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In-Space Fabrication and Growth of Affordable Large Interior Rotating Habitats

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Humanity's global impact on the environment, better understood now, but also greater, than in Gerard K. O'Neill's time, suggests that it is appropriate to develop an affordable tool of space settlement. The negative effects of micro-gravity on Earth-based life evolved for 1-g, and limited planetary surface area, support O'Neill's argument of the need for rotating space habitats large enough to preserve quality of life. The concept has added relevance, given that space based mining will soon provide access to materials, in the form of water and shielding, required for habitat development. How habitats may affordably be realized is thus a significant question, since cost and risk for direct assembly of 1-g structures at present appear prohibitive. (We note that "bola" or beaded habitats appear workable, but are not intended to address the quality of life issues central to space settlement.) Our NASA funded research has uncovered what is arguably the first direct pathway to space settlement with the potential to be affordable. The goal of our research was to find a design for a rotating tensegrity habitat structure capable of periodic self-similar expansion from a small seed structure, and of delivering a large and growing interior volume while maintaining life support and general habitability. Demonstrating the feasibility of this approach would reduce upfront risk for investors by orders of magnitude and make space habitat construction an affordable proposition. Although completion of such structures may require decades of work, they should be capable of being economically viable from the start. Capable of attaining 1-g at an early point in their growth arcs, they will mature into thriving space villages that will be secure both economically and in terms of food production. Each will have the capacity for zero gravity industrial production, and each will offer more than 90 acres of recreational woodland and lakes to a population that may number in the mid to high four figure. There are research efforts towards both lunar and asteroid mining that are currently in high gear, suggesting that space habitat development based on this model can occur much sooner than has been generally anticipated. Allocating resources to the development of this technology will both accelerate development of the cis-lunar economy, and greatly strengthen any incipient plans to plant a colony at Mars.

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I. Nomenclature

N	=	Nodal matrix
C_S	=	String connectivity matrix
C_b	=	Bar connectivity matrix
W	=	External force on each nodes
λ	=	Force densities in the bars
γ	=	Force densities in the strings
S	=	String matrix
ρ_s	=	Density of string material
σ_s	=	Yield strength of string material
$tr(\cdot)$	=	Trace of the matrix in the parentheses

II. Foreword

A renowned southern preacher, on being asked the secret of success for his sermons, is said to have replied, "First I tell 'em what I'm going to tell 'em; then I tell 'em, and then I tell 'em what I told 'em." We have followed his advice, and it will be seen that there is an element of repetition in what follows, the intent being to aid readers in coming to grips with subject matter, much of which will be unfamiliar to them. We will first give a brief introduction to the subject as a whole and our approach to it. Next, there will be a discussion of the major design features, while the final section will include a more detailed examination of key features, and will touch on our engineering calculations, approach to life support, and expectations as to economic viability.

III. Motivation

Rotation of a pressurized environment in free space has long been proposed to simulate Earth's gravity, allowing the occupants to avoid the negative side effects on human health that arise from extended exposure to microgravity. These side effects are so numerous and well documented in the literature that we will not recite them here. To simulate Earth gravity at a rate of rotation slow enough that noticeable side effects for occupants are avoided requires a large radius structure. We have taken as our baseline a rotation rate of 2 rpm at a radius of 224 m, as being sufficient to provide a comfortable simulation of Earth's gravity, in which most people will have only occasional sensory awareness that they are in a rotating environment.

Previous approaches to the design of rotating space habitats can be classified into two types, unitary and modular. Most efforts to date have focused on the unitary approach, where the habitat is constructed whole in a single extended operation, and then set to rotate. The challenge of constructing in space a spinning structure that gives a comfortable simulation of 1-g means that all unitary designs will be impractical until after we have already established a very secure space economy by other means. By contrast, the modular approach, sometimes referred to as the bola or beaded habitat approach starts with two habitable modules, sized to fit in available launch fairings. These are joined together in orbit by a long cable and then set to rotate about their common center. Additional pairs of modules connected by cables may then be added until a complete ring is formed. The approach is clearly feasible but is limited by the constraints of available launch fairings, and so lacks the spaciousness needed for long term psychological comfort and the nurture of families. The benchmark of environmental quality for raising children must be the presence of trees and landscape.

After a long period of preparation, we may now be ready to consider what it will take to enable space settlement. Accordingly, this paper will argue for developing a technology for in-space fabrication and growth of affordable large interior rotating habitats, each starting from a small seed structure.

History is full of examples where new technology becomes an engine of profit and development, and we believe that will turn out to be the case here. Space habitats like we are describing, capable of supporting the population of a small town, with immediate access to managed recreational woodland, and with a secure and varied food supply, will play a crucial role in the coming deep space economy. The advent of lunar tourism has been anticipated for several years, and now we know that ice with the potential for commercial extraction exists in the lunar polar craters. When ice mining begins, as now seems certain, lunar surface tourism will follow, leading to the establishment and growth of permanent communities at the lunar poles. Regular passenger service between Earth and the Moon will become a requirement, and expandable rotating habitats of the kind we are describing may be at the center of this traffic. We can foresee initially small shuttles that grow into spacious habitats offering resort-style accommodations cycling out to lunar orbit and back

2, 3 or 4 times a month, and similarly providing a system of Aldrin cyclers in support of a potential colony on Mars.

Rotation, of course, plays a pivotal role in all of this, so it is important to remember that all of our present knowledge about human responses to rotation come from centrifuge studies on the ground. These are necessarily incomplete, however, and the gaps must be filled by studies in space. One thing we have learned is the need to limit the gravity gradient which a standing adult will experience from head to foot, and this suggests that an optimal strategy for our habitat will be to commence rotation at 4 rpm until 1-g and a radius in excess of 56m is reached, and then reduce the rate of rotation each time a new expansion occurs, so as to maintain 1-g. But it is interesting to note that we already have some evidence [1] to suggest that the experience of rotation in space will be substantially less unsettling than in rotating centrifuges on Earth, because of the absence of conflicting frame of reference data that the brain is required to process. Experience in orbit will provide essential new insights into such questions.

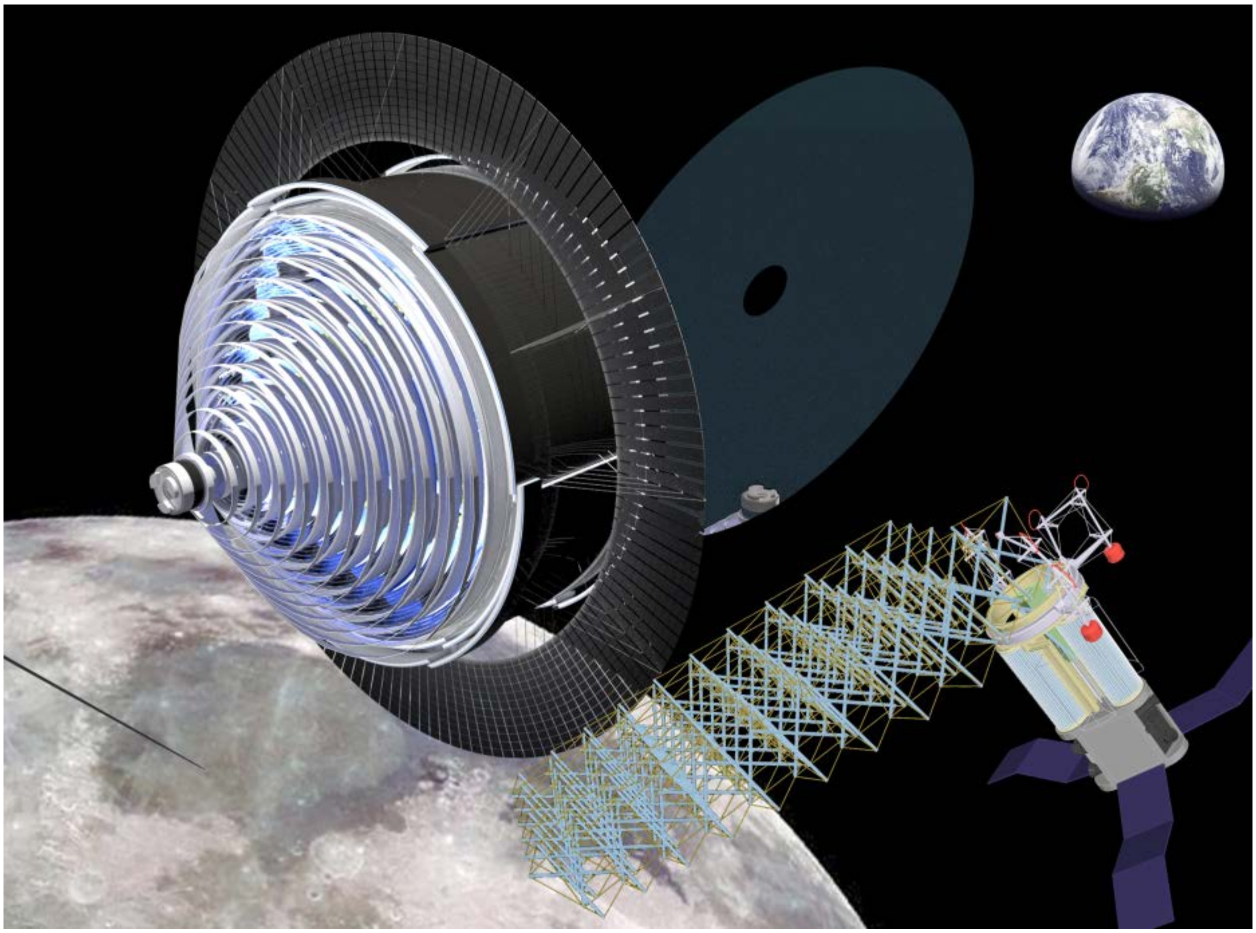

Fig. 1 Three-quarter view of the mature habitat showing lateral and dorsal radiators, solar panels on the cylindrical section, and primary reflectors. A tensegrity robot is assembling a tensegrity plate at lower right.

