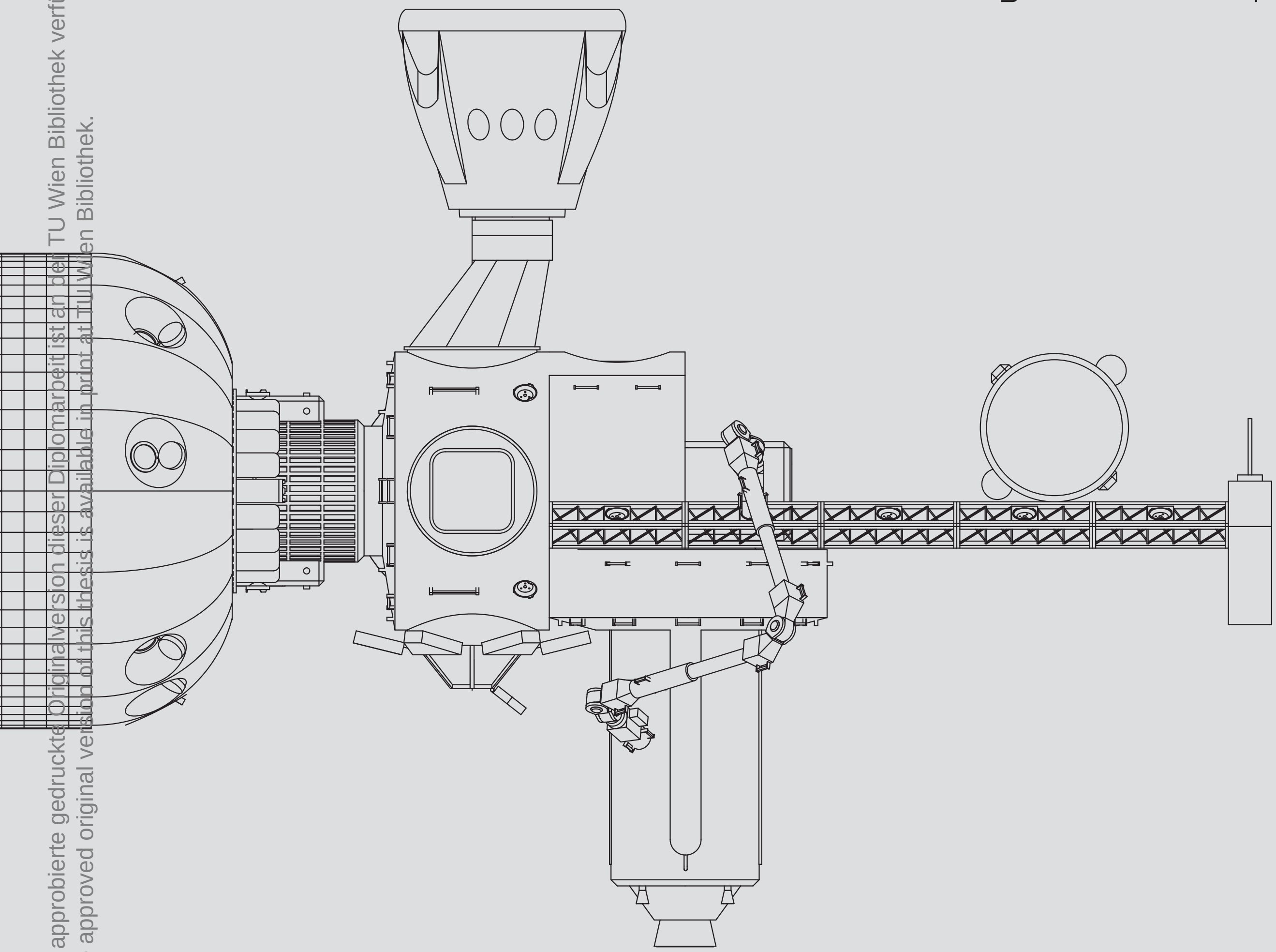
Cleaning up the Final Frontier

Orbital Debris as a Potential Resource

The Story of Three Space Stations



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Cleaning up the Final Frontier - Orbital Debris as a Potential Resource: The Story of Three Space Stations

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Abstract

Since the launch of Sputnik 1 in 1957 the presence of human-made objects in space has drastically increased. As of now, there are over 2000 active satellites in orbit, yet they amount to only 10% of the artificial objects tracked in the proximity of our planet. The remainder is considered space debris, and besides the traceable large objects it comprises undetectable, smaller debris pieces with an estimated count surpassing 100 million. Debris of any size poses an imminent risk to all current and future space missions and could even lead to the creation of an impenetrable debris belt around Earth.

Worldwide, concepts and technologies are being developed to remove debris from orbit. The vast majority is based on capturing and de-orbiting the debris, causing it to burn up during atmospheric re-entry. However, because launching any type of material into orbit is immensely expensive, orbital debris also presents a potentially valuable resource that could be utilized for future on orbit construction.

The initial aim of this work was to conceive an orbital facility for the recycling of space debris. The first two iterations of the space station presented in this book disintegrate spent rocket stages and turn them into feedstock for on orbit additive manufacturing utilization. However, this idea remains conceptual, since it involves technologies that yet have to be researched and developed. Further, the examination of debris material properties

will be necessary and additional concepts for on orbit applications have to be devised to make debris a viable resource in the future. Therefore, the main focus of this work shifted towards the architecture and design of an orbital space station suited for these research tasks.

The resulting space station R3-Debris (Research concerning Resource utilization and Recycling of Debris) is capable of housing a four person crew on 6-12 month missions and up to 8 people during crew exchange periods. It contains a shredder for rough processing, a robotic arm and a truss platform for storing captured debris. Inspired by inflatable module concepts like NASA's TransHab and based on the dimensions of Bigelow Aerospace's BA-330, particular attention was given to the design of the station's joint habitation and work module. Its interior layout features private quarters, a social hub, hygiene and sports facilities, a greenhouse and work areas including a dedicated workshop, material processing and research section arranged in a nonconflicting way within the module's limited volume.

Abstract Deutsch

Seit dem Start von Sputnik 1 im Jahr 1957 ist die Anzahl menschlich gefertigter Objekte im All drastisch gestiegen. Derzeit gibt es über 2000 aktive Satelliten, dennoch bilden diese nur 10% der künstlichen Objekte, die in der Nähe unseres Planeten beobachtet werden. Die restlichen 90 % werden als Weltraummüll bezeichnet. Darüber hinaus existieren, Schätzungen zufolge, mehr als 100 Millionen kleinere, nicht registrierbare, Trümmerstücke. Trümmer jeder Größe stellen ein unmittelbares Risiko für alle gegenwärtigen und zukünftigen Weltraummissionen dar und könnten sogar zur Bildung eines undurchdringlichen Trümmergürtels um die Erde führen.

Die überwiegende Mehrheit der bereits erdachten Konzepte und Technologien zur Beseitigung von Weltraumtrümmern basiert auf der Idee des Auffangens und dem Entfernen der Trümmer aus ihrer Umlaufbahn, durch das Verglühen beim Wiedereintritt in die Atmosphäre. Das Hochbringen von Material jeglicher Art in die Umlaufbahn ist immens teuer. Weltraumtrümmer stellen daher auch eine potenziell wertvolle Ressource dar, die bereits vor Ort verfügbar ist und für zukünftige Bauarbeiten im Orbit verwertet werden könnte.

Ausgangspunkt dieser Arbeit war die Konzeption einer orbitalen Anlage für das Recycling von Weltraumtrümmern. Die ersten beiden Iterationen der Raumstation, die in diesem Buch präsentiert werden, zerkleinern verbrauchte Raketenstufen und verwandeln sie in Rohmaterial für

additive Fertigungszwecke im Orbit. Diese Idee bleibt jedoch konzeptionell, da die notwendigen Technologien noch erforscht werden müssen. Auch sind Untersuchungen des Materialzustandes und die Definition weiterer Anwendungsmöglichkeiten nötig um Weltraumtrümmer in Zukunft als Ressource zu etablieren. Der Schwerpunkt dieser Arbeit liegt auf dem räumlichen Entwurf einer orbitalen Raumstation, die für ebendiese Aufgaben geeignet ist.

Die orbitale Station R3-Debris (Research concerning Resource utilization and Recycling of Debris) ist in der Lage, eine vierköpfige Crew auf 6-12-monatigen Missionen und bis zu 8 Personen während der Crew-Austausch-Phasen zu beherbergen. Sie enthält einen Technologiedemonstrator für die grobe Verarbeitung der Trümmer, einen Roboterarm und eine Fachwerkplattform zur Lagerung von aufgefangenen Trümmerstücken. Inspiriert von aufblasbaren Modulkonzepten wie dem TransHab der NASA und basierend auf den Abmessungen des BA-330 von Bigelow Aerospace wurde besonderes Augenmerk auf das Design des kombinierten Wohn- und Arbeitsmoduls der Station gelegt. Die Innenausstattung umfasst private Bereiche, eine soziale Zone, Hygiene- und Sporteinrichtungen, ein Gewächshaus und Arbeitsbereiche, einschließlich einer speziellen Werkstatt sowie Einrichtungen für die Erforschung und Bearbeitung des Trümmermaterials, die innerhalb des begrenzten Volumens des Moduls konfliktfrei angeordnet sind.

Acknowledgments

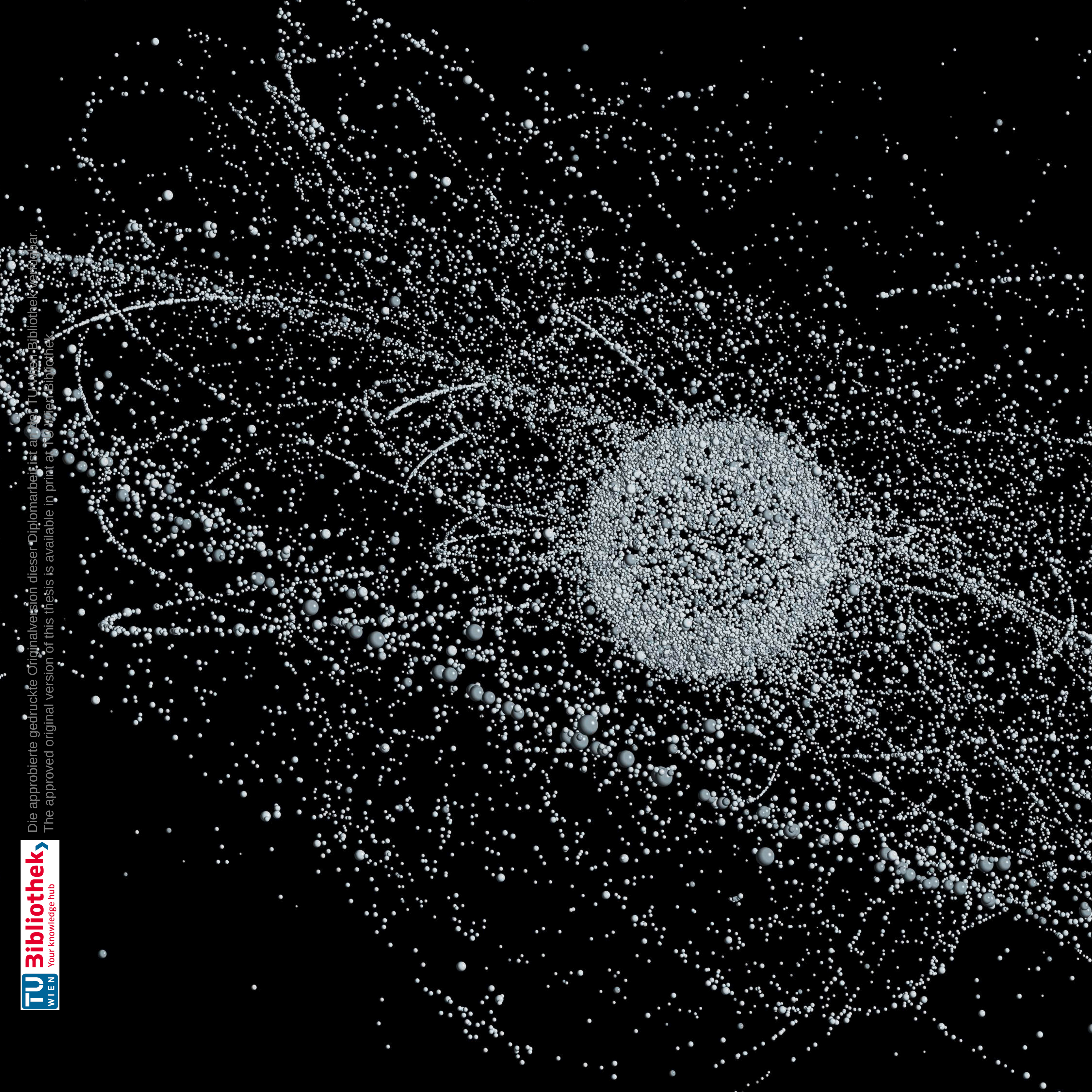
I would like to express my gratitude and deep thanks towards all the people who supported me and contributed to this work during its development. First and foremost, to my parents Lubica Matasova and Milan Radic for their continuous encouragement and aid, which allowed me to pursue and complete my studies. To my friends and fellow students for their help, input and continuous discussions, especially: Niklas Heiss, Erik Mothwurf, Dominik Fill, Lorenz Seidl, Nina Lucia Groß and Lukas Röthel. To Dipl.-Ing. Dr.-Ing. Sandra Häuplik-Meusburger, for the supervision, her expertise, patience and efforts to encourage me to present my work at various congresses and workshops and for letting me profit from the contacts in her vast network. To Ass.Prof. Mag.art. Fridolin Welte, Dipl.-Ing. Mag.art. Christoph Meier, Univ.Prof. Dipl.-Ing. M.Arch. Tina Gregoric Dekleva, Dipl.-Ing. Dr. Carsten Scharleman and M.Arch. M.S. Brent Sherwood for their time, expertise and feedback. To the entire space architecture community for inspiration and helpfulness. And finally, to Dipl.-Ing. Walter Fritz, Ing. Kornelia Fischer, Ronald Buchinger and the entire model making workshop staff, not only for being the best employer and colleagues one could wish for, but also for their continuous support and for letting me stay and providing me with a workspace after my contract had expired.

Preface

One might wonder how an architecture student ends up working on a diploma thesis concerning orbital debris and the design of space stations. Well, I have been a huge fan of Science-Fiction and interested in almost anything space related for as long as I can remember. The first time I had been confronted with the orbital debris problem, was in a documentary screening at the Smithsonian National Air and Space Museum in 2013. The severity of the problem surprised me, and it has been on my mind ever since. During my studies, I was vaguely aware of space architecture as a profession, and just before I had to start working on my architecture diploma, I found out that Dr. Sandra Häuplik-Meusburger is providing an opportunity at my university to engage in this field. I didn't hesitate to contact her and one thing led to another, resulting in a quite unique diploma topic.

With this book, I want to spread awareness of the orbital debris issue and depict my journey as an architecture student exploring the field of space architecture. A project relevant selection of the basic knowledge I had to acquire, the design methods and information I found useful to approach such a task, alongside some innovative technical developments in the field over the last years are summarized in the following chapters. In the second half of the book three iterations of the space station, I set myself the goal to design, are presented. The intended task of the station adapts and changes during the development phase, and I clarify why and which changes were made.

Table Of Contents



01 The Orbital Debris Problem

Introduction

The first object ever to be successfully launched into a stable orbit around Earth, was the Soviet satellite Sputnik I back in 1957. Since then the presence of human-made objects in space has drastically increased. As of March 2019, the satellite database of The Union of Concerned Scientists (UCS) lists over 2000 active satellites orbiting around Earth.[1] However, roughly at the same time, the US Space Surveillance Network (SSN) tracked 19,524 artificial objects in the vicinity of our planet.[2]

So approximately 90% of the tracked objects are inactive, not responsive or without a function at all, whilst being artificially made. This is the definition of orbital debris. The Number given above, however, only refers to debris pieces that are large enough to track. Smaller debris can only be estimated and are believed to have a population larger than 100 million pieces.

This following chapter explains the origins of space debris, offers a deeper look into their size, current numbers and material composition, lays out the short and long term risks and presents the argument concerning the necessity for active debris removal (ADR) with an overview of current approaches. Finally, it touches upon the topic of space property law and who the debris belongs to and the related potential complications that are posed for the task of cleaning up Earth's orbits, beyond the technological and financial ones.

< **Orbital Debris Vizualizatiton**
Debris pieces not to scale.
Credit: Roosegarde Studio

1 UCS, UCS Satellite Database, March 2019
2 NASA, Orbital Debris Quarterly News, August 2019

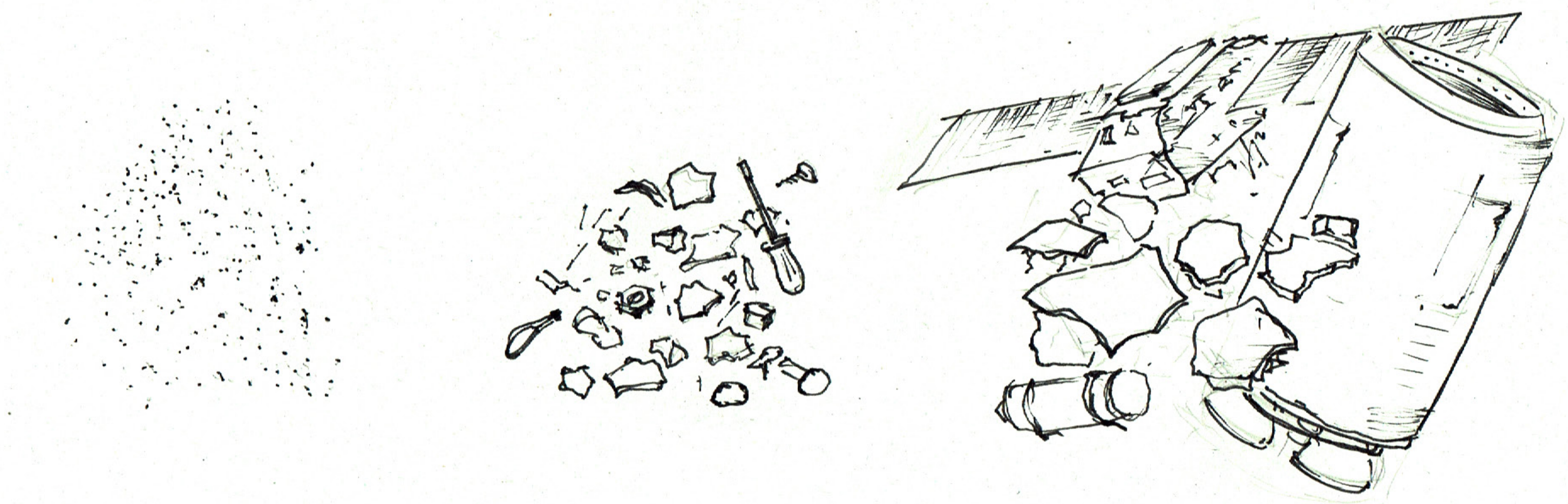
Origins, Size & Numbers

Debris Sizes >
Large - Medium - Small
Credit: Author

Remnants of the launch process, like spent rocket stages, separation bolts, chips of paint, etc. or deactivated satellites are the main contributors to the large debris population. However, the harsh environment of outer space, with cosmic and solar radiation and extreme temperature shifts, can wear the material of debris pieces down and lead to break-ups and fragmentations or even explosions of fuel tanks with residue fuel in them, causing the debris population to grow.

A widely accepted categorization of orbital debris, is one by size. Large debris is anything above 10cm in diameter, medium debris ranges from 1 to 10cm and small debris is any object below 1cm in diameter. Whilst it is possible to track large debris in real time, the medium and small debris population can only be estimated by statistical models. The European Space Agency (ESA) provides such estimates for all three size categories. An estimate for large debris is also provided, with the assumption that some debris pieces got overlooked by detection and tracking methods. The estimated numbers as of January 2019 are as follows: 34.000 pieces of large debris, 900.000 pieces of medium debris and 128.000.000 pieces of small debris with a combined mass of more than 8400 tons.[3] Albeit quantitatively outnumbered by medium and small debris, large debris represents approximately 99% of the total debris mass in Orbit.[4]

3 ESA, Space Debris by the Numbers, January 2019
4 Liou, 2011



Small Debris

Estimated amount: **128.000.000**
Paint flakes, fuel droplets

Medium Debris

Estimated amount: **900.000**
Small fragments, tools, separation bolts, screws

Large Debris

Estimated amount: **34.000**
Large fragments, deactivated satellites, spent rocket stages

Materials & Density

One property of space debris that is often overlooked, is its density. In order to provide more accurate orbital debris engineering and prediction models, for collision avoidance or calculation of debris proliferation in the future, it is important to have an understanding of the debris material density distribution. Opiela provides a study focused on this specific topic.[5]

In it, the wide range of material densities are classified into three representative values: High density (e.g. steel), medium density (e.g. aluminum) and light density (e.g. plastic). Further, the composition of debris from upper rocket stages is stated to consist of 90% high density materials and 10% medium density materials and the one of payload debris to be 70% low density, 27% medium and 3% high density. Additional examples of material components of debris are given based on their densities:

High density: steel, stainless steel, steel-nickel-chrome alloys and copper
Medium density: aluminum, titanium and paint
Low density: fiberglass, graphite-epoxy composites plastics, beryllium, phenolic resins and foam

Interior of a Propellant Tank >
Welding work performed inside the liquid nitrogen tank of the Space Launch System (SLS).
Credit: NASA

5 Opiela, 2009

Risks & Kessler Syndrome

When looking at the hazards and dangers of orbital debris, one has to differentiate between the short-term and the long-term risks. Due to their high velocities of up to 20.000 km/h, debris of any size poses a risk to current and future space missions. At this speed, even a tiny flake of debris can cause a satellite to fail upon impact or penetrate the layers of an extra vehicular activity (EVA) suit. Currently a 3-5% chance of mission loss is given over the lifetime of a satellite due to debris impact.[6] This is the short-term risk of orbital debris. The long-term risk was firstly described in 1978 by Kessler and Cour-Palais.[7] They propose that once the density of the debris population surpasses a certain threshold, collisions between large debris pieces would occur and significantly increase the debris population as a result of their fragmentation. Subsequently this would lead to further collisions in a cascading manner, eventually leaving us with an impenetrable debris cloud around our planet, rendering our satellite and communication networks ineffective whilst posing serious limitations onto future spaceflight attempts.

