Orb2: Spherical Space Station Designed for Single Launch and On-Orbit Assembly

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Orb2: Spherical Space Station Designed for Single Launch and On-Orbit Assembly

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With upcoming heavy and super-heavy lift rockets targeted for launch in 2021, a new class of payloads can be launched into low Earth orbit. This paper presents a design for a space station capable of being lifted by a single Blue Origin New Glenn vehicle. Once assembled on-orbit, it contains more than twice the pressurized volume of the International Space Station.

The pressurized volume of traditional space station modules is limited by the dimensions of the payload fairing. The proposed Orb2 design consists of a spherical habitation module and a cylindrical service module. The habitation module avoids the volume limitation by being launched in a flat-packed stack and assembled and welded robotically in orbit. Using CAD and finite element analysis, this paper shows that the habitation module contains approximately 2000 m^3 of pressurized volume, with a mass of 24 tons, and can hold four times the standard atmospheric pressure. Moreover, the Whipple shield configuration is identical to the heavily protected sections of the International Space Station. The service module has a much smaller, traditional cylindrical design and its role is to provide all the life support, necessary utilities, and docking ports. Furthermore, the paper explains the assembly procedure and welding method required to convert Orb2 from its launch configuration to the fully assembled space station.

I. Nomenclature

LEO = low Earth orbit
ISS = International Space Station
PAS = payload adapter system
MMOD = micrometeoroids and orbital debris
FEA = finite element analysis
g = gravitational force, $9.81 m/s^2$
EBW = electron beam welding

II. Introduction

Historically, the preferred space station design always consisted of individual cylindrical modules which were launched into LEO one at a time. This approach is highly advantageous due to its simplicity—the module can be fully assembled, equipped, and tested on the ground. However, the module can never be wider or longer than the internal volume of the launch vehicle's payload fairing. Therfore, the cylindrical modular design might not allow for use cases such as in-orbit manufacturing, assembly of larger objects, or comfortable space hotels. A space station consisting of multiple smaller modules will suffer from high surface-to-volume ratio, resulting in a large area with required MMOD protection, thus, increased mass.

These limitations are well known and can be addressed in multiple ways. The authors of [1] propose a design for modular structures based on a truncated octahedron, which can be joined in a tight formation with high volumetric efficiency. Bigelow Aerospace suggests expandable modules, such as B330 [2] or BEAM [3, 4], the latter being a test article currently docked at the ISS. The recent TESSERAE [5, 6] effort works on launching flat-packed wall segments capable of on-orbit self-assembly into a truncated icosahedron inspired structure, which is larger than the payload fairing. This paper proposes an approach that resembles TESSERAE in a few ways but arrives at the proposed design through a different set of goals and constraints.

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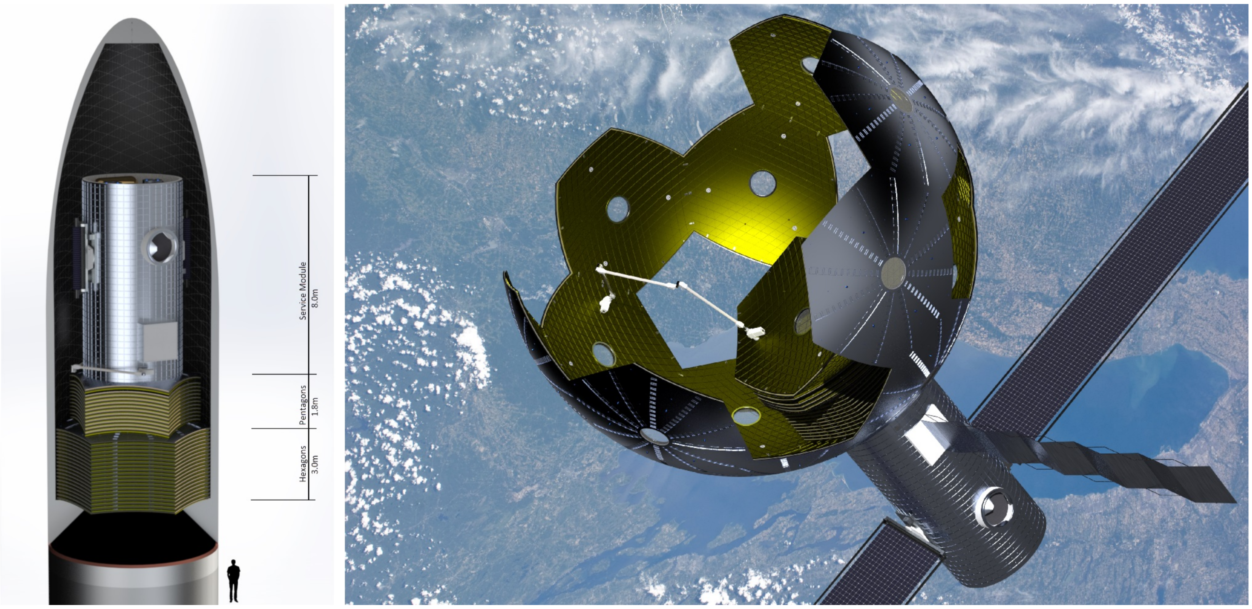

Fig. 1 Left: render of Orb2 in the launch configuration within the New Glenn's payload fairing (human for scale). Right: render during the on-orbit assembly.