IV. Design Evolution for an Expandable Rotating Habitat

A. How Rotation and Growth Drive Habitat Geometry

The requirements of process and function can have very specific outward expressions. Consequently, when new requirements are added to the mix, this can lead to radical shifts in how these functions are manifested.

We experienced this with regard to the shielding and pressure containment functions. In a Low Earth Orbit context these can tend to be viewed as merely two aspects of the structural envelope. When translated to a long-duration deep space context, with both rotation and expansion added in, we realized that we were in a new ball game, and that potential growth mechanisms for the two functions were very different. We eventually decided to embody the shielding and pressure containment functions in two separately rotating structures, because their potential growth mechanisms were physically so different as to be in fundamental conflict, and incapable of being combined in a single integrated structure. Two separate structures emerged, linked by bearings, allowing the shield to rotate much more slowly than the pressure hull, and to greatly reduce its structural mass component while retaining the control advantages of rotation. In turn, this allowed us to choose a pressure hull enclosure of tensegrity membranes, including wall membranes that were both flexible and transparent, because the entire pressure hull was already completely protected from impact damage by the rigid and separately rotating shield. The choice of a flexible wall membrane made possible a pressure hull expansion mechanism in which a rolling flexing slope reversal of the newly added outermost pressure walls plays a key role. Although a flexible pressure membrane is a radical idea, the benefits that flow from it are proportionately great. There are alternative means, other than mass and rigidity, for ensuring safe containment of atmospheric pressure, such as electronic monitoring, multiple bulkheads, post-expansion fire suppression coatings, and the use of flying robotic drones to seal punctures from the interior. Intelligent deployment of such measures will be sufficient to ensure acceptable levels of safety.

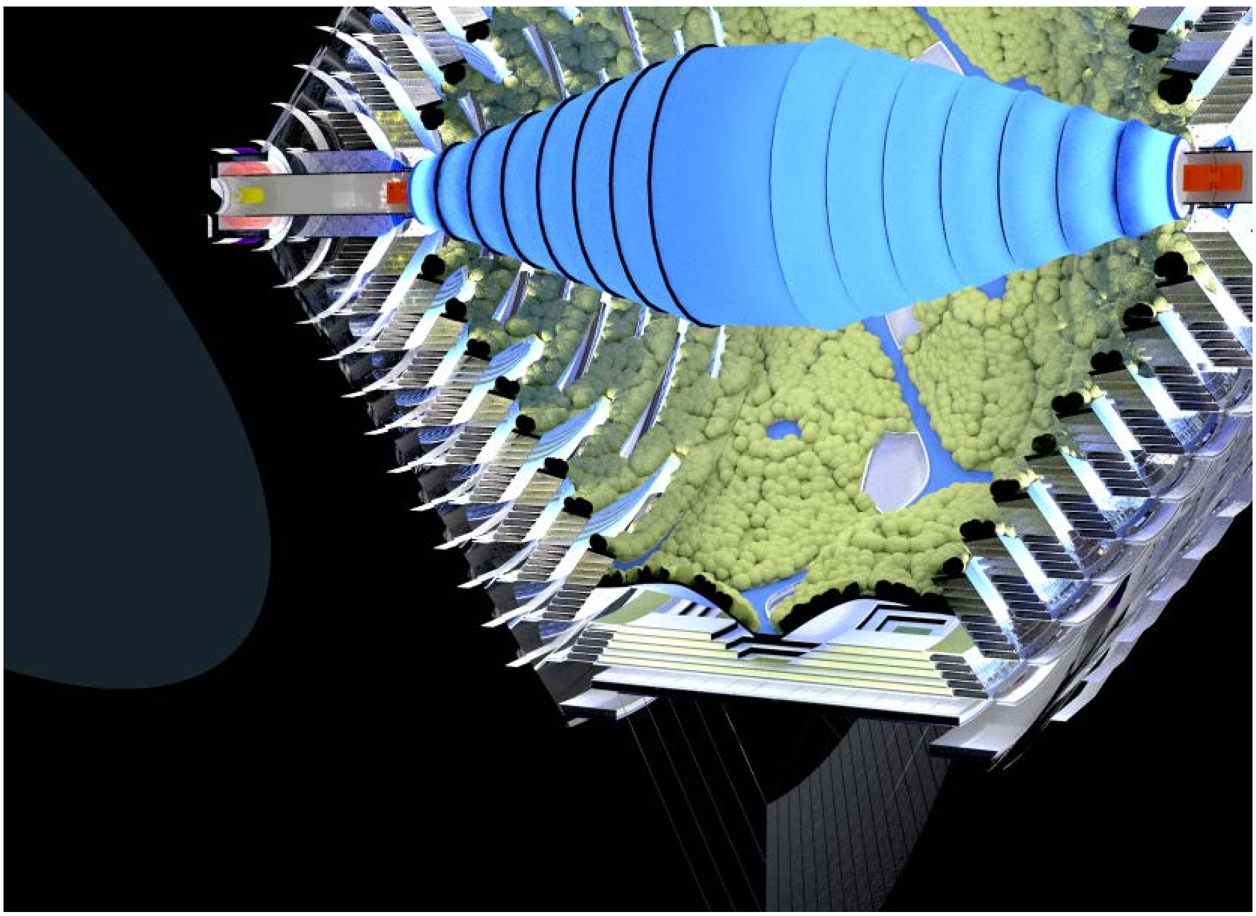

Fig. 2 Interior of the mature habitat. At top center is the central reflector housing the zero-gravity workshop (ZGW). 10,000 trees and a dozen lakes provide recreational space for residents. The agricultural levels at each side are in darkness, while the floors immediately above them with views to the interior are experiencing daylight. 1-g living space at the bottom is lit by the lowest light shafts at either side and by the large central skylights. Five floors of apartments, offices, and atriums, are topped by a continuous open-air urban mall. Beneath the pressure hull floor, the three sections of the shield floor can be seen. Shield thickness grows from initially 0.5m to 5m at maturity.

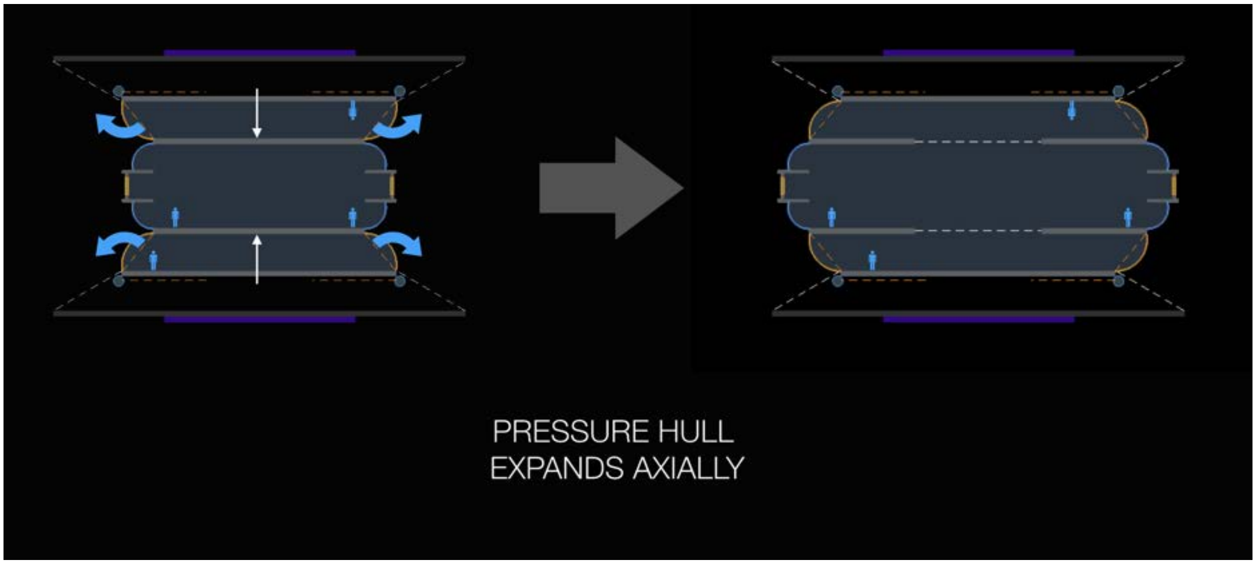

Fig. 3 The first expansion of the habitat immediately following deployment in orbit. This transformation will be repeated throughout the habitat's growth arc. The docking port is just visible in the previous illustration.

