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# Use of a Lunar Outpost for Developing Space Settlement Technologies

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**While space settlement/colonization appears technically achievable in the 1 to 5 AU region containing the Moon, Mars, and small bodies, its cost has so far seemed too high to seriously consider initiating any related efforts. However, the NASA Vision for Space Exploration (VSE) may have the necessary scope to support the eventual development of a test-bed for the technologies required for space settlement in this region. The polar lunar outpost being considered in the VSE can provide a starting point for developing a lunar surface habitat with a 1-G level of gravity, an Earth-surface level of radiation and a Closed Ecological Life Support System (CELSS). Biosphere II provides an initial estimate of what is required for an eight-person habitat with a CELSS. The VSE outpost includes Lunar In-Situ Resource Utilization (ISRU), which has the potential of being enlarged to provide most of the material needed for the habitat, including the structure of a centrifuge to supply artificial gravity, the shielding for radiation protection and the atmosphere, water and soil for a CELSS. The full development of this lunar habitat will also require the long-term development of an Earth-Moon logistics system that goes beyond the scale currently envisioned in the VSE. In the nearer term, such a lunar habitat and its ISRU/logistics infrastructure can significantly enhance the Moon's utility by extending the time that humans can remain on the Moon and reducing the need for supplies from Earth. In the longer term, the technologies associated with the habitat and its infrastructure can provide the basis for a feasible approach to space settlement.**

## I. Introduction

The focus of this study is an initial concept for a lunar-surface habitat that provides an Earth-surface gravity and radiation environment, plus a Closed Ecological Life Support System (CELSS) to minimize the need for logistics support from Earth. A CELSS is here defined as a materially closed system that employs natural processes, such as plant and animal growth, to regenerate the atmosphere, water, and food that humans need. While such a habitat can facilitate human activities on the moon, its more fundamental importance is seen as the contribution it could make to space settlement, which is here considered synonymous with space colonization. Section II reviews the status of space settlement and what is required to make progress in that direction. Section III presents one concept for the lunar habitat just referred to. Section IV examines what is required to develop such a habitat. Section V addresses how this habitat and the infrastructure to develop it could then be applied to the larger objective of space settlement.

## II. Status of Space Settlement

### A. Appeal

The underlying logic of space settlement or colonization is clear. It is premised on the innate desire of humans for growth and new frontiers, as well as the desire to avoid threats to the human species as a whole. These threats include natural ones (disease, asteroid impact, nearby stellar explosion, disturbances of the sun, destructive process from inside the earth, etc) as well as human-induced ones (warfare, destruction of the environment, global societal breakdown).

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Support for space settlement has been expressed by a number of leading figures. A few examples follow.

*1*. The originator of the fundamentals of space flight technology, Konstantin Tsiolkovsky, first recognized its promise about 100 years ago and said, "Men….will reach other Suns, and use their fresh energy instead of the energy of their dying luminary[1]."

*2*. In 1975 NASA sponsored a space settlement study that developed a detailed and seemingly achievable plan for a community of 10,000 located at the Earth-Moon L5 point[2]. The foreword to the report resulting from this study contained the following statement by James C. Fletcher, the NASA administrator at that time, "…, settlement in space is not an authorized program, and no man can now say if or when such a dazzling venture may be formally undertaken. But by their efforts to put numbers on an idea, to assess the human and economic implications as well as technical feasibility, the participants in this effort have provided us with a vision that will engage our imagination and stretch our minds."

*3.* An informative and serious discussion of rationale and approaches for space settlement was developed in a 1986 document Pioneering the Space Frontier - Report of the National Commission on Space[3], which was appointed by President Reagan and chaired by former NASA Administrator Thomas Paine. One of the Commission's findings was that, "Exploration and settlement have an additional close connection because the distances we must traverse to reach all objects in space beyond our Moon are so great, and the times required to reach them are so long, that humans can best travel to them in ships that are much like movable settlements[3]."

*4.* More recently, in 2005, the current NASA administrator, Michael Griffin, stated, "If we humans want to survive for hundreds of thousands or millions of years, we must ultimately populate other planets[4]."

**B. Challenge**

Despite this widespread recognition that space settlement is important, nothing more than small studies has resulted. The primary reason seems to be that space settlement is viewed as so challenging that there does not seem to be any realistic way to approach it. If space settlement is defined as humans living around other stars, then it is clear that current scientific knowledge is inadequate to support such an undertaking at this time. However, if space settlement is limited to a 1 to 5 AU region (which contains the Moon, Mars, and small bodies such as comets and asteroids), and if space settlements in this region are designed to provide Earth-like gravity and radiation environments, then the objective looks technically feasible. Yet, despite apparent technical feasibility, the total estimated cost has continued to look too great to justify initiating such an effort.

**C. Possible Approach**

With the 2004 initiation of the NASA Vision for Space Exploration (VSE), the planned architecture of future space missions may have changed enough to warrant a re-examination of whether there might exist an economically feasible path to space settlement in the region of 1 to 5 AU.

Supported by the White House and Congress, the VSE includes the major goal to "Use lunar exploration activities to further science, and to develop and test new approaches, technologies, and systems, including use of lunar and other space resources, to support sustained human space exploration to Mars and other destinations[5]." While this is not an explicit plan for space settlement, it appears to have the scope to support such an objective through its intent to make use of lunar resources and enable open-ended human space exploration. The NASA VSE also appears to be open to international partnering, which potentially allows more to be accomplished. According to the current NASA administrator, "We hope to enlist international partners, to bring some of the elements that we won't be able to afford to build. We don't have big habitats, laboratories, power stations, things like that for a lunar base. We don't have them in our budget.[6]"

Although the NASA VSE program and its international components are far from being concretely defined, much of VSE study to date has been focused on the development of a permanently crewed lunar base at one of the two lunar poles. Such a base can provide significant support for developing a lunar habitat having a CELSS and providing an Earth-like environment with respect to radiation protection and gravity.

While the development of such a habitat looks like it will require a significantly more capable infrastructure (particularly in the areas of Earth-Moon logistics and lunar ISRU) than is now planned in the VSE, this augmented infrastructure and the habitat can, in the nearer term, greatly enhance the utility of the Moon, and, in the long term, provide most, if not all, of the fundamental building blocks for space settlement in the 1 to 5 AU region. Therefore, it appears useful to look at the development of such a habitat in more detail.

