAP) to L2. It is also possible that the Next Generation Space Telescope (NGST) will be stationed in at L2.

The curvature of the effective potential near L1 and L2 reveals them to be saddle points:

$$\frac{d^2U_\Omega}{dx^2} = \mp 9\Omega^2, \quad \frac{d^2U_\Omega}{dy^2} = \pm 3\Omega^2, \quad \frac{d^2U_\Omega}{dxdy} = \frac{d^2U_\Omega}{dydx} = 0$$

Solving for the eigenvalues[71] of the linearized evolution, we find:

$$\lambda_\pm = \pm\Omega\sqrt{1+2\sqrt{7}} \quad and \quad \sigma_\pm = \pm i\Omega\sqrt{2\sqrt{7}-1}$$

The presence of a positive, real root tells us that L1 and L2 are dynamically unstable. Small departures from equilibrium will grow exponentially with an e-folding time of

$$\tau = \frac{1}{\lambda_+} \approx \frac{2}{5\Omega}$$

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[71] In mathematics, an **eigenvector** of a transformation is a non-null vector whose direction is unchanged by that transformation. The factor by which the magnitude is scaled is called the **eigenvalue** of that vector.

For the Earth-Sun system $\Omega = 2\pi year^{-1}$ and $\tau \approx 23$ days. In other words, a satellite parked at L1 or L2 will wander off after a few months unless course corrections are made.

The L3 Point is very unstable and a weak saddle point of the effective potential with curvature

$$\frac{d^2U_\Omega}{dx^2} = -3\Omega^2, \quad \frac{d^2U_\Omega}{dy^2} = \frac{7M_2}{8M_1}\Omega^2, \quad \frac{d^2U_\Omega}{dxdy} = \frac{d^2U_\Omega}{dydx} = 0$$

To leading order in M2/M1, the eigenvalues of the linearized evolution matrix are:

$$\lambda_\pm = \pm\Omega\sqrt{\frac{3M_1}{8M_2}} \quad \text{and} \quad \sigma_\pm = \pm i\Omega\sqrt{7}\ .$$

L3's orbit is exponentially unstable, with an e-folding time of roughly $\tau = 150$ years.

The stability analysis around L4 and L5 is rather surprising. While these points correspond to local maxima of the generalized potential, which usually implies a state of unstable equilibrium, they are in fact stable. Their stability is due to the Coriolis force. Initially a mass situated near L4 or L5 will tend to slide down the potential, but as it does so it picks up speed and the Coriolis force kicks in, sending it into an orbit around the Lagrange point. The effect is similar to when a hurricane forms on the surface of the Earth: as air rushes into a low pressure system it begins to rotate because of the Coriolis force and a stable vortex is formed. The curvature of the potential near L4 is given by:

$$\frac{d^2U_\Omega}{dx^2} = \frac{3}{4}\Omega^2, \quad \frac{d^2U_\Omega}{dy^2} = \frac{9}{4}\Omega^2, \quad \frac{d^2U_\Omega}{dxdy} = \frac{d^2U_\Omega}{dydx} = \frac{3\sqrt{3}}{4}\kappa\Omega^2$$

Where $\kappa = (M_1 - M_2)/(M_1 + M_2)$. The Eigenvalues of the linearized evolution matrix are found to equal:

$$\lambda_\pm = \pm i\frac{\Omega}{2}\sqrt{2-\sqrt{27\kappa^2-23}}$$
$$\sigma_\pm = \pm i\frac{\Omega}{2}\sqrt{2+\sqrt{27\kappa^2-23}}$$

The L4 point will be stable if the eigenvalues are imaginary. This will be true if

$$\kappa^2 \geq \frac{23}{27} \quad \text{and} \quad \sqrt{27\kappa^2-23} \leq 2$$

The second condition is always satisfied, while the first requires

$$M_1 \geq 25 M_2 \left( \frac{1+\sqrt{1-4/625}}{2} \right)$$

When L4 and L5 yield stable orbits they are referred to as the Trojan points after the 3 Trojan Asteroids, Agamemnon, Achilles and Hector, found at the L4 and L5 points of Jupiter's orbit. The mass rations in the Earth-Sun and Earth-Moon system are easily large enough for their L4 and L5 points to be home to Trojan satellites, though none have been found to date.