This chain of events is known as the Kessler Effect or Kessler Syndrome and it is presumed to have already begun with the 2007 Fengyun 1-C Breakup after a Chinese anti-satellite missile test and the 2009 hypervelocity collision between the American Iridium 33 and the inactive

The 2009 Hypervelocity Satellite Collision >
Between Iridium 33 and the inactive Kosmos 2251
Created over 2000 new large debris pieces.
Credit: Wikimedia Commons / User: Rlandmann

6 Bonnal et al., 2013
7 Kessler & Cour-Palais, 1978

Russian Kosmos 2251 satellites. These events together have more than doubled the debris population in the region of space below 1000km.[8]

According to Liou, almost all future collisions will occur in low Earth orbit (LEO) the region of space up to an altitude of 2000km, medium Earth orbit (MEO 2000-35.768km) and the geostationary orbit (GEO 35.768km) will practically not be affected. The highest potential for debris proliferation, comes from catastrophic collisions. This is an event in which the impact energy to target mass ratio of colliding objects exceeds 40j/g, resulting in a total fragmentation of both objects. The most probable contributors for a catastrophic collision are large intact debris pieces, considering their great mass.[9]

There are currently two major ways to protect spacecraft from short term risks of orbital debris. Firstly, against small debris or micrometeorites a special type of shield was conceived called the Whipple Shield (see page 74) secondly, multiple agencies like the SSN track most large debris pieces and warn spacecraft operators when there is a chance of collision so that they can initiate evasive action in time. However, these maneuvers require extra propellant and can seriously impair mission goals or shorten mission life.[10] Potential measures against the long term risk are presented in the next chapter.

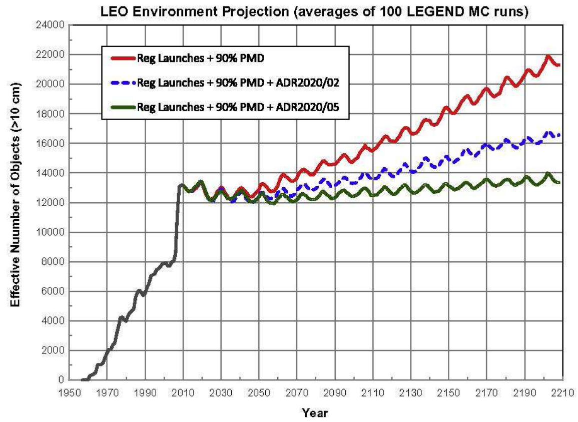
8 Liou, 2006
9 Liou et al., 2006, 2009, 2010
10 ESA, Automating Collision Avoidance, October 2019

The necessity for ADR[11]

One measure against potential future orbital debris proliferation is the implementation of postmission disposal (PMD) guidelines. The Inter-Agency Space Debris Coordination Committee (IADC) implemented such guidelines in 2007, suggesting that spent rocket stages and satellites at the end of their lifetime should be transfered into a 25-year decay orbit, resulting in a burn up in Earth's atmosphere.[12] Even though 25 years is a fairly generous time, in which the mitigated piece of debris could still lead to a collision, the PMD guidelines remain only guidelines and the space-fairing nations are not bound by any law to follow them.

Numerous Studies by Liou, Johnson et al., focusing on potential debris collisions in the next 100 to 200 years, using NASA's orbital debris evolutionary model LEGEND, suggest that even if we would suspend all future launches and the PMD mitigation measures would have a 90% success rate, the debris population will continue to increase. Further simulations were run with an assumed launch rate based on the previous decades of spaceflight. The results of the studies suggest that at least 5-10 large debris pieces, have to be removed from orbit actively per year, to ensure a stable debris population.[13]

Unfortunately, early estimations from 2010 place the PMD compliance values at roughly 14% with later studies



Simulated LEO Population Growth
All three curves assume a PMD of 90%. ADR2020/02 describes a scenario with active debris removal begining in 2020 with 2 large objects removed per year, ADR 2020/05 describees the same scenario with 5 large debris pieces removed per year.
Credit: Liou, 2011, Figure 6

11 Active Debris Removal
12 IADC, Space Mitigation Guidlines, 2007
13 Liou et al. 2006, 2009, 2010, 2011

putting the number even as low as 8%.[14] Besides, a future launch rate is fairly difficult to predict. Companies from the private sector are now developing their own launcher vehicles, most notably Space X, introducing reusable launchers with their Falcon series rockets. Reusability is the key factor with which the company hopes to provide more launches per year, whilst reducing their cost.

Additionally, large constellations of satellites are planned in the future to provide worldwide Internet coverage. Boeing's planned constellation features 2900 satellites and Space X is devising a two step implementation with 2800 and 7500 satellites respectively. In total the Federal Communication Commission (FCC) received requests for over 17.000 satellites to be launched in the next ten years.[15] Therefore it is likely that even more than 5-10 large debris pieces have to be removed per year to ensure a stable environment.

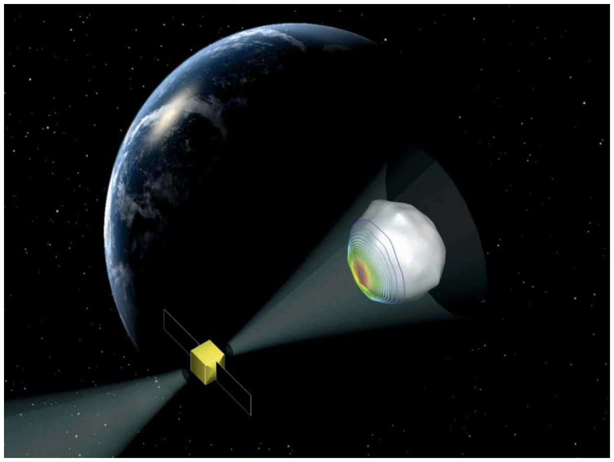
On the other hand, late studies and simulations indicate, that parameters such as launch and explosion rates, magnitude of solar activity and compliance with PMD might have a higher influence on the outcome of the future debris population, than the number of debris pieces removed per year with ADR. More and continuous research is required to determine the true necessity for ADR and weather to prioritize the short term or the long term risks posed by orbital debris.[16]

14 White & Lewis, 2014
15 UNOOSA/COPUOS, February 2019
16 White & Lewis, 2014

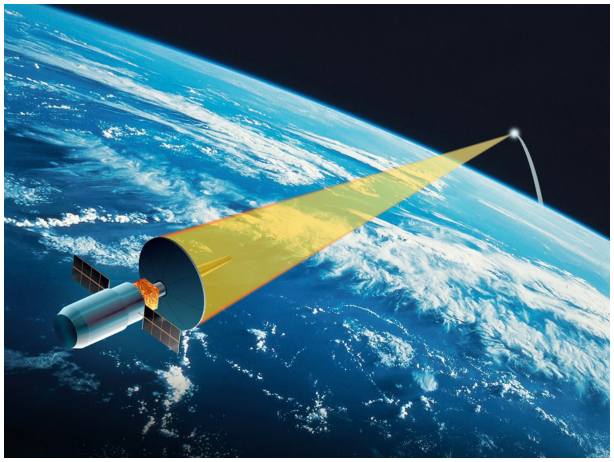
ADR Approaches for Large Debris

A lot of different approaches for ADR have been suggested over the years. The most popular concepts and techniques concerning large debris will be presented on the following pages. These concepts mainly focus on the capture and sole deorbiting of the debris, using different means to propel the acquired target towards Earth subsequently leading to a burn up during atmospheric reentry. The main technologies considered for this approach can be grouped as follows: **Contactless methods** (laser, ion beam shepherd); **Loose-contact methods** (net, hook, harpoon, clamp) and **Rigid-contact methods** (electromagnetic tether, robotic arm). Each of these technologies has to be installed on to or delivered by a spacecraft that rendezvous with the debris. The categories above indicate how close and precise this rendezvous act has to be.

The rendezvous with and capture of debris is highly complex for multiple reasons. **(1)** The debris does not contribute to the rendezvous procedure; it lacks visual cues, radar corner-reflectors or any other commonly used equipment for similar missions carried out by the ATV, HTV, Soyuz, Progress or Dragon. **(2)** The debris is potentially tumbling, with a movement possibly higher than 6°/s, that would have to be passivised in order to guarantee a controlled collection and **(3)** The visual and physical state of the debris may differ from the one that is expected: in the case of rocket upper stages, the white thermal protection layer covering its surface, could have



The MOSAIC Ion Beam Shepherd
Artist Visualisation
Credit: ESA Nebula Lybrary



Space Based Laser
Artist Visualization
Credit: SBL IFX Team / Deagle

turned black due to the thermal fluxes encountered during the atmospheric phase of the launch.[17] Referring to the work of Hakima and Emami[18] the different approaches for ADR are summarized and presented below.

Contactless methods:

Laser - By directing a high powered laser beam onto a debris piece, it causes the targeted surface to ablate (a form of vaporization) which produces a momentum change due to the ejected vapor, similarly to an impulse delivered by a rocket. For this method no contact or close rendezvous maneuvers are necessary and the spacecraft generating the laser beam can keep a safe distance to the debris. Furthermore, it requires no extra propellant to move the selected debris. The disadvantages of this method are the limited control, the danger of explosion of the target due to the very high temperatures needed to achieve ablation and the possible disintegration of the optical elements of the laser over time.[19]

Ion Beam - The ion beam shepherd (IBS) is a spacecraft concept that exerts a thrusting force, by producing an ion beam directed towards the debris to modify its orbit and/or attitude. It has a primary and opposing secondary propulsion system in order to keep a safe distance to the object being pushed in front of it. The IBS, similarly to the laser method does not require contact with the debris. The main risks being the failure of maintaining

17 Bonnal et al., 2013
18 Hakima & Emami, 2018
19 Ibid.

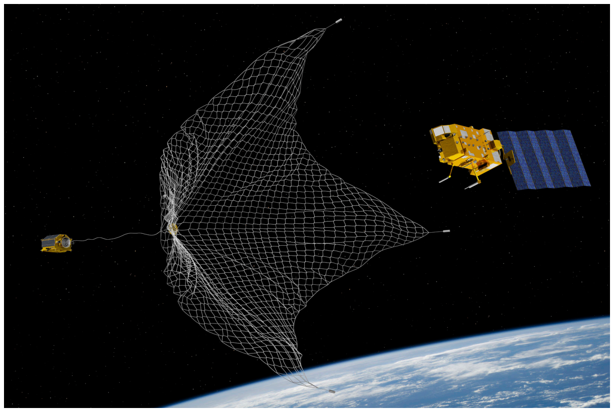
the distance to the targeted object, which most likely will result in a catastrophic collision and a loss of mission or the misalignment of the ion beam force to the objects center of mass, which could cause a breakup of the debris.[20]

Neither of the above mentioned methods provides a controlled re-entry, this is against current mitigation standards, that state that debris has to be de-orbited above the pacific, so that no inhabited area may suffer an impact of a potentially not completely burned up object.

Loose contact methods:

Throw Net - This method achieves capture of the target debris by deploying a net, which is closed once the debris is surrounded by it. The advantages being, the relatively large distance that can be maintained between the spacecraft and the target, limiting the collision risk; the material and lower precision requirements for the net opposed to rigid contact methods and the fact, that a single sized net can be used for debris of various sizes. However, the method may cause fragmentation of the target by exerting shock and vibration loads during the capturing phase or by enclosing a debris piece with large appendages like antennae or solar arrays. The largest risk is the possibility of missing the target and a subsequent failure of the mission, since the mechanism normally allows for only a single shot of the net.[21]

20 Hakima & Emami, 2018
21 Ibid.



e.Deorbit
A visualization of a throw net deployment as part of ESA's e.Deorbit mission.
Credit: ESA

Canadarm 2
Canadarm 2 with SpaceX Dragon Cargo spacecraft during berthing process on the ISS.
Credit: NASA

Similar advantages and disadvantages can be identified for the harpoon, hook and clamp concepts.

Rigid contact methods

Electrodynamic Tether (EDT) - By utilizing the interaction between the current flowing through a conductive tether and the earth's electromagnetic field, the electrodynamic tether presents a form of space propulsion that can generate thrust for a long duration while requiring little to no fuel or expendables.[22] The disadvantages of this method being the requirement of a rigid contact of the space craft with the debris, and the length of the tether which can be up to 10km, posing risks to active spacecraft in orbit. Further it may cause entanglement and subsequent failure during the deployment of the spacecraft.[23]

Robotic Arm - The operation of robotic arms (RA) in space is by now a highly established technology. The Canadarm was an integral component of the Space Shuttle program and enabled the construction of the International Space Station (ISS) which now features the second generation Canadarm2 as its Mobile Servicing System (MSS) next to the Japanese Experimental Remote Manipulating System (JERMS), the Russian Strela cranes and by 2021 the setup will be joined by the European Robotic Arm (ERA). In addition to this, removal of debris by RAs is one of the most studied ADR techniques. Similar to the EDT the RA method requires rigid contact with the debris. This poses a risk of

22 Hakima & Emami, 2018
23 Bonnal et al., 2013

fragmentation of the target debris and a too high relative attitude rate between the spacecraft and the debris could cause damage to the arm. A risk of missing the target during the capture procedure is also given, however it is not as severe as with the previously mentioned net method, since the arm can attempt this procedure several times if no incident occurs.

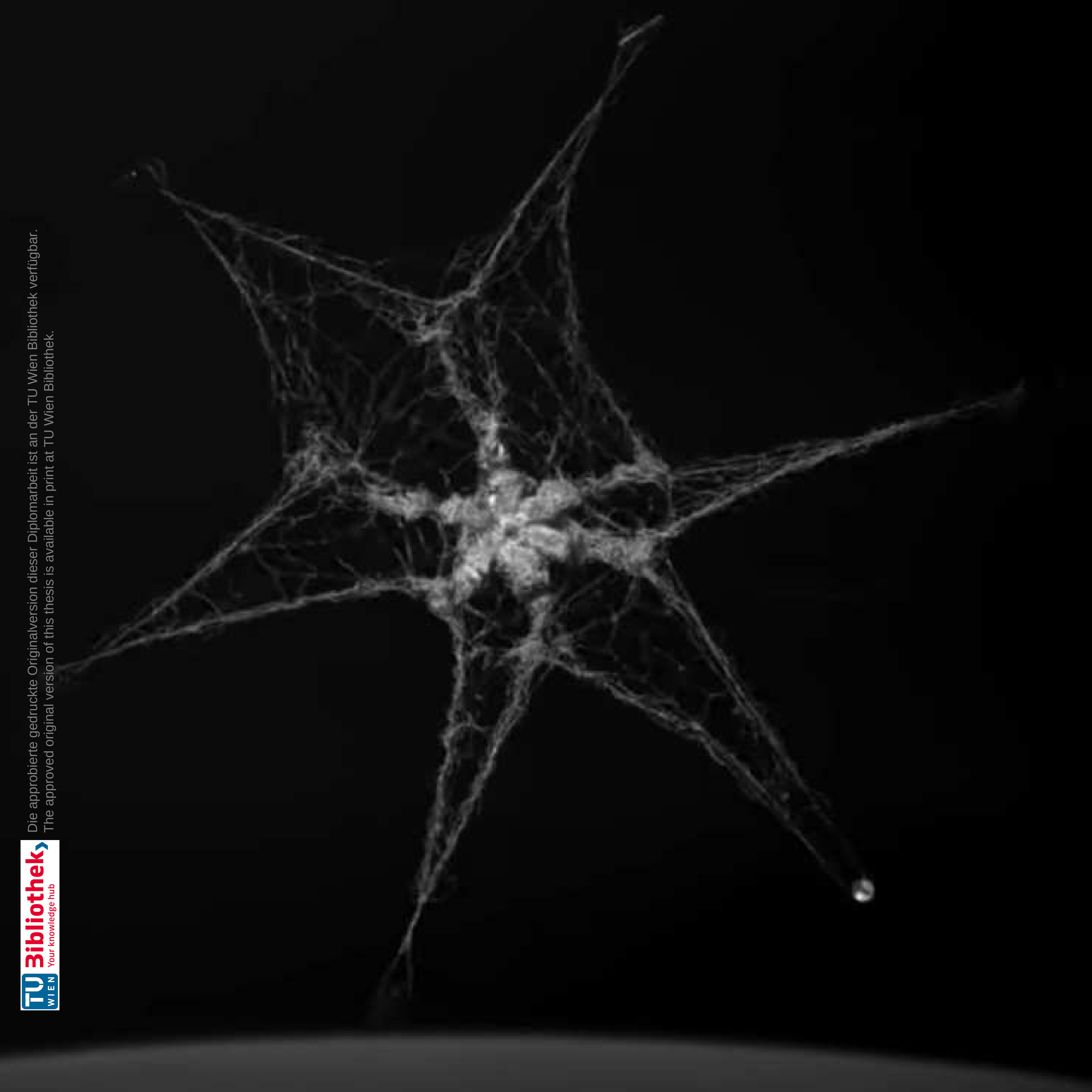
A spacecraft equipped with an RA can also be used to install sails or thruster deorbiting kits (TDK) onto the debris. While the former simply tries to reduce the targets altitude due to enhanced drag with the goal to speed up its orbital decay, the ladder could be utilized to maneuver the debris into specific orbits e.g. a space station for debris recycling.

Hakima and Emami compare the above mentioned methods with an analytic hierarchy and a utility-based process with the conclusion, that the Net, Laser and Arm methods are the most promising techniques for ADR.[24]

The first successful tests for in-orbit ADR technology have been performed by the RemoveDebris mission, that began in 2014 and was lead by the Surrey Space Centre. The actual in-orbit tests occurred in 2018 successfully deploying a harpoon and net and capturing a pre-launched target. The RemoveDebris satellite deployed a sail structure at end of its mission to increase drag and accomplish a burn up in atmosphere in March of 2019.[25]

Successful Throw Net Demonstration >
RemoveDebris image from the 2018 orbital throw net technology demonstration.
Credit: Surrey Nanosats SSC

24 Hakima & Emami, 2018
25 Aglietty et al., 2019

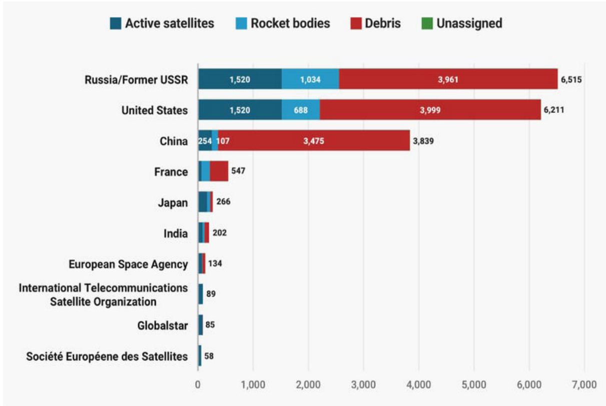


Who's Debris is it?

Besides the previously mentioned, legally non-binding, mitigation guidelines[26] there is no ruling on how to treat orbital debris. However, some of the articles in the five treaties conceived by the United Nations, dealing with outer space use and related activities, can be interpreted in a way, that they address this issue.

Article I of the Outer Space Treaty states that exploration and use of outer space *"shall be carried out for the benefit and in the interests of all countries, … and shall be the province of all [humankind]"* and article IX includes this following passage: *"…States Parties to the Treaty shall pursue studies of outer space, … and conduct exploration of them so as to avoid their harmful contamination…"* Since any piece of debris is potentially harmful to other spacecraft and can be seen as contamination, the states parties should be responsible for the removal of respective debris they have produced.[27]

A further problem is the property claim of owning entities to their spacecraft. According to Article VIII of The Outer Space Treaty, even if pieces of a craft are found after a breakup or partial burn up on land, where the owning party has no jurisdiction, the residing party is responsible to identify and notify the owner and to ensure that the debris can be reclaimed safely and in its integrity.[28] Currently, any individual state's or company's



Orbital Debris Distribution by Possession
2017 distribution of debris, by possessing country or company and type.
Credit: Space-Track.com / Business Insider

26 IADC, Space Debris Mitigation Guidelines, 2007
27 The Space Review, November 2017
28 UNOOSA, The Outer Space Treaty, 1967

ADR attempt can only target debris pieces that belong to them, so each space-faring nation would have to develop their own programs for ADR removal. An approach to this problem tackled internationally or by an impartial agency is obviously more reasonable as it saves development cost as well as administrative resources, but it calls for a new set of laws or an international agreement of sorts.