The proposed space station design, named Orb2[*] for *Orbital Orb*, is driven by the following criteria: to be launched to LEO in a single launch while maximizing the internal pressurized volume. It must be pressurized and temporarily habitable for human crews, who would utilize subsequent crewed launches to set up the interior equipment for their needs. The choice of the launch vehicle is driven by its lift capacity and the payload fairing volume. There are two vehicles with a payload mass to LEO of over 40 tons and ar first commercial launch targeted for year 2021: Blue Origin's New Glenn [7] and SpaceX's BFR [8]. Given that New Glenn is a more conservative design and that the Payload User's guide is already available[†]. with all the detailed information, the proposed design focuses only on this vehicle.

Section III explains the author's reasoning behind the spherical design of the habitation module and the utilization of geometric properties of Goldberg polyhedra with the choice of truncated icosahedron in particular. The relevant capabilities and limitations of New Glenn, which ultimately drive the design choices, are described in Section IV. Section V contains all the design details of the habitation module—final dimensions, mass, MMOD protection, FEA pressure simulation, etc.—and the requirements for the service module. The proposed on-orbit assembly procedure (see Figure 1 for visualization) including the requirements for the assembly and welding with a robotic arm is described in Section VI. The paper is concluded in Section VII.

III. Sphere Segmentation Inspired by Truncated Icosahedron

A. Sphere—From First Principles

Space station pressure walls are very expensive to manufacture and launch into space due to their significant mass. Assuming each section of the pressure wall has uniform thickness and MMOD protection, the mass and the cost of a pressure vessel increases linearly with respect to its surface area. To reduce the cost, a space station should be designed in a way that minimizes the surface area for a given volume. The object with the lowest possible surface-area-to-volume ratio is a sphere; as such, it should theoretically have the lowest cost per internal volume.

Moreover, a spherical pressure vessel experiences uniform stresses across its surface and requires thinner walls and stiffening ribs (e.g., isogrid) than any other shape.

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[*] For additional information and assembly video, visit `https://www.orb2.com`

[†] Available on request here: `https://www.blueorigin.com/new-glenn/new-glenn-payload-users-guide`

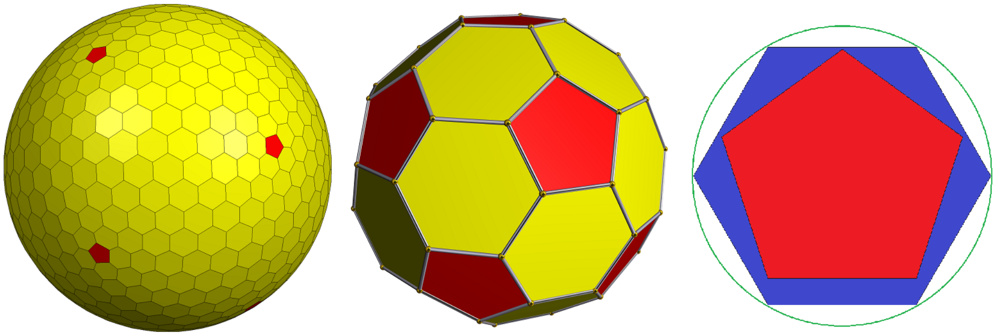

Fig. 2 Left: example of a large Goldberg polyhedron: $GP_v(5,5)$ [10]. Center: truncated icosahedron [11]. Right: payload fairing's horizontal plane projection and fit of hexagon (blue) and pentagon (red) inside of it.

B. Desired Segmentation Properties

In order to launch a large sphere into space, it must be split into a set of partial sphere surfaces (segments), each smaller than the rocket's payload fairing. There are infinitely many ways of dividing a hollow sphere into segments. The author selected these general properties as criteria for a good sphere segmentation: space utilization of the payload fairing, ease of manufacturing, and ease of assembly.

These criteria can be formalized as:

1) Minimal number of uniquely shaped segments—multiple different segment shapes are harder to manufacture.
2) Individual segment shapes have symmetry properties—irregular shapes are harder to manufacture.
3) Each segment's surface area is close to the area of the circumscribed circle of the largest segment—all segments are similar in size, thus, utilizing the payload fairing space.
4) Individual segments are close in diameter of their circumscribed circles—the segments are close to circular shape, thus, utilizing the payload fairing space.
5) Minimal number of segment edges meet at each vertex—a vertex with too many connected segments would make the assembly and welding difficult.

C. Goldberg Polyhedra and Truncated Icosahedron

Goldberg polyhedra [9] make up a family of polyhedra consisting of hexagons and pentagons. While the pentagons are always regular, the hexagons are generally not. Any Goldberg polyhedron has exactly 12 pentagon faces and a variable number of hexagonal faces. The left part of Figure 2 shows an example of a large Goldberg polyhedron. The Goldberg polyhedra meet the aforementioned criteria in the following way:

1) Just two segment types: pentagons and hexagons.
2) Pentagons are symmetrical, hexagons are symmetrical or close to symmetrical.
3) Pentagons are just slightly smaller than hexagons—not too much space wasted (see Figure 2, right).
4) Hexagons fill the circumscribed circle with 83% coverage, pentagons with only 55%. However, there are only 12 pentagons total (see Figure 2, right).
5) Three edges meet at each vertex.