Given the stable characteristics of L4 and L5 either could be selected to host Vademecum. Either one would be reasonably accessible from both Earth and Moon".

# Annex 5

## Optional Transportation beyond LEO[72]

Once we have decided that it is safe to move Vademecum further out in space, from LEO to L4/L5, we would use solar sails as a transportation mechanism. The concept of solar sails was first proposed by Johannes Kepler[73] nearly 400 years ago. While Europe was much involved in naval exploration at the time, Kepler proposed to explore space using sails. He observed that comet tails were blown around by some kind of solar breeze. He therefore thought sails could capture that wind to propel spacecrafts the way winds move ships in the oceans. While Kepler's ideas were disproved, scientists have since discovered that sunlight does exert enough force to move objects in space. To take advantage of this force, NASA and other space agencies (including the Japanese Space Agency) have experimented with giant solar sails that could be pushed through the cosmos by light.

There are two pre-requisites to the solar sail-powered spacecraft:

- The need for a continuous force exerted by sunlight; and
- A sail made of lightweight materials including a large heat-resistant mirror.

Solar sails have only recently been confirmed as useful since it is only recently that technological advances have allowed for the above two conditions to be met. So far, materials were not light enough; and mirrors were not reflective and temperature resistant enough to be worth considering. Today, solar sails are made with very lightweight highly reflective material that is more than 100 times thinner than an average sheet of paper. This material is called CP-1. Another material currently being studied is an aluminum-reinforced Mylar that is approximately the thickness of a 1-ply plastic trash bag.

Light is composed of electromagnetic radiation that exerts force on objects it comes in contact with. This is why the reflective nature of the sail is so important because as photons (light particles) bounce off the reflective material, they gently push the sail along by transferring momentum to it. Because sunlight has so many photons and since they are constantly hitting the sail, there is constant pressure and thus a constant acceleration of the sail. Although the force of a solar-sail is initially less than that of a conventional chemical rocket, the solar-sail constantly accelerates overtime and achieves a greater velocity (like the tale of the "Tortoise and the Hare" with the rocket-propelled engine being the hare especially since the rocket-propelled ship will sooner or later run out of power in space, contrary to the sail which has an endless supply of power from the sun).

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[72] This annex extracted from www.howstuffworks.org, www.wikipedia.org

[73] German astronomer, born in 1571. He was a great inventor. Among others, he was the firs to explain planetary motion and to invent eyeglasses.

It is estimated that these sails could eventually travel at about 90km/sec, i.e., 10 times faster than the space shuttle's orbital speed of 8km/sec. When the sail is in the shade, a laser could take over to continue to provide the necessary propulsion to move the sail.

# Bibliography

## Papers/Articles

American Institute of Aeronautics and Astronautics (AIAA), and Space Studies Institute (SSI) – The Architecture of Artificial Gravity: Mathematical Musings on Designing for Life and Motion in a Centripetally Accelerated Environment – Theodore W. Hall in Space Manufacturing 8 Energy and Materials from Space, p. 177-186, November 1991

AIAA and SSI – The Architecture of Artificial Gravity: Theory, Form, and Function in the High Frontier – Theodore W. Hall in Space Manufacturing 10 Pathways to the High Frontier, p. 182-192, August 1995

AIAA and SSI – The Architecture of Artificial Gravity: Archetypes and Transformations of Terrestrial Design – Theodore W. Hall in Space Manufacturing 9 The High Frontier Accession, Development and Utilization, p. 198-209, September 1993

AIAA – Inhabiting Artificial Gravity – Theodore W. Hall, September 1999

AIAA – Asteroid Retrieval by Rotary Rocket – Jerome Pearson, January 1980

Antarctic Treaty Papers: A Brief History of the Antarctic Treaty System – Jack A. Bobo, Esq.