A possible scenario would be to, in a first act, dispossess all owners of debris already in orbit, optimally whilst accordingly reimbursing them. Cataloged lists exist for all trackable spacecraft and debris in space, showing to which nation and operator they belong, In a second step, some sort of PMD mitigation laws would have to be implemented by the UNOOSA or a similar body. E.g. if your spacecraft does not successfully deorbit during a five year period after mission completion, you lose any property claim to it. Besides increasing the PMD compliance numbers dramatically, this would make all debris remaining in orbit free to remove by an international agency, or if an adequate utilization is found, it could even inspire private companies to start mining and collecting debris for profit. Whatever the next developments may be, it is paramount that the task of cleaning up space is tackled with the same tenacity as is displayed during the attempts of conquering it. Otherwise we might forever cut our selves off from this final frontier.

02 Space Architecture I: Definition, Limitations & Vernacular

‹The International Space Station
With docked ATV-2 and Space Shuttle Endeavor on May 24th 2011.
Credit: ESA / NASA

Introduction

When approaching any new design project it is helpful to identify at least some of the limitations inherent to the specific design task ahead. In architecture this can be as banal as the actual boundary of a building site, how high it is permitted to build on it according to the land use plan, where it is situated, what its orientation towards the sun is, etc. Later on, knowing what material or construction type one is going to use poses further and more detailed limitations.

They help to focus the design process, keep one from wasting time and resources on ideas that are unrealizable, and truly understanding them permits one to potentially come up with viable out of the box solutions.

Of course, when considering space architecture, there are no building sites in orbit, nor is there a land use plan for the moon. However, there are many other factors that limit ones design possibilities. After giving a general introduction to the profession and its definition, the following chapter briefly summarizes and presents the most important and basic technical limitations, that are helpful to know if one is about to attempt a design in this field. Finally, the current vernacular of space architecture, with a focus on modularity and compatibility, is introduced by means of the International Space Station.

Space Architecture Definition

Space architecture is the theory and practice of designing and building inhabited environments in outer space.[1]

This is the mission statement from "The Millennium Charter", a manifest declaring the fundamental principles of Space Architecture, developed by members of the Technical Aerospace Architecture Subcommittee of the American Institute of Aerospace and Aeronautics (AIAA) and signed by 47 architects, designers, engineers and researchers, in Huston 2002. Häuplik-Meusburger and Bannova present a more elaborate description, referring to the same passage:

Following the quotation above, Space Architecture as a discipline comprises the design of living and working environments in space and on planetary bodies, such as the Moon and Mars and other celestial bodies. This includes space vehicles and space stations, planetary habitats, and required infrastructure. Earth analogs for space applications, simulations and test facilities are also included in the field of Space Architecture. Earth analogs may include Antarctic, airborne, desert, high altitude, underground, undersea environments and closed ecological systems. Space Architecture, as a discipline, is not new but has been emerging for at least 40 years. When NASA and the former Soviet Union turned their views towards long-term human missions, space architects and designers

1 AIAA/SATC, The Millennium Charter, 2002

were involved.

[…] Space Architecture is interdisciplinary and connects diverse fields such as aerospace engineering, architecture and design, human factors design, space sciences, medicine, psychology, and art. It therefore combines the accuracy of technical systems, human needs for working and living, the interface design for the relationship between humans, and the built and natural environments. It is simultaneously technical, humanistic and artistic and deals with the design process from a "big picture" perspective down to every detail of each component. In addition to traditional knowledge of planning and building processes, special knowledge is needed regarding how to design for humans in extreme environment and how to do so creatively.[2]

It has to be noted, that this book can neither provide nor identify the above mentioned necessary special knowledge in its entirety. However, it attempts to summarize the most important aspects of space architecture, as deemed relevant by the author, to equip a reader, inexperienced in this field with the means to better comprehend the concept definition process and designs presented in the final two chapters of this diploma thesis.

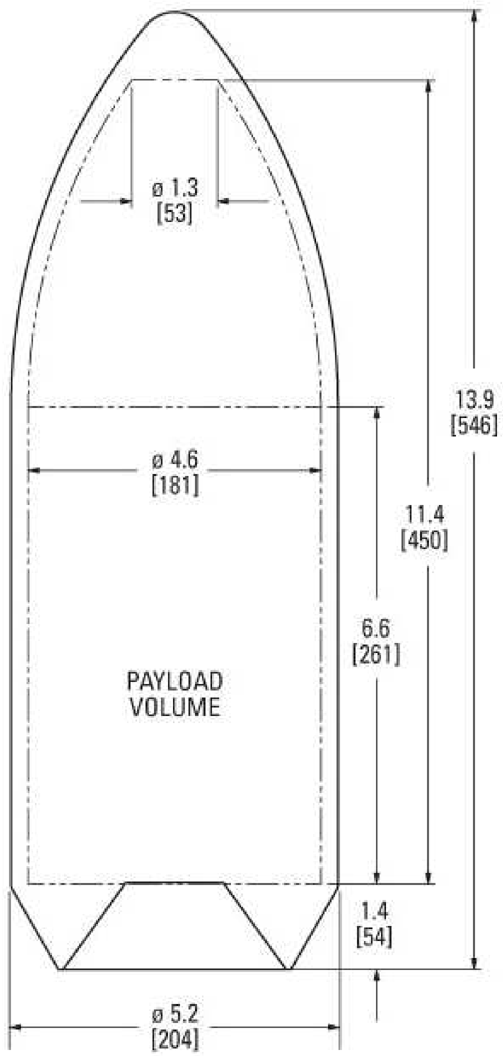
2 Häuplik-Meusburger & Bannova, Space Architecture Education for Engineers and Architects, 2016, p 1& 2

Launchers & Fairing Sizes

To get objects into orbit, or to the moon or any other celestial body, basically to leave Earth and escape its gravitational pull, one requires extreme forces currently only provided by launch vehicles. Regarded in a simplified way these vehicles consist of a propulsion element and a payload element. The propulsion element is a rocket equipped with one or multiple engines, burning solid or liquid propellant. Additionally it contains all electronic and navigational components to deliver the payload to its destination. The payload element is placed atop of this rocket in a protective fairing to withstand the strains of the launch process. Often launch vehicles are multi-staged to optimize the total mass that needs to be moved by discarding stages throughout the launch process.

Depending on the target destination a specific launcher has to be used, launches to Low earth orbit are not as fuel intensive as a trip to the moon or even mars

Many different launch vehicles have been developed since the dawn of the space age and new ones are continuously being added. They dictate the maximal size and mass of an object that can be launched from Earth, and hence play an important role in space architecture. Space X is focusing efforts on establishing an efficient reusable launcher, to reduce the overall kg to LEO cost - whilst providing a payload volume, comparable to other current single use launchers - with their falcon series rockets.



Falcon 9 Fairing Dimensions - Meters [Inches]
Taken from the Falcon 9 Launch Vehicle Payload User's Guide
Credit: Space X

Launcher Vehicles Comparison Table[3]

Launch Vehicle	Ariane-5	Proton-M	Delta IV	Atlas V	Falcon 9	SLS
Fairing Diameter Fairing Length	FD: 4.57m FL: 10.35m	FD: 4.1m FL: 10.8m	FD: 5m FL: 25.9m	FD: 5.4m FL: 23.4m	FD: 5.2m FL: 13.9m	FD: 8m FL: 25m
Mass Capabilities	LEO: 18 t GTO: 6.8t	LEO: 22t GTO: 6t	LEO: 13.36t GTO: 7t	LEO: 20.5t GTO: 7t	LEO: 13t GTO: 4.85t	LEO: 100t TLI: 45t
Remarks	Arianespace operates two versions of the Ariane 5 (ECA and ES), ensuring high-quality vehicles, that are standardized and repeatable in production and delivered ready for launch.	The Proton rocket family is one of the most successful heavy-lift boosters in the history of spaceflight.	The Delta IV launch system is available in five configurations: The Delta IV Medium (Delta IV M), three variants of the Delta IV Medium Plus (Delta IV M+) and the Delta IV Heavy (Delta IV H).	Atlas V is available in several variants, built around a LOX/RP-1 Common Core Booster (CCB) first stage and a LOX/LH2 Centaur second stage powered by one or two RL10 engines. Up to five solid rocket boosters (SRBs) can augment first stage thrust.	Falcon 9 is a two-stage rocket designed and manufactured by Space X for the reliable and safe transport of satellites and the Dragon spacecraft into orbit. It also available in the Falcon 9 Heavy configuration.	NASA's Space Launch System, with heavy lift capabilities to LEO and for Trans-Lunar Injections (TLIs) is under development and has an expected first launch in early 2021.

3 Häuplik-Meusburger & Bannova, 2016, p 303 - adapted by author, additional SLS information from: Spacenews.com, August 2019

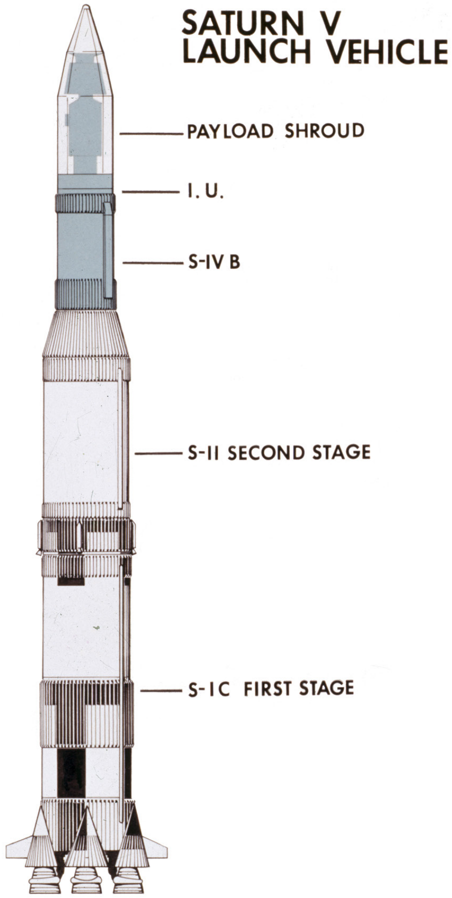
Assembly & Classes of Habitats

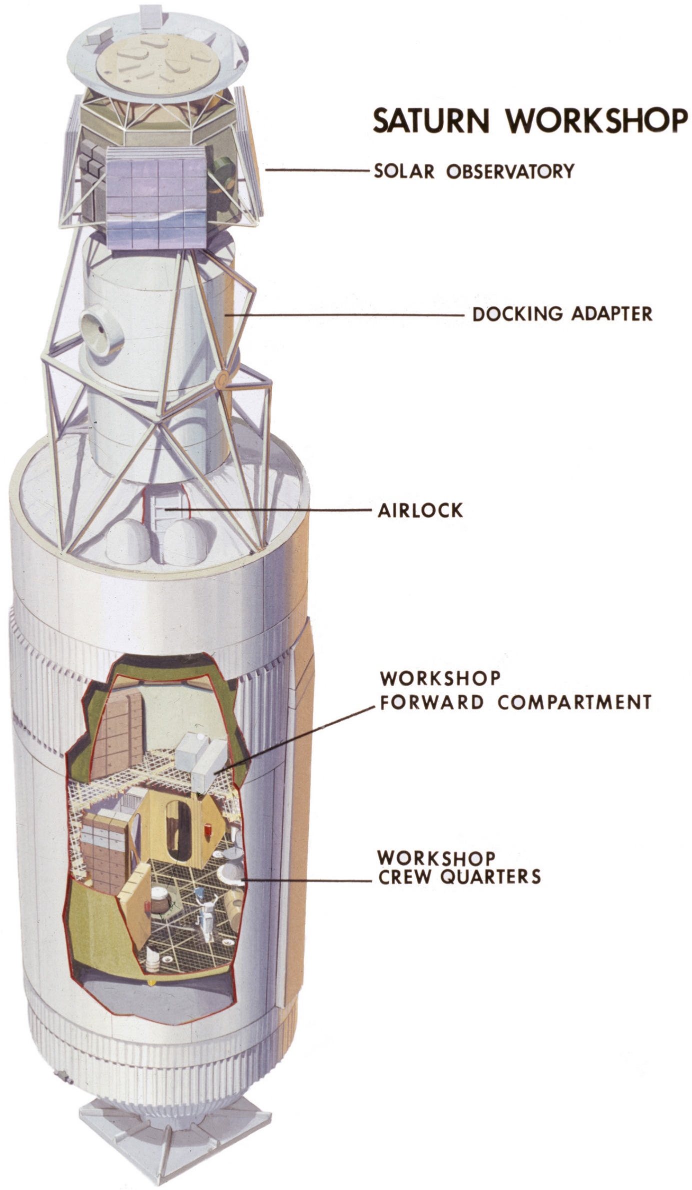
Up until the Mir Space Station, which was launched in 1986 and operational until 2001, all prior orbital space stations like the Russian Salyut Space Stations (1971 -1991) or the American Skylab (1973-1979) and the Apollo Lunar Module (ALM), the only extraterrestrial habitat on a celestial body up to this date, were launched into space as single modules or vessels, fully outfitted and ready to operate on arrival at their target destination (Ignoring minor deployment steps of solar arrays and radiators). With the exception of the Skylab and its orbital workshop, devised unconventionally inside the third Stage of the Saturn V rocket, resulting in the staggering dimensions of 6.6m in diameter and 14 meters in height, making it the largest single habitable module launched to space to this date, all mentioned examples were strongly limited by their launch vehicles mass and volume capabilities.

In 1986 the Soviet Union launched multiple modules that performed docking maneuvers and connected to one another around a node element in orbit in order to create their first larger space station: Mir. With the termination of the Apollo program and the United States focused towards the development of the space shuttle, a reusable space vehicle with a large cargo bay, capable of atmospheric reentry, the Saturn V rocket was retired and the Skylab approach was unrepeated. The Space Shuttle was also an integral part in the assembly steps of the ISS. It was to transport the modules of the station into space and connect them to

Skylab
On orbit in with deployed solar array and radiators.
Credit: NASA

Skylab Launch Configuration >
The orbital workshop is placed within the third stage of the Saturn V rocket, bypassing fairing size limitations.
Credit: NASA - Marshall Flight Centre


SATURN V
LAUNCH VEHICLE
PAYLOAD SHROUD
I. U.
S-IV B
S-II SECOND STAGE
S-IC FIRST STAGE


SATURN WORKSHOP
SOLAR OBSERVATORY
DOCKING ADAPTER
AIRLOCK
WORKSHOP
FORWARD COMPARTMENT
WORKSHOP
CREW QUARTERS

each other with the use of the on board robotic arm.[4] Even though space architecture and the volumes it creates are highly dependent on launcher fairing sizes, workarounds exist to bypass these limitations. According to Kennedy[5] habitats can be categorized into three classes:

Class I describes habitats that are pre-integrated, completely manufactured and constructed on Earth and fully outfitted and tested prior to launch. Once delivered on location they have immediate capability. They are limited in their size and mass depending on the launch vehicle capabilities.

Class II describes habitats that are prefabricated on Earth but require assembly or deployment aided by robotic or human time once at destination. Additionally, some or all internal outfitting has to be done on site. They are capable of partial subsystem integration and critical subsystems are Earth based and tested prior to launch. They are less restricted in size and mass by the launch vehicle capabilities.

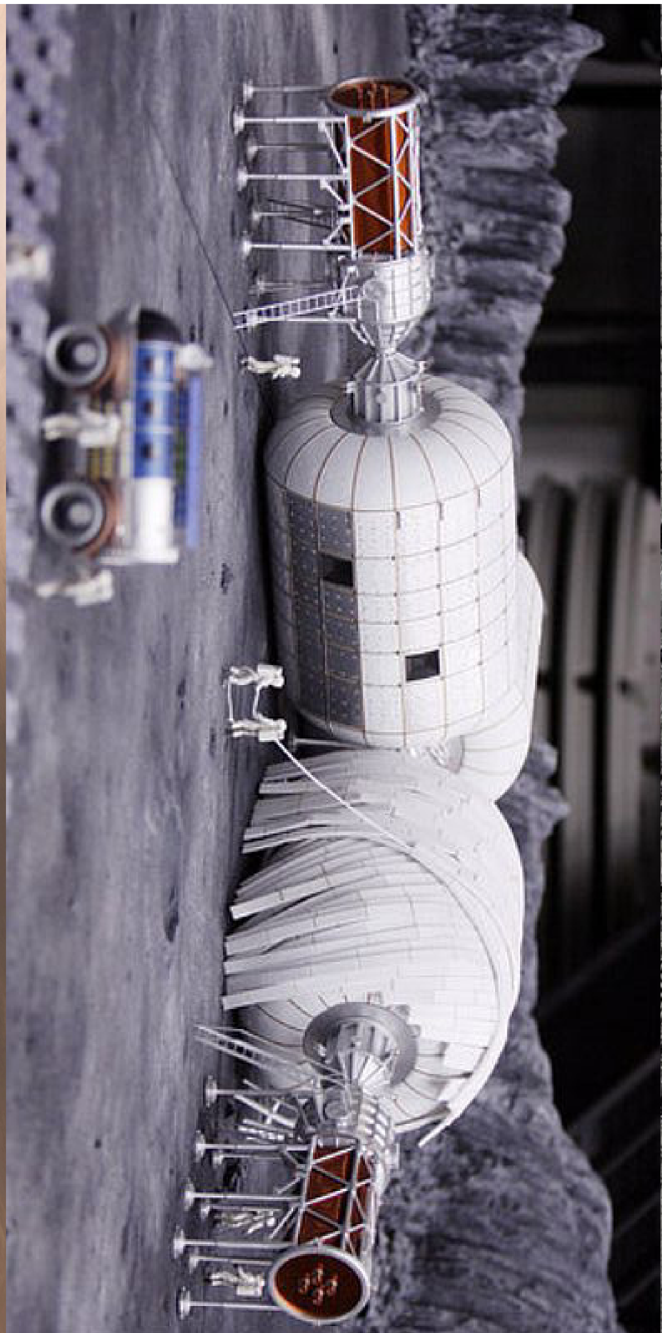
Class III describes habitats that are manufactured in-situ with space resources. Manufacturing capabilities and infrastructure, as well as robotic or human time during construction are required. All internal outfitting has to be performed on site, integration of subsystems is required, and all critical subsystems are Earth based and

4 Häuplik-Meusburger, Architecture for Astronauts, 2011, p 34-95
5 Kennedy, 2002

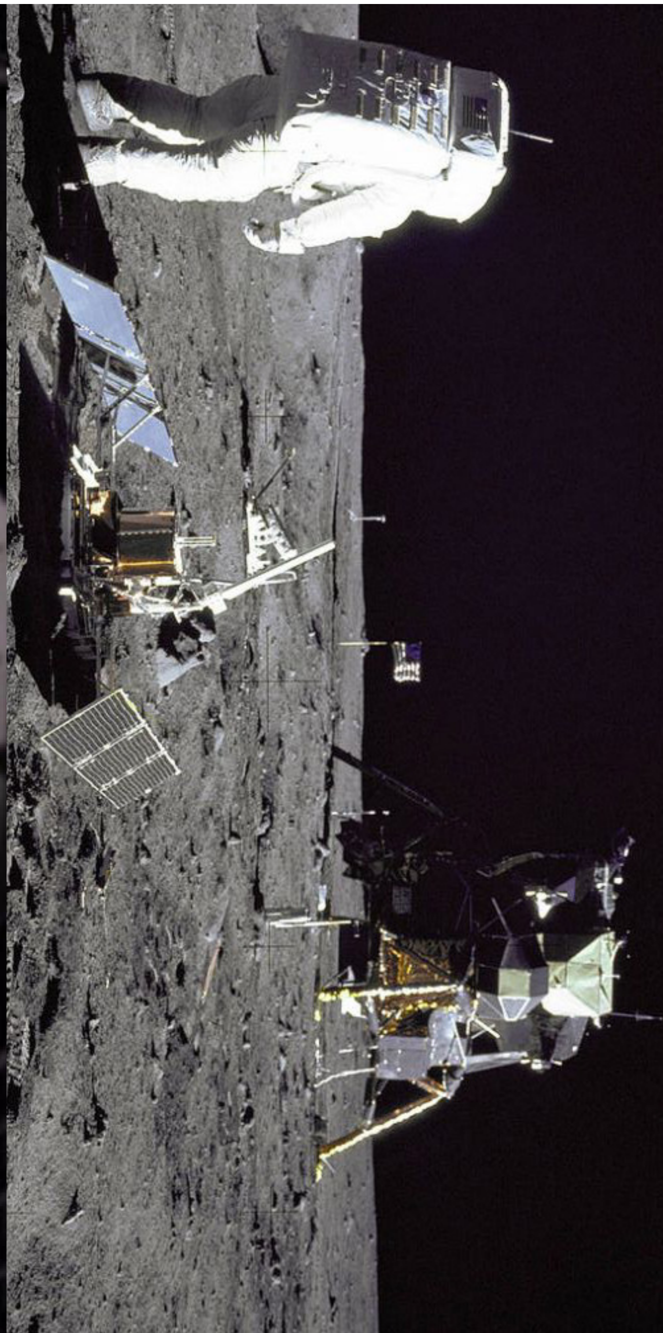
Classes of Habitats >
Class I: Buzz Aldrin in front of Apollo Lander Module
Class II: "Bigelow Moonbase" model.
Class III: Entry from NASA's 3D printed habitat challenge
Credit: I: NASA - II: Bigelow Aerospace - III: SEArch+ / Apis Cor / NASA