## III. A Lunar Habitat with CELSS and Earth-Surface-like Radiation and Gravity

### A. CELSS Support Requirements

The best currently available data for what is required to support a CELSS seems to come from Biosphere II, whose CELSS sustained eight people for two years, from Sep 26, 1991 until Sep 26, 1993. Figure 1 is a photograph of the overall Biosphere II enclosure. Figure 2 illustrates the different Biomes (environments) within the enclosure. Even though Biosphere II had numerous flaws, such as the disappearance of enough atmospheric oxygen during the two-year closure to require two new injections of pure oxygen, it remains the largest test of CELSS technology. Biosphere II provided more than 10 times (192 person-months) the previous record for the such a closed system, which was 3 persons for 6 months (18 person-months) in the Russian Bios-3[7] facility during 1972-1973. Bios-3 also required meat to be brought in monthly to augment the diet.


**Figure 1. Photograph of Biosphere II Facility in Oracle, Arizona**

While it is interesting to note that one of the original purposes of Biosphere II was to provide data for a Mars habit[8,9], the purpose here of looking at what it would take to implement an equivalent of Biosphere II on the lunar surface is only to get a first estimate of the required volumes, and types and masses of material for an 8-person CELSS. Any serious program to put a permanent CELSS habitat on the lunar surface would need to begin with study and testing going well beyond what was done for Biosphere II. A great deal of information has been published on Biosphere II, but one of the most thorough and informative references is a set of 22 peer-reviewed articles published in 1999[10].

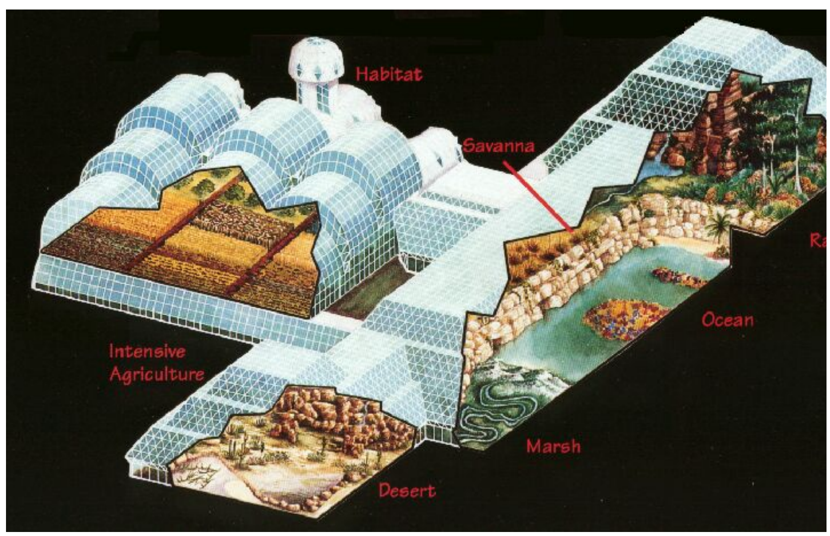


**Figure 2. Illustration of Different Biomes inside Biosphere II Facility**

From the perspective of what it would take to establish a Biosphere II-size CELSS on the lunar surface, the relevant questions then are not so much about how it worked internally, but rather on what would be required to support something similar of that scale at some location. Here, the location is taken to be the lunar south pole outpost that has been the focus of much recent NASA study. Section 4.3.6 of the NASA Exploration Systems Architecture Study (ESAS) Report[11] lists the desirable attributes of such a location: the possibility of constant sunlight, a less variable thermal environment, and the possibility of finding ice in the permanently shadowed Shackleton crater. All of these reasons are also supportive of this as an initial location for the habitat being discussed. In addition, the presence of an existing lunar outpost would be a pre-requisite for undertaking the much more ambitious task of building a CELSS habitat with an Earth-like environment.

Supporting a Biosphere II-size CELSS at the lunar south pole implies three sets of requirements: 1) those imposed by the overall shape, size and mass of Biosphere II, 2) direct resource requirements such as electrical power, cooling, etc, and 3) the earth-like environment (gravity, radiation protection, etc) in which the Biosphere II CELSS was originally implemented.

Figure 3 provides a plan view of Biosphere II that identifies the size, shape and layout of its major internal elements: a human habitat with 1,000 $m^2$, the Intensive Agriculture Biome (IAB) with 2,200 $m^2$, and ~6,000 $m^2$ wilderness biome consisting of a desert, savannah, rainforest, marsh and ocean[12]. It should be noted that the wilderness biome existed in part for research purposes and may therefore not have been fully required by the CELSS. This implies that Biosphere II could be scaled down or that a larger IAB could be established in the same enclosure if required. However, to remain consistent with the Biosphere II specifications, the lunar habitat concept in this study provides the full area for the wilderness biome. It also provides the ~3,600 $m^2$ area for the two Biosphere II "lungs". The lungs were external dome-like structures, one of which is visible in Fig. 1, that contained large internal bellows to accommodate the changing volume of the Biosphere II atmosphere caused by external temperature changes. The approximate total sizes and masses of the major elements of Biosphere II are summarized in Table I.

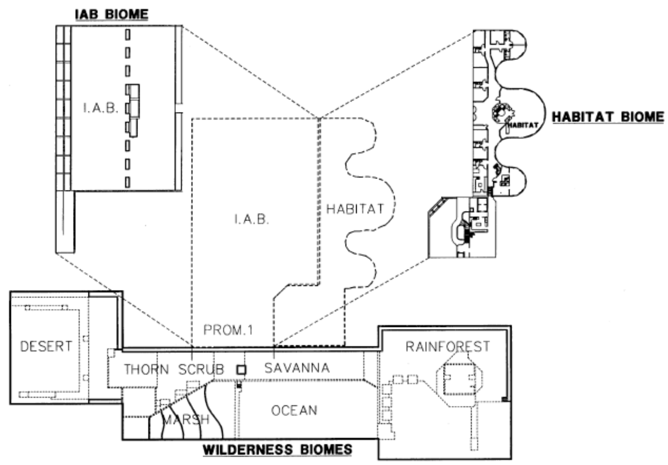


**Figure 3. Plan View of Biosphere II**

| Table I - Biosphere II Property | Quantity (approx.) |
|---|---|
| Maximum Internal Height (m) | 28 |
| Total Internal Area ($m^2$) | 12,700 |
| Total Internal Volume ($m^3$) | 200,000 |
| Water Volume ($m^3$) | 4,500 |
| Water Mass (kg) | 4,500,000 |
| Atmospheric Mass (kg) | 180,000 |
| Soil Mass (kg) | 25,500,000 |
| Total Internal Mass (kg) | 30,000,000 |

### B. Radiation Shielding Requirements

The Table I volume and area could be accommodated in a cylindrical volume with a diameter of about 130 m and a height of about 15 m. However, these dimensions do not seem ideal when considering radiation shielding. As documented in the NASA space settlement study[2] and elsewhere, the Earth's atmosphere provides a protective mass of about 1 kg/$cm^2$ (10,000 kg/$m^2$). This is about the mass density of radiation shielding that is recommended to protect humans who will be in space for indefinitely long periods. If the internal area of Biosphere II could be distributed over 4 levels, then the diameter and height of the cylindrical cavity come closer to being equal, resulting in a significant reduction of the very considerable mass of this shielding, as shown in Table II. In a 4-level cylindrical volume, the human habitat and IAB could be roughly distributed over the upper levels and the wilderness biome over the lower levels.