Asteroid Exploration and Utilization, The Hawking Explorer – Dr. George Botbyl – University of Texas at Austin, December 1991

Design Overview of an Asteroid Sample Return Capsule – Yoshifumi Inatani, and Nobuaki Ishii

Disturbing the Solar System – Alan E. Rubin – Princeton University Press, 2002

Evaluation of Direct Osmosis for Wastewater Treatment for Long Term Missions in Space – University of Nevada – Tzahi Y. Cath – November 2003 (slideshow)

The Harvard Gazette – $15 million grant will study bacteria at work – William J. Cromie, October 17, 2002

The Harvard Gazette – Pushing the envelope – Ken Gewertz, July 19, 2001

Interior Design for a Space Module – Martina Pinni, Arch.

ISS Water Recovery System – Hailey Hartwell (slideshow)

Laser-Trapped Mirrors in Space – Elizabeth McCormack (slideshow) – NIAC, 2002

LEDA – NASA Ames Research Center Annual Space Settlement Contest 2004 – Barsan Flaviu Valentin, Costea Dan Andrei, and Sigovan Carmen Maria

The Lunar Space Elevator – Jerome Pearson, Eugene Levin, John Oldson, and Harry Wykes – 55th International Astronomical Congress, Canada, October 2004

Mining the Foundation of the Future – Joe Fledderman, Kevin Sloan - Penn State University, 2001

NASA, JPL - Technical Support Package: Patched Off-Axis Bending/Twisting Actuators for Thin Mirrors – NASA Tech Briefs

NASA, Technical Support Package: Design Concepts for the ISS TransHab Module – NASA Tech Briefs – Lyndon B. Johnson Space Center

NASA, JPL - Technical Support Package: Multi-Layer Laminated Thin Films for Inflatable Structures – NASA Tech Briefs

NASA, Science and Technology Research Directions for the International Space Station

NASA, The Right Stuff for Super Spaceships – Science@NASA

NASA, The Pathway Less Travelled – Science@NASA

NASA, Waste Not – Science@NASA

NASA, Spinning Brains – Science@NASA

NASA, Have Blood, Will Travel – Science@NASA

NASA, Candlestick Rocket Ship – Science@NASA

NASA Glenn Research Center – Aerospace Flywheel Development Overview, Power and Propulsion Office

NASA SP-428, Retrieval of Asteroidal Materials – O'Leary et al. – Space Resources and Settlements

NASA/CR – Advanced Life Support Baseline Values and Assumptions Document – Lockheed Martin Space Operations– Anthony J. Hanford, August 2004

NASA/MAP – The Lagrange Points – Neil J. Cornish with input from Jeremy Goodman, 1999

NASA/TM – Exposure of Polymer Film Thermal Control Materials on the Materials International Space Station Experiment (MISSE) – Joyce Dever, Sharon Miller, et al., February 2002

Near-Earth Asteroid Mining – Caltech – Shane D. Ross, p. 107-181, December 2001

Near Earth Objects as Resources for Space Industrialization – Mark Sonter – Solar System Development Journal, August 2001

Online Searching with an Autonomous Robot – Sandor P. Fekete, Rolf Klein, and Andrea Nuchter, Germany, April 2004

Overall Design of Moon and Mars Colonies – Fillippo De Rose et al., Breman, Germany, September 2003

A Review of Fifty Years of Space Nuclear Fuel Development Programs – Samim Anghaie and Paul Harris – University of Florida

Sasakawa International Center for Space Architecture (SISCA) Outreach – The Manned Lunar Outpost (MLO): a NASA/USRA-Sponsored Study, December 1989