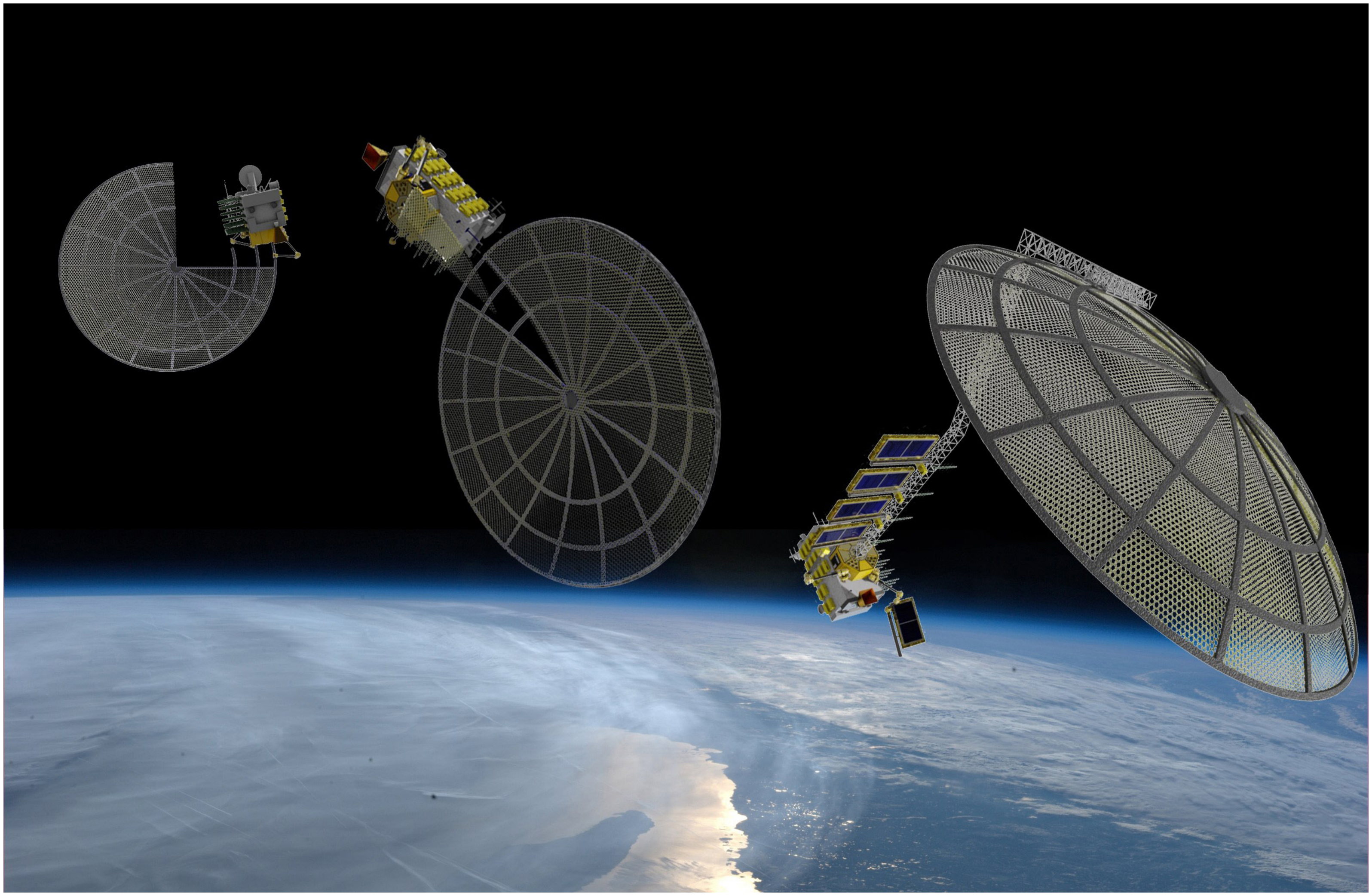
CLASS III

CLASS II



CLASS I





< **Archinaut One**
Artist Visualization
Credit: Made In Space

tested prior to launch. They are capable to create larger Volumes and unrestricted by launch vehicle size or mass capabilities.

When looking at orbital structures, the implementation of a Class II habitat is feasible. In fact Bigelow aerospace has already launched multiple inflatable spacecraft into orbit and currently has an inflatable module docked to the ISS for testing (see page 56). The construction of structures completely free of size restrictions is a far greater challenge. One that the company Made In Space (MIS) is tackling. They teamed up with NASA as part of NASA's IRMA (In Space Robotic Manufacturing and Assembly) Program. Together they developed the Archinaut, a platform that can print and assemble large constructions on orbit, solely relying on supply of raw material feedstock. MIS is also the frontrunner for stationary 3D printers in microgravity. The company operates the Additive Manufacturing Facility (AMF) on board of the ISS - the only commercially owned and operated fabrication system in space, which is solely responsible for raising the Technical Readiness Level of space-based polymeric AMF to the upper limit - and is developing in space printers that use metals as base material.[6] The extraction of raw materials from captured space debris, if this is scientifically and economically possible, and its utilization for an Archinaut type platform or an AMF, presents one possibility to achieve in situ resource utilization (ISRU) on orbit.

6 Patané, 2017

Vernacular, Orientation & Compatibility Explained by Means of the ISS

Due the assembly and construction tendencies of former spacecraft, described on the previous pages, Space Architecture developed a modular vernacular. Kennedy states the following as its main elements: Pressure vessels, for living and working, airlocks and nodes as transition spaces, docking or berthing connections between the individual elements or for external spacecraft and support structures. Technological components like power collection and distribution, thermal control, communications and propulsion with guidance/control are also included.[7]

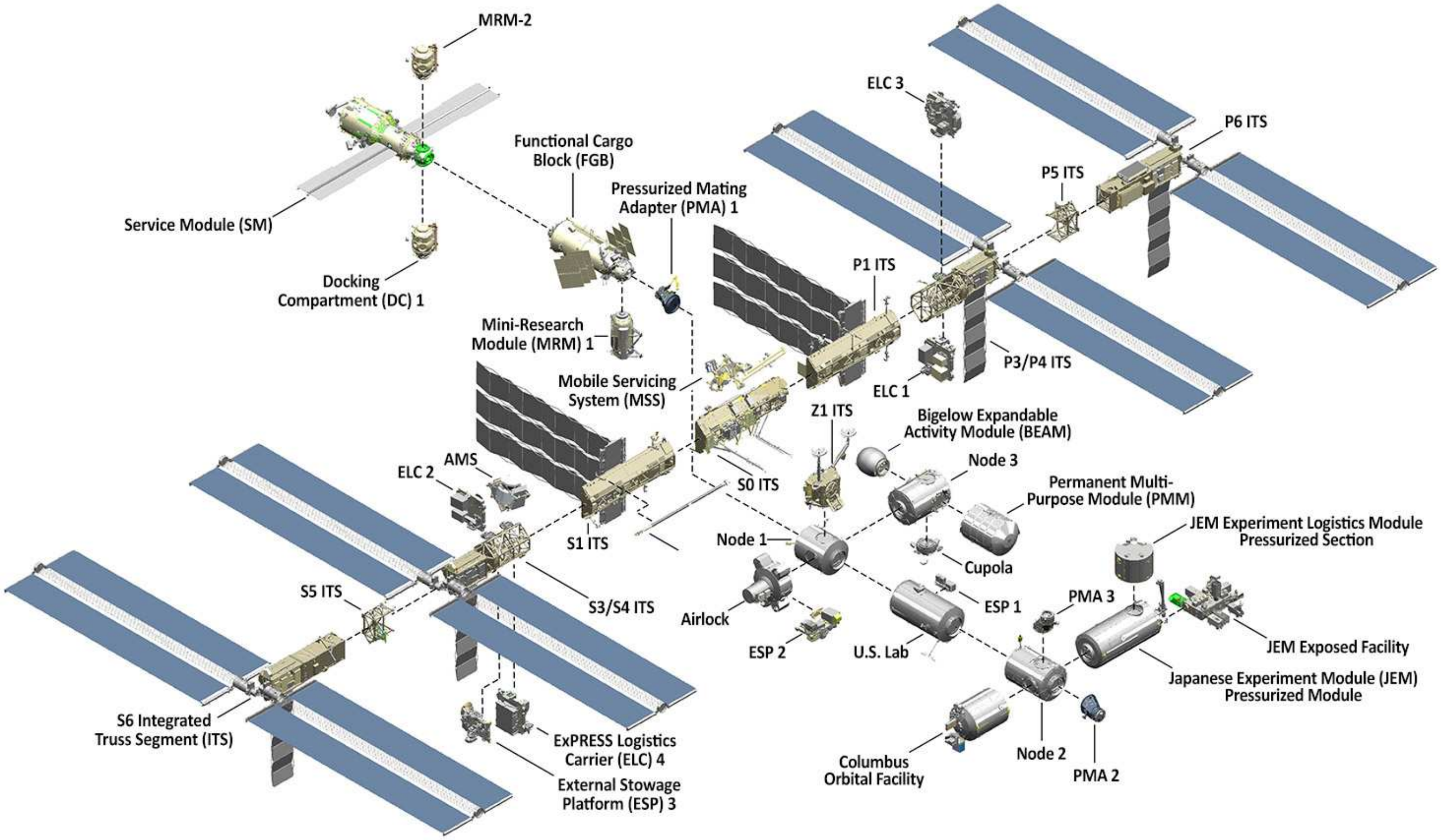
The best example for this type of architecture is the ISS. Described as one of the greatest geopolitical achievements to benefit humanity by NASA, it is also the most complex engineering and design project carried out beyond the earth's surface to date.[8] 42 assembly flights were necessary to get all the stations large modules and main components into orbit, 37 by the US Space Shuttle and 5 by the Russian Proton/Soyuz rockets. Additionally, over 221 spacewalks have been conducted for construction, maintenance and upgrade operations since the launch of its first module in 1998. The stations final configuration was achieved in 2011. It forms a network of multiple pressurized modules and nodes connected to a large truss system that supports the solar array and radiators. It has a pressurized Volume of 916 cubic meters (932 with the

7 Kennedy, 2002

8 Nixon, International Space Station - Architecture Beyond Earth, 2016, p 29, 283

Assembly Spacewalk
ISS Astronauts working on parts of the truss segment - Dec 12th 2006.
Credit: NASA

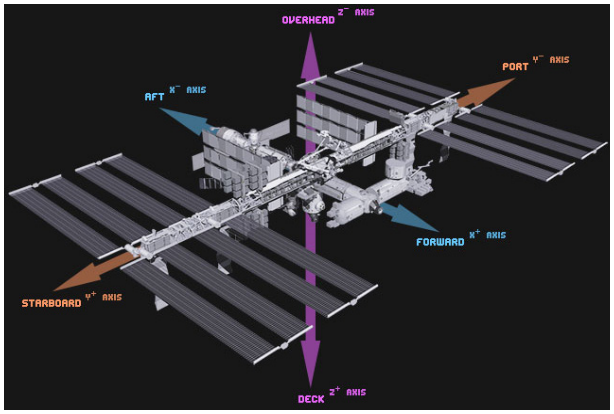
ISS Components Exploded View >
Current constellation of the ISS exploded into its modular components.
Credit: NASA


MRM-2
Service Module (SM)
Docking Compartment (DC) 1
Functional Cargo Block (FGB)
Pressurized Mating Adapter (PMA) 1
Mini-Research Module (MRM) 1
Mobile Servicing System (MSS)
ELC 3
P6 ITS
P5 ITS
P1 ITS
P3/P4 ITS
ELC 1
Z1 ITS
Bigelow Expandable Activity Module (BEAM)
Node 3
Permanent Multi-Purpose Module (PMM)
S0 ITS
S1 ITS
AMS
ELC 2
S5 ITS
S3/S4 ITS
Node 1
Cupola
JEM Experiment Logistics Module Pressurized Section
Airlock
ESP 1
PMA 3
JEM Exposed Facility
ESP 2
U.S. Lab
Japanese Experiment Module (JEM) Pressurized Module
S6 Integrated Truss Segment (ITS)
ExPRESS Logistics Carrier (ELC) 4
External Stowage Platform (ESP) 3
Columbus Orbital Facility
Node 2
PMA 2

expanded BEAM experiment, see page 56) and a habitable volume of 388 cubic meters, excluding visiting vehicles. It is 73 meters in length along the pressurized module central axis, 109 meters wide along the truss axis and has a total mass of approximately 420 metric tons.[9]

The position and orientation of an orbital craft can be described by internal X,Y and Z axes based on a Cartesian right-hand system, as it is done with the ISS: Its X Axis (Roll) describes the Forward (+X) and Aft (-X) direction of the station and often called the velocity vector because the station is traveling along its direction. It is aligned with the pressurized module axis. The Y Axis (Pitch) runs along the truss axis and defines the Starboard (+Y) and Port (-Y) sides. The Z axis (Yaw) defines the stations Nadir (+Z) and Zenith (-Z) orientation.[10]

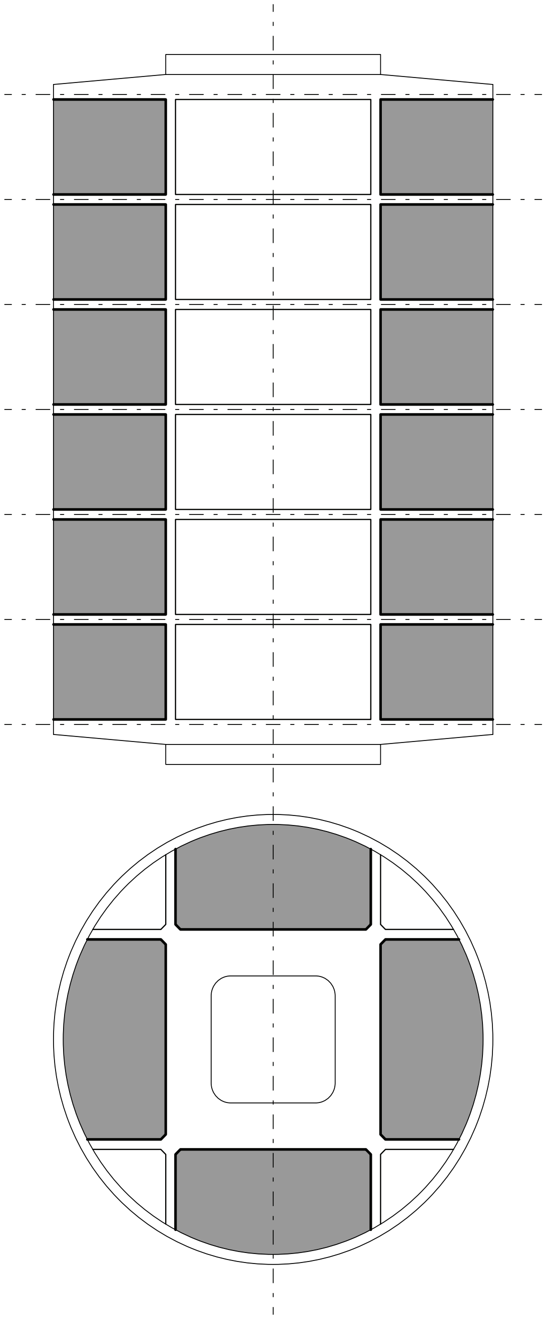
Due to the vast number of nations and companies involved in the construction and operation of the ISS, some of the modular design components in various scales require standardization and have to be compatible. The diameter of the standard ISS module was determined by the maximal capacity of the Space Shuttle payload bay (4.5m), its length was determined by the Shuttle's launch mass capabilities (15.851kg).[11] The station utilizes a rack system, for the efficient integration and interchangeability of hardware. A *Four-Standoff-Rack* configuration was implemented throughout



Orientation
The International Space Station's coordinate system.
Credit: NASA

Four-Standoff-Rack Configuration >
Rack layout of a typical ISS module.
Credit: Häuplik-Meusburger, 2011 - Adapted by author

9 NASA, ISS Facts and Figures, October 2019
10 Nixon, 2016, p 25
11 Kennedy, 2002



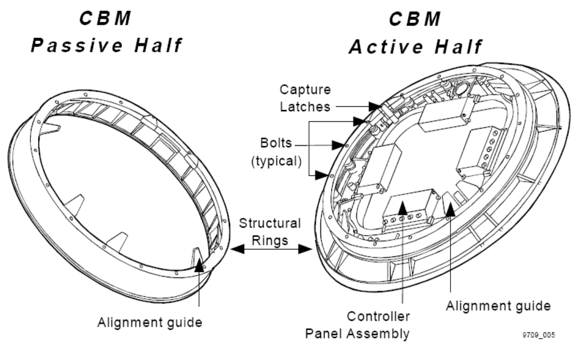
most of the station's modules. I.e. racks can be fixed on all four sides of the circular module section to trusses containing utilities. The majority of stowage, equipment and experiments are accommodated in International Standard Payload Racks (ISPR). They are 2 meters in height, 1.05 meters wide 85.9 Centimeters deep.[12] A further example is the use of Cargo Transport Bags: Containers with the basic dimensions of 50 x 42 x 25 centimeters that usually come in half-, double- or triple configurations. They are used for storage of various cargo throughout the station. Multipurpose Cargo Transport Bags (MCTB) can be utilized for other functions, like containers for waste, separation elements or sound insulation, after their contents are unpacked.[13]

One other important compatibility factor are docking and berthing mechanisms. They enable the connection between modules, nodes and spacecraft. To differentiate: Docking is a process that can be autonomously performed by a spacecraft through controlled flying. Berthing requires the aid of a robotic arm to capture, handle and move the spacecraft or module to the desired location and corresponding interface mechanism. Many different docking and berthing mechanisms have been developed throughout the years. The ISS contains a number of them and in fact has become a veritable test bed for these technologies.[14] The

12 Häuplik-Meusburger & Bannova, 2016, p129
13 Baccus et al., 2016
14 Seedhouse, Bigelow Aerospace - Colonizing Space One Module at a Time, 2015, p 95

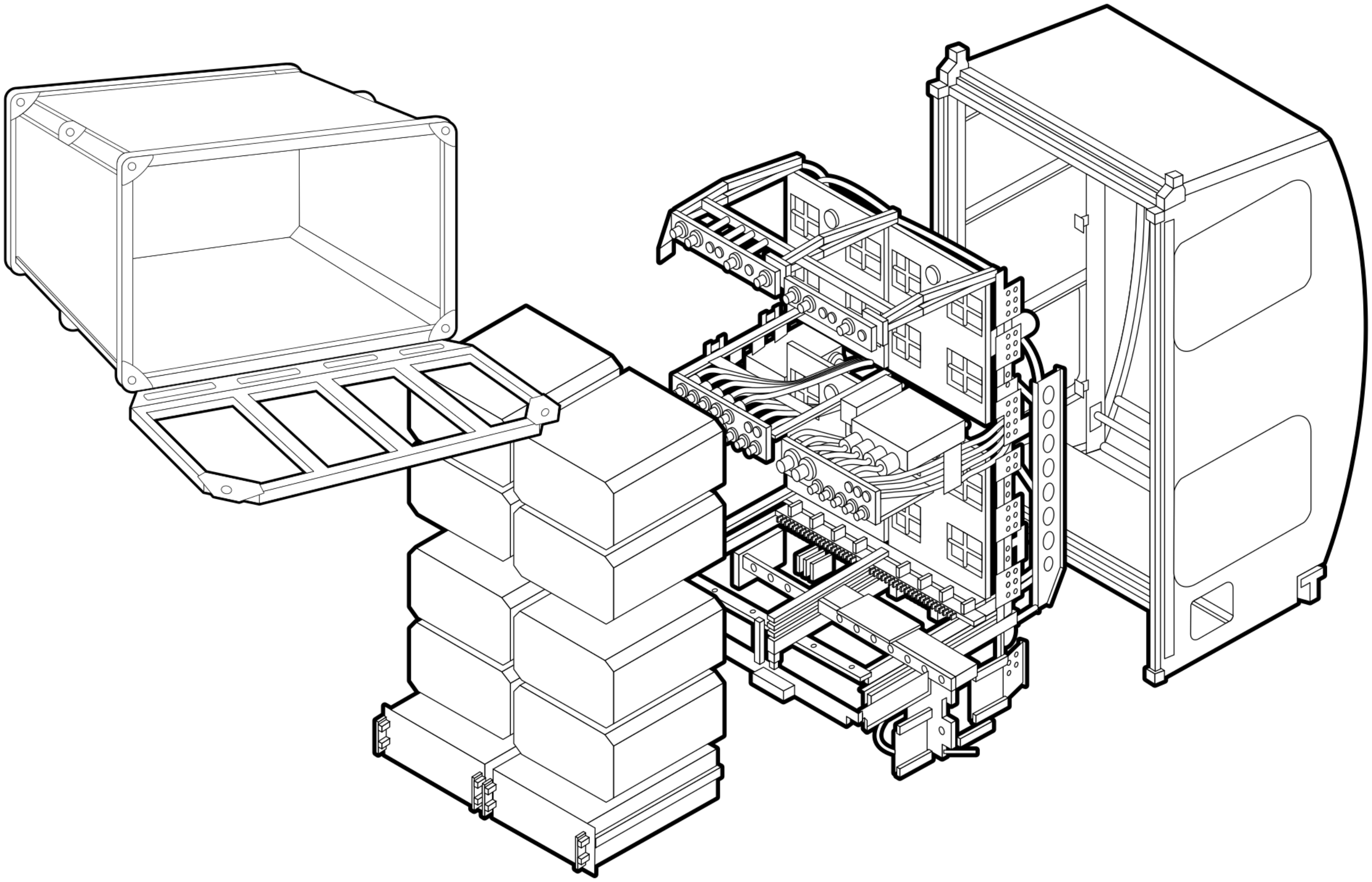
berthing mechanism utilized most throughout the station is the Common Berthing Mechanism (CMB) it is made up of an active and a passive half. It offers a square shaped passage with a dimension of 127 centimeters.[15] Docking Systems typically have smaller openings, the NASA Docking System, capable of docking and berthing, has a circular passage of 80 centimeters in diameter.[16]