A member of the Goldberg polyhedra family that most of the world is familiar with is the soccer ball. This polyhedron is formally called truncated icosahedron (see Figure 2, center) or also Goldberg polyhedron $GP_v(1,1)$ in Conway notation. It consists of 32 faces—20 regular hexagons and 12 regular pentagons—this regularity is important both for ease of manufacturing and for the ability to substitute any face with another face of the same type.

For the purpose of this paper, only sphere segmentation inspired by the geometry of truncated icosahedron is considered. This decision is based on the Orb2's final mass and dimension limitations in launch configuration, which are imposed by New Glenn and the single launch requirement.

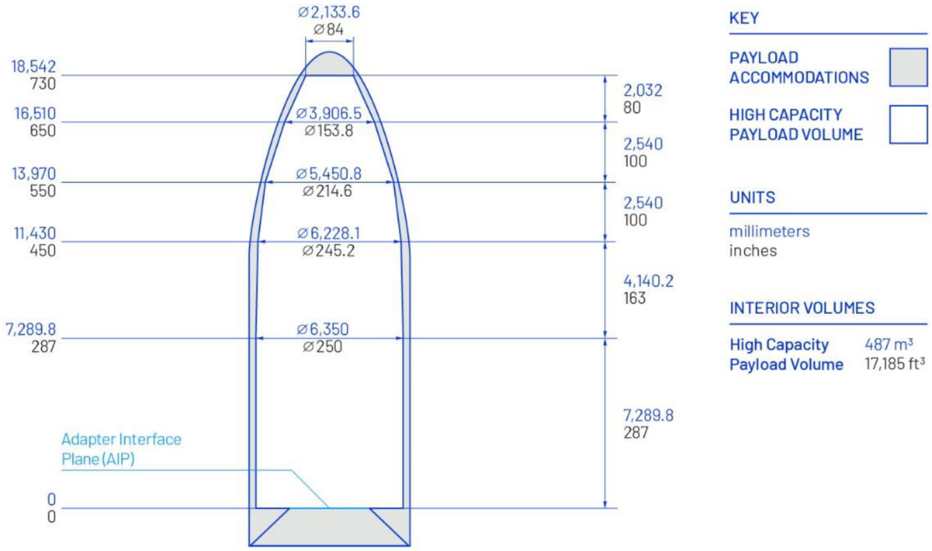

Fig. 3 Dimensions of available space within the New Glenn's payload fairing. Figure taken directly from the Payload User's Guide.

IV. New Glenn's Capabilities

A. Payload Fairing Dimensions

Orb2 is designed specifically to be launched by Blue Origin's New Glenn rocket. As such, its design and dimensions are driven entirely by the rocket's capabilities, internal dimensions of the payload fairing, center of gravity, and expected G-loading during the launch. All this data was obtained from the New Glenn Payload User's Guide, revision C.

To fit the payload fairing, the largest horizontal dimension of the hexagon segment was designed to be exactly 6300 mm. This leaves 50 mm margin with respect to the available diameter of 6350 mm (see Figure 3).

B. PAS – Constraints on Weight and Center of Gravity

While the New Glenn's available payload fairing volume is sufficient, the specifications of currently offered *high capacity* PAS are significantly more limiting.

Although New Glenn is capable of lifting a 45-ton payload to LEO, the PAS is limited to only 37,200 kg. Moreover, for this maximum payload, the center of the gravity of the payload must be below 4 meters above the adapter interface plane (see left blue plot in Figure 4).

The CAD models, on which the shown renders and simulations (in Section V) are based, estimate mass of 24 tons for the habitation module, leaving 13 tons available for the service module. Based on the weight distribution of the service module, the center of gravity is between 4 and 5 meters above the adapter interface plane, slightly higher than allowed. However, the CAD designs are not thoroughly optimized and result in much higher strength and weight than potentially required. There are multiple possible solutions to the PAS center of gravity limitations:

1) Reduce weight by optimizing the design, which will result in higher allowed center of gravity.
2) Engineer the service module in such a way that its center of gravity is very low.
3) Convince Blue Origin to upgrade the PAS so the capabilities of the New Glenn can be fully utilized.
4) Design and build custom PAS.

V. Design Details

A. Habitation Module and Its Segments

The largest module, as seen in Figure 5, is the habitation module consisting of 20 hexagonal and 12 pentagonal wall segments welded together. The segments are designed to fit into the New Glenn's payload fairing and stack on top of each other during the launch. The role of the habitation module is to provide a large continuous pressurized volume for