B. Overview of Principal Design Features of the Mature habitat

The axis of rotation of the habitat will be perpendicular to the ecliptic plane. A pair of free-flying elliptical mirrors will be stationed above and below the habitat, oriented diagonally to the sun's rays so as to direct light to the sidewalls of the habitat. The entire system will be comprised of a set of engineered tensegrity structures, for maximum mass efficiency and the ability for controlled change of shape by altering the lengths of tension cables. Three concentric structures linked by two sets of bearings will make up the main body of the habitat.

1. Expansion Mechanisms of the Pressure Hull (Part I)

The form of our habitat reflects the solution we found for how to make an expandable pressure hull. Any efficient pressure containment structure tends to be spherical but, for our purposes, a double cone is more practical, with its faces subdivided into concentric rings that are distended by internal pressure. Each ring covers a radial interval of five floors and results from a prior growth event, similarly to the rings of a tree. After adding a new separately pressurized outer ring, of similar (or larger) breadth, and by including a suitable gather of pressure hull material, the old outer floor that is now enclosed can separate into two parts, causing the newly added pressure wall on either side to roll outwards into a new sloping configuration matching its neighbors. The need for this transitional move is the underlying reason for requiring a flexible pressure wall membrane. Initially, this slope change involves a full slope reversal for rapid axial growth but then reduces to half for the main radial growth sequence.

For dimensional convenience, we set the overall sidewall profile, ignoring curved sections, at a slope of 53.12° to the axis of rotation. This is the angle whose tangent is 4/3 deriving from the 3,4,5 right triangle. (An alternative choice of 60° was used in our engineering calculations, but the angle of 53.12° also appears within the bounds of rotational stability and produces a more open interior.) For the same reasons, we set the floor-to-floor height at 4m, and the increment of habitat expansion at 5 floors, or 20m, giving the on-slope increment of pressure membrane growth as 25m. So as to allow for both the agricultural growth floors and the habitable interior volumes to receive sunlight, we anchored each group of 5 floors to the inclined pressure wall membrane at its base, and then raked it inwards away from the membrane, with the same 53.12° slope to the horizontal, but in the reverse direction for reasons that will become apparent in a moment. Finally, we set the depth of the agricultural floors at 15m. Iterating these choices results in a series of inclined agricultural floor stacks separated by 10m wide light shafts, a configuration reminiscent of a louver blind. We added the mechanisms to recreate Earth's diurnal cycle by fitting the sloping window walls of these floor stacks with mirrored shutters that either admit light to each growth floor or divert it up the light shafts to the axially located central reflector (see next section).

2. Expansion Mechanisms of the Pressure Hull (Part II)

For the lateral expansion just described to be useful, we must devise a method for assembling and attaching the new pressure hull floor and walls to the rotating pressure hull. A brief outline that will be enlarged upon later is that the walls are already rolled up and attached underneath the existing outer pressure hull floor and that the new floor is assembled on the interior of the shield floor in sections, and then rises into the correct position as the sections are cinched together. We positioned a set of self-propelled robotic arms, riding on rails attached to the interior face of each shield wall, to hold the new floor in place, and on command, these gradually accelerate the new floor until it is rotating in sync with the pressure hull. (These also used for loading of construction materials onto the shield floor.) At this point, pre-positioned stowed Michell trusses attached to the underside of the old outer floor of the pressure hull deploy down and secure themselves to the new floor. The robot arms then release and retract, decelerating to rest, while the pre-attached and stowed window walls at the edge of the old outer floor release and roll down to be zip-closed to the new floor. The new space is then pressurized, completing the addition of the new floor to the pressure hull.

3. Three Concentric Bodies Make up the Habitat

We chose to set the rotation rate for the outer radiation shield at around 0.2 rpm because this will provide adequate traction for operations on the interior surface of the shield floor panels. By contrast, the goal for the interior pressure hull will be 2rpm, and the innermost body of the three, a central reflector, will be non-rotating so as to house a micro-gravity industrial space, or 'Zero Gravity Workshop' (ZGW). All of these structures have conical surfaces at either side that are periodically extended during the habitat's radial phase, together with short cylindrical mid-sections that are developed during the late stage axial growth phase.

4. The Radiation Shield and its Radiator Systems

A pair of axial docking hubs are located at either side of the shield. The conical sidewalls of the shield are assembled using blocks formed out of stacked layers of optical glass fiber made from fused silica, mined from asteroids or the Moon. The blocks are held in a tension cable network, and expansion of the shield walls occurs through the addition of new material at the open edges of the shield and also by gradual thickening through the addition of new layers of these blocks. The shield floor is always enclosed between the outer edges of the shield walls and is comprised of 3 sections, a broad inner central section, and two narrower overlapping side sections. The proportions of these 3 sections are chosen to give continuous access on both sides for the loading of construction materials while still maintaining line of sight shielding of the pressure hull from a direct view of the sky, and thus from exposure to galactic cosmic radiation and solar proton events.

The wall and floor sections of the shield structure together support a two-stage system of radiators. During the late stage expansion of the habitat when the floor of the habitat is being widened without any increase in radius, there is a clear interior pathway for radiative transfer across the rotational clearance between the pressure hull floor and the shield floor. This is employed using arrays of radiative cooling panels to transfer heat across this space and out to a growing array of radiators suspended outboard of the shield floor, and positioned edge on to the sun. By contrast, during the preceding radial growth phase, the space between the pressure hull and shield floors is frequently blocked by assembly and attachment of new pressure hull floors, and therefore cannot be used for radiative heat transfer. For this reason, we created a complementary heat rejection system that sheds heat sideways through the walls of the habitat. These lateral radiators provide heat rejection during the radial growth process, while the dorsal radiators deliver heat rejection in the late stages of the growth process when radial growth is complete, and axial growth is underway. We will address these systems in more detail in Section V Part C.

5. Structure of the Pressure Hull

We have seen that the sidewalls of the pressure hull are comprised of curvilinear panels that have a span of 25m on-slope. The material we chose for this function is UHMWPE for its properties of toughness, transparency, and flexibility. The wall thickness will vary somewhat between the floors, but will be on the order of 1mm thick, and can be formed with 90% transparency or better. It can also be fiber-reinforced if required for additional strength. The pressure hull floors will be of the same material, in a woven cable mat, but without the requirement for transparency. The structure of the weave is a multi-layer engineered tensegrity network calculated to carry all the anticipated floor loads with an appropriate safety factor.

6. Primary and Secondary Floors of the Pressure Hull

Our design anchors every fifth interior floor of the agricultural stacks to the pressure hull wall, and every one of these floors, together with its interior neighbor across the adjacent light shaft - forming the roof of the next stack down-slope - each of these floors originally comprised a section of the outermost floor of the habitat, and was therefore subject to atmospheric pressure load in addition to normal floor loading, so in structural terms, we consider these to be primary floors because of their additional load-bearing capacity. All the other intermediate floors in each stack are designed only to carry normal floor loads and are, therefore, secondary floors. Every secondary floor entered the habitat as payload in the form of stowed construction materials carried on board during the spin-up and attachment of a new primary or pressure hull floor, and each new pressure hull floor when it is being assembled is comprised of four side-by-side cylindrical floors joined by three built-in and pressure-locked separation joints. At a certain point during the completion of each new floor addition, a command is issued that enables the old outer pressure hull floor to separate into these four equal width parts, using built-in restraint cables to control the rate of expansion against the force of the habitat's atmospheric pressure. This four-part separation is what gives rise to the louver blind-like agriculture stacks and provides the channels for light to reach the interior.

7. The Central Reflector and Micro Gravity Industrial Space

During the interior day, when the crops are in darkness, the central reflector receives light through the light shafts and reflects the light down to the valley floor and onto the terraced interior surfaces of the agricultural stacks at either side. Industrial processes that require weightlessness will be housed within this central reflector. The surface panels of the reflector are brought in through the docking hubs at each side and assembled in mid-air during each expansion phase of the habitat, taking advantage of the effective zero gravity along the axis.