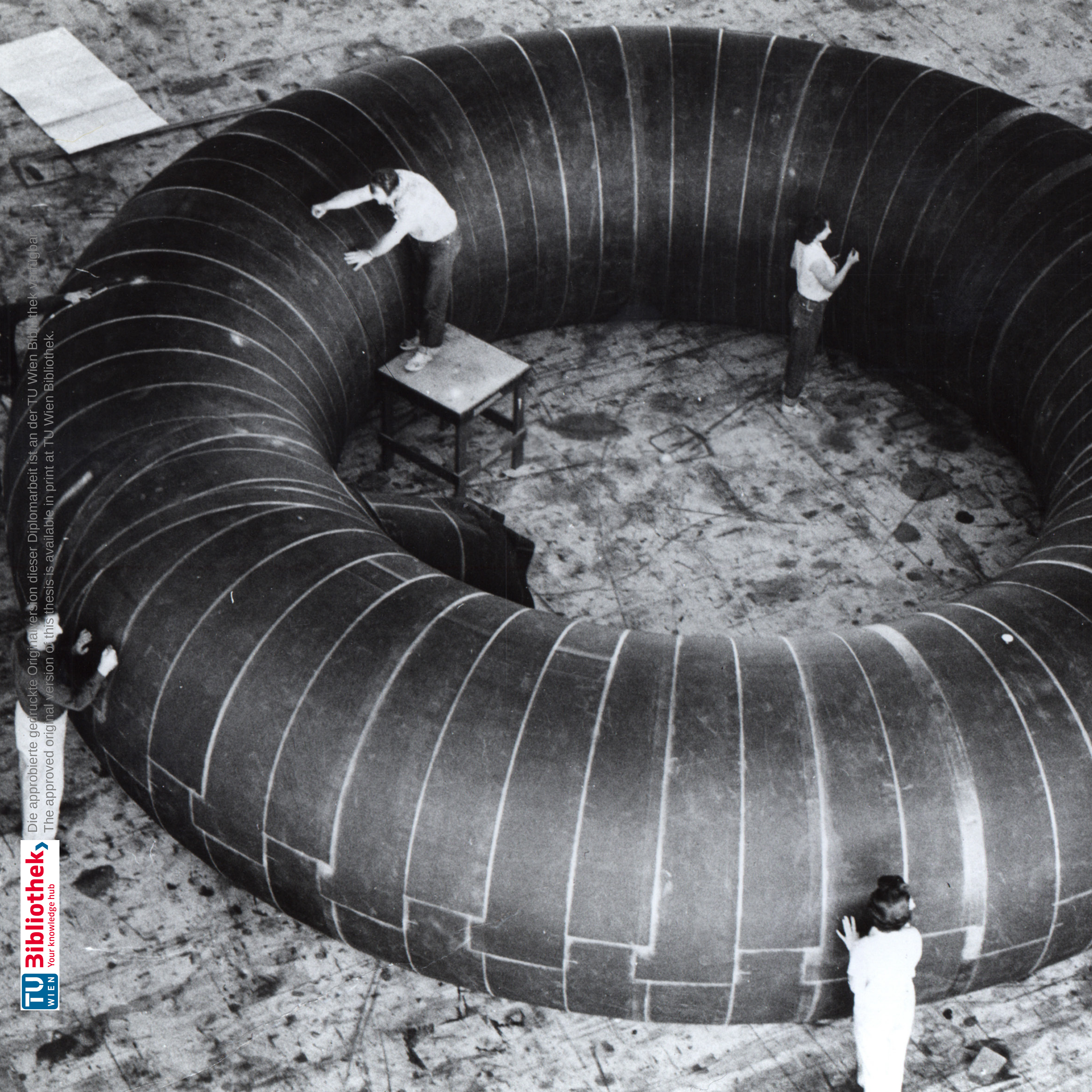
15 NASA, Advanced Docking/ Berthing System Seal Workshop, 2004
16 International Docking Standard, 2013



Common Berthing Mechanism
Active and Passive half of the CBM.
Credit: NASA

International Standard Payload Rack >
Exploded view of an ISPR with lockers.
Credit: NASA





03

Inflatables: More Space Less Mass

< **Erectable Manned Space Laboratory**
Goodyear testing the toroid inflatable prototype in 1961
Credit: NASA

Introduction

As specified in the previous chapter, two of the main limitations concerning building beyond Earth are weight and size. The goods have to be light enough to allow lifting them into orbit by current launchers whilst fitting into the payload fairing capsules atop of them.

Since the late 50s there is an ongoing pursuit to overcome these limitations by implementing so called inflatables: Modules, with a shell comprised of multi-layered high-tech textile- and stress-bladder-systems, that are not only lighter than the typical aluminum/titanium honeycomb shell variants, but also allow the creation of larger spaces whilst utilizing the same launchers. They are launched in a compressed vacuum-folded state and inflated upon arrival at the target destination.

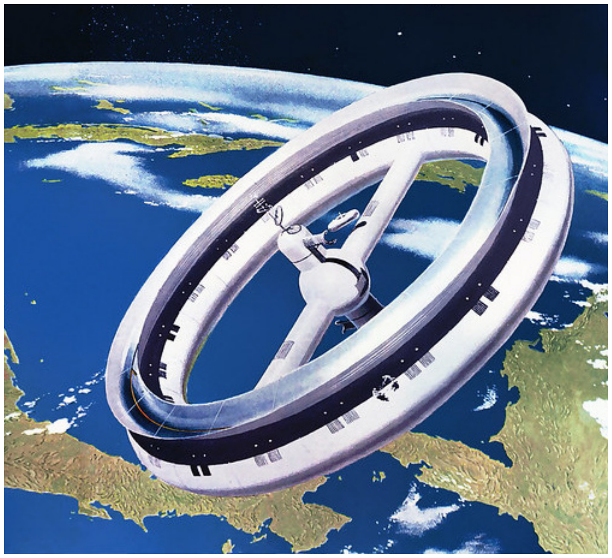
In this chapter a brief history of the development of inflatables is given. From the first practical attempts by the Johnson Space Center and Goodyear up to the Bigelow BEAM module, currently being tested on the ISS, with a preview of modules, planned in the future by the same company. The basic principles of pressurizing, folding and unfolding as well as the layer configuration and the integrated micro-debris protection are showcased by means of NASA's TransHab project. Further, the possible future integration of "smart layers" in the inflatable shell, viable basic geometrical shapes for inflatables, as well as the challenge of installing windows in inflatable modules are presented and explained.

Brief History of Inflatable Structures

Ideas for inflatable technology to be applied in space operations were already contemplated as early as 1945, when Wernher von Braun conducted a study for an American crewed space station. The basic toroidal design that spun around a central power module to create artificial gravity evolved over the following years and the 1952 version spanned 75 meters in diameter and housed a crew of 80. The design was further improved by forming the stations toroid out of smooth, donut-shaped inflatable sections made from reinforced rubber. Although von Braun's prediction that this station would become reality in a few decades did not come true, it lead to researchers at NACA (National Advisory Committee for Aeronautics) Langley to speculate about the technology, necessary to develop such an orbital outpost.[1]

At the same location, the Echo project, an experiment to test effects on large lightweight structures in orbit, was initiated in 1956. Once NASA was founded in 1958 and NACA dissolved, NASA took over the project that was currently in the stage of developing inflatable structures for space-satelloons (a nickname comprised of the words satellite and balloon). The Echo satellite was a 31m diameter aluminized-polyester balloon, that inflated after orbital insertion, made out of 12.7 micrometer thick material known as Mylar. Up to 18.000kg of air were needed during inflation tests on the ground to fill the 68kg

1 Seedhouse, Bigelow Aerospace - Colonizing Space One Module at a Time, 2015, p 18-19



The Von Braun Wheel
Space station design by Wernher von Braun
Credit: Chesley Bonestell

Echo Satellite
Inflation test 1961, Diameter 31m
Credit. NASA

balloon. However, once in orbit, only a few kilograms of gas sufficed. The launch of the Echo 1 failed in 1960. The Echo 1A was successfully deployed in the same year, and in 1964 the Echo 2 was launched achieving an improved balloon smoothness due to an upgraded inflation system. With their immense diameter and shiny surface, the Echo satellites have been described as perhaps the most beautiful objects launched into space. The challenge to pack such a large structure in the limited space of a Thor-delta fairing, later led to inspire the TransHab design.[2]

In 1960 Langley researchers began to examine the feasibility of various space station configurations. Following their experience with the Echo Satellites, they knew an inflatable structure could be safely protected in a fairing throughout the rough atmospheric transit. Combined with the fact that an inflatable would considerably lighten the payload, requiring less propellant, and that they wanted to push their home-developed technology, they soon agreed a self inflating deployable design was the way to go. Their first idea was the Erectable Torus Manned Space Laboratory, a space station consisting of a flat inflatable unitized torus about 7m in diameter. A major selling point of this design was that all its elements were part of a single structure, and could be launched into orbit on one booster. The Langley team built and tested many models, including a full-scale research model constructed by Goodyear. Unfortunately, results of studies conducted by

2 Seedhouse, 2015, p 19-22

Langley engineers showed that mass distribution within the torus would change when astronauts moved from one part of the station to another leading to a slight oscillation.[3]

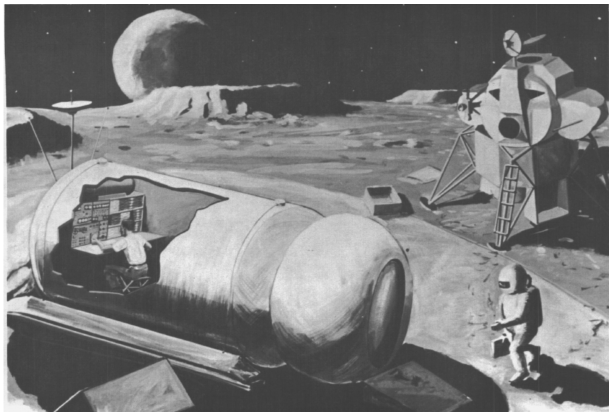
Besides, NASA wasn't really sure if it actually needed a space station, and realized if they wanted to pursue the inflatable design idea, they needed to develop a more rigid inflatable, the biggest problem being possible micrometeorite impacts. Especially big hits could prove disastrous for an inflatable module. In 1961 President Kennedy's lunar landing speech definitely pushed the focus away from a space station as a priority for NASA.[4]

Although technology based on hard aluminum shells became predominant during the next years, inflatable technologies were not forgotten. The Soviet Union also realized their advantages, and in 1965 Alexi Leonov was the first man to accomplish a space walk through a cylindrical inflatable airlock connected to a Voskhod-2 spacecraft.[5]

Goodyear also continued their research into possible inflatable applications, and developed a design for a cylindrical lunar shelter with an airlock that could support a crew of two for a period of up to 30 days. During its research Goodyear presented a flexible fabric made from Nomex unidirectional cloth coated with a Viton B050 elastomer for inflatable applications. The materials strength properties could be enhanced by laminating Nomex/

1965 Deployable Airlock
Prototype attached to the actual Voskhod-2 descent module featuring a Berkut space suit.
Credit: Anatoly Zak/ Russianspaceweb.com

3 Seedhouse, 2015, p 22-23
4 Ibid., p 24-25
5 Ibid., p 26



Stay Time Extension Module
Visualization of Goodyear's lunar inflatable module.
Credit: Goodyear/ NASA

Viton layers together. Combined with a flexible cable that ensured structural integrity during deployment and after inflation, made it an ideal candidate for inflatable habitat application.[6]

After Apollo, not a lot happened considering inflatable design. Not because the technology was doubted, but because there was no significant advocating for it. By the mid 1970s the concept came to a halt at NASA, and was only briefly revived after the Bush administration talked about returning to the Moon and Mars in the late 1980s, putting engineers yet again in front of the challenge to get a significant amount of volume into space in a limited rocket fairing. The result was the 1989 proposal for an inflatable habitat concept for a Lunar Base. At the same time a feasibility study of inflatable modules to be used in a future space station, possibly the space station Freedom (which would later be renamed to ISS) was conducted by the Lawrence Livermore National Laboratory, leading to the development of a prototype inflatable sphere in 1989.[7]

The most significant application of inflatable technology in the space sector over the past few decades was the use of air bags to soft-land payloads on surfaces of celestial bodies. The soviets pioneered this method for their unmanned Luna-9 lunar probe in 1966, and went on to reuse it in 1996 in the post-Soviet mars-96 mission. In the same year NASA delivered their Mars Pathfinder utilizing a

6 Seedhouse, 2015, p 26
7 Ibid., p 29

similar technology, and used it again in 2003 to place two Mars Exploration Rovers on the surface of the planet.[8] However, when considering pressurized, life-supporting habitats comprised of fabric layers, the space suit must not be forgotten. It is essential for EVAs, and can be regarded as the smallest habitation module.[9]

The idea of an inflatable habitat was most popularly revived in 1997 as an option for a crew and habitation module of the ISS, known as the TransHab. Thanks to the lead of William Schneider, who had previously worked on the micrometeorite protection of the Space Shuttle, the responsible team at Johnson Space Center (JSC) was able to solve the most pressing issue of inflatable design: A valid protection against micrometeorite impacts, utilizing a Nextel/foam combination.[10] Even though it would have saved NASA a significant amount of money (The Unity Node built by Boeing cost the company 300m, while the TransHab's price tag was at 200m during preliminary tests), generated more habitable space for astronauts, and pioneered new technology, the program was canceled by Congress in 2000, due to the revealed US $ 4.8 billion over-budget state of the ISS program.[11]

Besides the rise of the private sector company Bigelow Aerospace, focused on inflatable habitat design, that will be presented more comprehensively later on, the 2000s brought

Apollo 14 EVA Suit
Worn by Alan Shepard.
Credit: NASA/ Mark Avino

8 Seedhouse, 2015, p 32-33
9 Häuplik-Meusburger & Bannova, 2016, p202
10 Seedhouse, 2015, p 30
11 Ibid., p 31

Planetary Surface Habitat with Airlock
Mock-up Unit from 2007.
Credit NASA/ ILC Dover

with it further studies concerning inflatable structures. Under NASA's Advanced Exploration Systems (AES) program, in 2007 ILC Dover developed a planetary surface habitat prototype utilizing a hybrid deployable system, that combined rigid metal elements and flexible membranes, and consisted of a habitat and airlock unit. Later in 2010 the same company developed the X-HAB Lunar Habitat, including a prototype. A hybrid structure, cylindrical in form, with two rigid metal end-caps connected by a deployable flexible mid section made from Vectran. The habitat is usable in its packed form, and can be expanded to support more crew in its deployed state.[12]

With the plans to establish a permanent moon village after launching a new space station orbiting around the celestial body in the future, space agencies, companies, engineers and architects alike again face the same challenge as so many before them: Delivering a lot of space in a limited rocket fairing. Inflatable, deployable structures remain a very attractive solution for this problem. As a conclusion a quote from space architect Chris Kennedy, who was part of the TransHab development team, is presented:

Inflatable structures […] will change how we think about designing habitats and laboratories, hotels and resorts for space. They will also revolutionize the space architecture world by opening up the possibilities of shapes and sizes to create a human settlement of the solar system.[13]

12 Häuplik-Meusburger & Özdemir, 2012
13 Kennedy, 2002

Bigelow Aerospace

Even though the promising TransHab project was unfortunately canceled due to budgetary reasons, it inspired Robert T. Bigelow to found Bigelow Aerospace in 1999. A company in the private sector, shrouded in secrecy until it became known that its plan was to develop inflatable space habitats for commercial use in 2004.[14] The company was promised assistance by the JSC and it was hoped that it could launch inflatable habitats into orbit by the end of the decade. Unfortunately, following the Columbia Shuttle disaster in 2003 and the subsequent decommission of the Shuttle program, the Russian 3 seat Soyuz became the only spacecraft capable of delivering crew into space. Bigelow didn't want to compete with NASA, who had to secure places for future Astronauts of the ISS, for the limited Soyuz seats. Since it was a factor out their hands when the next crew-capable transport vehicle would be developed and approved, they had no way of guaranteeing their clients access to their planned inflatable modules. This delayed the development plans of the company.[15]

Nevertheless Bigelow launched Genesis I in 2006. The standalone inflatable watermelon shaped orbiting capsule, fully fitted with power, control, communication and flight system components, various measuring instruments and a window, successfully expanded after reaching its target orbit. Its technologies were redundant and as many as third

Genesis I
Picture taken from the deployed inflatable on orbit.
Credit: Bigelow Aerospace / NASA

14 Seedhouse, 2015, p 67
15 Ibid., p 67-68

Inflatable Modules
Bigelow inflatable module mock-ups in the company's Las Vegas Facility 2011.
Credit: NASA / Bill Ignalls

of the systems aboard the Genesis I were there to evaluate technologies for future inflatables.[16] 660 days after launch the spacecraft completed its 10.000 orbit and so traveled over 430 million kilometers. This amounts to more than 1.150 return trips to the moon. All systems operated nominally, with some far exceeding their predicted lifespan, and proved that inflatable habitat technology was viable for long term orbital habitats. In 2007 Genesis II was launched with upgraded technologies and altered experiments on board. Both spacecraft were predicted to have a 12 year orbital life, with a continuously decaying orbit leading to an eventual burn up in Earth's atmosphere.[17] As of November 2019, they both remain in Orbit.[18]

Bigelow planned to launch another module named Galaxy, further elaborating the Genesis vehicles, but in 2007 the company announced that they would not proceed with the plan, due to rising launch costs and the success of the Genesis missions. Instead, they would directly move on to their crew-rated vehicle, the Sundancer, as next craft to place into orbit.[19] With a 180 cubic meter volume, it was to accommodate a crew of 3, and to be equipped with a connecting node and a propulsion bus, laying the foundation for Bigelow's even larger BA-330 module. It was expected to be part of Bigelow's first commercial space station, estimated to be finished in 2014, and complemented by an

16 Seedhouse, 2015, p 74-75
17 Ibid., p 80
18 Heavens Above, Genesis I & II tracking, November 2019
19 Seedhouse, 2015, p 82

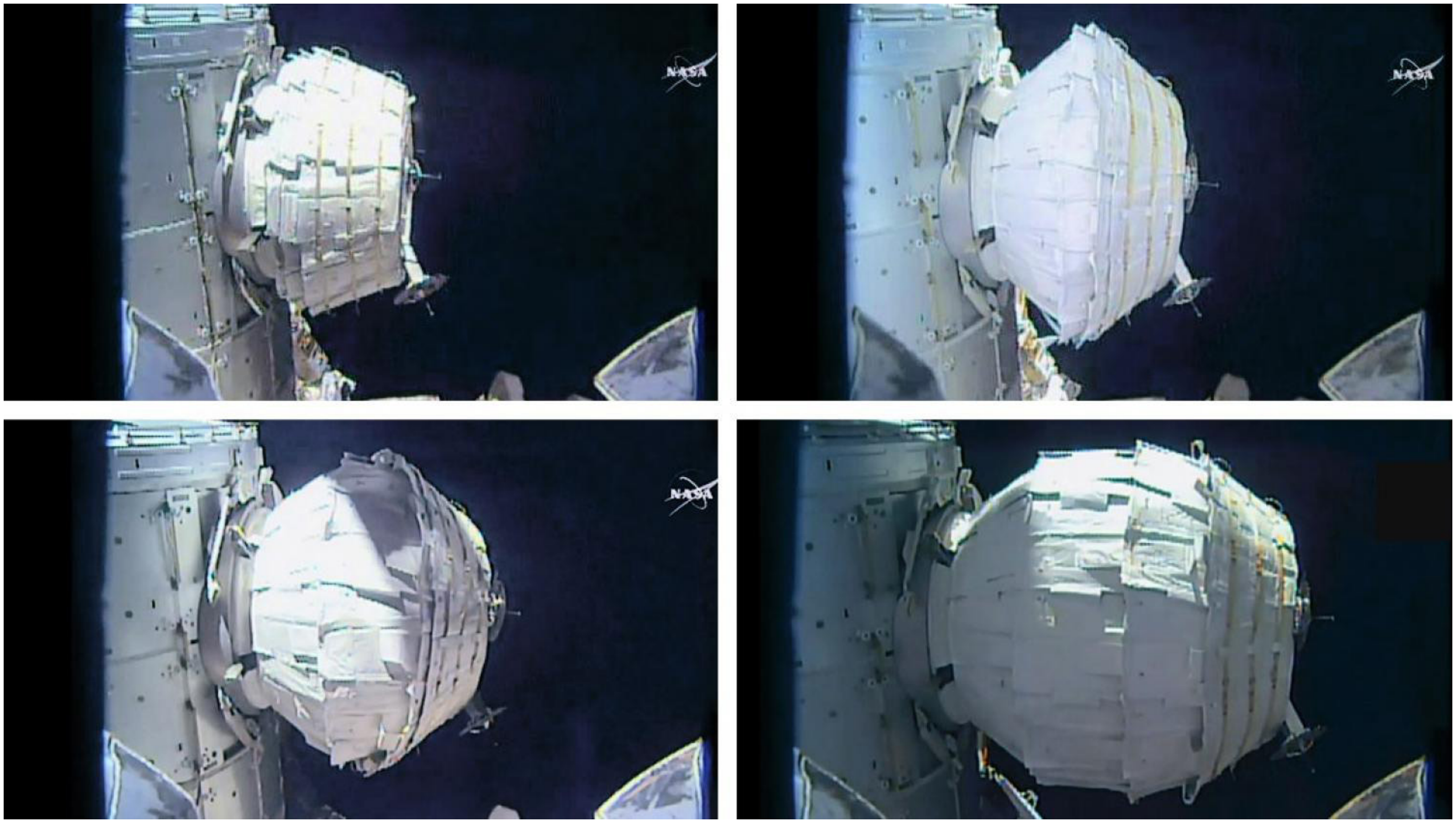
even larger station in 2016. The mock up of the station built on Bigelow's factory floor, which first consisted of two Sundancer and one BA-330 Module, and was later changed to two BA-330 Modules, went by the name Space Complex Alpha. In 2010 Bigelow formed agreements with six sovereign nations to utilize the commercial space and in anticipation expected to hire more than 1.000 employees for their production plant, that was to start production in 2012. However, due to further delays in the development of commercial vehicles to transport people into orbit, this expectations weren't met and Bigelow had to reduce their workforce from 115 to 51 in 2011. On a more positive note for the company, the same year, managers of the ISS Program held a meeting to discuss the prospect of adding a Bigelow Aerospace module to the ISS.[20]

