Use of a Lunar Outpost for Developing Space Settlement Technologies

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The type of polar lunar outpost being considered in the NASA Vision for Space Exploration (VSE) can effectively support the development of technologies that will not only significantly enhance lunar exploration, but also enable long term crewed space missions, including space settlement. The critical technologies are: artificial gravity, radiation protection, Closed Ecological Life Support Systems (CELSS) and In-Situ Resource Utilization (ISRU). These enhance lunar exploration by extending the time an astronaut can remain on the moon and reducing the need for supplies from Earth, and they seem required for space settlement. A polar lunar outpost provides a location to perform the research and testing required to develop these technologies, as well as 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 types of spinning space vehicles or stations envisioned to provide artificial gravity can be implemented and tested on the lunar surface, where they can create any level of effective gravity above the ~1/6 Earth gravity that naturally exists on the lunar surface. Likewise, varying degrees of radiation protection can provide a natural radiation environment on the lunar surface less than or equal to ~1/2 that of open space at 1 AU. Lunar ISRU has the potential of providing most of the material needed for radiation protection, the centrifuge that provides artificial gravity; and the atmosphere, water and soil for a CELSS. Lunar ISRU both saves the cost of transporting these materials from Earth and helps define the requirements for ISRU on other planetary bodies. Biosphere II provides a reference point for estimating what is required for an initial habitat with a CELSS. Previous studies provide initial estimates of what would be required to provide such a lunar habitat with the gravity and radiation environment of the Earth's surface. While much preparatory work can be accomplished with existing capabilities such as the ISS, the full implementation of a lunar habitat with an Earth-like environment will require the development of a lunar mission architecture that goes beyond VSE concepts. The proven knowledge of how to build such a lunar habitat can then be applied to various approaches for space settlement.

I. Introduction

The focus of this study is an initial concept for a lunar habitat that provides an Earth-like environment and minimizes the need for logistics support from Earth. While such a habitat will facilitate human activities on the moon, its more fundamental importance is seen as the contribution it could make to widespread and permanent space settlement, which is here considered synonymous with space colonization. This study begins with a review of the status of space settlement and how it can be advanced by the lunar habitat being considered. It then presents one possible design approach for such a habitat. This is followed by outlines of an approach for developing such a lunar habitat and of a follow-on program leading to space settlements.

II. Status of Space Settlement

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

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from inside the earth, etc) as well as human-induced ones (warfare, destruction of the environment, global social breakdown).

Support for the importance of space colonization has been expressed by a number of authorities. A few examples follow. The discoverer 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].” 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]. This study included supporting statements by James C. Fletcher, the NASA administrator at that time. 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. More recently, in 2005, the current NASA administrator stated, “If we humans want to survive for hundreds of thousands or millions of years, we must ultimately populate other planets[4].”

However, despite widespread recognition that space settlement is important, little if anything concrete seems to have ever been done about it. The primary reason for not initiating a space program for that specific purpose seems to be that it is viewed as so challenging that there does not seem to be any realistic way to begin to approach it. Even if the technology is considered achievable, then the required effort is estimated to be of such a magnitude as to make unrealistic any possibility of obtaining the required funding.

However, things may have changed enough to warrant a re-examination of space settlement. First, Biosphere II[5] significantly increased knowledge of Closed Environmental Life Support System (CELSS) technology. Biosphere II sustained eight people for two years, from Sep 26, 1991 until Sep 26, 1993. This is more than 10 times the previous record for the number of person months in a closed system, which was in 1972-1973 with 3 persons for 6 months in the Russian Bios-3[6] facility. 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 best existing data point for a long-term CELSS. Figure 1 is a photograph of the overall Biosphere II enclosure. Figure 2 illustrates the different Biomes (environments) within the enclosure.

Second, in 2004 and with the support of the White House and Congress, NASA initiated a new Vision for Space Exploration (VSE), which 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[7].” While this statement does not provide a specific plan for space settlement, it has the potential 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. We have got transportation 'to and from' in our budget.[8]"

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 required support for developing a lunar habitat having a CELSS and providing an Earth-like environment with respect to radiation and gravity. While the development of such a habitat looks like it will require a more powerful infrastructure, particularly in the area of Earth-Moon logistics, than is now planned in the VSE, this augmented infrastructure will also facilitate later using such a habitat as a building block for space settlement.