SISCA Outreach – Planetary Missions and Settlements, September 1987

SISCA Outreach – Project Leap, August 1987

SISCA Outreach – The SpacePost Project, December 1987

SISCA Outreach – In Pursuit of International Space Benefits, July 1987

SISCA Outreach – The Artificial Gravity Science & Excursion Vehicle (AGSEV)

SISCA Outreach – Space Radiation Health Hazards: Assessing and Mitigating the Risks, September 1989

SISCA Outreach – Astrotectonics: Construction Requirements and Methods in Space, June 1989

SISCA Outreach – Inflatable Space Structures, June 1988

SISCA Outreach – Living in Space: Considerations for Planning Human Habitats Beyond Earth, December 1988

Spaceport News - Plant experiment helps provide air and water on ISS – September 19, 2003

The Space Environment and its Interaction with Space Travellers – Prof. Dava Newman (slideshow) – Massachusetts Institute of Technology

TEBA - NASA Ames Research Center Annual Space Settlement Contest 2003 – Horia Mihail Teodorescu and Lucian Gabriel Bahrin

The Technical and Economic Feasibility of Mining the Near-Earth Asteroids – Mark Sonter – Space Future, October 1998

United Nations – Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies

Update on International Space Station Nickel-Hydrogen Battery On-Orbit Performance – American Institute of Aeronautics and Astronautics – Fred Cohen and Penni Dalton

The World Bank, Global Economic Prospects 2005

## Books

Un peu de Science pour tout le Monde – Claude Allègre – Fayard, France, 2003

The Complete Idiot's Guide to NASA – Veteran Astronaut Thomas D. Jones, Ph.D., and Michael Benson – Alpha, 2002

The Complete Idiot's Guide to Theories of the Universe – Gary F. Moring, M. A. – Alpha, 2002

The Complete Idiot's Guide to The Sun – Jay M. Pasachoff, Ph. D. – Alpha, 2003

Entering Space – Robert Zubrin – Tarcher/Penguin, 1999

Du Côté de la Découverte : Astronomie – Hachette, France, 2002

Cosmos – Carl Sagan – Random House, 1980

## Websites

http://www.adl.gatech.edu/research/tff/ph1final_radio.html - Task Report: Exploration of large-scale construction using Radio Waves

http://www.antarctica.ac.uk/About_Antarctica/Treaty/treatyperu.html - The Antarctic Treaty Explained http://www.ari.net/moon/forum/mp/mp-4/bootstrap.html - Bootstrapping Space Communities with Micro Rovers and High Tensile Boot Laces (Tethers)

http://www.artificial-gravity.com/ssi-1991-hall.pdf - Architecture of Artificial Gravity

http://www.artificial-gravity.com/sw/SpinCalc/SpinCalc.htm – Artificial Gravity

http://www.asi.org/adb/m/02/07/apollo-cost.html - Artemis Project

http://www.asi.org/adb/02/06/index.html - Study on Inflatable Lunar Habitats

http://www.belmont.k12.ca.us/ralston/programs/itech/SpaceSettlement/designer/sphere.html - Cylinder-Space Settlements

http://www.bioproducts-bioenergy.gov/about/presentation2.asp - Biomass Research & Development Initiative

http://www.boeing.com/commercial/777family/background/back5.html - Boeing Composite Materials

http://www.cygo.com/cgi-bin/yabb/yabb.pl?board=spacecities – Space Cities

http://www.cygo.com/wsd/index.php - The CYGO Library

http://www.estec.esa.nl/structures/images/infworkshop2002.pdf - Materials to build the space station

http://www.howstuffworks.com – General research in science pages

http://hyperphysics.phy-astr.gsu.edu – Artificial Gravity

http://www.lifeinuniverse.org/noflash/LIScolony-09-01-03.html - Colonisation and Space Cities

http://web.mit.edu/12.000/www/finalpresentation/environment/radgrav.html - Radiation and Zero-G

http://www.ll.mit.edu/ST/sbv/rad_in_space.html - MIT - Radiation in Space

http://paperairplane.mit.edu/16.432J/Space /sbe/description/schedule_2003.htm – MIT – Space Biomedical Engineering &Life Support Syllabus