8. Main Sequence and Late-Stage Growth Modes

The initial or 'Main Sequence' growth method that has been described in some detail up to this point balances both radial and axial growth, and maintains a relatively narrow outer floor. This strategy is optimized for building volume and reaching the radius that we have set as a goal. Once this radius is attained, however, the strategy must change to one of increasing 1-g floor area by growing the axial dimension. Happily, the previous growth methodology is flexible enough that it can now be applied to pure axial growth. For each new growth event, a pair of new airlock walls, continuous around the circumference, are assembled, one on each side of the habitat below the inner edge of the first overhead floor. Expansion occurs by unhitching and rolling up the existing outer pressure hull wall membranes at each side on this outermost level – the outer doors of the airlocks – adding a new floor extension, rolling down the outer wall again, but now with an outward lean so that it zip-closes to the new floor with a reverse slope, and then re-pressurizing both airlocks and re-opening the inner pressure wall or door of each airlock. Once all is secure, the overhead restraining cables, still in place, are carefully unreeled still further, while stored volumes of additional atmospheric gases are released. This process is repeated until the proportional limits required to prevent tumbling of the habitat are approached. These limits can, in theory, be breached by using active stabilization measures, but additional measures, for example, to maintain balance in food production, would also then be required.

9. Interior Landform Construction

The interior ground planes of the mature habitat are constructed using engineered tensegrity as their structural paradigm, and automated algorithms for their calculation, and are designed to echo landforms that might be found on Earth, carrying a minimum two meter depth of soil in addition to a full load of organic material in the form of trees and other plants. Twelve small hills are arranged on the valley floor with a winding water body between them and a small lake located in a crater-like depression on each hilltop. In the same manner, on top of each 5-floor agricultural stack, the sidewalls of the valley are braided together into an interlocking 15m wide series of landscaped sinusoidal walkways. Bridges at intervals across the light shafts allow the inhabitants to walk from the valley floor to near the axis of their habitat on either side.

10. Interior Pressure Hull Option to Conserve Required Nitrogen Volume

Given the need to provide a breathable atmosphere, availability of affordable supplies of bulk nitrogen present a potential constraint for the growth of the habitat since known sources of nitrogen in the inner solar system outside Earth are limited, and the interior atmospheric volume will grow with the cube of the radius. To mitigate this, it may be desirable to construct an interior pressure membrane to limit the atmospheric volume. This may be done by anchoring a counterpart to the exterior transparent pressure membrane to the inner edge of each agricultural stack.

C. Growth of the Agricultural Floor Stacks

We have already discussed in some detail how new floors are added to the pressure hull, but some further detail must be given regarding how the agricultural stacks emerge from this process. At the same time that the slow release of restraint cables is opening up the central space, parallel separations must also take place in the two seams in the pressure hull floor that lie either side of the central seam. The separation of these side seams is what opens up the base of each new light shaft that separates the top or roof level of every newly created agricultural stack from the bottom floor of the next neighboring stack upwards (or inwards). Construction materials that were brought on board with the new outer floor will be assembled into the intermediate floors for the new stacks. Each new outer floor comes equipped with hardware on its underside that comes into play during the next subsequent expansion event. This equipment comprises roll down wall panels, radiative cooling panel sets, and finally, stowed Michell trusses that deploy downwards 20m in the subsequent expansion, tying onto the next outer floor to provide rotational stiffness to the habitat. In the subsequent expansion, the radiative cooling panel sets will be used to shed heat out to the lateral radiators, along with the heat transfer panels that will radiate heat across the vacuum clearance separating the pressure hull from the shield. The top of every Michell truss is connected to the inner edge of its parent floor segment (i.e., at the outer edge of the adjacent light shaft) while its bottom edge extends down and secures to the outer edge of the new pressure hull floor below. The dimensions we chose for the cross-section ensure that the Michell truss will be positioned in a vertical orientation (although they will also function in a sloping orientation).

D. Growth Modes of the Shield

Our shield is designed to provide operational clearance from the pressure hull side walls in normal operations. In order to preserve its axial bearing connections with the pressure hull when the shield expands to make room for a coming pressure hull expansion, we include a shift capable tensegrity bearing that will be discussed in detail in the next section of this paper.

The shield walls follow the same overall conical alignment as the pressure hull walls, and like the pressure hull walls, the shield walls will also need to be transparent to admit sunlight. The material that we will use for the shield walls is fused silica, which has ideal properties in this regard. The raw materials for its production are abundant on the Moon and in the asteroid population, as on Earth. The shield wall will be comprised of fused precision silica blocks held in place by a tension cable harness, in the form of an engineered tensegrity structure, and with optical gel between the blocks. Optical fiber of a transparency superior to what can be achieved in Earth's gravity field has been made on the International Space Station, and it appears likely that the glass blocks we require will be assembled from similar space fabricated optical fibers. (Production of these blocks using an automated facility can begin well in advance of habitat deployment.) The required volume of shield material will be relatively small, to begin with, increasing only as the habitat grows in size, and there is abundant energy for the process in the form of sunlight. Also, the vacuum conditions and absence of gravity-driven convection can be exploited to advantage in this process. Therefore, we consider this to be a second-order problem that will be solved at the right time, with the appropriate allocation of resources.

By contrast, the shield floor need not be transparent, but will instead need to be flexible, and arranged in overlapping tensegrity plate panels whose curvature can be altered as the shield floor radius increases. As we touched on earlier, these panels will be tied together so as to form a unified structure, with the individual panels able to be extended, both radially and in the circumferential direction, to enable the growth of the structure. In addition to struts and tension cables, each panel comprises a three-layer sandwich of shielding materials. The inner and outer layers of the sandwich will comprise bags of regolith slag – from robotic mining operations for water to make propellant – surrounding a middle layer of water bags, water being the most efficient shielding material readily available from ISRU mining operations. The proportions of the layer thicknesses in this shield we have tentatively set at 1:2:7 from outside to inside, starting with a thin meteor bumper layer to protect the water layer. This arrangement allows the water layer to leverage the efficacy of the interior regolith layer, reducing the level of secondary radiation progressively as the overall thickness of the shield is increased. By including strategically placed dormant layers of unfilled water bags within the thickness of the interior regolith layer, it becomes possible to grow the overall thickness of the shield floor, while maintaining the relative thicknesses of the three layers, entirely by adding materials from inside the shield. This is accomplished by a.) adding more regolith bags (and new layers of empty water bags) from the interior, together with b.) pumping the water from its initial outer location to the next inward layer of waiting unfilled bags, and c.) topping up the new water layer from the interior.

E. Docking Hubs and Shift-capable Bearings for the Shield

As we have seen, the shield system as a whole is comprised of three parts, two conical walls, and a floor. Each shield wall is provided with a central shielded docking hub, and both shield walls together overlap and enclose the central shield floor, which acts as a single compound tensegrity plate structure, able to adjust its dimensions as required. The left and right shield walls and the shield floor system must act together as a whole, and require suitable connections to enable this. The entire shield floor assembly must be periodically expanded and move outwards as a whole, following the expansion of the shield walls, and a system of radial rail segments, with captive bogies, will provide the required connection to enable this adjustment while preserving structural continuity.

As noted earlier, to ensure that the pressure hull and shield systems maintain their proper axial alignment and provide space to accommodate the axial expansion of the pressure hull during growth events, a pair of axial shift-bearings will be provided. These will have a permanent magnet bearing interface and be suspended within a tensegrity harness that allows the full axial displacement, or shift, required during the differential expansion steps of pressure hull and shield required to accomplish the overall expansion of the habitat. If the above-specified measurements apply, a shift capability of 15 m will be required from each bearing harness, matching the axial displacement capability built into each newly added pressure hull floor. The form of these shift bearings is arranged so that each inner bearing ring surrounds the external loading deck adjacent to its axial docking airlock and cargo airlock.

V. Essential Subsystems

A set of key mechanical subsystems that enable the habitat's expansions and its routine day to day operations will now be described.

A. Rail-mounted Self-propelled Robotic Arms

We have noted that the critical maneuver for the success of the expandable habitat concept is the assembly and adding of a new floor to the rotating pressure hull, and so we will take a closer look at this process.