Therefore, it appears useful to revisit the approaches for space settlement to see if there now exist more realistic technical and programmatic ways to advance it. Section III presents one concept for a lunar habitat. Section IV looks at the infrastructure required to develop such a habitat, and Section V addresses how this habitat could then be applied to the larger objective of space settlement.

III. A Lunar Habitat Based on Biosphere II

The purpose of looking at what it would take to implement Biosphere II in space is not that Biosphere II, as it was implemented, represents a workable approach toward a space habitat, but only that it represents the best currently available data point on what is required. From the perspective of what it would take to establish

Biosphere II at some relevant location space, the questions are not so much about how it works, but rather on what would be required to support something equivalent at the specified location. For this study 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[9] lists the desirable attributes of such a location: the possibility of constant sunlight, a more benign 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 a Biosphere II equivalent. In addition the presence of an existing lunar outpost is a requirement for undertaking the much more ambitious task of building a CELSS habitat with an Earth-like environment.

Supporting a Biosphere II equivalent at the lunar south pole implies three sets of requirements: 1) those imposed by its intrinsic 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 it was originally implemented. 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[5].

Figure 3 provides a plan view of Biosphere II that identifies the size, shape and layout of its major internal elements: the human Habitat, the Intensive Agriculture Biome (IAB), and the wilderness biome which is made up of smaller interconnected biomes representative of a desert, rainforest, ocean, etc. The total approximate size and mass of these major elements of Biosphere II are summarized in Table II.

Table II - 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

The above volume and area could be accommodated in a cylindrical volume with a diameter of about 130 m and a height of 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 III. In a 4-level cylindrical volume, the human habitat and IAB could be roughly distributed over the top two levels and the wilderness biome could be distributed over the lower two levels. It should be noted that the Biosphere II wilderness biome was not fully required to support the human CELSS. In part the wilderness existed for research purposes. This implies that Biosphere II could have been scaled down, or could have supported more people, or that a larger CELSS-vital biome could be established in the same enclosure if required.

Table III - 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

On the lunar surface the option certainly exists to provide the habitat with shielding by putting it underground or covering it with regolith, but this introduces other problems. First, such a habitat 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, particularly when considering what is required to provide a comfortable 1 G environment. For human health and comfort, the NASA space settlement study[2] specified a widely held estimate of centrifuge with a rotational rate of 1 RPM and a radius of about 1 km to keep the Coriolis force low enough. Thus, this habitat would need an underground cavern two km in diameter or a regolith roof of the same size.

Taking the approach that the Biosphere II equivalent habitat will provide its own shielding, 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 make the radiation shield itself out of aluminum (which has a good abundance in the lunar regoith and is itself structurally strong) and to support it against the centrifugal force using a set of radial steel rods separated from each other by no more than 10 meters. Table IV shows initial sizing requirements and Fig. 4 shows the general arrangement for the Biosphere, its surrounding radiation shield and the support rods on a centrifuge at the lunar south pole. Three points need 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.

What Table IV 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 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[10], which are summarized Table V.

Table IV -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	700	700

Table V- 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. The required utility equipment would be expected to be distributed on the rotating structure as much as possible to minimize the need for rotating connections.

Steel (MPa)		
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

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 variation in gravity if the centrifuge spin axis is 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 establish a rotating habitat even on the lunar equator, possibly via a pair of counter rotating habitats that would react against each to precess at the required rate.

IV. Requirements for Developing an Earth-Like Lunar Habitat

Having described 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, CELSS technology can be developed and tested on the Earth. The near vicinity of the ISS provides a 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, when the VSE/ESAS human infrastructure begins to develop on the moon, it can make use of proven technologies for lunar ISRU, CELSS and artificial gravity.

However, while the current VSE/ESAS approach (Ares-1, Ares-V, etc) looks adequate for a lunar outpost that makes some use of these technologies, it may not be capable of enough ISRU to completely develop the habitat. The NAWQ ESAS report[9], 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 uncrewed Ares V launch as shown in Fig. 5. Each cargo launch requires an expendable Ares V and Altair Lunar Lander, and the current baseline is 2 cargo missions per year.