http://paperairplane.mit.edu/16.432J/Space /sbe/eva/eva/space_env.htm – MIT – The Space Environment

http://www.physics.montana.edu/faculty/cornish/lagrange.pdf - The Lagrange Points
http://www.nada.kth.se/~asa/dysonFAQ.html - Dyson FAQ

http://www.nas.nasa.gov/services/education/spacesettlement/basics/wwwwh.html#who – Space Settlement Basics

http://www.grc.nasa.gov/www/aero/base/zero.htm - NASA Glenn Research Center – Zero CO2 Research Project

http://www.nasa.gov/vision/space/travelinginspace/radiation_shielding.html - Radiation Shielding

http://www.nasatech.com/briefs/jan01/msc22900.html - Advanced Rigid/Inflatable Spacecraft Habitation Module

http://www.nasatech.com/briefs/nov00/msc22957.html - PBO Fiber Blends: A Promise for the Future

http://trs.nis.nasa.gov/archive/00000696/01/tm213688.pdf - Radiation Shielding

http://ifmp.nasa.gov/codeb/budget2001/html/fy01_hsf_ss.htm - ISS Fiscal Year 2001 Estimates Budget Summary

http://lifesci3.arc.nasa.gov/SpaceSettlement/designer/sphere.html - NASA Ames/Stanford 1975 Summer Study

http://lifesci3.arc.nasa.gov/spacesettlement/75summerstudy/ - Summer Study 1975

http://lifesci.arc.nasa.gov/lis/programs/cosmos/cosmos_after_1990/1990.html - Programs, Missions, and Payloads

http://www.oosa.unvienna.org/treat/ost/outersptxt.htm - UN Treaty on Space

http://www.nsf.gov/od/opp/antarct/anttrty.htm - The Antarctic Treaty

www.rso.cornell.edu/scitech/archive/97sum/plants.html - Hydroponic Agriculture

http://peswiki.com/index.php/Directory:Nanotechnology – Nanotechnology

http://www.popsci.com/popsci/aviationspace/dde95b4a1db84010vgnvcm1000004eecbccdrcrd.html - MIR Fire Problem

http://physics.bu.edu/~duffy/py105/Rotationalkin.html – Artificial Gravity

http://www.space.gc.ca/asc/eng/esa_sectors/space_science/life_science/raisa.asp - CSA - Space Life Sciences

http://www.spaceprojects.com/iss/ - ISS Cost

http://www.src.le.ac.uk/projects/swift/summary.html - Swift - University of Leicester

http://www.scientific.co.uk/aerospace/webres/interplanetarypropulsion.htm - Aerospace Scientific Research on Interplanetary Propulsion

http://www.techbriefs.com/news/apr05/recycling_040405.html - Advanced Water Recycling for Use in Space & on Earth

http://www.ucsusa.org/clean_energy/renewable_energy/page.cfm?pageID=78 – How Biomass Energy Works

http://en.wikipedia.org/wiki/Initial_public_offering - Initial Public Offering

http://en.wikipedia.org/wiki/high_earth_orbit - High Earth Orbit

http://en.wikipedia.org/wiki/low_earth_orbit - Low Earth Orbit

http://en.wikipedia.org/wiki/lagrange_point - Lagrange Point

http://en.wikipedia.org/wiki/materials_science - Materials Science

http://en.wikipedia.org/wiki/moon - Moon

http://en.wikipedia.org/wiki/hohmann_transfer_orbit - Hhmann Transfer Orbit

http://en.wikipedia.org/wiki/heat_shield - Atmospheric reentry

http://en.wikipedia.org/wiki/Human_adaptation_to_space - Human Adaptation to Space

http://en.wikipedia.org/wiki/composite_materials - Composite Materials

http://en.wikipedia.org/wiki/hydroponics - Hydroponics

http://en.wikipedia.org/wiki/coriolis_force - Coriolis Effect