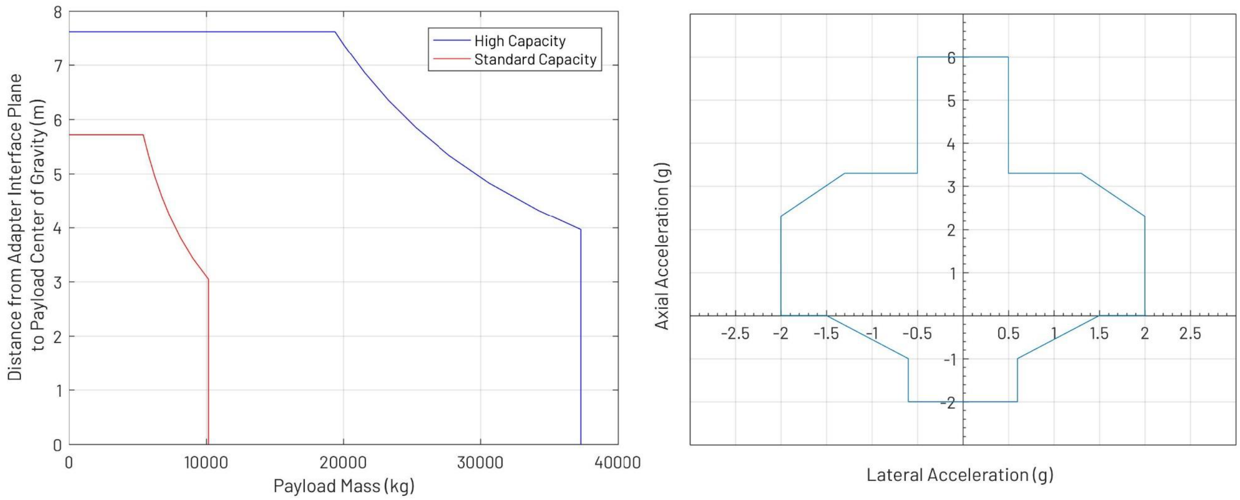

Fig. 4 Left: highest allowed distance from adapter interface plane to payload's center of gravity. Right: envelope of lateral and axial acceleration during the launch. Both figures taken directly from the Payload User's Guide.

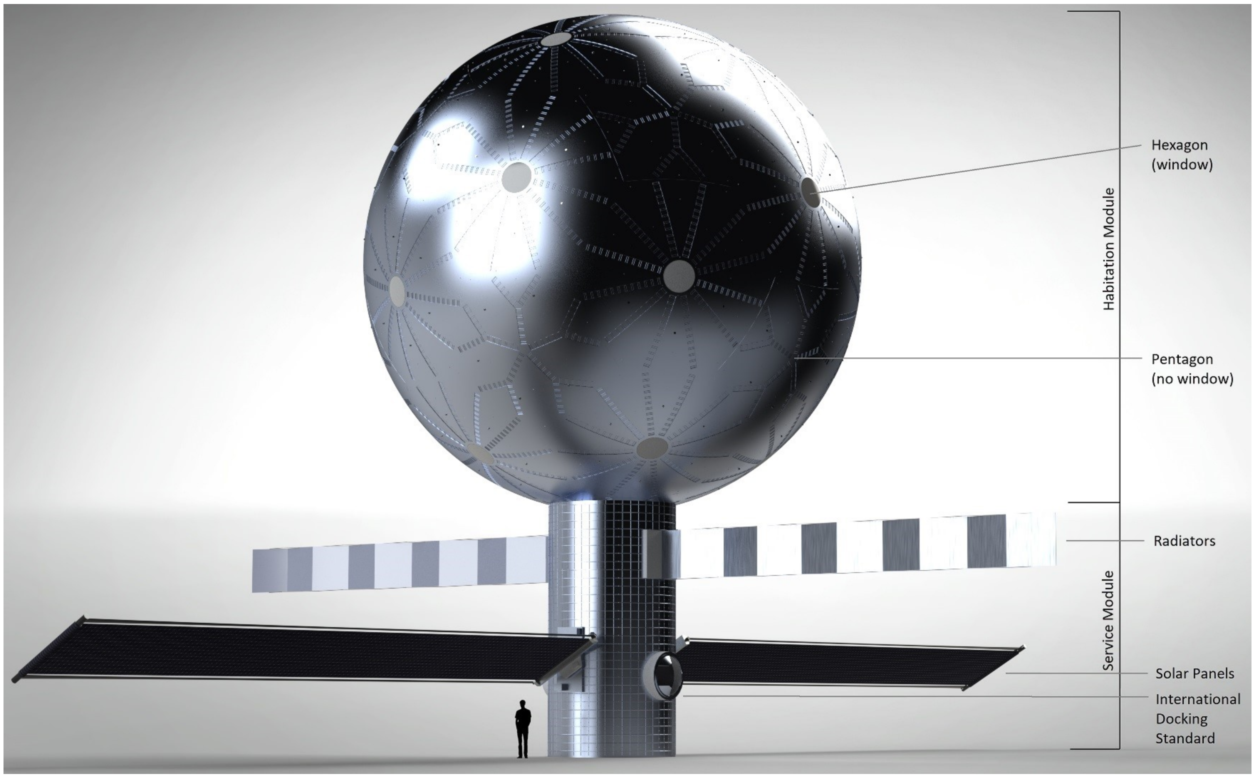

Fig. 5 Render of the fully assembled Orb2. Note the smaller service module in the lower part and the large spherical habitation module in the upper part of the image.