Robotic tugs will transfer the materials for the construction of the new floor from delivery vessels onto the left and right shield floors. At a suitable height on the interior face of each shield wall, a circular rail will be mounted, on which will ride a set of self-propelled robotic arms equipped with stabilizer wheels at the end of outrigger arms. These stabilizer wheels will rest on the interior surface of the shield wall to provide additional stability and leverage when handling loads. The robotic arms will grasp the pallets of construction materials and lift them up onto the edges of the center shield floor panels, which will act as a workbench on which the sections of the new pressure hull floor will be assembled. These individual floor sections will be connected together by tension cables, acting in a manner similar to shoelaces to gradually cinch the panels together. As the new pressure hull floor starts to raise up off the shield floor workbench, it will be grasped by the rail-mounted robotic arms so that its position remains carefully controlled. At the point that all of the open joints between the new pressure hull floor sections are fully locked and zip-sealed, the new floor will be in its correct relationship to the rotating pressure hull overhead, and the rail-mounted robotic arms will engage their drive mechanisms to slowly accelerate the new floor to match rotation with the pressure hull. When this point is reached, stowed Michell trusses overhead (attached to the underside of the pressure hull) will deploy so as to reach down and anchor to their attachment points on the new floor. (As noted earlier, every new floor that is added will have certain equipment attached on its underside, including radiative cooling panels, rolled and stowed window walls, and Michell trusses to resist torsional oscillations.) At the same time, the rail-mounted robotic arms will release their grip, retract, and decelerate to rest with respect to the shield. Airlocks located in the pressurized floor overhead will enable construction workers in pressure suits to inspect the new floor and monitor the ongoing operations. The rolled and stowed window walls overhead will unfurl, and zip-close to the new floor and to each other, and pressurization of the new floor will begin. After the new floor is pressurized, inspected, and certified, the next step will be to unseal the overhead separation seams in the floor above, and slowly release the coiled restraint cables, allowing the axial extent of the pressure hull to expand by the designated amount, typically 15 m in each direction. The final step in this cycle will be for the shield walls to be extended, and for a pair of new circular rails to be attached to their interior faces. Once this is done, the rail-mounted self-propelled robotic arms will reach down, grasp the new rail, and relocate themselves to run on these new rails.

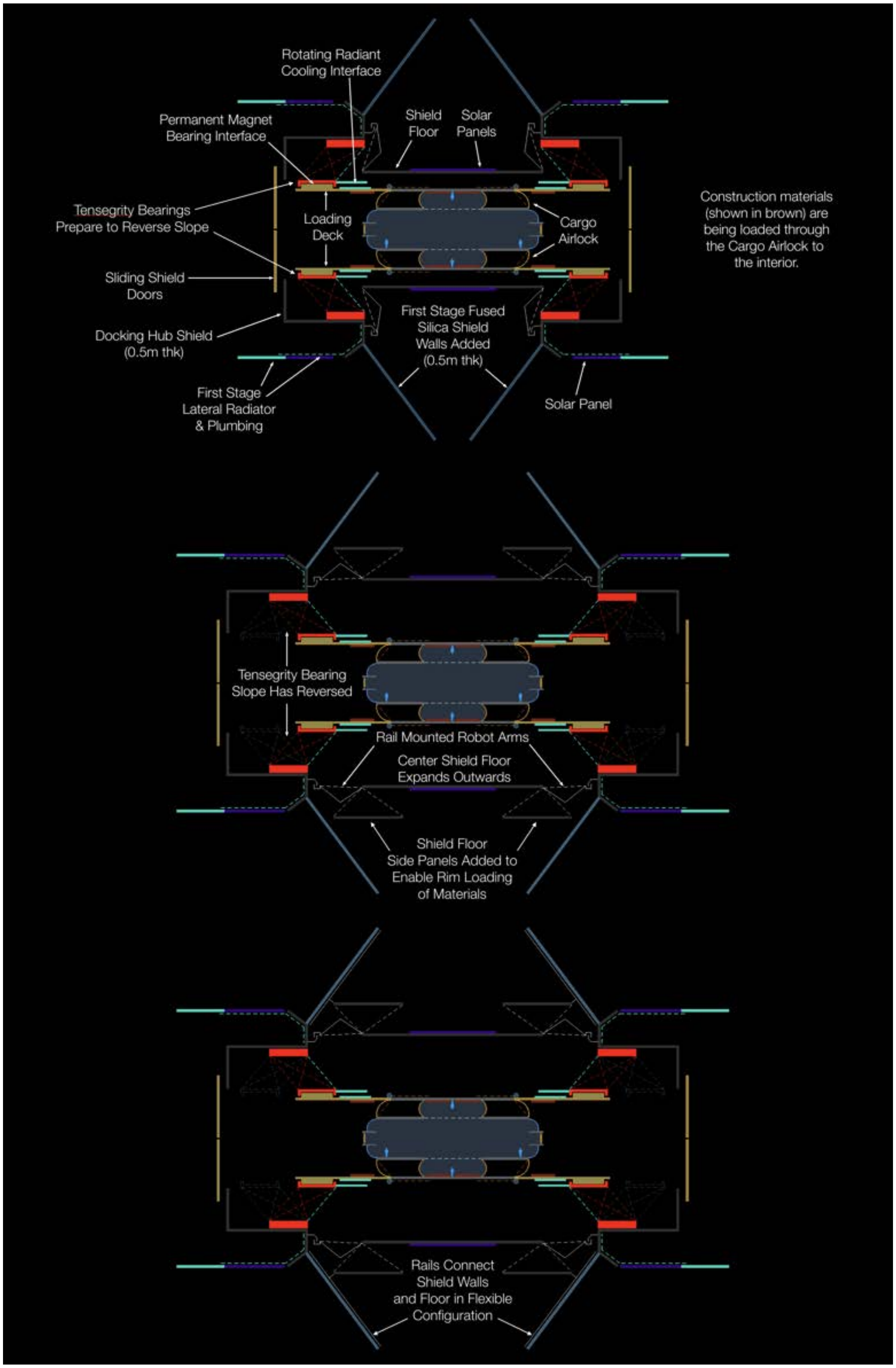

Fig. 4 This series of images shows a sequence of operations soon after the initial deployment.

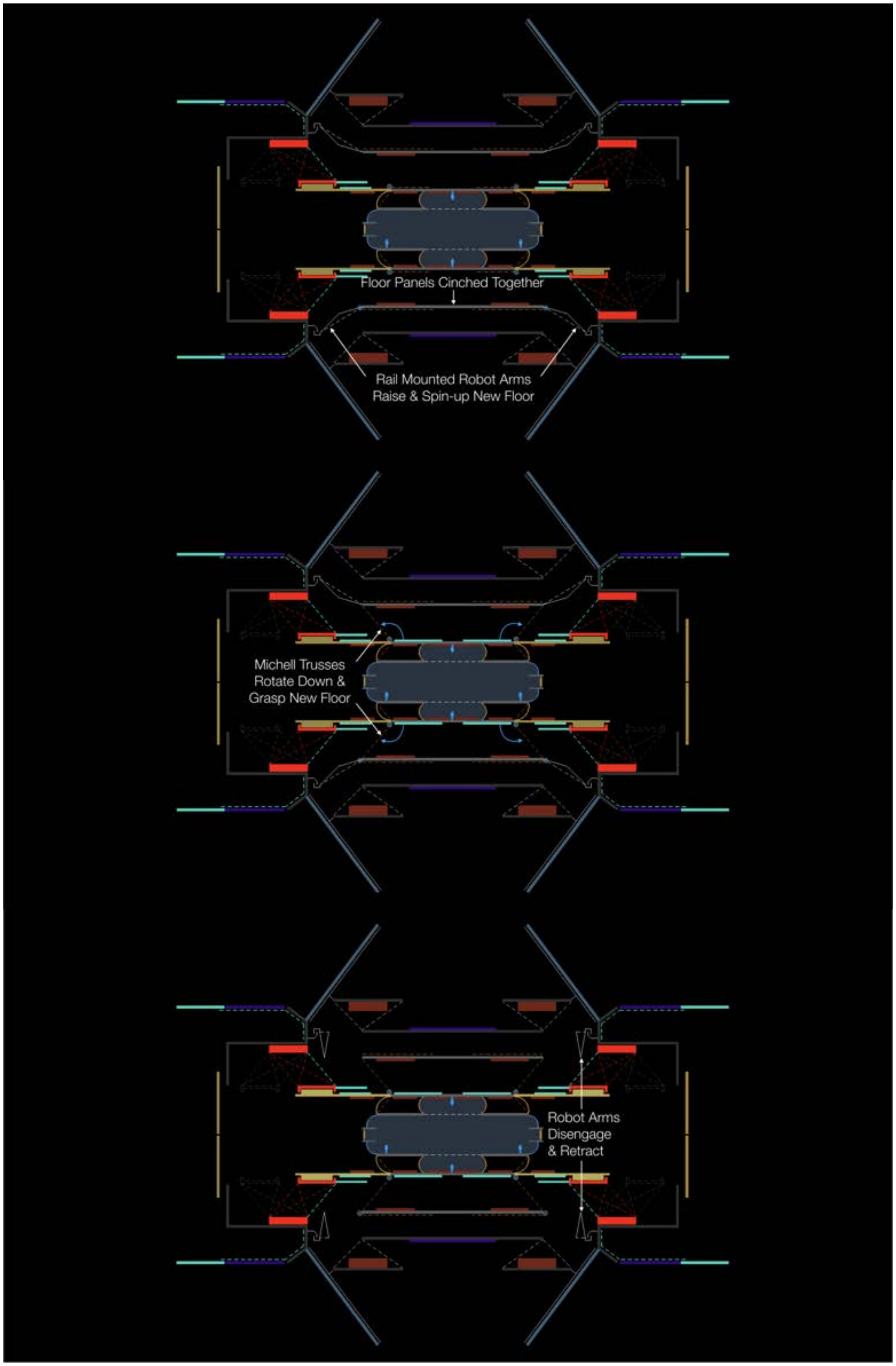

Fig. 5 In these images the newly assembled pressure hull floor is being spun up and grasped by the Michell trusses on the rotating pressure hull.