On the Moon, multiple options for radiation shielding exist. A habitat could be placed underground or covered with lunar regolith, but then such a habitat design could not be used in any orbit or trajectory where it would need to have its own radiation shielding. Second, the excavation of an underground cavern or the building of a regolith cover could be an even greater undertaking, considering the large area required to provide an Earth-like gravity environment using centrifugal force.

| Table II - Biosphere II Equivalent Property | Approx Quantity (1 Level) | Approx Quantity (4 Levels) |
|---|---|---|
| Radius (m) | 64 | 32 |
| Area of single Level ($m^2$) | 13,000 | 3,200 |
| Height per level (m) | 16 | 16 |
| Number of Levels | 1 | 4 |
| Total Area on All Levels ($m^2$) | 13,000 | ~13,000 |
| Total Height (m) | 16 | 64 |
| Total Volume ($m^3$) | 200,000 | 200,000 |
| Circumference of Level (m) | 400 | 200 |
| Area of Enclosing Cylinder ($m^2$) | 32,500 | 19,300 |
| Mass of Enclosing Cylinder at 10,000 kg/per $m^2$ (kg) | 325,000,000 | 193,000,000 |

### C. Earth-Like Gravity Requirement

For human health and comfort, the NASA space settlement study[2] specified a widely-held requirement for a centrifuge with a rotational rate of 1 RPM and a radius of about 1 km in order to keep the Coriolis effects low enough. Figures 4 and 5 are is illustration of the NASA study design for a torus-shaped orbiting habitat that provided these features. Thus, a lunar-surface habitat would need either an underground cavern two km in diameter or a regolith roof of the same size. Alternatively, on the Moon, it would be possible to provide a 1 G environment using a circular track two km in diameter, built either under ground, or on the surface but with a thick regolith cover. However, none of these appears applicable to a habitat in space.

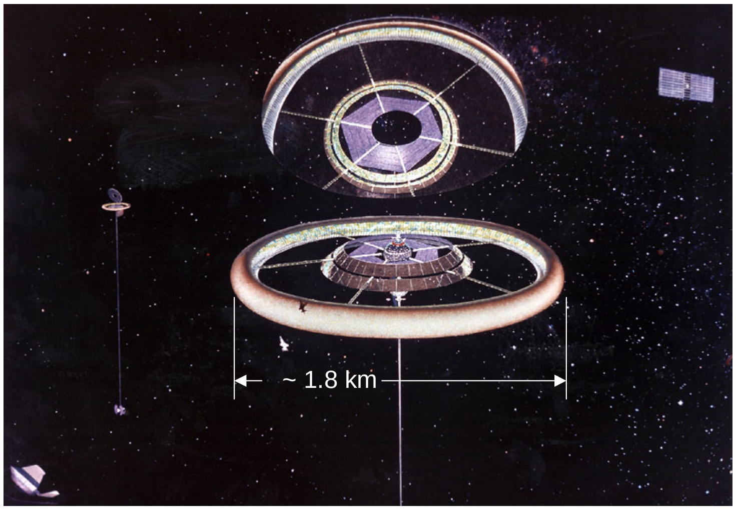


**Figure 4. 1975 NASA Summer Study Design for a rotating Torus-shaped Orbiting Habitat to provide a 1 G environment. Note large mirror above to reflect sunlight into ring of mirrors in center of torus.**

Taking the approach that a Biosphere II-size habitat will incorporate a radiation shield and be mounted on a centrifuge, the next issue is how to keep it from falling apart due to the immense centrifugal forces mostly imparted by the massive shielding. It should be noted that the NASA space settlement study addressed this issue by specifying that the torus inhabited by 10,000 persons would rotate inside a stationary radiation shield going part way around the small radius of the torus. For the eight-person Biosphere II equivalent, the support option selected is to 1) make the radiation shield itself out of aluminum (which has a good abundance in the lunar regolith and is itself structurally strong) and 2) to support it against the centrifugal force using a set of radial steel rods separated from each other by no more than 10 meters. The reason for a set of radial rods rather than one sufficiently large one is to distribute the reaction to the centrifugal force.

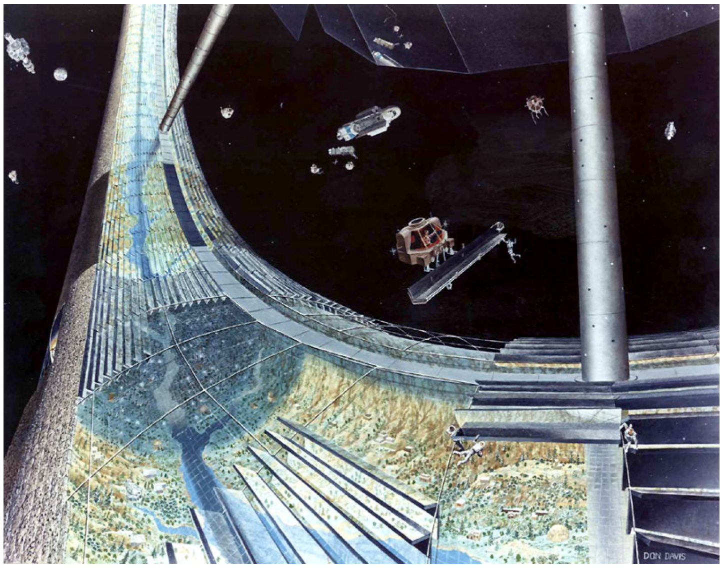

**Figure 5. Illustration of rotating torus-shaped habitat inside stationary radiation shielding with louvers to block radiation but pass light from the ring of mirrors.**

Table III summarizes the initial sizing requirements. Figures 6 and 7 show the general arrangement for the CELSS habitat, its surrounding radiation shield and the support rods on a centrifuge located at the lunar south pole. Three points are to be noted: 1) the side shield needs to extend by twice the thickness of the shield to reach the exterior surfaces of the top and bottom shields, 2) the radial rods have to be slightly thicker for the four level habitat because the interior habitat material has to be supported by fewer rods, 3) neither the mass of the internal structure to support 3 floors of the 4 level habitat nor the added mass for the radial rods to support their own weight have been calculated because they are small compared to the mass of the radiation shield.

Table III shows is that the total mass of the radial steel rods is about 10% of the mass of the habitat itself. As seen by those within the habitat, the steel rods supporting the floors of the habitat will each be about 10 inches in diameter and separated from each other by at least 30 feet. Steel Rods supporting the aluminum side wall will be about 5 meters apart for a 4 level habitat and 10 meters apart for a single level one.