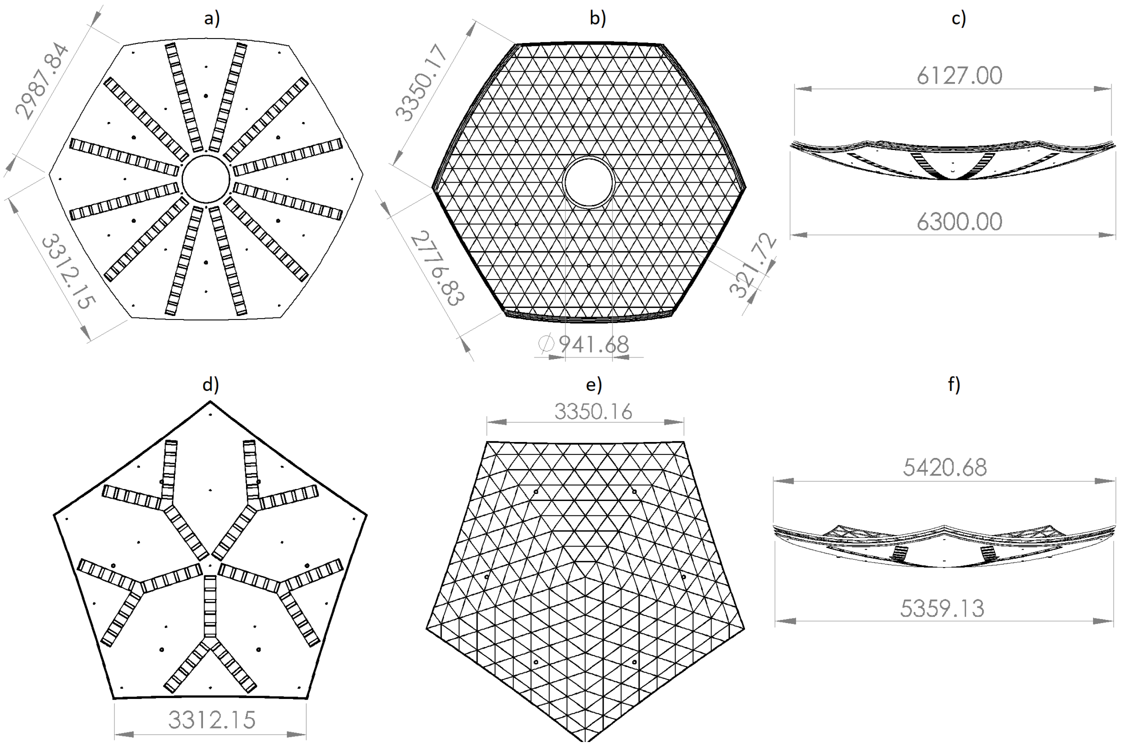

Fig. 6 Drawings of the segments produced from the CAD models, dimensions in millimeters. Hexagon outer view (a), hexagon inside view (b), hexagon side view (c), pentagon outer view (d), pentagon inside view (e), pentagon side view (f).

the human crew to live and work in. Safety is a crucial factor; as such, the habitation module provides robust MMOD protection.

The assembled habitation module is basically a hollow sphere with outer diameter of 15.84 m and inner diameter of 15.58 m. Based on the SolidWorks CAD models, the weight of the empty habitation module is 24 tons: 850 kg for each hexagon and 600 kg for each pentagon. After the assembly, the habitation module alone contains roughly 2000 m^3 of internal volume, more than twice the volume of the whole ISS.

The individual dimensions of each segment can be seen in Figure 6.The largest dimension of hexagon (Figure 6, c) is 6300 mm, exactly as intended in order to fit into the New Glenn's payload fairing. Notice that while the outer side dimension of the hexagon (Figure 6, c) is larger than the inner side, it is the opposite for pentagons (Figure 6, f). This is intentional—the assembly sequence (see Section VI) requires the pentagons to be fitted from the inside, forcing the outer dimensions to be smaller. The unusual structures on the outer side of both hexagons (Figure 6, a, d) and pentagons are indents in the outer Whipple shield with handles for extravehicular activity. The isogrid for structural support is visible on the inside views, with each rib approximately 320 mm long.

B. Materials and MMOD Protection

The habitation module's design lends itself to having uniform MMOD protection and rigidity all around its spherical surface. As such, all the hexagons and pentagons share design parameters of the pressure vessel and the Whipple shield. Any change in these parameters has a major impact on weight, strength, MMOD protection, and height of the stack during the launch.

The proposed design implements an identical configuration of the stuffed Whipple shield and pressure vessel thickness as the most exposed and critical parts of the ISS (see Ref. [12], page 12). It is designed to stop a 13 mm diameter aluminum sphere travelling at 7 km/s. A Whipple shield this strong all around the habitation module should make it less likely to be penetrated by MMOD than the ISS.

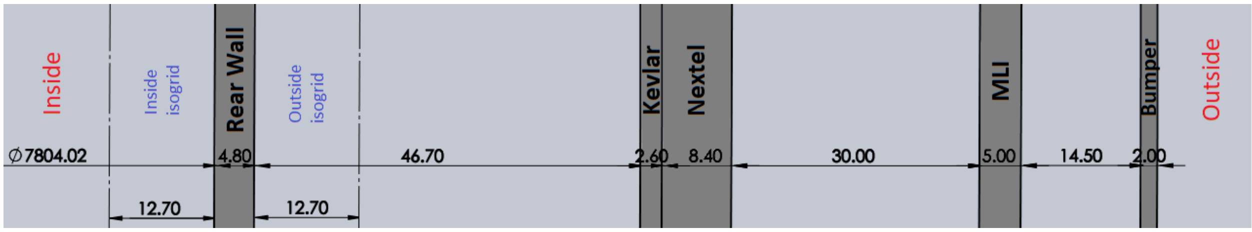

Fig. 7 Stuffed Whipple shield configuration. Dimensions in millimeters.