This scale of architecture seems inadequate due to the amount of material required. 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 VI 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, 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[11]. 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[12].

However, even though the volume of materials processing required for space settlement is accomplished on Earth, the number of people required poses a major problem for equivalent space ISRU. For instance, 1,400 people work at the Bingham Canyon mine[13]. Obviously, many others indirectly support these 1,400 workers by providing fuel, food and many other services. This leads to the associated technical challenge of performing very large scale in-space ISRU largely autonomously. Not only does the ISRU processing have to be automated, but the construction and maintenance of all of the processing equipment also has to be largely automatic. Finally, if there is to be a space settlement capable of growing itself, then the actual manufacturing of additional ISRU equipment also has to be highly automated.

There are two ways in which this problem can be somewhat mitigated. The first 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. The second 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, even with the above mitigations, a much larger, more efficient and fully reusable Earth-to-Moon logistics system looks necessary to build the envisioned lunar habitat. A first step would be to evolve the Ares V into a reusable system, which looks technically possible. If this approach pushed technology too far, an intermediate approach would be a fully reusable Shuttle to go from Earth to LEO, 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 capable not just of sending surface material into space, but also of acting as a “mass brake” to bring to a gradual and controlled stop payloads on a hyperbolic trajectory that grazes the lunar surface. Figure 6 is an artist’s concept of a lunar mass driver. For example, the NASA space settlement 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 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 design or size the ISRU system.

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, and then use the lunar mass driver/brake to get between the LTO and the lunar surface, as illustrated in fig. 7. 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 more reasonable for building up the very large scale ISRU needed to build the lunar habitat described above.

In conclusion, while there is no known technical barrier to very highly automated, very large scale in-space ISRU, it does look like the single most technically challenging problem for developing the lunar habitat. This is partly because it comprises many challenging sub-problems such as how to cost-effectively develop the required electric power generation capability, operate in the environment of the moon, and sufficiently automate all aspects of ISRU, including the construction and maintenance of the equipment required for ISRU.

V. Approach to using the Lunar Habitat for Space Colonization

As stated above, the long term value of the lunar habitat is the contribution that it could make to space settlement or colonization, which involves more than just the moon. The following is a very brief outline of one possible, example approach to this broader goal.

An initial step to consider is whether the above the lunar habitat and its supporting infrastructure could eventually begin to pay for itself. Without having economically self supporting human space missions, the larger goal of space settlement is probably impossible.

One possibility is lunar tourism which could become possible with an economical means for getting large payloads between the Earth and Moon. For lunar tourism, more than one (or a larger) Biosphere II-equivalent habitat could be implemented at the lunar outpost 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 it is not necessary to equip all habitats having the ability to provide an Earth-like environment also with the ability to recycle their food supply, i.e., a CELSS. Carbon Dioxide can be broken down to oxygen and carbon using a Bosch process[20]. Other physical-chemical processes[20] can recycle water. Human food needs amount to about 1 kg per day, so it looks like missions of even up to 10 years could be done more effectively having stored food, but fully recycled air and water, with just a relatively small crew space needing full radiation shielding and a 1-RPM, 1-G centrifuge. From this perspective the 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. Figure 7 shows the orbit arrangement. 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 a logistics system efficient enough for lunar tourism will also enable vastly more lunar science and exploration, as well as use of the lunar surface for astronomy,

The next logical step would appear to be to develop a larger version of the Earth-Moon cycler having a CELSS and a substantial ion propulsion system. The powered habitat would support human missions to and from Near Earth Objects (NEOs) in about 1-AU orbits to minimize delta V requirements.

The main objective of the NEO missions would be to adapt the lunar ISRU technology to the essentially gravity-free environment of the NEOs. With such a low level of gravity, NEO ISRU will not require a mass driver/brake. Therefore it would be more efficient to build more and larger versions of the orbital powered habitat from NEOs. 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.

In parallel with the NEO effort, it is expected that a NEO cycler could be further advanced to be 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 orbit synchronization with the orbit 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 Biosphere II equivalent habitats on the Mars 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.