Besides the need to provide radiation protection and a 1 G environment for a Biosphere II equivalent lunar habitat, the actual Biosphere II had significant utility requirements[12], which are summarized in Table IV.

| Table III - Centrifugal Habitat Property | Single Level Habitat | Four Level Habitat |
|---|---|---|
| Diameter of Interior (m) | 128 | 64 |
| Height of Interior (m) | 16 | 64 |
| Density of Aluminum (kg/m$^{3)}$ | 2,700 | 2,700 |
| Required Areal Density of Radiation Shield (kg/m$^2$) | 10,000 | 10,000 |
| Required Thickness of Radiation Shield (m) | 3.7 | 3.7 |
| Required Height of Side Shield (m) | 23.2 | 71.2 |
| Volume of Side Shield (m$^3$) | 36,000 | 56,000 |
| Combined Volume of Top and Bottom Shields (m$^3$) | 96,000 | 24,000 |
| Total Volume of Radiation Shield (m$^3$) | 132,000 | 80,000 |
| Total Mass of Radiation Shield (kg) | 357E6 | 216E6 |
| Total Mass of Biome Materials (kg) | 30E6 | 30E6 |
| Total Mass of Habitat (kg) | 387E6 | 245E6 |
| 1-G Acceleration (m/sec$^2$) | 9.81 | 9.81 |
| Centrifugal Force of Habitat under 1 G of centrifugal acceleration (N) | 3800E6 | 2400E6 |
| Tensile Strength of A514 Structural Steel (MPa) | 700 | 700 |
| Steel Cross Sectional Area Required to support Centrifugal Force of Habitat (m$^2$) | 5.43 | 3.45 |
| Length of Steel (m) | 1000 | 1000 |
| Volume of Steel (m$^3$) | 5430 | 3450 |
| Density of Steel (kg/m$^3$) | 7850 | 7850 |
| Mass of Steel (kg) | 42.6E6 | 27.1E6 |
| Ratio of Steel Mass to Habitat Mass | 0.11 | 0.11 |
| Centrifugal Force of Side Wall (N) | 955E6 | 1490E6 |
| Centrifugal Force of Habitat except for Side Wall (N) | 2844E6 | 925E6 |
| Centrifugal Force of 100 sq m of Habitat, except for side wall (N) | 22E6 | 29E6 |
| Diameter of Steel Rod to Support 100 sq m of habitat Except for Side Walll (m) | 0.20 | 0.23 |
| Number of Steel Rods to Support Habitat except for Side Wall | 130 | 32 |
| Number of Same Diameter of steel Rods to support Side Wall | 44 | 52 |

| Table IV- Biosphere Utility Requirements | Value |
|---|---|
| Peak Electric Demand (kW) | 3000 |
| Peak Cooling (kJ/h) | 35.5E6 |
| Peak heating (kJ/h) | 11.1E6 |
| Daytime Entering Solar Energy (kJ/h) | 27.1E6 |

The habitat utility requirements on the moon will be quite different due to the change in environment, particularly the thermal environment. Also, due to its totally enclosing radiation shield, such a lunar habitat would have to have internal lighting that provided a spectrum sufficiently close to that of sunlight on the surface of the Earth. It should be noted that the Russian Bios-3 environment had artificial lighting, whereas Biosphere II used the sunlight that came through its transparent enclosure. As much as possible of the required utility equipment should be on the rotating structure to minimize the need for rotating connections.

Given the use of a centrifuge to provide a 1 G environment, the polar location of the lunar outpost provides the additional advantage that the spin axis of the centrifuge can be aligned with the spin axis of the moon. As the location gets closer to the equator, the challenge arises of either a 1/60 Hz apparent variation in gravity if the centrifuge spin axis remains parallel to the lunar rotation axis or of having to force the centrifuge to precess if it is not parallel. Given the slow (~28 day) rotation rate of the moon, it looks technically feasible to apply forces that would cause the centrifuge to precess fast enough, even on the lunar equator.

## IV. Requirements for Developing the Lunar Habitat

Having outlined one concept for a CELSS lunar habitat with an Earth-like environment, it is now possible to look at what would be required to develop it. First, it should be noted that a great deal of the required technology development can be accomplished on Earth and with exiting space capabilities, such as the ISS. As was done with the Bios-3 and Biosphere II, much of the CELSS technology can be developed and tested on the Earth. The near vicinity of the ISS provides a suitable location for in-space testing of a human rated centrifuge that can provide a sufficiently Earth-like gravity environment. ISRU techniques can be researched and tested on the Earth (with lunar simulants where needed), followed by small-scale validation on the Moon with robotic missions launched on existing rockets. Thus, as the VSE human infrastructure begins to develop on the moon, it can make use of well-tested technologies for lunar ISRU, CELSS and artificial gravity.