From the outside to the inside (left to right in Figure 7), these are the individual Whipple shield layers, materials and purpose:

- Rear wall & Pressure vessel: 4.8 mm thick Aluminum 2219-T87.
- Kevlar 29 style 710, 6 layers, 2.6 mm: Ballistic protection.
- Nextel AF62, 6 layers, 8.4 mm: Thermal shock resistance.
- Multi-layer insulation (MLI): For thermal protection only, does not help against MMOD.
- Bumper: 2 mm thick Aluminum 6061-T6.

C. Atmospheric Pressure Stress Analysis

The pressure wall is not only needed for MMOD protection but also for holding the atmosphere inside the habitation module—it needs to safely support a pressure of 1 atm (101, 325 Pa). This can be analyzed using FEA simulations (the author used SolidWorks FEA tool) on the pressure vessel's CAD model. As mentioned above, the pressure vessel is 4.8 mm thick and is strengthened with isogrid structure on both sides of the pressure vessel. The isogrid ribs are 32 cm long, 12.7 mm high, and 2 mm thick.

The highlight of the FEA simulation result shown in Figure 8 is that the maximum stress on the pressure vessel is only 1/4th of the material's (aluminum 2219-T87) yield strength of $3.95 \cdot 10^8$ N/m^2. Another interpretation is that the pressure vessel could hold almost 4 times the standard atmospheric pressure without getting permanently deformed.

This estimate is conservative when compared to the result obtained by the thin wall approximation formula for spherical pressure vessels: $\sigma = pr/2t$, which can be rewritten as

$$p_{\max} = \frac{2\sigma_{\mathrm{m}} t}{r} = \frac{2 \cdot 3.95 \cdot 10^8 \cdot 0.0048}{7.804} = 4.8\,\text{atm},$$

where $p_{\max}$ is the maximum inside pressure, σ_{m} is the material's yield strength, t is the wall thickness and r is the sphere radius. Consequently, it gives the whole habitation module a large safety margin, which could be potentially traded for lower weight.

Note that the FEA model does not include windows. Moreover, this FEA simulation assumes immovable fixtures for the sides of the pressure vessel, which causes slight non-uniformity of the results. In reality, these sides would be welded to the neighboring segments and the whole habitation module would "inflate" uniformly when pressure is introduced.

D. G-forces During Launch

Blue Origin also specifies the expected G-forces that the payload can experience during the launch (see Figure 4, right), and the payload must be designed to withstand it. This can be also evaluated with FEA simulations. A positive 6 g axial acceleration was simulated for the pressure wall of the hexagon on the bottom of the launch stack—the segment experiencing the highest stress during the launch due to all the weight above it. The resulting stress of the pressure wall is $3.2 \cdot 10^6$ N/m^2, which is less than 1 % of the material's yield strength of $3.95 \cdot 10^8$ N/m^2. Moreover, with the current CAD design, the stress on the rods and sockets holding the individual wall segments and service module together are well within the material yield strength limit.

E. Service Module

While the habitation module provides living quarters or work space, the service module has to provide everything else—power generation, air and oxygen supply, water reclamation, heat management, communications, station keeping, attitude control, docking ports, and secondary pressurized space for emergency.

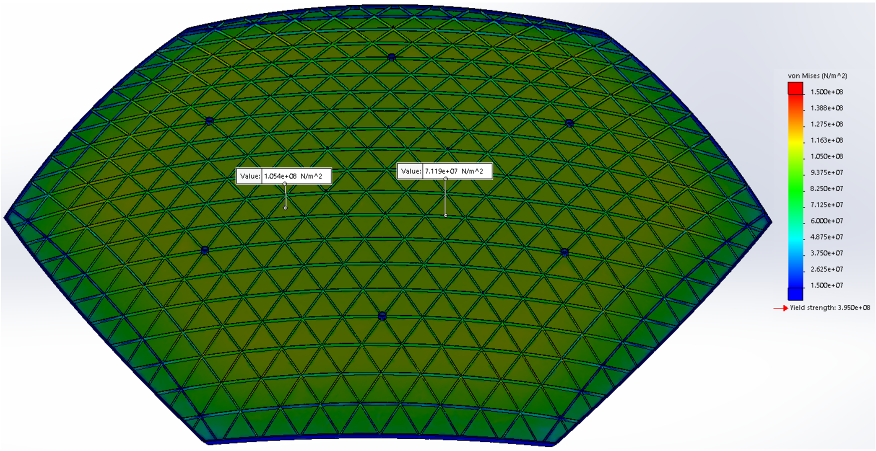

Fig. 8 Results of the FEA pressure analysis for $101,325\,\mathrm{Pa}$. The stress value on the pressure vessel (left datapoint) is $1.054 \cdot 10^8$ N/m^2, value on the isogrid rib (right datapoint) is $7.119 \cdot 10^7$ N/m^2. Material yield strength is $3.950 \cdot 10^8$ N/m^2.