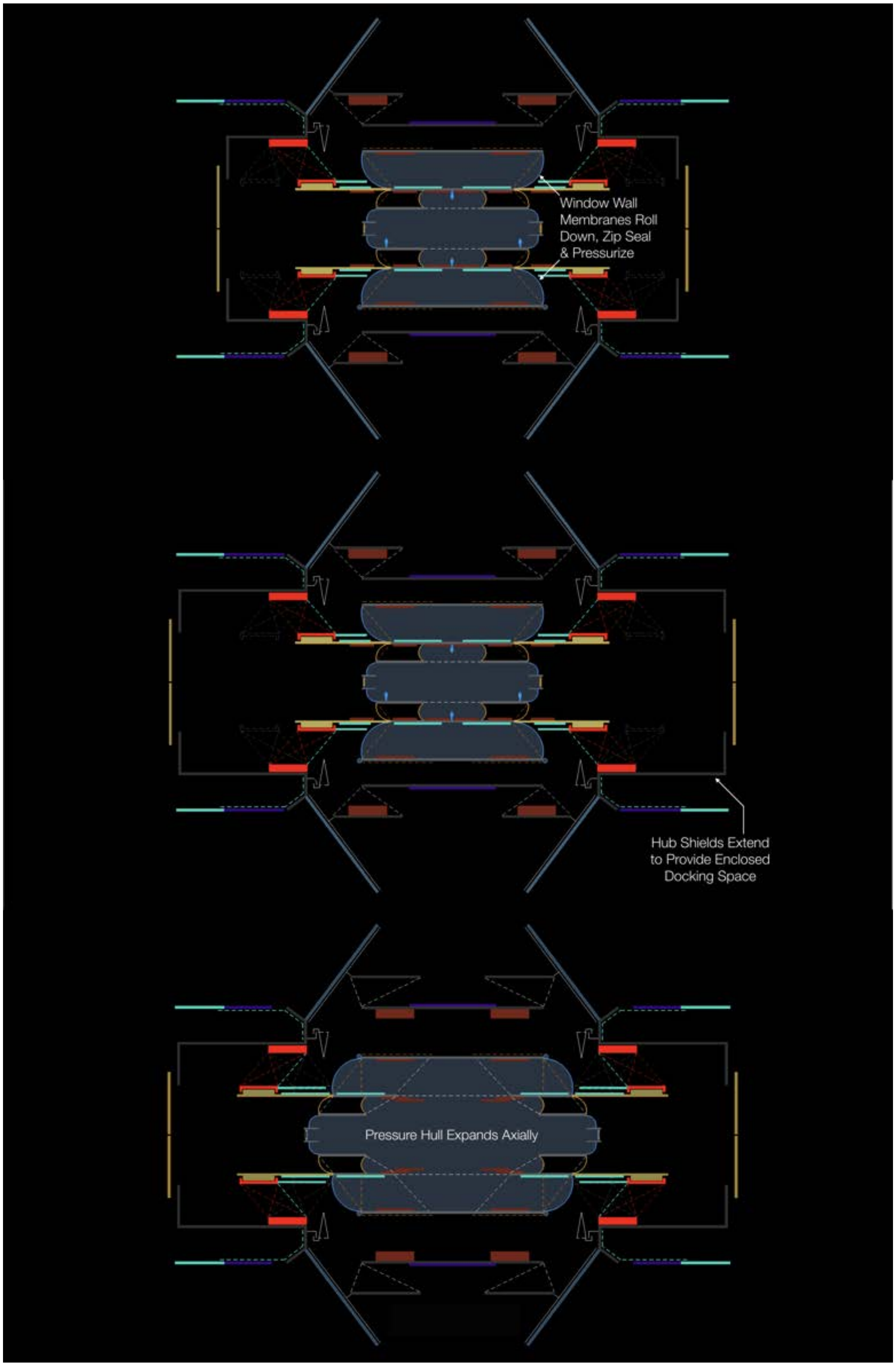

Fig. 6 The stowed window walls under the pressure hull's existing floor are rolled down and zip-closed to the new floor, followed by axial expansion.

B. Details of Diurnal Light Management

The sunlight reflected from the 45° inclined primary mirrors will pass through the shield wall, through the pressure hull wall and through the inclined window wall of each agricultural stack, striking inclined ceiling reflectors that will then illuminate the horizontal growing floors. Supplementary LED illumination will be provided as needed, using power from solar arrays located on the outer surface of the shield floor. For each of the growing floors, top-hinged shutter doors will be mounted to the exterior face of the sloping window wall, allowing sunlight to be closed off from the crops so that it may be redirected to the interior. Outside the lowest growing floor will be a catwalk at the outer edge of which is mounted a movable louver mirror array that is able to allow sunlight straight through, or direct it upwards through the inclined light shafts that separate the agricultural stacks. Since this solution will not work for the other four floors (each louver array would block the one below it) so the outer face of the shutters on the remaining four floors are covered with an array of small horizontal linear prisms, with silvered rear faces, and the internal geometry of these prisms is arranged so that light exits at a steep angle into the inclined light shafts. With a single bounce off the shaft walls, the light reaches the central reflector and then angles down to the ground surfaces below. The system allows not only diurnal light control but also custom-tailored seasonal variations to accommodate the needs of the various plant and crop communities of the habitat.

C. Heat Rejection Strategies

A consequence of using the shield floor as a workbench for adding floors to the pressure hull is that the most direct route for heat rejection – through the floors of the pressure hull and shield – will be unavailable during the greater portion of the habitat's growth arc since the shield floor will be repeatedly required for construction and assembly activities. (The silver lining is that after radial expansion ceases and axial expansion begins, this route immediately becomes available, in time to handle the blossoming waste heat footprint of an expanding population.) Up until then, however, the other available pathway must be used – i.e., through the walls of the pressure hull and shield. Radiant cooling panels will be routinely located in the ceilings of each floor, and coolant pumped from there out through the edge of each primary floor to a cylindrical radiator array that is mounted to, and rotates with, the pressure hull. A cylindrical radiant cooling panel, concentric with the cylindrical radiator, will be mounted to the inside face of the shield wall, on an extendable and retractable frame, and positioned with a suitable clearance from the radiator to absorb its thermal radiation. From here, a circuit of flexible pipes will carry the coolant to cylindrical radiator segments mounted externally on the shield wall. These radiators will be edge-on to sunlight from the primary mirrors, but will receive direct sunlight from the sun during half of their rotation period. Consequently, they will need to be constructed of materials configured to act as second surface mirrors to reject the sun's energy, while still retaining the ability to radiate longer wavelength thermal radiation, in a manner similar to the spacesuits designed for use by astronauts on the Moon's surface. These linked thermal transfer systems will occur in line with each primary floor of the habitat. As noted earlier, once the radial expansion is completed, the direct radiant pathway out through the shield floor will become available. Radiators pre-installed on the underside of the outer pressure hull floor will be matched with radiant cooling panels installed on the shield floor interior. These, in turn, will be linked to a dorsally mounted array of radiator panels, suspended around the median of the shield floor. This array will be edge-on to direct light and heat from the sun, and capable of being extended as required.

D. Freight Elevators, Shuttles, and Lifeboats

Radial pathways will be preserved at intervals through the shield mounted radiant cooling panels, and their support frames, to allow for the passage of freight elevators running on radial rails. These vehicles will be equipped to switch tracks and travel on the circular rails left over from previous use by the robotic arms. In this way, they will be able to access a wide range of lateral docking ports in the pressure hull provided for this purpose. Each elevator car may be up to 4 stories high, and their breadth will be governed by the space available at the highest floors of the habitat that they serve. They may also be equipped with thrusters, so that after descending to the lowest level, they are able to exit through the continuous loading doorways of the left and right side shield floors, to act as shuttles between the habitat and visiting spaceships. This idea can be further extended to the provision of 4-story lifeboats that are stowed all around the rim, at intervals, on the left and right shield floors. In the event of a need to evacuate, these would rise up so as to be level with the main habitable floors, and dock there to take on passengers.