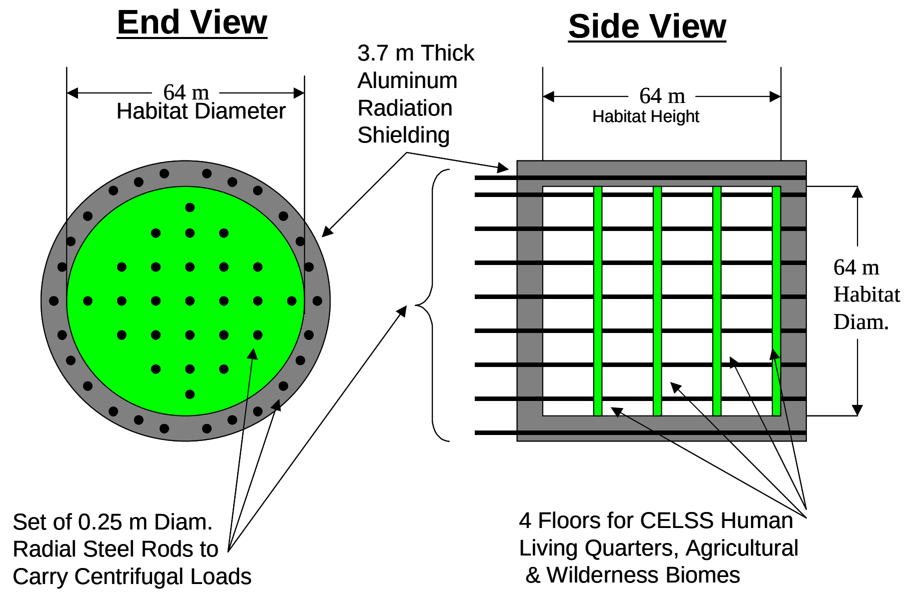


**Figure 6. Cylindrical, 4-Level, Biosphere II- Sized CELSS Lunar Habitat Surrounded with Radiation Shield.**

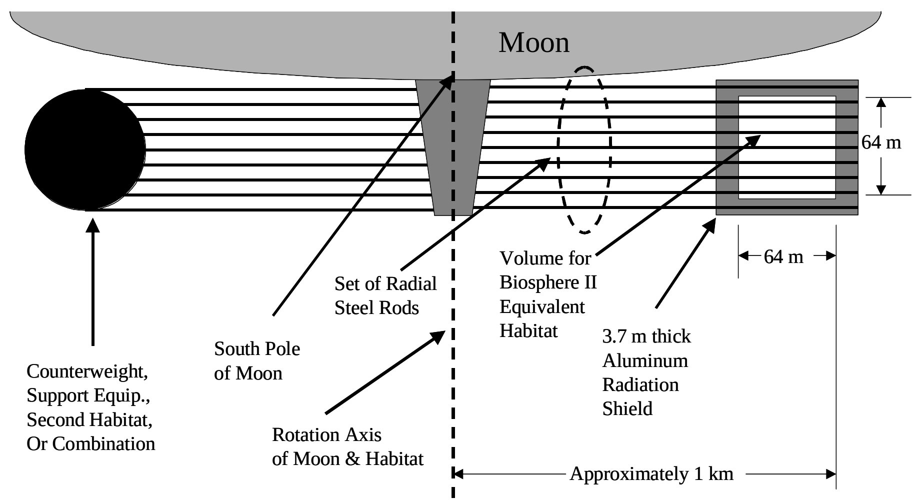


**Figure 7. Concept for Lunar Habitat Mounted on 1-G Centrifuge at Lunar South Pole (not to scale).**

### A. ISRU

The NASA ESAS report[11], which lays out an initial plan for accomplishing the VSE, envisions the ability to land between 10 and 20 metric tons of cargo on the moon using a single un-crewed Ares V launch as shown in Fig. 8. Each cargo launch requires an expendable Ares V and an expendable Altair Lunar Lander. It is understood that 2 cargo missions per year are planned. While the current VSE/ESAS approach (Ares-I, Ares-V, etc) looks adequate for lunar ISRU limited to producing oxygen for crew needs and possibly propellant, it does not look capable of supporting enough ISRU to develop the habitat.

This scale of VSE/ESAS architecture seems inadequate due to the amount of material required for the habitat. Radiation shielding is one driving requirement for a massive volume of ISRU-derived resources. For reference, the NASA space settlement study[2] estimated that about 10 million metric tons of radiation shielding would be required, which constitutes more than 90% of the total mass of this torus-shaped habitat for 10,000 persons. Another consideration that leads to the need for very large scale ISRU is the apparent scarcity of certain elements, based on the lunar regolith analyzed to date. Table V shows a current estimate for such abundances. The NASA space settlement required about 40,000 tons of water[2]. Assuming that the water would come from combining lunar oxygen and hydrogen and that 1/9 the mass of water is hydrogen, then 80 million tons of lunar regolith would have to be processed, given the ~50 Parts Per Million (PPM) by weight of lunar hydrogen.

While these amounts might seem overwhelming, this scale of materials processing is already being done on the surface of the Earth. The Bingham Canyon open-pit mine in Utah, which is the largest copper mine in the world, removes 50 million tons of ore annually[13]. In addition, materials with very low abundances can be profitably mined on Earth. Gold can be economically extracted in densities of less than 1 ppm[14].

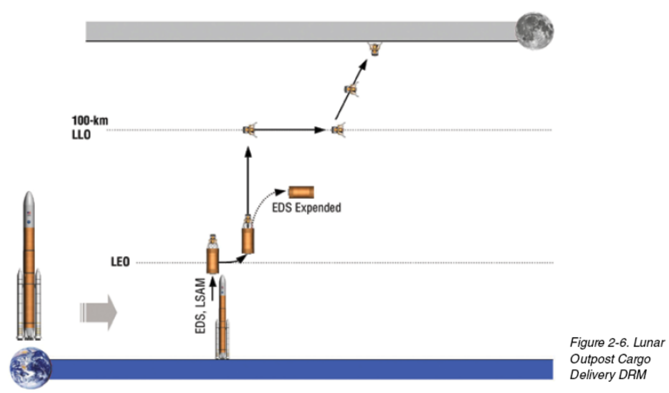


**Figure 8. Lunar Outpost Cargo Delivery Design Reference Mission (DRM).** Taken from Fig. 2.6 of the NASA ESAS Report.

However, even though the volume of materials processing required for space settlement is comparable to that associated with mining on Earth, the number of people required on Earth poses a major problem for equivalent space ISRU. For instance, 1,400 people work at the Bingham Canyon mine[15]. Obviously, many others indirectly support these 1,400 workers by providing fuel, power and many other services. This leads to the associated technical challenge of performing with very few on-site humans not only very large-scale in-space ISRU, but also the maintenance of all of the processing equipment. Finally, if the cost of bringing all of this large-scale ISRU equipment to the Moon is prohibitive, then much of the actual manufacturing of lunar ISRU equipment also has to be a highly automated lunar process.

**Table V – Lunar Elemental Abundances (in Parts Per Million (PPM) by weight.**

| Element | Lunar Highland | Lunar Lowland | Earth |
|---|---|---|---|
| *Oxygen* | 446,000 | 417,000 | 466,000 |
| *Silicon* | 210,000 | 212,000 | 277,000 |
| *Aluminum* | 133,000 | 69,700 | 81,300 |
| *Iron* | 48,700 | 132,000 | 50,000 |
| *Calcium* | 106,800 | 78,800 | 36,300 |
| *Sodium* | 3,100 | 2,900 | 28,300 |
| *Potassium* | 800 | 1,100 | 25,900 |
| *Magnesium* | 45,500 | 57,600 | 20,900 |
| *Titanium* | 3,100 | 31,000 | 4,400 |
| *Hydrogen* | 56 | 54 | 1,400 |
| *Phosphorus* | 500 | 660 | 1,050 |
| *Manganese* | 675 | 1,700 | 950 |
| *Carbon* | 100 | 100 | 200 |
| *Chlorine* | 17 | 26 | 130 |
| *Chromium* | 850 | 2,600 | 100 |

There are two ways in which this problem can be somewhat mitigated. One is to have operators on Earth perform as much of the ISRU-associated labor as possible using remotely controlled robots. The remote control of the Russian Lunakhod rover on the moon is an example of this approach. Another is to make optimal use of the Earth-Moon logistics capability. For instance, it seems less costly to bring such things as micro-processors from Earth than it would be to develop a microprocessor factory on the Moon. However, these mitigations can at best only somewhat reduce the need for highly autonomous, large-scale lunar ISRU.