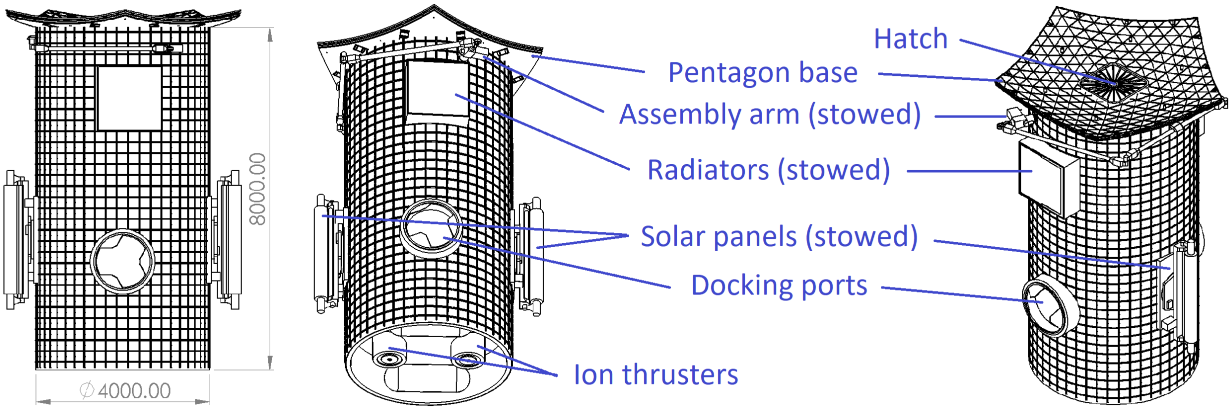

Fig. 9 Left: potential placement for the required features. Right: service module dimensions used in this paper.

The reason for having a separate pre-assembled service module is to reduce the level of novelty and complexity of the design. Its diameter and length are in a typical range for an ISS module, and its individual functions were successfully designed 30 years ago and tested on the ISS. However, housing all the previously mentioned utilities in a single module might prove challenging. It might require some evolutionary technological and packaging improvements over ISS designs.

The description of the service module is short for two reasons. First, this paper focuses on the viability of the habitation module in order to create a large pressurized volume. Second, the dimensions and the layout of the service module are not severely restricted by the New Glenn's payload fairing, therefore, the service module design is subject to change. As a result, the remainder of this subsection describes just one of many possible designs.

Assuming the habitation module's mass of 24 tons and New Glenn's LEO payload mass of 45 tons, the service module can weigh up to 13 tons with off-the-shelf PAS and up to 21 tons with a custom PAS. Figure 9 shows the cylindrical service module which is 4 meters in diameter and 8 meters in length. The cylindrical part is built with a permanently attached pentagonal segment—when the habitation module is being assembled, the first hexagon segments are attached to this pentagon segment. Moreover, this pentagon segment provides the connection between the service module and the habitation module through an air-tight hatch. Figure 9 also shows a potential placement of radiators, solar panels, docking ports, ion thrusters, and the stowed assembly arm on the outside of the service module.

VI. On-Orbit Assembly

A. Assembly and Welding Robotic Arm

Orb2 is launched in a stacked form, and once in space, it needs to be converted into its mostly spherical form. This is the purpose of the assembly arm: assembling the sphere and welding it permanently together. It is stowed on the outside of the service module during the launch and then activated in orbit.

It is important to realize that the assembly process can take several months and happens in microgravity. These conditions allow the arm to move extremely slowly and be generally weak, even when moving heavy wall segments. Due to the low latency in LEO and slow movement, the arm can be both partially automated or directly controlled from Earth if needed.

The assembly arm moves the wall segments from the top of the stack into their intended position in the sphere. After a wall segment is placed into its designated location, there are multiple potential ways to temporarily hold it in place before the actual welding, such as actuated clamps, actuated bolts, or tack welds. To achieve this, the robotic arm has to include the following features:

- Ability to latch onto the inner surface of the wall segments. The wall segments would have grapple fixtures that the the arm can securely attach itself to.
- Similar to the Canadarm 2, both arm ends can connect to the grapple fixtures.
- Sufficient power system for movement and welding provided by the main solar array. The power is connected through the already placed wall segments, and then through the grapple fixture to the arm.

B. Electron Beam Welding

The assembly is finalized by welding all the wall segments together from the inside with an EBW gun. Below are all the relevant properties of EBW which make it perfectly suited for this application—a more detailed description of the EBW technology is beyond the scope of this paper and can be read about in [13]:

- Requires high vacuum environment—a critical point that limits the use of EBW to very expensive projects with high precision requirements. However, it is a perfect property for on-orbit welding.
- Autogenous welds only—no additional material. The filler material is provided by melting the base metals.
- Square butt joints—EBW is best used on square butt joints. The two welded pieces are flat and parallel to each other.
- Precisely controllable weld penetration depth by regulating the power—the supported material thickness is from fraction of a millimeter to around 30 cm.
- Welding speeds are in tens of centimeters per minute, possibly in meters per minute.
- Energy efficient—around 90 % of the input power reaches the welded part. This also results in low waste heat and easier cooling.
- The distance between the electron beam gun and the welded part can be as high as 75 cm.