The final step would be to build a cycler for the asteroid belts 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 propulsion to rendezvous with habitats built from asteroid ISRU, assuming that the habitats were placed in an orbit that met the cycler orbit. Figure 8 shows how a 4-year cycler orbit would pass beyond the asteroid belts and be able to rendezvous every 20 years with habitats developed from main-belt asteroid ISRU and located in a 5-year orbit. A possible implementation would be four 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 would also 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.

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 5 year orbit habitats. This mass diver will put the material into a phasing orbit form 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 goals of a space colonization program can be said to have been accomplished by the time that a system of space settlements grows large enough to be capable of sustaining itself and growing with no more help from Earth than would be covered by trade. The existence of the four cyclers, twenty communities, and the supporting ISRU operations at main belt asteroids might adequate for this.

VI. Conclusion

A technical approach has been outlined for space colonization that might be accomplishable with realizable resources. The important technical questions are whether this outline is realistic, and whether there might be a better approach. The most important resource question is to come up with a realistic estimate of the effort required to implement whatever looks like the best (and least expensive) technical approach to space colonization. Just coming up with a credible technical approach and a credible associated cost estimate would be a project of no small magnitude. This leads to the question of if required resources could be made available to perform an adequate study. The approaches discussed in this study may be able to help progress toward the nearer goal of seriously studying whether there is a realistic approach toward the farther goal of space colonization.