The Bigelow Expandable Activity Module (BEAM) was the long awaited next testing step for the company, after the Genesis missions, on their way to eventually realize their flagship module, the BA-330. As a continuation of Bigelow's partnership with NASA, the module falls under the agency's Advanced Exploration Systems (AES) program. It was announced in January 2013, and set to arrive at the ISS in 2015.[21] The actual launch was moved to April of 2016, and the module successfully expanded and pressurized the following month on May 28th.[22]

The BEAM is a fairly small inflatable. It is 4 meters

BEAM Unfolding >
The Bigelow Extension Activity Module deploying after attachment to Node-3 of the ISS in 2016.
Credit: Bigelow Aerospace / NASA

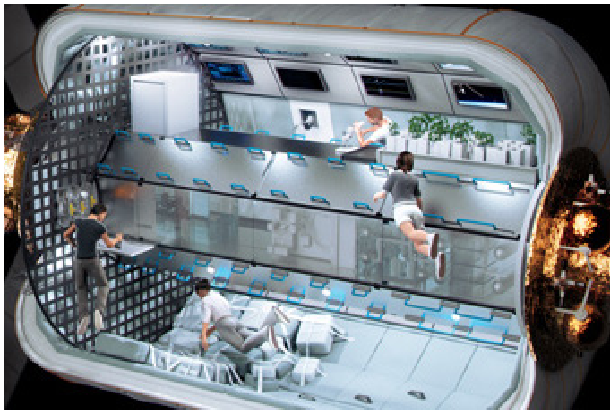
20 Seedhouse, 2015, p 82-85
21 Seedouse, 2015, p 87
22 NASA, A look inside the space station's experimental BEAM module, August 2017



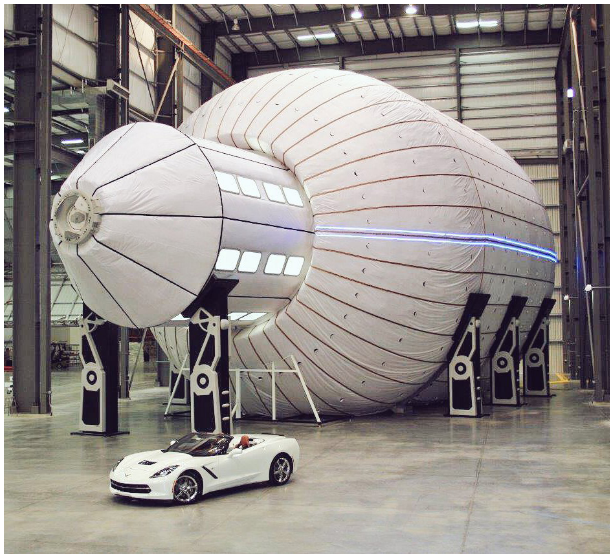
long, 3.2 meters in diameter and roughly cylindrical in shape. It only expands the pressurized volume of the ISS by 2%. The fabric wall consists of several sets of layers, Externally, a cavity air space is covered by connected sheets of aluminum foil, acting simultaneously as an insulator and a version of a Whipple Shield that disperses smaller debris upon impact (see page 74). It is followed by a thin metal sheet, separated and placed over a thicker sheet, to protect against larger micrometeorite impacts. To protect the module against external or internal penetration, the inner layers are comprised of several sheets of Vectran. Tests have shown that the walls of BEAM will be at least as resistant against micrometeorites and radiation, as hardshell aluminum modules. With the benefit, that high energy cosmic rays just pass through, unlike with metal which leads to them forming a secondary shower of high energy x-rays. One square meter of BEAM's wall only ways 25 kilograms compared to the 110 kilograms per square meter on standard module.[23]

Known in the beginning as the Nautilus, the later renamed BA-330 represents the leading product amid Bigelow's planned modules and the main component of the company's planned commercial space stations. Unfortunately, development of the spacecraft is being constantly hampered. The first estimated launch was set in 2008 on a proton-class booster.[24] With significant delay, in 2016 the company signed a contract with the United

23 Seedhouse, 2015, p 93
24 Ibid., 2015, p67



BA-330
Cutaway visualization of the BA-330 module.
Credit: Bigelow Aerospace



BA- 2100 / Olympus Module
Mock-up of the large inflatable module with a car for scale.
Credit: Bigelow Aerospace

Launch Alliance (ULA) to launch two BA-330 modules in Atlas V rockets by 2020.[25] The number in the spacecraft's name represents the 330 cubic meters of Volume the module offers in its fully expanded state. 6,7 meters in diameter and an initially conceived length of 9,5 meters, that got expanded to 16,7m during development, by elongating the modules structural core beyond the inflatable shell (that now houses an aft and forward propulsion and fuel system, aft and forward docking, a power generation and thermal radiation system, an airlock with an EVA port, and an emergency safe haven[26]), it has an expected mass of 20 metric tones, a radiation protection equivalent or better than the ISS and a ballistic protection superior to that of the aluminum shell module design.[27]

After the establishment of the BA-330, the company has the next step already planned: The Olympus or BA-2100 module. Again, the number stands for 2100 cubic meters of usable Volume after deployment. Over six times as large as its predecessor, and an estimated mass of 70 metric tones, it could be launched into LEO utilizing NASAs controversial Space Launch System (SLS). The controversy can be roughly summarized as a result of immense development cost delivering little innovation, besides a heavy payload lift capability, only slightly exceeding that of a Saturn V rocket, already used in the late 60s for the Apollo missions.[28]

25 Space.com, Private Space Habitat to Launch in 2020, April 2016
26 Bigelow, BA-330 description, 2018
27 Seedhouse, 2015, p 125
28 Ibid., p 124-126

Inflatable Layer Structure

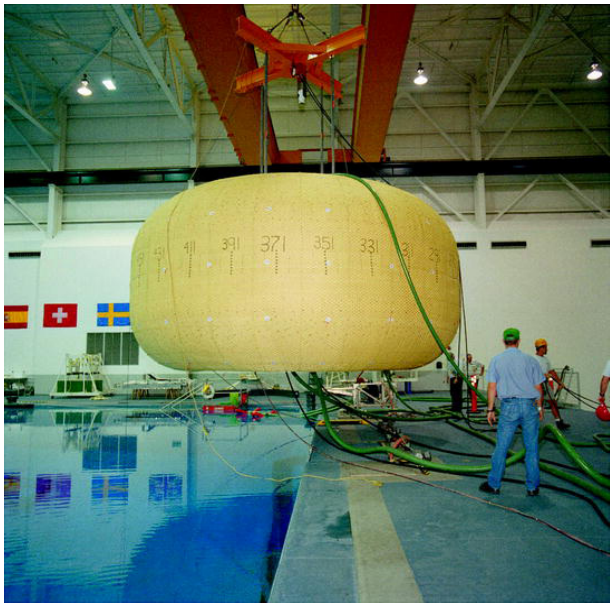
Inflatable structures are comprised from different layers of fabrics, that can also include rigid elements stacked together, to create the outer shell and pressure hull of a habitat. In a large scale habitat the number can exceed 60 Layers and have a total thickness of up to 20 inches (50,8cm). Referring to Valle et al.,[29] The main components of the layer assembly are broken down into 5 sub-assemblies and described below, from the pressurized side to the exterior:

1. **Inner Liner Layer:** Acts as a scuff layer and barrier for the crew, it is flame and puncture resistant, easy to clean, durable and provides acoustic dampening.

2. **Bladder Layer:** This is considered the most critical layer and acts as gas/air barrier. It is designed to be oversized when compared to the restraint layer, so that it does not bear any pressure force, and effectively passes the load on to the restraint layer. Bladder materials are typically polymeric and require permeability, temperature flexure and manufacturability testing. The TransHab was designed with multiple redundant bladders with felt cloth separations between the individual bladders.

3. **Restraint Layer:** This is the structural layer of the inflatable, it carries the high membrane loads caused by the internal pressure of the module and must be stiff, strong, yet also flexible and foldable. There are a number of different options from single bladder design

29 Valle et al., March 2019

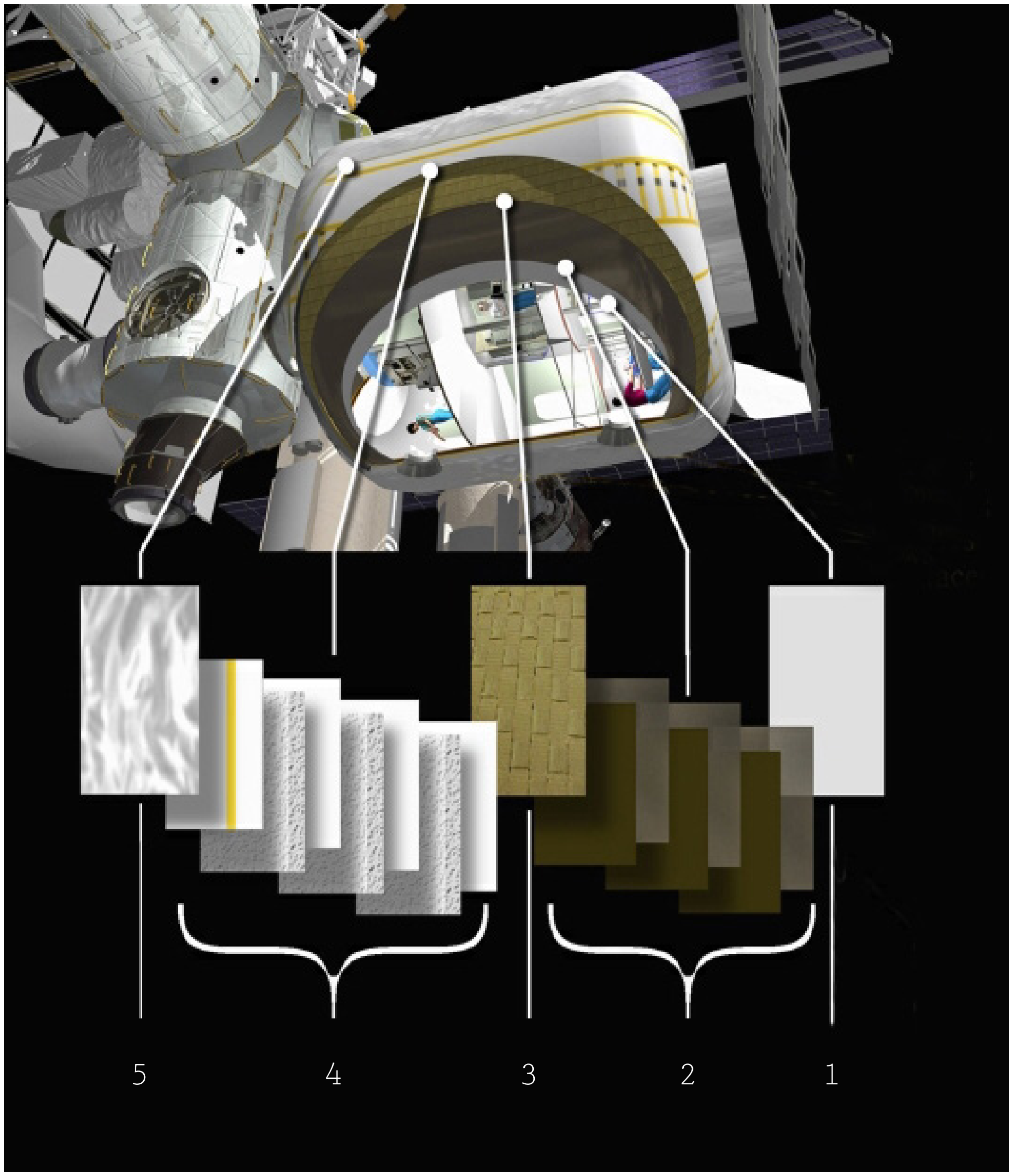


Restraint Layer Test
TransHab restraint layer hydrostatic test of a full scale diameter prototype.
Credit: NASA

over broadcloth design up to a tight-webbing variant, as used in the TransHab, depending on the pressure it has to contain. In order to fulfill NASA-STD-5001 design standards, structures must be tested by a factor of 4. If an inflatable is to operate at 1 Atmosphere (~14.7 psig) it has to be able to contain over 58.8 psig.

Special attention is to be given to indexing between the bladder layer and the restraint layer: They must be connected with seams that don't damage either structure to ensure a folding and unfolding that guarantees a functional lineup once fully deployed, so that the bladder layer can efficiently transfer all the pressure forces to the restraint layer. Since most large scale habitat designs, like the BA-330 or the TransHab, include rigid bulkheads at either end of the inflatable module, the connection between the rigid structure and the softgood shell is also a vital component in inflatable design.

4. **MMOD Protection Layer:** Micrometeoroids and orbital debris (MMOD) present a high risk for spacecraft, especially in LEO, due to the high debris density. To protect against impact a special kind of multi-layer assembly, usually comprised of interchanging ceramic fabric bumper layers and low density foam layers, is required. In launch configuration, the foam layers are vacuum packed resulting in a very thin stack-up of the MMOD layer. Once deployed, the foam layers expand, creating thick spacing between the ceramic layers and so utilizing the principles of a


5
4
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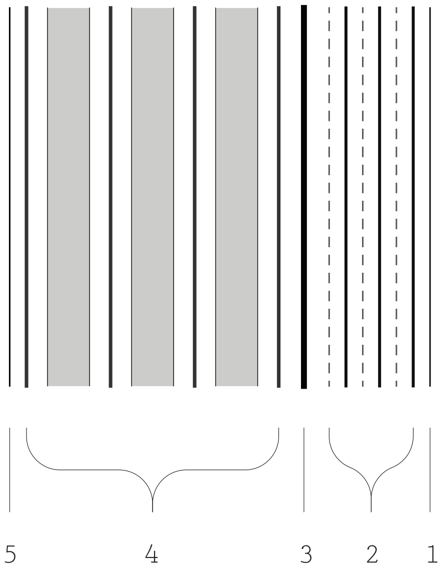


1. Inner Liner Layer
2. Bladder Layer
3. Restraint layer
4. MMOD Protection
5. Thermal Insulation Layer

Layers of an Inflatable Shell
Diagrammatic section detail.
Credit: Author, based on TransHab design

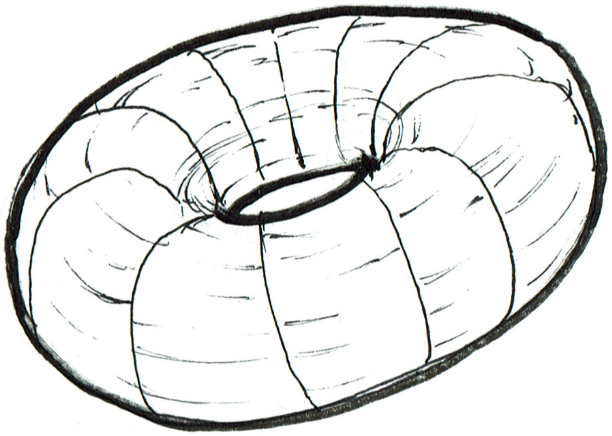
< TransHab Layers Cutaway View
Credit: NASA

Whipple Shield: Each non foam layer disperses the incoming projectile into smaller fragments, so that once it reaches the restraint layer, only dust or molten droplets remain.

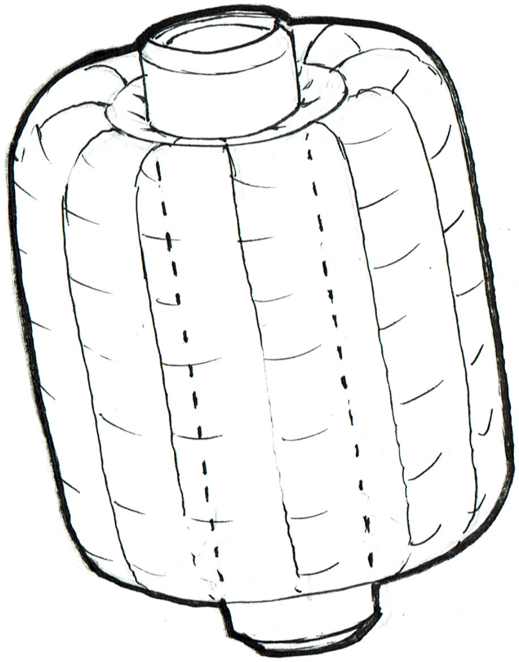
5. **Thermal Insulation Layer:** The outermost major layer is the passive thermal protection system. It utilizes NASA's multilayer insulation (MLI), applied in EVA space suits, and is composed of very thin sheets of reinforced double aluminized material, sandwiched on both sides by a double aluminized polyamide film. The MLI stack-up is very thin and flexible. Atop of this layer a deployment system layer is mounted, incorporating deployment chords and straps that hold the softshell taut in its packed state and are released before the modules inflation with air. This layer is intended to execute a controlled and predictable deployment of the structure. Finally, to protect against atomic oxygen, which is especially prevalent in LEO, very reactive and can damage exposed spacecraft materials, a layer of Betaglass fabric is applied.

In 2005 the InFlex program was initiated. Residing under NASA's Exploration Systems Architecture Study (ESAS), it intends to research and develop multi-functional intelligent flexible (InFlex) materials for deployable space structures. The main objectives feature the development of materials and layers with a health monitoring system or power generation and storage capabilities, like flexible photovoltaic elements and batteries. Further focus lies on development of self-healing, low permeation, anti-microbial and anti-radiation materials.[30]

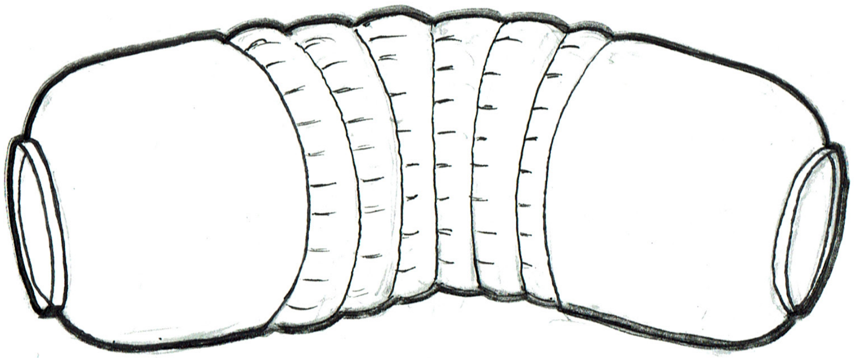
30 Cadogan & Scheir, 2006



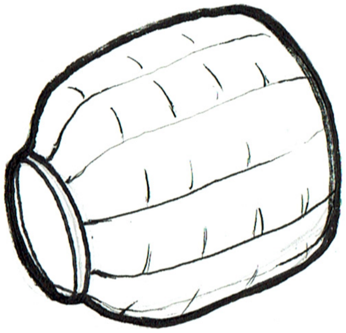
Torus



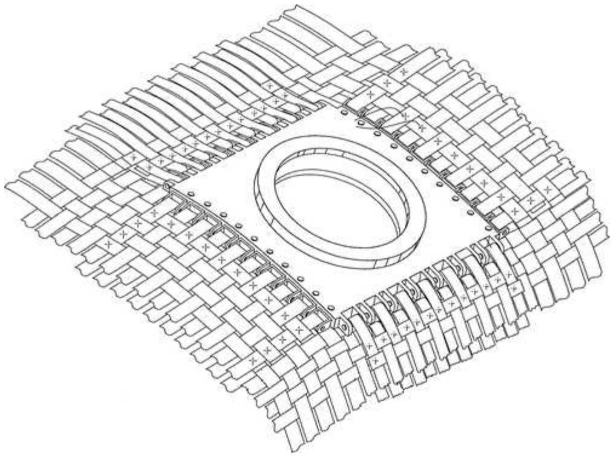
Rounded Cylinder with Rigid Core



Hardshell Module with Inflatable / Deployable Section



Sphere



Window in Inflatable
Perspective of rigid panel as viewed from the outside of the module. Restraint Layer latches attach to rigid plate containing window frame. US Patent 7509774 B1
Credit: NASA / USA

< Shapes of Inflateble Modules
Credit: Author

Geometric Shapes & Windows

Not only a regard towards layer and material composition is important when designing an inflatable module. Its geometrical shape and configuration are also important. Due to the high pressure forces it must contain, cylinder, capsule, torus and sphere geometries are possible. While combination of hardshell modules with expandable inflatable elements offer some advantages they present some concern regarding their pressure seal safety.[31]

In order to generate an opening in a softshell inflatable wall, the engineers of the TransHab first confronted with this task, had to come up with some ingenious out of the box thinking. Cutting a hole into to the individual layers wouldn't suffice, due to the dramatic reduction in tensional loading of the layers and the circumferential integrity of the structure. Additionally, with the major crux being that the opening had to be made through the bladder and the load bearing restraint layer, the design had to prevent gas from escaping the inflated module, and be foldable to ensure packing and deployment of the structure. The solution, concieved by the engineering team, was a rectangular rigid frame with attachment points on either side through which the flexible load bearing straps of the restrain liner could be looped through, guaranteeing an even distribution of the loads. The frame supported a round opening in which the actual window-frame would be inserted, affixing the inner, outer and bladder layers.[32]

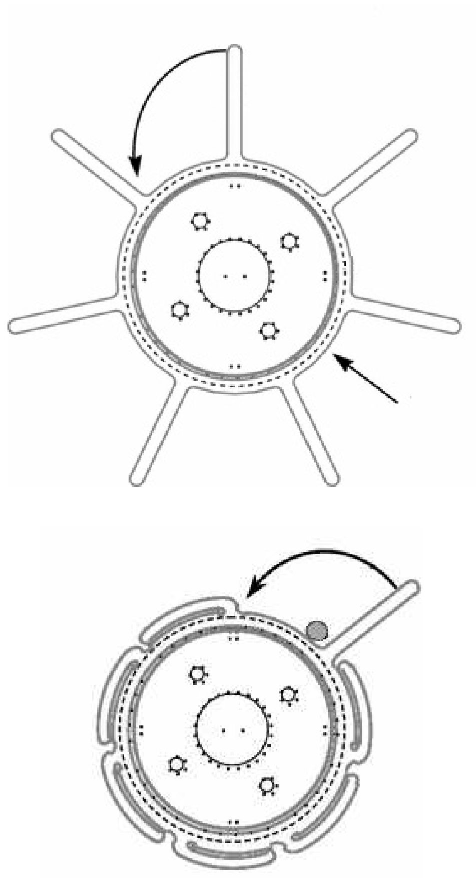
31 Häuplik-Meusburger & Bannova, 2016, p 180
32 Seedhouse, 2015, p 50-51

Transhab Architecture

Broken down to the basic components, the TransHab design consists of a structural core with an inflatable shell attached to it. The shell was to be vacuum comprised and folded around the structural core and deployed by inflation, once delivered to its destination. A successful folding and deployment of a full scale test model was demonstrated in NASA's JSC Chamber A vacuum environment in 1998.[33]

The design of the structural core includes at least one longeron, one body ring and two endplates with two end rings to secure the inflatable shell. It further includes a cylindrical water tank with an internal accessible cavity for radiation protection, an airlock and several support system structures.[34] The inflatable shell consists of a multi-layered elaborate fabric conglomerate described in detail on page 60.