Welded parts are generally significantly weaker in the joints than the original material. This also applies for EBW of heat treated and artificially aged aluminum 2219-T87, which retains only 40 % of its original strength [14]. To compensate, the welded sides of the pressure wall are thickened to be 6× times the regular pressure wall thickness.

It is important to note that, to the author's knowledge, the only welding experiments ever performed in space were done (including EBW) by the Soviet crew of Soyuz 6 in 1969 [15]. This test almost ended in a disaster when they nearly ruptured their pressurized capsule. However, it was concluded that the weld quality was in no way inferior to Earth-based welds.

C. Assembly Procedure

During the launch, Orb2 is in its stacked launch configuration. Approximately 10 seconds after the New Glenn's first stage finishes its burn and the second stage starts its burn, the payload fairing is jettisoned. This leaves the accelerating rocket's second stage with the stack attached (Figure 10, a).

After the second stage with the payload reaches the desired orbit, the second stage separates and decelerates. At that point, the service module's solar arrays (and potentially the radiator arrays) are unfolded to provide power. The assembly arm activates, moves onto the stack (Figure 10, b), and starts assembling the habitation module using the hexagons from the top of the stack.

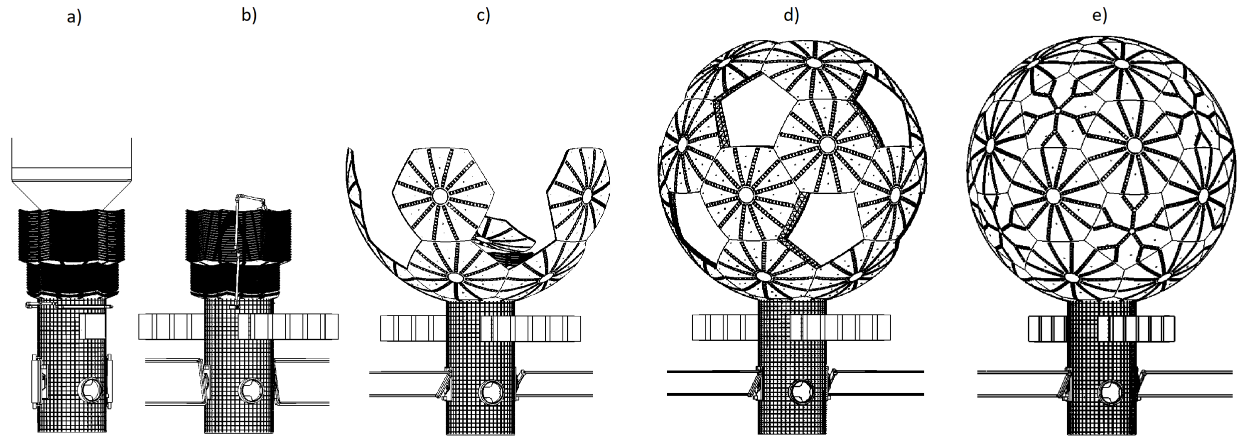

Fig. 10 The assembly sequence. Note that all the assembly and segment placement is done from the inside.

The robotic arm continues the assembly with the hexagonal pieces (Figure 10, c), provisionally attaching them to those already in place.

After all hexagons are taken from the stack and placed into their designated locations, only pentagons remain on the stack. The pentagons are designed to be placed into their respective locations from the inside, perfectly fitting into the remaining empty spaces (Figure 10, d).

When all pentagons are placed (Figure 10, e), the assembly arm takes a detailed photograph of every connected edge and sends it to the ground crew for analysis. The arm then starts welding the individual edges, again sending captures for expert analysis. After the welding is finished, the arm stows itself securely on the inside of the habitation module.

The service module starts slowly releasing the air from its pressurized tanks into the habitation module. With each air pressure increment, the airtightness can be analyzed. After the atmospheric pressure reaches 1 atm and the test evaluation period is concluded, the ion thrusters slowly move the space station into its intended orbit. At that point, the assembly is finished, and the set-up crew can launch with all the interior equipment.

VII. Conclusion

The author has proposed a design for a space station with over 2000 m^3 of pressurized volume, which can be sent to orbit and assembled using a single launch of the New Glenn rocket. The paper explained the reasoning behind the geometry of the habitation module and how the whole space station fits into the payload fairing. The viability of the Orb2 design with respect to mass and strength was shown using FEA simulations. The focus of this paper is primarily on the habitation module and its assembly, while leaving all the life support, utilities, and propulsion to the classically built service module. This makes the potential construction significantly easier and viable with today's technology.

There are two possible multi-launch extensions of the proposed design. First is to create larger spherical structures based on more complex Goldberg polyhedra. The other is to connect multiple Orb2's and create artificial gravity (Moon or Mars equivalent) by spinning the resulting complex around its center of gravity.

To further validate the proposed design in the short term, a lot of research needs to be focused on robotic EBW in microgravity. The author believes that this is an uncharted research territory with a potentially large impact on space colonization and exploration.

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