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

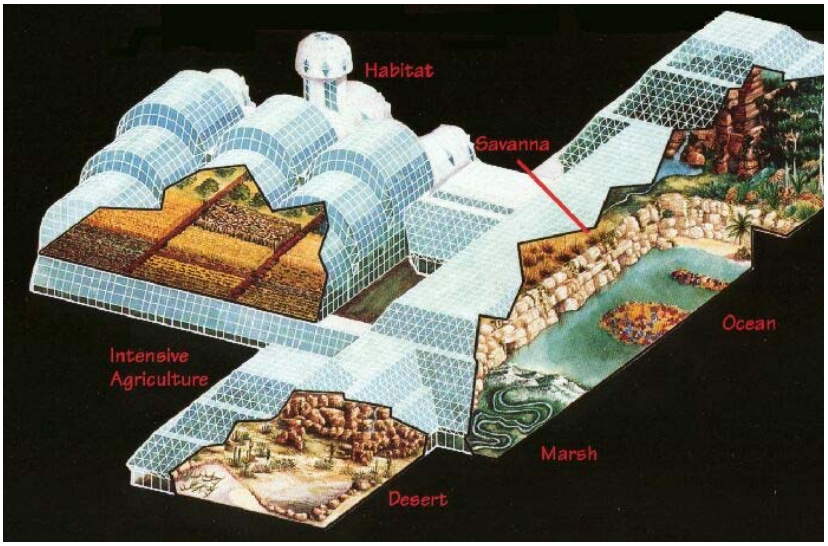


Figure 2. Illustration of Different Biomes inside Biosphere II Facility

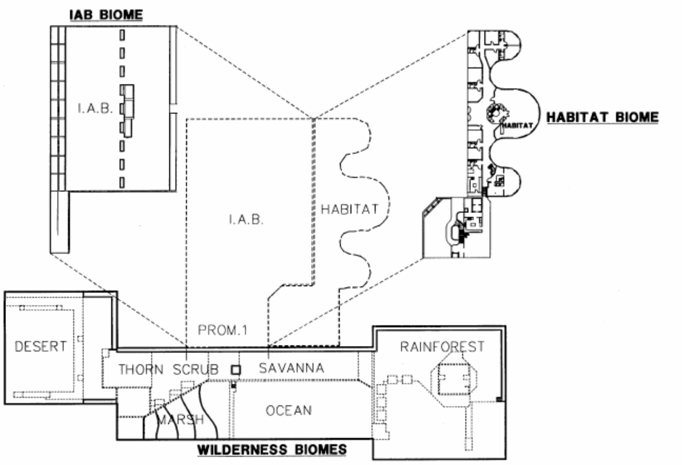


Figure 3. Plan View of Biosphere II

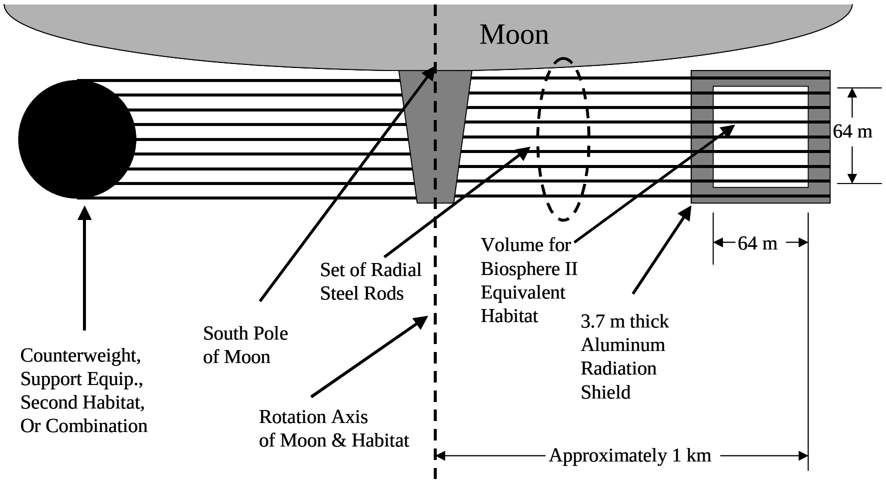


Figure 4. Biosphere II Equivalent Lunar Habitat Mounted on 1-G Centrifuge and Surrounded with Radiation Shield.

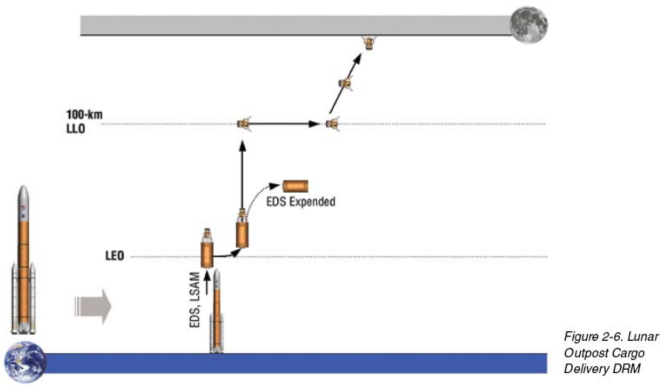
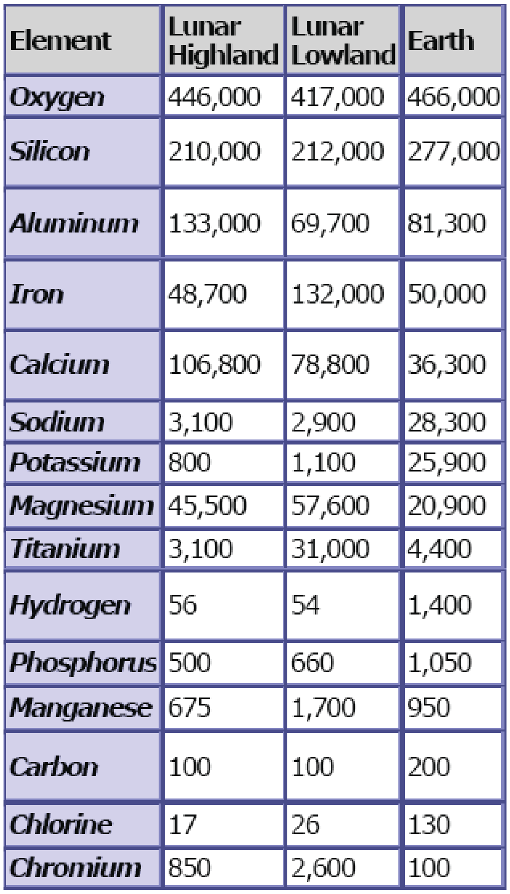


Figure 5. Lunar Outpost Cargo Delivery Design Reference Mission (DRM). Taken from Fig. 2.6 of the NASA ESAS Report.