Thus, very highly automated, very large scale in-space ISRU looks like the single most technically challenging problem not only for developing the lunar habitat, but also for supporting any space settlement efforts that might follow. This is partly because ISRU comprises many sub-problems such as how to cost-effectively develop the required electric power generating capability, operate in the environment of space, and sufficiently automate all aspects of ISRU, including the construction and maintenance of the equipment required for ISRU. None of these sub-problems looks technically impossible, but each will be challenging in its own right.

### B. Earth-Moon Logistics

Even assuming that the previous ISRU problem can be solved, a much more capable and efficient, fully reusable Earth-to-Moon logistics system still looks necessary to develop the envisioned lunar habitat. A first step would be to evolve the Ares V into a reusable system, which looks technically possible. At his point, the ARES V is actually a partially reusable system, based on its planned use of re-useable Shuttle solid boosters. If a fully reusable Ares V approach pushed technology too far, an intermediate approach would be a fully reusable Shuttle to go from Earth to LEO and back, combined with a fully reusable space tug that would perform a burn to go from LEO to a Lunar Transfer Orbit (LTO) and then return to LEO via aero-braking.

A second step would be the development of a lunar pole mass "driver/brake". This would be capable of not only acting as a mass driver to send surface material into space on a hyperbolic trajectory, but also of acting as an electric brake to bring to a gradual and controlled stop payloads on a hyperbolic trajectory that grazes the lunar surface. Figure 9 is an artist's concept of a lunar mass driver. For example, the 1975 NASA summer study[2] assumed that a lunar mass driver would deliver raw lunar materials to the vicinity of the Earth-Moon L5 point where they would be processed into products needed by the habitat. The reason given by that NASA study for processing in space rather than on the lunar surface was easier access to solar power in orbit than on the surface of the moon, most of which is in darkness half the time for periods of about 15 days. However, while the study discussed these and other ISRU aspects, it did not develop a conceptual design for the required ISRU system.

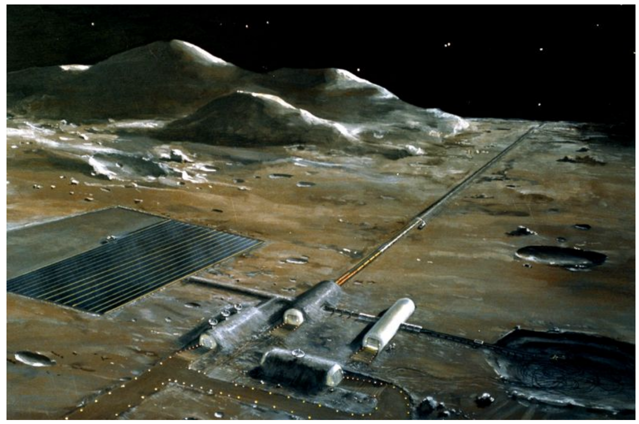

**Figure 9. Artist's Concept of Lunar Mass Driver**

Having a lunar mass driver/brake would eliminate the need for a lunar Lander and ascent vehicles, as well as for their propellant. Thus, payloads traveling between the Earth and the Moon would use the reusable Ares 5 to get between Earth and the LTO. Then the payload would be diverted from the LTO into a surface-grazing trajectory from which the lunar mass brake would bring it to a stop. To go from the lunar surface to the Earth would begin with the mass driver, then a rendezvous with the reusable Ares V in LTO, followed by re-entry into the Earth's atmosphere, as illustrated in fig. 10. Taken together, this provides an efficient and fully reusable system for transferring payloads in either direction between the surfaces of the Earth and Moon. The Ares V should be able to launch more than 50,000 kg into a LTO. Initial plans for the Space Shuttle envisioned a launch a week. At that launch rate, this approach is in principle capable of delivering 50,000 kg of cargo per week to the Moon. This capability looks necessary for developing the very large scale ISRU needed to build the lunar habitat described above.

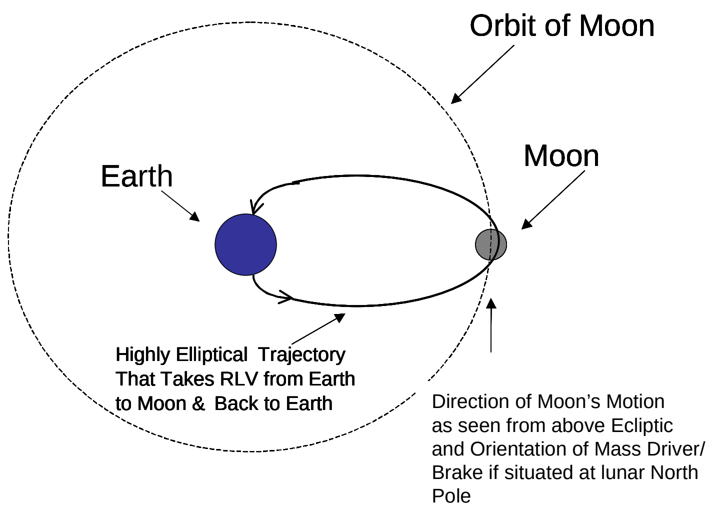


**Figure 10. Orbit Arrangement for a Reusable Ares V, Lunar "Cycler", and Lunar Mass "Driver/Brake"**

Thus, the overall sequence of steps would seem to be to first establish the lunar outpost according to the plans of the VSE. If the lunar habitat were to be undertaken, then the next step would be the development of the re-useable ARES V. The resulting lower logistics cost should then enable the capabilities of the lunar outpost ISRU to be built up to where it in turn could support the development of the lunar mass driver/brake. With the driver/brake, logistics costs should then be further reduced enough to grow the ISRU to where it can provide the material required by the CELSS, Earth-environment habitat described above.

While a reusable Areas-V and a lunar mass driver/brake are certainly major undertakings, they still do not seem overall as technically challenging as large-scale, space ISRU.

## V. Approach to using the Lunar Habitat Technologies for Space Colonization

As stated previously, the fundamental value of the lunar habitat is the contribution that it could make to space settlement or colonization, which involves far more than just the Moon. However, there are also a number of significant contributions that this habitat and its infrastructure can make to a lunar program, which will be covered first because they appear more near-term.

### A. Lunar Program Applications

An initial consideration is whether the above the lunar habitat and its supporting infrastructure could eventually begin to pay for themselves. Without the basis of some economically self-supporting human space missions, the larger goal of space settlement is probably impossible.

One possibility is lunar tourism, which could become feasible with the just-discussed logistics systems for efficiently getting large payloads between the Earth and Moon. For lunar tourism, more than one (and larger) lunar habitats could be developed to serve as hotels. Additionally the lunar mass driver could put enough ISRU derived material into the LTO to build a "cycler" version of the habitat there. It would called a cycler because it would continually cycle between the Earth and moon in the LTO.