VI. Landscaping the Interior

All of the previous discussion has concerned the growth of the essential habitat envelope and structure. We will now briefly focus on the build-out and interior furnishing of the habitat to enhance its habitability through the construction of an interior landscape. In providing the substrate for the habitat's managed woodland ecosystem, this feature of the design plays a major role in the bioregenerative life support system, a subject which will be addressed further in the section of this paper devoted to that topic. Whereas the design of the structure up to this point has been the subject of preliminary structural analysis, this area of the design is still a work in progress at the conceptual stage. We have a geometric model, and an outline structural concept for the support of the hillside and the valley floor topography, combining tensegrity plate with catenary suspension cable geometry for the support of a minimum 2m thick layer of soil, to be synthesized from regolith, and of the associated plumbing to handle drainage.

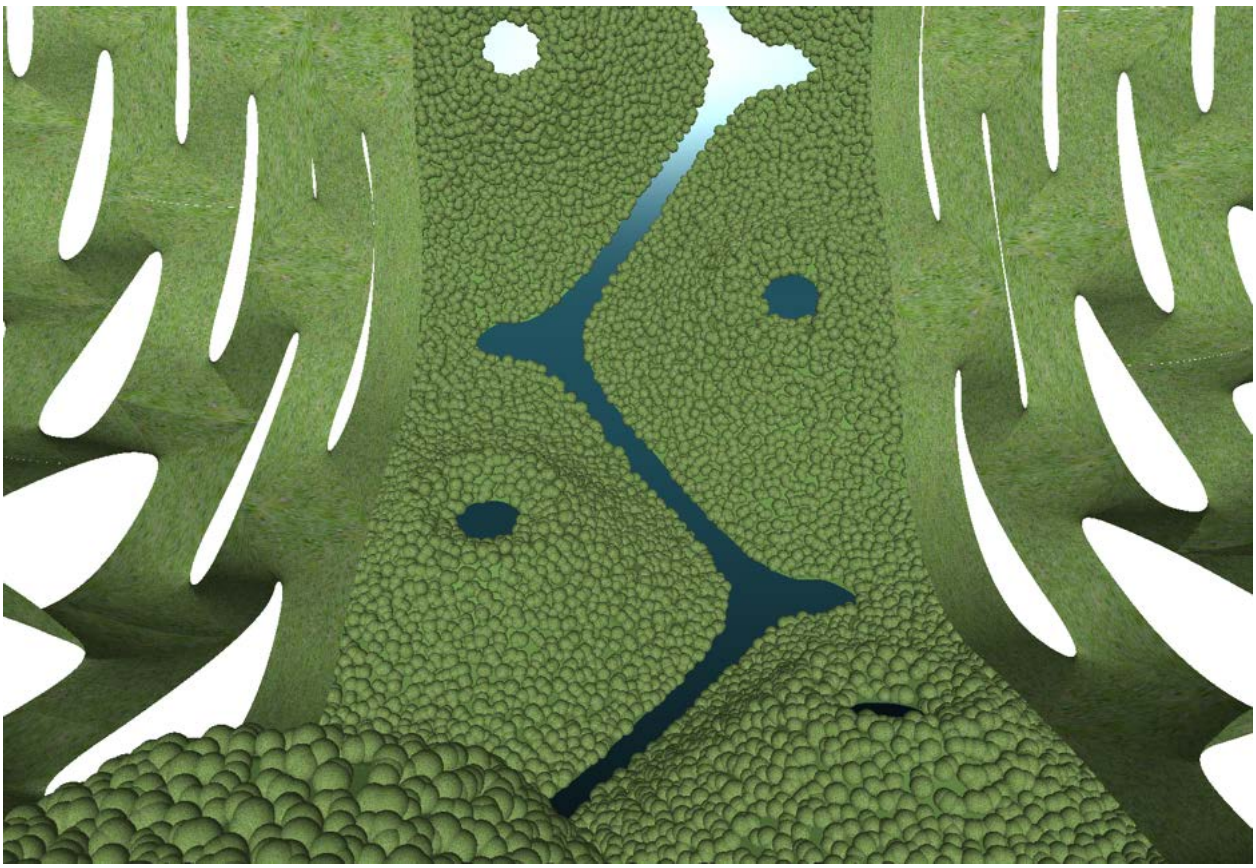

Fig. 7 This diagrammatic interior view shows the topography of the valley floor and the adjoining hillside land surfaces in its pure form, with the central reflector removed. The inhabitants can walk from the valley floor to the axis of the habitat on either side using the land bridges that cross the light shafts at intervals.

VII. Tensegrity System

Structure mass is one of the most important concerns for space missions. For this space habitat design, we seek to design the minimal mass structure to sustain centrifugal and atmospheric forces. Does a continuum structure guarantee a minimal mass structure? The answer is not always. For example, Skelton et al. [2] proved T-Bar and D-Bar tensegrity systems require much less mass than a single continuum bar under compression. In fact, tensegrity solutions have provided the minimal mass for all of the fundamental structural loading conditions in engineering mechanics [3, 4]. Biological systems provide perhaps the greatest evidence that tensegrity concepts yield the most efficient structures [2].

Tensegrity is a stable network of bars and strings, where bars only take compression, and strings take tension [5]. All structural members are axially loaded, and hence the structural efficiency in strength to mass is very high. There is no material bending, so the static and dynamic model of the structure model is more accurate [6]. This feature increases the precision achievable by feedback control (which relies on the accuracy of the dynamic model). Feedback control will be used at different stages of the manufacturing and growth processes to limit vibrations or to make changes in shape, or for robotic assembly during growth. Our effort in this endeavor is to provide a permanent residence for human beings in outer space. Permanent or long-term presence of humans in space without gravity is detrimental to their health. As tensegrity is the solution to fundamental structural engineering problems, we choose it to be the basis of our space habitat. The objective of this section is to design a minimum mass cylinder to sustain loads due to atmospheric pressure and centrifugal forces while providing the required stiffness for any unexpected change in pressure.

A. Minimum Mass for Cable Network

The governing equation of tensegrity statics is given as:

$$NK = W,\ K = C_S^T \hat{\gamma} C_S - C_B^T \hat{\lambda} C_B, \tag{1}$$

where N is the nodal matrix, where each column represents the coordinates of each node, (where tension members connect to compressive or other tension members), γ and λ are force density vectors of strings and bars, $\hat{\gamma}$ is a diagonal matrix of the elements of the vector γ. C_S and C_B are connectivity matrices (with 0, -1, and 1 contained in each column) of strings and bars, and W is external force on the nodes [7]. The atmospheric pressure and the centrifugal forces from the rotation provide all compressive forces needed to stabilize the inflated structure. Concentric tensegrity cylinders composed of a cable network will support all applied forces. For a cable network, there would be only strings. Multiply Eq. (1) by N^T to get:

$$C_S^T \hat{\gamma} C_S = S\hat{\gamma}S^T = WN^T, \tag{2}$$

where S, the string matrix, satisfies $S = NC_S^T$.

Yielding is the mode of failure for the strings. Using the same material for all the strings, the minimum mass M required for the cable network is:

$$M = \frac{\rho_s}{\sigma_s}\Sigma\gamma_i||s_i||^2 = \frac{\rho_s}{\sigma_s}tr(S\hat{\gamma}S^T) = \frac{\rho_s}{\sigma_s}tr(WN^T), \tag{3}$$

where ρ_s and σ_s are density and yield strength of strings. From Eq. (3), we know that minimum mass required by the cable network structure only depends upon the external force matrix W and node position matrix N.

We implement a Double-Helix Tensegrity (DHT) structure [8], which is a class-2 tensegrity structure with one set of bars following a clockwise pattern and another set of bars following an anti-clockwise pattern. It can provide radial and torsional stiffness to the structure due to all the diagonal strings shown in the structure. As mentioned earlier, the static analysis shows bars are not needed in the DHT cylinder as atmospheric pressure provides enough outward force. Eq. (3) provides the minimum mass of the structure to take these loads subject to yielding constraints. The required structure must serve as a membrane to hold the air pressure. We designed a continuous membrane with UHMWPE cords (or ribbons/straps) of differing thicknesses and orientations derived from the DHT topology. Moreover, the relative rotational motion between two concentric cylinders must be stabilized to avoid oscillations due to relative movements of people and equipment in each cylinder. Chapter 4 of the book *Tensegrity Systems* describes the minimal mass structure to take torsional loads, and this is a special tensegrity architecture [2]. We call it a Michell configuration in honor of the 1904 work by Michell on a continuous version of the torsion problem. Thus, we add a Michell structure in between the DHT cylindrical layers. The detailed calculation is given in [9].