Figure 6. Artist's Concept of Lunar Mass Driver

Table VI – 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

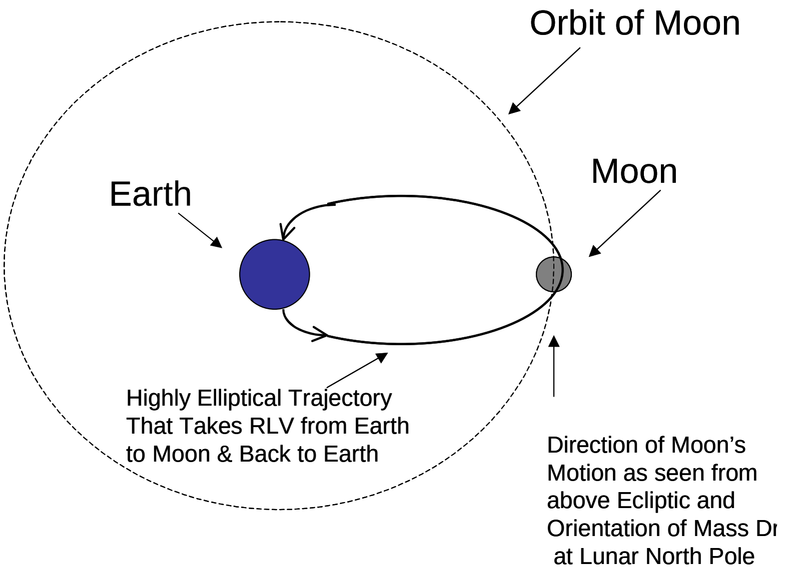


Figure 7. Orbit Arrangement for a Reusable Ares V, Lunar "Cycler", and Lunar Mass "Driver/Brake"

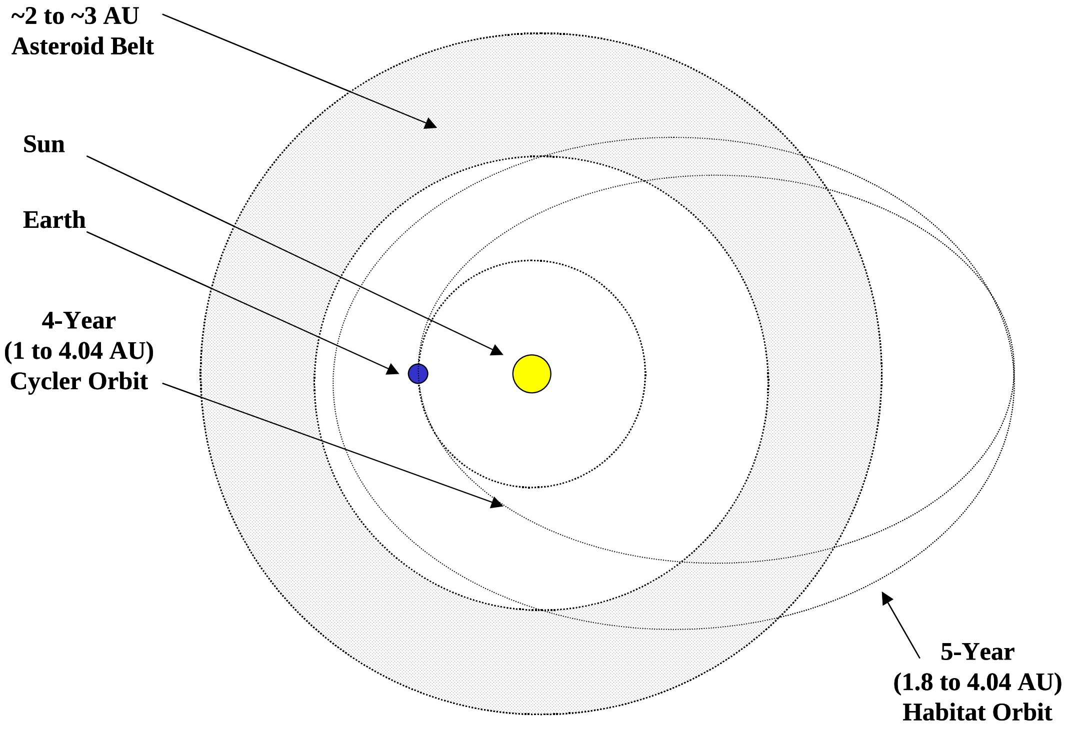


Figure 8. Cycler Orbit to Support Habitats built from Main-Belt Asteroid ISRU