This brings up the point that a CELSS is not necessarily required by all habitats having the ability to provide an Earth-like gravity and radiation environment. Carbon Dioxide can be broken down to oxygen and carbon using a Bosch process[12]. Other physical-chemical processes[12] can recycle water. Human food needs amount to about 1 kg per day, so it looks like a habitat for missions of even up to 10 years could be less massive with stored food, but with fully recycled air and water, and in which just a relatively small crew space would provide full radiation shielding and a 1-G environment. From this perspective, the initial value of a CELSS lunar habitat is more that of providing a technology test-bed.

The Earth-Moon cycler could thus be smaller because it would not need to provide a CELSS for the approximately 3 days it takes to travel between the Earth and the Moon. However, the cycler would provide lunar tourists with the comfort of a 1-G environment and protection from space radiation, particularly from unpredictable large solar flares. Tourists would ride the reusable Ares V from the Earth's surface to the cycler, travel comfortably and safely in the cycler for about 3 days until near the moon, land on the moon using the mass brake, and then reside comfortably in one of the lunar habitats for as long as desired. The return to earth would be via the mass driver, then another 3 days in the Earth-Moon orbit cycler, followed by Earth re-entry via a reusable Ares V. Going to and from the Moon in this manner could require only a few hours in zero-G, although it would permit more zero-G time for tourists who desired it.

Another benefit is that the logistics and habitats required for lunar tourism will also enable vastly more lunar science and exploration, as well as use of the lunar surface for astronomy.

### B. Space Settlement Applications

The following is a very brief outline of one of many possible approaches to this broader goal.

Some important contributions to space settlement can be made on the lunar surface by using the habitat to determine if there are viable countermeasures that can reduce the need for Earth-surface-equivalent gravity and radiation protection on long human space missions. The centrifuge can create any level of effective gravity above the ~1/6 Earth gravity that naturally exists on the lunar surface. Likewise, the radiation level inside the habitat can be increased from an Earth-surface level to that of open space. For instance, it may be found that much of the CELSS can take lower gravity or higher radiation or both, thus allowing the Earth-like environment to be restricted to just the crew habitat.

The first space settlement option is to increase the number of size of habitats on the moon so as to develop an actual space settlement on the lunar surface.

The next step would appear to be to use the lunar mass driver to develop an in-space version of the habitat having a propulsion system powerful enough to get it to and from Near Earth Objects (NEOs), i.e., it would be a NEO-cycler. The target NEOs would be in about 1-AU, low inclination orbits to minimize delta V requirements.

The initial objective of the NEO missions would be to adapt the lunar ISRU technology to the essentially gravity-free environment of the NEOs. With a low level of gravity, NEO ISRU will not require a mass driver/brake. Therefore, it would be more efficient to use NEO rather than lunar ISRU to build more and larger versions of the orbital powered habitats. A series of such habitats among the NEOs, along with the exiting lunar infrastructure, would itself constitute a modest, but viable accomplishment of space settlement or colonization. Figure 11 shows one concept for a NEO settlement located at the Sun-Earth L5 point.

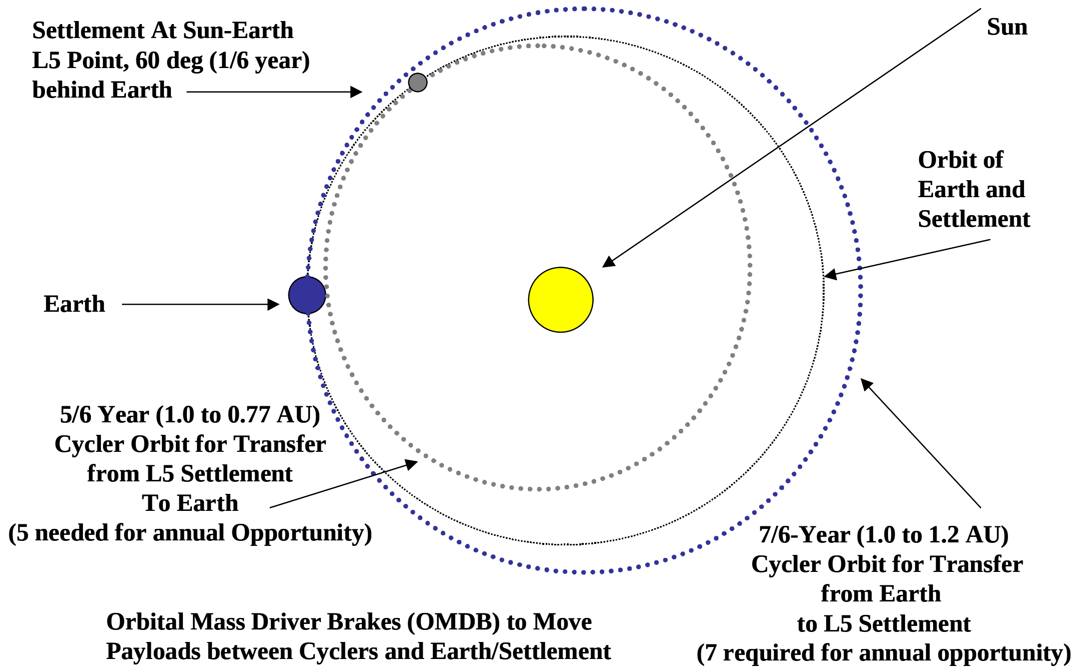


**Figure 11. Settlement at Sun-Earth L5 Point and cycler orbits to Provide Earth-Settlement Travel**

Another result of the NEO effort could be that the NEO cycler could be evolved to become a Mars ("Aldrin") cycler. There need to be multiple Mars cyclers ("up" and "down" versions) and they will require Earth flybys and propulsion to keep their orbits synchronized with the non-resonant orbits of Earth and Mars. Analyses have shown that efficient low thrust propulsion may be sufficient for this[14]. This cycler would enable a safe, comfortable and robust exploration of Mars, along with the establishment of a Mars outpost with large scale ISRU, thus providing the means to develop habitats and then settlements on the Mars surface equivalent to those on the lunar surface.. The presence of a thin atmosphere on Mars may make it preferable to put the centrifuge under stationary radiation shielding. The high rotation rate of Mars (essentially that of Earth) will make it challenging but seemingly not impossible to build centrifugal habitats near or on the Martian equator.

However, a Mars cycler has relatively high Earth and Mars fly-by velocities, which in turn leads to the desirability of building mass driver/brakes in orbit, possibly in Sun-Earth and Sun-Moon L2 orbits. With these orbiting mass driver/brakes, it would be possible to move payloads to and from the cyclers as they passed Earth and Mars without extensive use of propellant. If the payload sent to a cycler equaled the mass taken from it then no net momentum would be imparted to the mass driver/brake. Whatever momentum was imparted could be efficiently compensated for over a longer period by use of an ion propulsion system on the mass driver/brake.