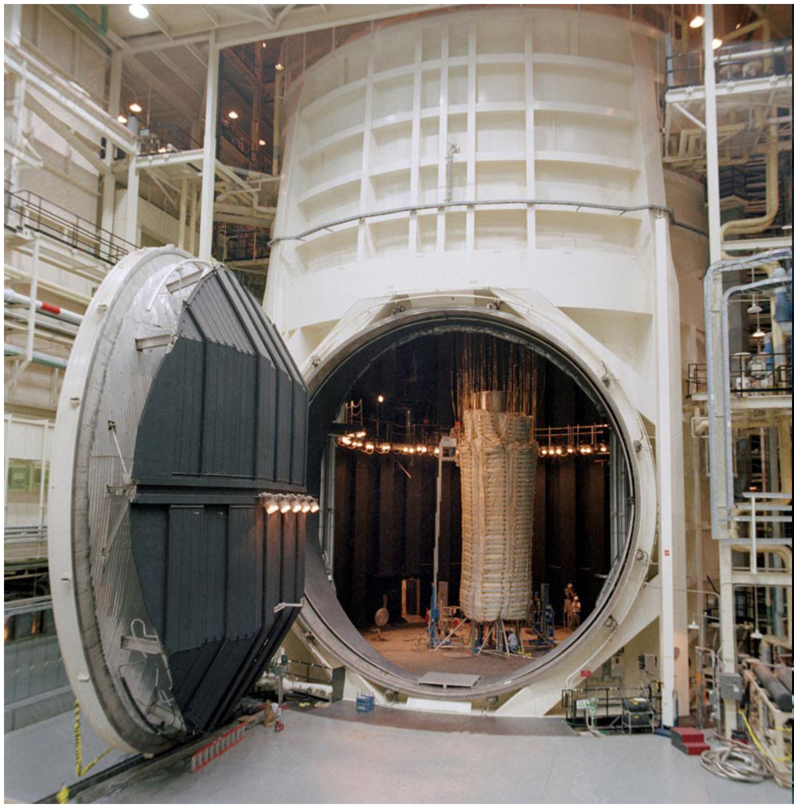
After shell inflation, the crew would have needed to perform finishing outfitting steps, to make the module fully operational. Parts of the longerons could be deployed to form floor struts, and the shelf elements, contained inside the core structure, could be positioned depending on the required layout of the module.[35]

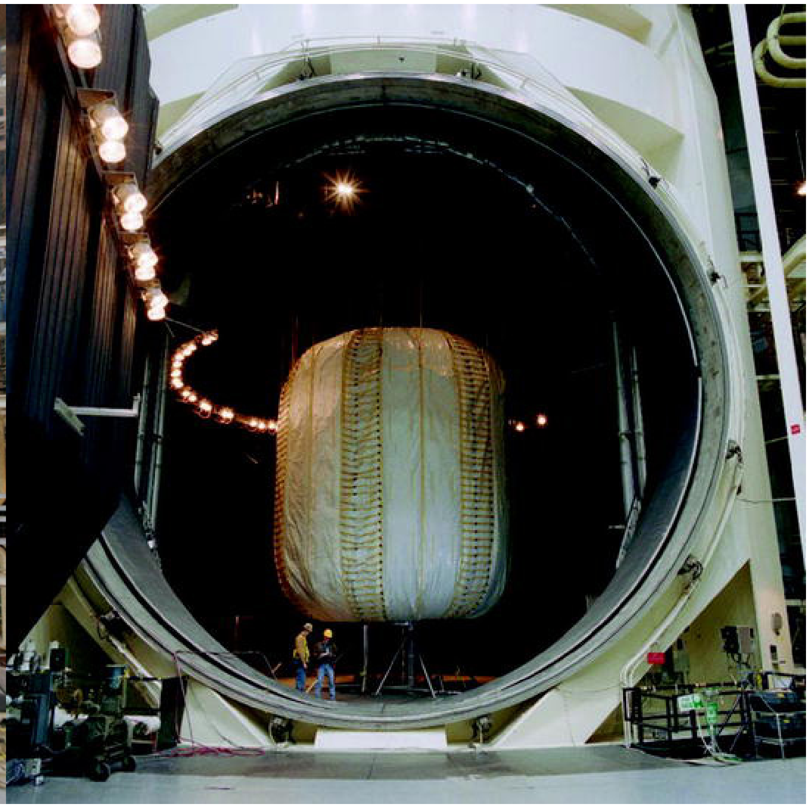


TransHab Folding Concept
Every third gore pushed in. Remaining gores folded over.
Credit: NASA

TransHab Unfolding Test >
Packed and deployed state of a full scale shell prototype in vacuum test chamber.
Credit: NASA

33 Häuplik-Meusburger & Bannova, 2016, p 287
34 Seedhouse, 2015, p 44-46
35 Häuplik-Meusburger & Bannova, 2016, p238-239





The module was designed with a local vertical orientation and segmented into 4 levels:

Level 1 contained the wardroom table, galley plus equipment and a soft stowage system.

Level 2 included the water tank protected crew quarters and technical facilities. Part of the floor was left open to enlarge the wardroom area below.

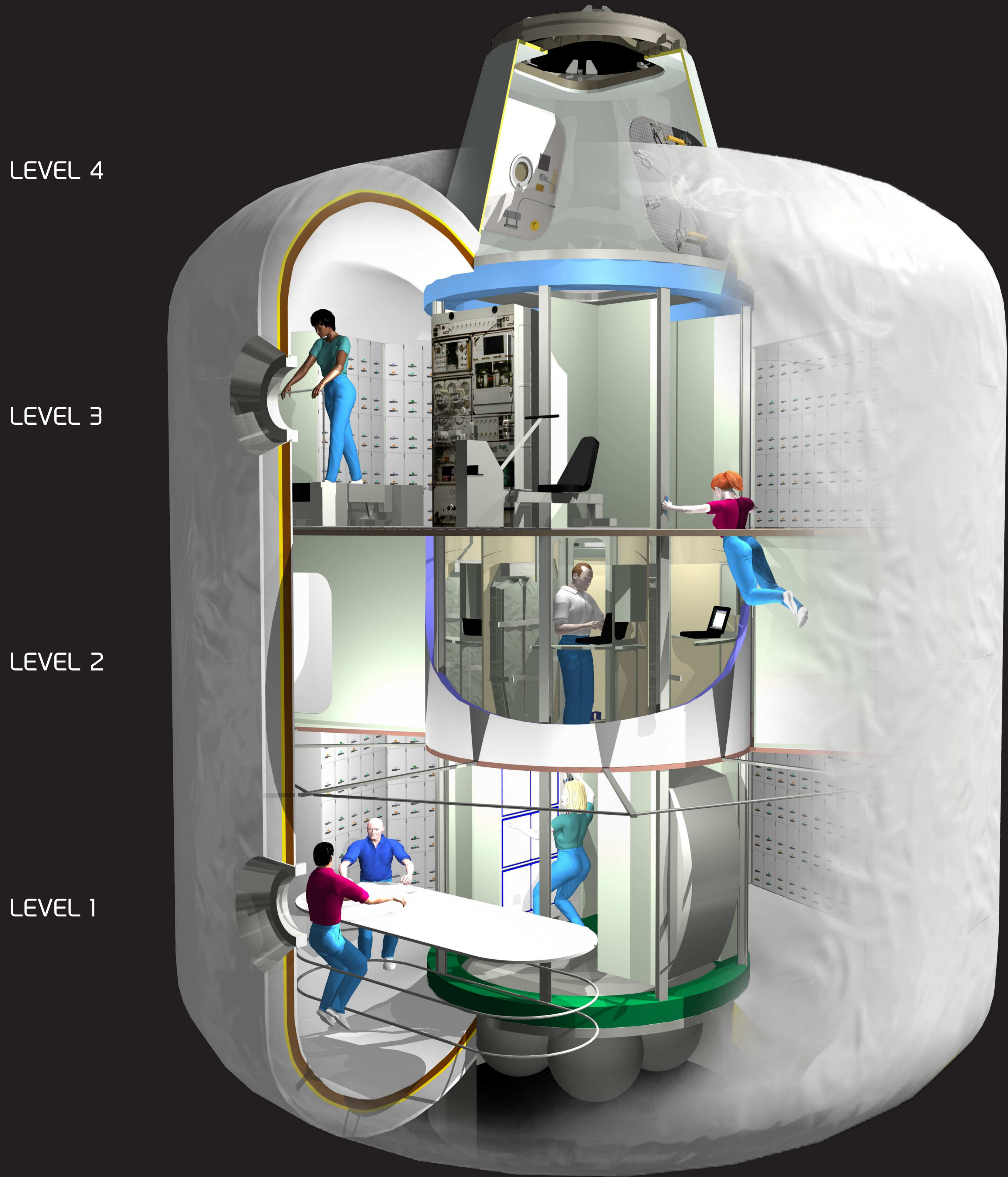
Level 3 contained Hygiene and exercise facilities as well as another soft stowage system.

Level 4 was the Airlock.

Levels 1 and 3 had a hight of 2.7 meters and level 2 a height of 2 meters.[36]

36 Seedhouse, 2015, p 55-59

TransHab >
Cutaway visualization of the modules interior.
Credit: NASA


LEVEL 4
LEVEL 3
LEVEL 2
LEVEL 1


EXIT

04 Space Architecture II: Hazards, Habitability & Microgravity

< **Sleeping in Microgravity**
Astronauts Thomas D. Jones and Mark L. Polansky during their sleep shift in the Destiny laboratory on the ISS in 2001.
Credit: NASA

Introduction

As architects on Earth, we rarely have to deal with extremely hazardous life conditions. Our biosphere protects us from the dangers of space and provides us with a breathable air, water and nourishment. Earth also has an inherent gravitational pull, and our main design principles are based around it. Be it the calculations for the structural integrity of a building, the necessity for stairs with standardized step ratios, the situating of appliances on the floor and on the walls up to a limited height, or the integration of possibilities to sit or lie down for tired out users. These principles have to be reconsidered when approaching space architecture.

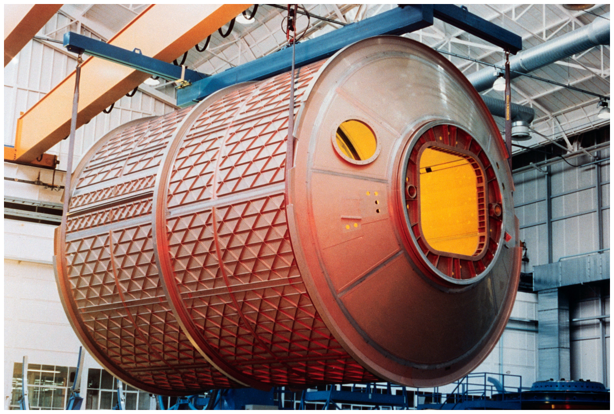
This chapter presents the main hazards of space, one should be aware of when designing beyond our planet. Further, the topic of habitability and potential stressors for a crew within an enclosed space station, limited in volume, are discussed and potential countermeasures presented. Finally, different types of gravity are introduced with a focus on the microgravity environment, which can be described as weightlessness, experienced by the crew of orbital space stations. Elaborations are given concerning its effects on the human body, and on the design possibilities and requirements of such an environment.

Hazards of Space

The implied job of a space architect is to create an environment that is safe and comfortable for people to live and work within.[1] To accomplish this task, the first priority is to provide and maintain suitable environmental conditions that can sustain human life, and offer protection from the hazards present beyond Earth's atmosphere and magnetic field. The most important components to achieve these conditions are presented below:

Pressurized Vessels: The lack of an atmosphere on the surface of the Moon, the hazardous atmospheric conditions on Mars and other planetary bodies and the vacuum conditions of outer space make human survival impossible. It is necessary to provide a breathable atmosphere within the habitat. This is achieved by pressurizing and saturating the habitable volume with an atmospheric composition that reflects sea-level conditions on Earth (Nitrogen 78%, Oxygen 21%, Argon 0.9%, Carbon dioxide 0.03%) at 1 Atmosphere Pressure (~14.7 psig) This is NASA's standard for long term habitation, but composition and atmospheric pressure may vary if so required by specific equipment or operational tasks (EVAs, greenhouse, labs). Such conditions that offer a comfortable and Earth-like atmosphere, and mainly do not require a donned pressure suit, are also referred to as shirt-sleeve-environment.[2]

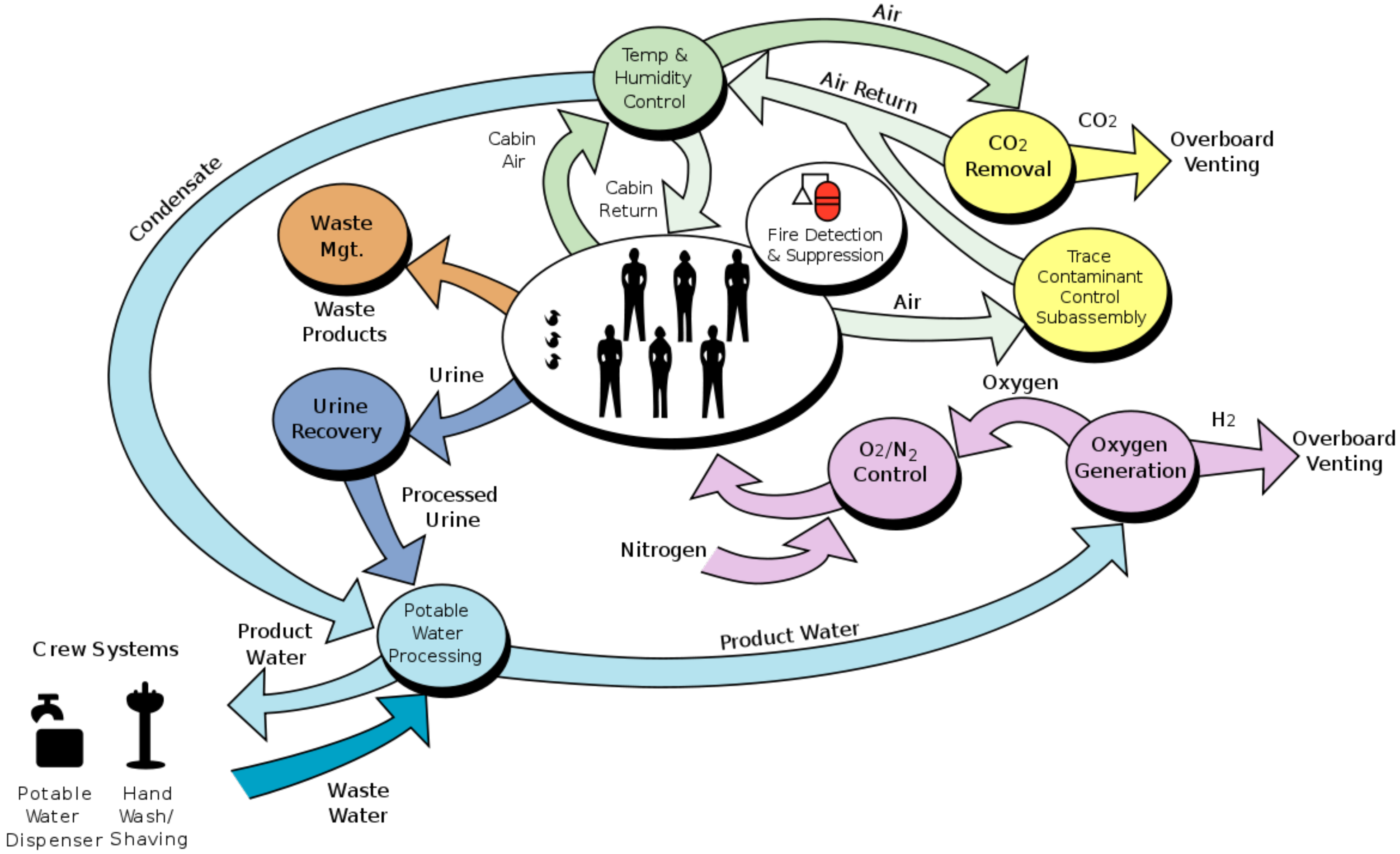
Life Support System: On the ISS the Environmental Control and Life Support System (ECLSS) provides the habitable



Hardshell Module
ISS pressurized module during assembly.
Credit: NASA

ISS ECLSS Cycle >
Environmental Control and Life-Support System diagram.
Credit: NASA

1 Häuplik-Meusburger & Bannova, 2016, p 105
2 Ibid., p 106

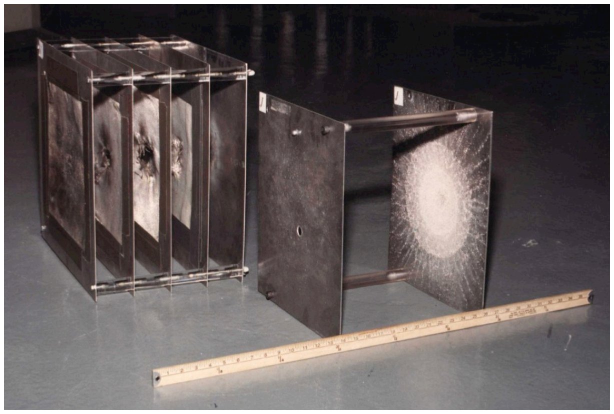

Air
Temp & Humidity Control
Air Return
CO2
CO2 Removal
Overboard Venting
Condensate
Cabin Air
Cabin Return
Fire Detection & Suppression
Waste Mgt.
Waste Products
Air
Trace Contaminant Control Subassembly
Urine
Urine Recovery
Oxygen
H2
Oxygen Generation
Overboard Venting
O2/N2 Control
Processed Urine
Nitrogen
Potable Water Processing
Product Water
Product Water
Crew Systems
Potable Water Dispenser
Hand Wash/ Shaving
Waste Water

environment. It consists of the following components located in the US Destiny module and the Russian Zvezda service module: An air vitalization system, an oxygen generating system, water coolant loop systems, an atmospheric revitalizing pressure control system, an active thermal control system, a supply water and waste water system, a waste collection system, temperature and humidity control and a fire detection and suppression system. The water recovery system, designed to recycle crew member urine and wastewater for reuse as clean water, reduces the net mass of water and consumables required to sustain a crew of six by 6800 kg per year. The oxygen generation system converts wastewater, urine and condensation into hydrogen and oxygen by electrolysis. The oxygen is released to the stations interior and the hydrogen is utilized in the Sabatier reactor to create water.[3]

Micrometeoroids and Orbital Debris (MMOD) Protection: Micrometeoroids are very small meteoroids that can reach high velocities and affect orbital habitats as well as habitats on the surface of celestial bodies, that have no or insufficient atmosphere to neutralize these high speed projectiles. Orbital debris is mainly a threat to spacecraft and habitats in the LEO regime. The main way to protect against MMOD, whilst avoiding thick and heavy walls, is a special type of shield conceived by Fred Whipple. The so called Whipple Shield: In its basic

3 Häuplik-Meusburger & Bannova, 2016, p 212-214

ECLSS Racks
Components of the Environmental Control and Life-Support System used on the ISS, fitted into International Standard Payload Racks. From left to right: Shower rack (not installed on ISS), waste management / WC rack, water recovery system racks 1 & 2, oxygen generation system rack.
Credit: NASA



Whipple Shield Demonstration
Simple and stuffed version of the Whipple Shield concept after demonstration.
Credit: NASA

form, it consists of one thin outer layer sheet, a cavity and a thicker inner layer sheet, both usually made of aluminum alloy. The idea is to break up, melt or vaporize the impacting projectile after the perforation of the outer sacrifice layer, and so disperse its mass and reduce its momentum, whilst it traverses the cavity between the two layers, making it unable to penetrate the inner layer.[4] There are further developed versions installed on satellites, probes or on the ISS, like multilayer shock shields or stuffed Whipple shields, which are filled with a high strength-material like Kevlar or Nextel aluminum oxide fiber.[5] Additionally, an orbital spacecraft can be warned, by a surveillance agency like the SSN, in case of a predicted impact and perform an avoidance maneuver. This is however only possible if both constituents of the potential collision are being tracked.