B. Dynamics of the Structure

It is also important to know the dynamic behavior of the structure. A compact matrix form for the full system dynamics including string masses is given by [10]:

$$\ddot{N}M_s + NK_s = W + \Omega P^{\mathsf{T}}, \tag{4}$$

where

$$M_s = \begin{bmatrix} C_{nb}^{\mathsf{T}}(C_b^{\mathsf{T}}\hat{J}C_b + C_r^{\mathsf{T}}\hat{m}_b C_r) & C_{ns}^{\mathsf{T}}\hat{m}_s \end{bmatrix}, \tag{5}$$

$$K_s = \begin{bmatrix} C_s^{\mathsf{T}}\hat{\gamma}C_{sb} - C_{nb}^{\mathsf{T}}C_b^{\mathsf{T}}\hat{\lambda}C_b & C_s^{\mathsf{T}}\hat{\gamma}C_{ss} \end{bmatrix}, \tag{6}$$

$$\hat{\lambda} = -\hat{J}\hat{l}^{-2}\lfloor \dot{B}^{\mathsf{T}}\dot{B}\rfloor - \frac{1}{2}\hat{l}^{-2}\lfloor B^{\mathsf{T}}(W + \Omega P^{\mathsf{T}} - S\hat{\gamma}C_s)C_{nb}^{\mathsf{T}}C_b^{\mathsf{T}}\rfloor, \tag{7}$$

where C_{nb}, C_b, C_{sb}, C_{sb}, C_{ss} represent different connectivity matrices for bar to string, string to string and bar to bar nodes. For a cable network, there would be only strings. Eq. (4) yields to:

$$\ddot{N} M_s + N K_s = W, K_s = C_s^T \hat{\gamma} C_s. \tag{8}$$

These equations provide an accurate nonlinear dynamic model of the entire habitat structure, at any stage of the construction. Digital computer simulations of these equations predict how the habitat will respond to any control forces, any internal or external disturbances, any dynamic movement during construction phases, or any external events such as a meteorite or micro-meteorite strikes or docking events. These equations allow efficient design since safety margins can be chosen more precisely and reliably. The detailed analysis is discussed in [11].

VIII. Self-sustained System

Food requirements thus far have focused on the minimal survivable needs of highly trained astronauts. We seek to keep a large population healthy in the presence of possible plant diseases and crop failures. Some references [11–13] claim that 250m^2 of agriculture space per person is required for survival, but some reports [14–17] claim that a variety of food choices are required for health, if for no other reason than to survive if a disease wipes out a particular crop. These reports suggest 300m^2 crop space per person, and that is the requirement we used. The roots of plants seem to grow toward moisture, with influence also from the gravitational field, while the tops of plants seem to grow toward the light. The details of the energy are given in [16, 18].

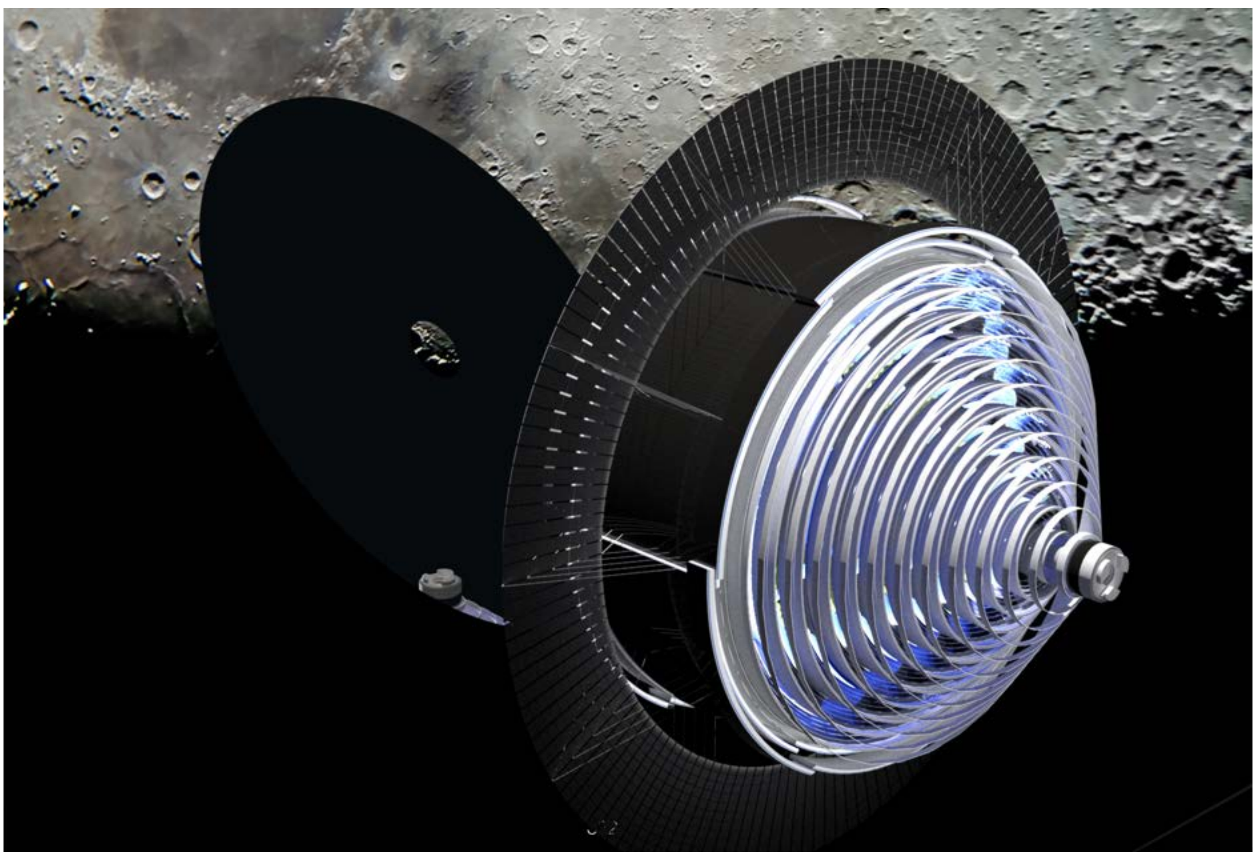

Fig. 8 A mature habitat near the Moon. Between the lateral radiators glimpses of the interior are visible through the light shafts.

To maximize the efficiency of plant growth, research will be required, in a variable gravity environment, to determine the specific role that gravity levels play on plant growth of specific plant species. Similarly, the intensity and spectrum of the light can be optimized for each plant species. The habitat is designed to provide sufficient light for agriculture and for the interior habitable space through a 24 hr diurnal cycle that switches available light between these two zones.

IX. Commercial Value

The habitat must have commercial value for sustainability, so the inhabitants would include a wide variety of trade skills. Commercial activities would employ skilled labor with an appropriate mix of typical community support populations. New industries could be fostered by In-Space-Resource Utilization (ISRU), together with a habitat environment that provides any level of gravity, from 0 to 1-g (earth gravity).

The unparalleled commercial value would derive from the habitat as a way-station for jumping off on space missions, with technical and training support for those missions, greatly reducing the cost of space missions from the earth. The "zero-gravity workshop" (ZGW) is the first cylinder that starts the habitat growth, the longitudinal axis of which is the spin axis of the habitat. The habitat could also support mining operations by processing raw material in the ZGW.

The ZGW is designed to serve as a manufacturing factory, heavy equipment storage, research lab, docking port, and the external surface of the ZGW serves as a chandelier to spread light to the open interior living spaces. Certain pharmaceutical products produced in the ZGW might not be possible to make on earth. ZGW has potential research value beyond our current imagination.

Of course, tourism (i.e., low gravity basketball, space view, spacewalk, multi-gravity level experience) is another valuable industry for the habitat. The habitat has beautiful open spaces with trees and water to give the permanent inhabitants some sense of familiarity with their earthly home. Visitors can experience the gravity of the Moon and Mars without going to the Moon or Mars.

X. Conclusion

The expandable 1-g habitat concept presented here has the potential to finally realize O'Neill's vision of settling the high frontier using large rotating space habitats, by making it affordable. The mechanisms and structural systems required to support this capability, although they are a little larger with each step, are essentially the same each time and do not involve any exotic technology. Structural and dynamic stability for the proposed design has been verified, and first-order economic feasibility, assuming the development of robotic asteroid and/or lunar mining for the acquisition of water and shielding material, has been demonstrated, both of which are radically less expensive than any direct from Earth scenario (our calculations suggest that launch costs from Earth would have to fall below $5/kg for the launch of all elements from Earth to be comparable). Finally, we hope in the near future to conduct ground-breaking research into the mathematical modeling of bio-regenerative life support systems. A thorough understanding of this subject will be required to realize the promise of the present research.

Acknowledgments

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