A final step would be to build a Earth-main-belt cycler and use it to support the development of habitats derived from main belt asteroid ISRU. There is the possibility of a cycler orbit that would not need adjustment to rendezvous with habitats built from asteroid ISRU, assuming that the habitats were located in an orbit whose period was in resonance with the cycler orbit. Figure 12 shows how a 4-year cycler orbit would pass by the Earth and then beyond the asteroid belts, while being able to rendezvous every 20 years with a habitat or cluster of habitats located in a 5-year orbit that also passed through the asteroid belt. A possible implementation would be four cyclers (or groups of cyclers) in the 4-year orbit and 20 habitats (or groups of habitats) spaced at 3 month (1/20) intervals the 5-year orbit. That would result in one natural rendezvous every year.

From a propulsion standpoint, such a combination of orbits could be supported efficiently using orbital mass driver/brakes. One orbital mass driver/brake would be located in a sun-Earth L2 orbit where it would provide the ~6 km/sec Delta V to get payloads between the L2 orbit and the 4-year asteroid cycler orbit. The mass driver/brake would have ion propulsion to gradually compensate for the momentum transfer that would be generated if the driven mass did not match the braked mass. Similar orbital mass driver/brakes would be located at each of the 20 collections of habitats in the 5-year orbit.

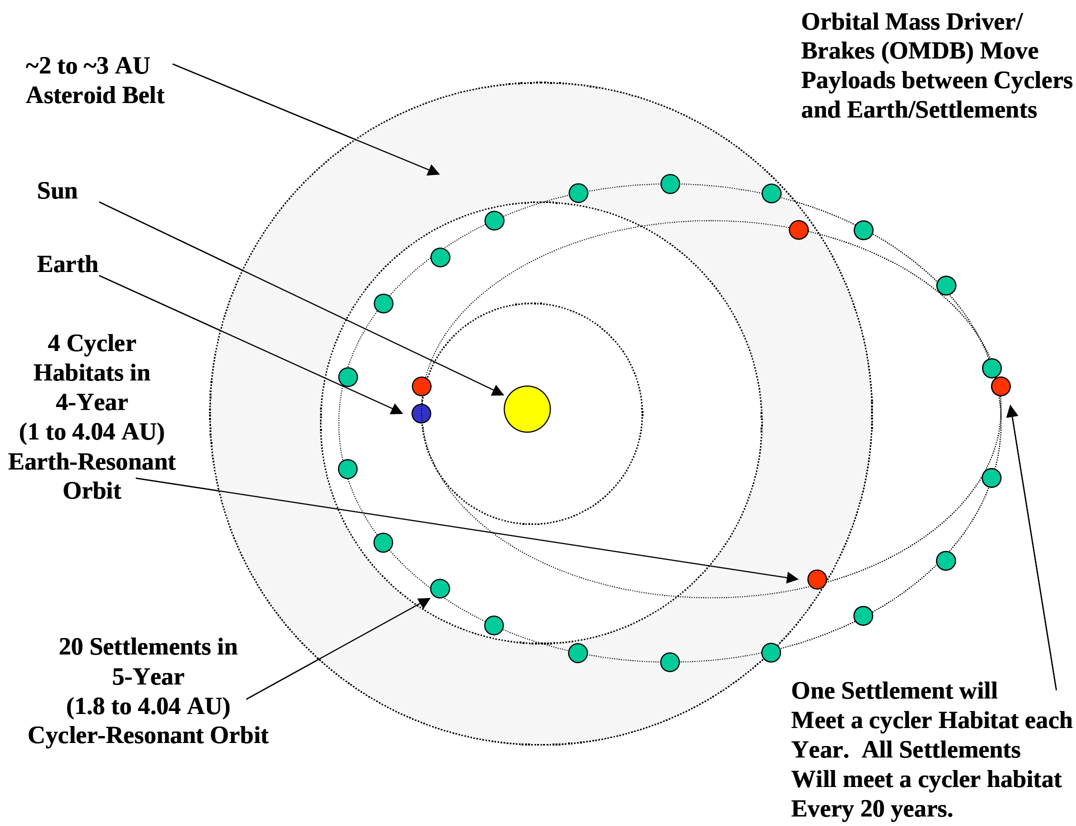


**Figure 12. Cycler Orbit to Support Habitats built from Main-Belt Asteroid ISRU**

One feature of the 5-year orbit is that is passes through the entire width of the asteroid belt. Thus, every main belt asteroid will come relatively (subject to inclination) close to the 5-year habitat orbit, although essentially never when a habitat is also at that orbit location. Thus a mass driver will be needed at each of the asteroids that is selected for ISRU to provide material for the habitats in the 5 year orbit. This mass diver will put the material into a phasing orbit, from which it should be possible for low thrust ion propulsion to bring the ISRU material to rendezvous with one of the 20 collections of habitats.

The total mass of the millions of small bodies in the asteroid belts is estimated to be more than $10^{21}$ kg[17]. Assuming that just 1% of this material is suitable for building habitats, then $10^{19}$ kg would be available for that purpose. The torus-shaped space settlement in the NASA study supported 10,000 humans and had a total mass of about $10^{10}$ kg. In principle, $10^{19}$ kg of asteroidal material would then be sufficient for $10^{9}$ of these habitats supporting $10^{13}$ humans. This is more than 1,000 times the current 6.7 billion human population on Earth. Because about 90% of the mass of this toroidal space settlement was for a radiation shield that could have been made of a variety of materials, it is likely that much more than $10^{19}$ kg of asteroid material would be of use for habitats. Based on concepts developed by Gerald O'Neill, even more people could be supported with a given mass of asteroid material using cylinders, each 4 miles in diameter, 20 miles long and each capable of "supporting a population of several million people[18]".

The goal of a space settlement program could be defined as having been accomplished when a system of space settlements grows large enough to be capable of sustaining itself and continuing to grow without requiring support from Earth. Trade with Earth would be assumed to continue because it would be valuable or enhancing, but not because it would be required for survival of the space settlements. The material in the main asteroid belt appears at least adequate for developing a set of space settlements that have this degree of self-sufficiency.

## VI. Conclusion

A technical approach has been outlined for space colonization that might be accomplishable over a long term with realizable resources. However, it does not appear reasonable to expect any serious efforts to be made along these lines until there is a consensus that a technically and programmatically viable approach exists to an acceptable space settlement goal. Just coming up with a credible technical approach and resource estimate would be a project of no small magnitude. The approaches discussed above may be able to help progress toward the immediate goal of a thorough-enough study of what is required for space settlement and whether it can be made programmatically acceptable.

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