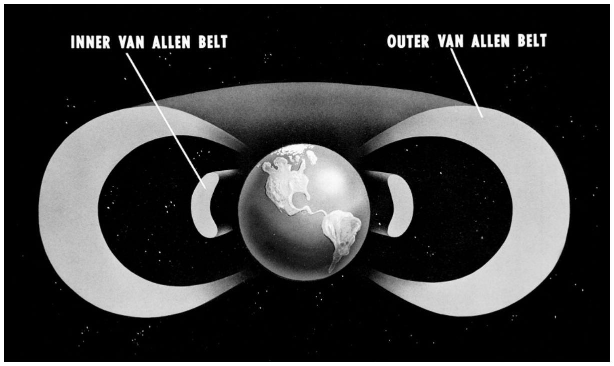
Radiation Protection: Earth is protected by its atmosphere and magnetic field from harmful ionizing and non-ionizing radiation deriving out of Galactic Cosmic Rays and Solar Particle Events.[6] The magnetosphere deflects or captures incoming radiation particles in two toroid shaped regions surrounding our planet named the Van Allen Belts. The outer belt can swell and varies strongly in size. The inner belt was believed to be relatively stable, but

4 Seedhouse, 2015, p95
5 Häuplik-Meusburger & Bannova, 2016, p 190
6 Ibid., p 108

after the launch of the Van Allen Probes in 2012, it was discovered that it can also expand during Solar Particle Events and even enclose the orbit of the ISS (approx. 400km altitude). Unless such an Event occurs, the Van Allen belts provide protection from harmful particles to the ISS.[7] However, habitats need to have radiation shielding properties, rigorous ones when the craft is destined to traverse the Van Allen belts and face open space. Possible protections achievable with current technologies are deployable or permanent water shelters, polyethylene or the ISRU of Regolith. Emerging technologies include ION shielding, Nanotubes or magnetic field shielding utilizing superconductive magnets.[8]

Astronauts also require consumables, at best high-nutritional, well-balanced and tasty food to maintain health and activity. It must be easy to prepare but still appealing. Further, large amounts of it have to be stored whilst maintaining quality.[9] The crew follows the same hygiene routines in space, as humans do on Earth. However, especially in microgravity the related hygiene procedures are different and require special devices and techniques.[10] Once these basic measures towards human survivability are ensured, the design process can focus on further habitability issues.

7 Space.com, Van Allen Belts - Facts and Findings, 2018
8 Häuplik-Meusburger & Bannova, 2016, p 190
9 Meusburger, 2011, p 218
10 Häuplik-Meusburger & Bannova, 2016, p 107



Van Allen Belts
This early schematic of the Van Allen Belts' structure was created after the first American satellite discovered their existence in 1958
Credit: NASA / Goddard Space Flight Center

Stressors

In order to provide an environment that supports human well-being, safety and productivity, it is viable to identify potential stressors to these qualities and to be familiar with architectural countermeasures that can be applied. Among the common stressors are *problems associated with interior space, food, hygiene, temperature, décor, lighting, odor and noise.*[11] A selection of these will be presented in more detail below.

Isolation and Privacy: It is indicated in literature and interviews with astronauts that the crew's requirement for privacy levels increases with mission length. This is also shown in research from analogue environments, where the need for private space increases under prolonged isolation and confinement.[12] A main architectural challenge is to provide adequate and adjustable design for different levels of privacy within a habitat. Privacy conditions affect the crew and each individual member differently, depending on their social and cultural background.[13] Besides, isolation and confinement has severe psychological and social effects on the crew.[14] Limited interior space, can lead to a lack of privacy ,and feelings of claustrophobia. Countermeasures can be the design of an adequate interior layout, providing sufficient

11 Connors et al., p 60
12 Stuster, Kanas & Manzey, Connors et al., as presented in Häuplik-Meusburger & Bannova, 2016, p 121
13 Ibid.
14 Connors et al. as presented ibid., p 110,

Wardroom Table Skylab
Credit: NASA

< Dining on the ISS
Crews from three countries sharing a meal in the Zvezda module of the International Space Station, 2001
Credit: NASA

windows, and virtual reality.[15] In fact, when asked what he would add or change about the ISS' architecture, Alexander Gerst, astronaut and ISS commander, replied after a moment of reflection: "More windows!"[16]

Social Interaction and Leisure: Apart from the necessity to provide privacy, it is also vital to design and offer spaces and architectural solutions for social interaction and leisure activities to maintain a crew's psychological health. Such an activity can be sharing a dinner together, which should be done at least once a day, in order to help dissipate any potential tendencies towards divisiveness.[17] On Skylab missions, the crew had a large area available for food preparation and dining for the first time, and was eating together on a specially designed table. Astronauts generally dislike talking to a colleague who is upside down while dining, and here they also refused to float over the table, as it was seen as bad manners.[18] In another case, cosmonauts were tasked with tending plants during their stay on Salyut. Even though it was challenging to complete the plant development cycle, they found great joy in the work.[19] This activity, besides offering a recreational quality, can be coupled with scientific experiments and provides fresh produce if successful, which in return

15 Häuplik-Meusburger & Bannova, 2016, p 120-121
16 The author briefly met Alexander Gerst after participating in a workshop at ESA's ESTEC campus in Holland.
17 Bluth as cited in Connors et al., p 64
18 Häuplik-Meusburger & Bannova, 2016, p 131
19 Leonov & Lebedev as cited in Connors et al., p 78

encourages positive mood in the crew.

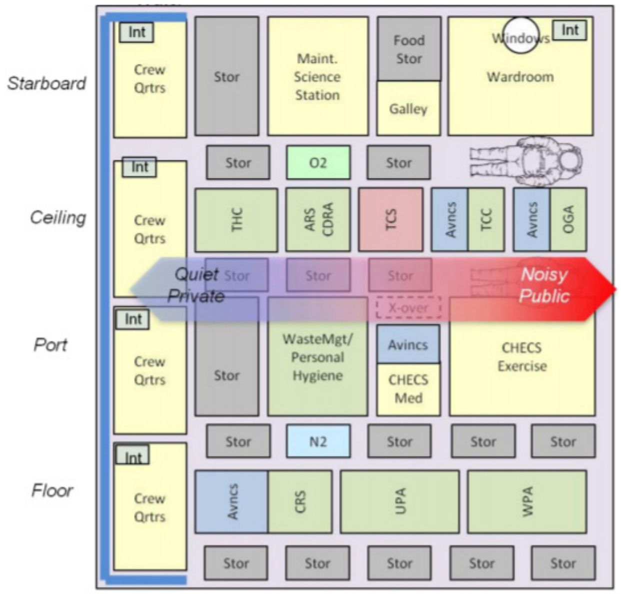
Odor: In order to make it comfortable and safe, the design of a habitat needs to offer means to remove unpleasant and harmful odors from the internal atmosphere as soon as possible. Additionally, to allow for activities and experiments that can potentially lead to the release of non desirable gases, space has to be provided, where such an event does not affect the rest of the habitat.[20]

Lighting & Colors: Besides acting as viable cues for orientation (especially in a microgravity environment, which will be discussed in the next sub-chapter) lighting and colors are important contributors to other aspects of habitability. Since natural light is not always available – e.g. the ISS orbits Earth every 90 minutes, causing frequent changes from light to dark levels - artificial light is required for living and working. Lighting design does not only fulfill a functional purpose, but is also relevant for visual comfort and aesthetics.

Colors can be used in various ways: For spatial orientation, as used on the Mir space station, or ISS; For color-coding of objects, like it is done with food containers; To increase instrument visibility through contrasting; For safety reasons or for differentiation; Or to increase comfort or spaciousness by using specific colors. One of the design requirements, defined by NASA, is one of consistency: Same colors shall be used for the same applications throughout the space module.[21]

20 Häuplik-Meusburger & Bannova, 2016, p 118
21 Ibid., p 119

Interior of a Mir Module
Interior color scheme (floor-walls-ceiling) of one of the stations modules, displayed on a mock-up from the "Russia in Space" exhibition, 2002 at the Airport Frankfurt.
Credit: CC / User: Bricktop



Zoning Diagram of ISS Habitation Module
Detailed zoning diagram of all four sides of the ISS habitation module.
Credit: Brand N. Griffin

Zoning & Functional Adjacency:

Zoning is a design guiding principle. It describes the grouping of elements that share common resources or attributes. Commonly, this includes defining and separating noisy and quiet areas, placing crew access functions like a galley/wardroom or personal hygiene in comfortably reachable places and prioritizing them in relation to subsystems which don't have to be accessed as often. Functional adjacency is another helpful design tool which offers a guiding point on proximity or separation of various functions to each other e.g. galley should be close to the dining area, private quarters separated from waste management or noisy functions.[22] Through implementations of these principles and by running through many iterations during the design development, a lot of potential stressors for the crew, like noise, privacy and efficiency issues can be avoided.

22 Häuplik-Meusburger & Bannova, 2016, p156

Gravity Types / Microgravity

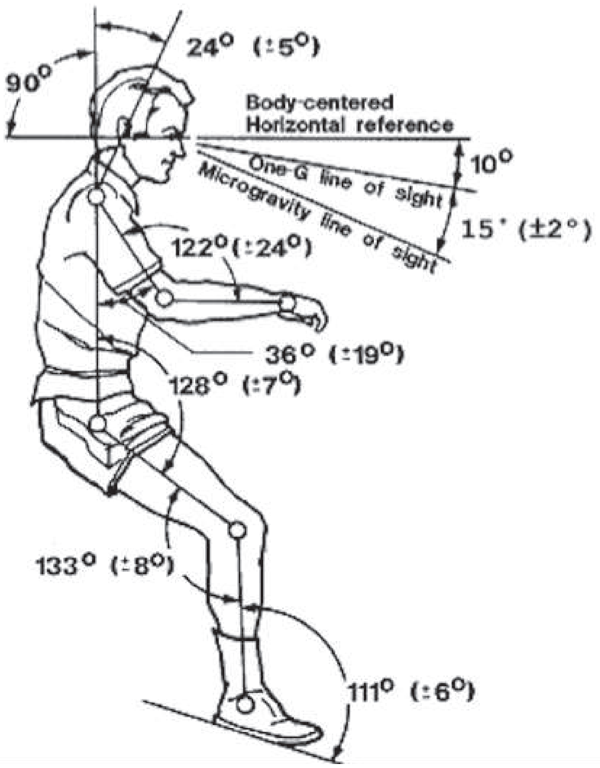
An important factor for the design of space architecture is the type of gravity that design will be operating in. We can roughly differentiate between Earth gravity, which is described by an acceleration of 9.8m/s² and called 1G, partial gravity on smaller celestial bodies with less mass like the Moon (1/6G) or Mars (1/3G), microgravity, on spacecraft traveling on circular orbits and artificial gravity. Different gravity conditions often require substantial differences in design.[23] This sub-chapter will focus on microgravity, its effects on the human body and facets of space architecture and human factors design it concerns.

A spacecraft moving with a certain velocity parallel to the surface of a body it is orbiting, while constantly falling towards it, creates very small gravity forces. This is called microgravity. While it certainly affects scientific experiments, that utilize sensitive machinery, it is effectively not experienced by an inhabiting crew. Instead, they perceive the sensation of Zero-G or weightlessness, a condition, in which the effect of gravity is canceled out by the inertial force resulting from the orbital flight.[24]

In such an environment, the human body assumes a specific posture called the Neutral Body Posture (NBP). It is relaxed, lengthened and joints are naturally aligned.[25]

Sleeping in Space
Marsha Ivins takes a nap on the Space Shuttle Atlantis
Credit: NASA

23 Häuplik-Meusburger & Bannova, 2016, p 111
24 Häuplik-Meusburger, 2011, p 18
25 Häuplik-Meusburger & Bannova, 2016, p 113



Neutral Body Posture
Graphic showing the natural relaxed state of the human body in an microgravity environment.
Credit: NASA / MSIS

Compared to a neutral body orientation on Earth, the head is tilted down; Ankle, knee and hip height increase; Elbow, wrist and shoulders are raised and elbows abducted.[26] However, since the original NBP graphic, presented in the 1985 *Man-Systems Integration Standard*, was based on only 3 male astronauts of the Skylab 4 crew, and a further survey of the STS-57 crew showed that none of the astronauts exhibited this exact typical NBP, variations based on individuals have to expected.[27]

Microgravity further poses a serious health risk for the crew. Even after relatively short-term space missions, changes in bones, muscles and brain neurophysiology were experienced. Long-term US Skylab and Russian Mir missions showed physiological changes including bone deterioration, fluid shifts and muscle atrophy. In order to minimize these negative effects the necessity for on board exercise equipment was recognized. However, even with multiple hours of daily exercise, for example on a treadmill under a 1G load, about 1% of bone mineral content is lost during LEO flight missions.[28] It was also discovered that astronauts who spent months in microgravity showed signs of swollen optic nerves, flattened eyeballs and blurred vision. It is suspected that this is due to an accumulation of bodily fluids such as blood and water floating towards and causing pressure in the head area, when not affected by the

26 NASA HIDH, as cited in Häuplik-Meusburger, 2011, p 19
27 Ibid., p18
28 Clément, as cited in Bannova & Häuplik-Meusburger, p 112

steady tug of gravity. A recent study found stalling or a reverse of direction in the blood flow of some subjects, and even discovered a blood cloth that formed during an astronaut's stay on the ISS.[29] Further research is required on microgravity and health issues. Artificial gravity is theorized about as one possible solution for this problem.[30]

An additional challenge, posed for the design in microgravity, is the one of orientation. Cues to which the human body is used, like "Up" and "Down" or sunlight coming from "above" are connected to the force of gravity and lacking in this environment. Further, the body position can assume any orientation in weightlessness. This, on the one hand, is an opportunity to utilize the whole volume of a habitat, instead of being restrained to a floor area. On the other hand; a faulty design can easily lead to disorientation of the crew or impair efficiency.

People are either vestibular or visual dominant. For the ladder colors are especially important in regards of special orientation. The Soviets and Russians introduced a color coded system mimicking "Earth orientation" in their Mir modules to define walls (beige/yellow), ceiling (light blue/white) and floor (brown).[31] Lighting is also used to define the local "Up" on most modules of the ISS. NASA has established the following orientation design

ISS Lighting
In most ISS modules light is used as indicator for the local "Up"
Credit: NASA / Robert Frost

Exercise >
Astronaut Reid Wiseman using the T2 Treadmil on the ISS
Credit: NASA

29 The Atlantic, An Alarming Discovery in an Astronaut's Bloodstream, 2019
30 Hall, as presented in Häuplik-Meusburger & Bannova, 2016, p 133
31 Ibid., p 119

requirements within a module exposed to microgravity:[32]

- Constant orientation within one activity center.
- Visual orientation cue to allow quick adjustment to the orientation of the activity center or workstation.
- Separation of activity centers with different orientations

Another major part of microgravity design is the necessity for restraints. Similar as on Earth, to complete a force coup in zero-G, one uses his or her arms and legs. The major difference is that on Earth gravity holds ones feet to the floor, in weightlessness restraints are necessary for this purpose. As they are for any performance of basic functions such as sleep, dining, toilet, computer work, experiments or photography.[33] Examples of restraints are: handhold restraints, waist restraints, torso restraints foot restraints and tethers such as bungee straps and harnesses. On the ISS the most common restraints are handrails.[34]

To conclude, some considerations for microgravity design are presented on the right., taken from Space Architecture for Astronauts and Engineers:[35]

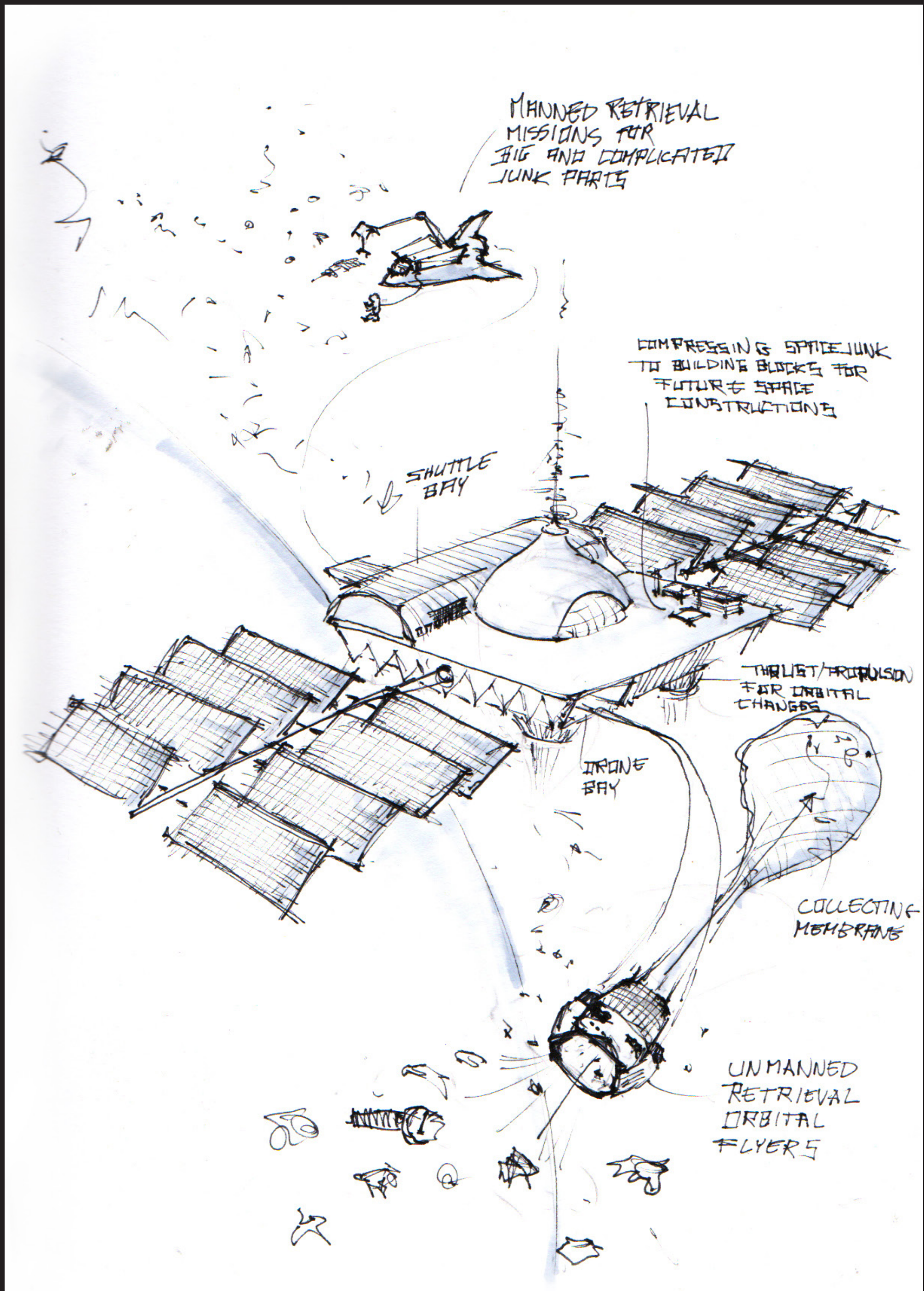
- **Human mobility and operations:** Movement is effortless but restraint systems are needed for people and equipment. A person may be stranded in the middle of a large space module if there are no means provided to pull to or push

Restraints
Handrails and foot restraints in the Columbus module of the ISS
Credit: NASA

32 NASA MSIS as presented in Häuplik-Meusburger & Bannova, 2016, p 114
33 Häuplik-Meusburger, 2011, p 29
34 Häuplik-Meusburger & Bannova, 2016, p 115
35 Ibid., p 113

from for propulsion.

- **Psychological adaptation:** Need of visual cues to establish a local vertical and avoid spatial orientation confusion.
- **Physical adaptation:** Loss of muscle mass, bone density and body fluids produce deconditioning.
- **Engineering design challenges:** Microgravity influences fluid systems and negates heat convection.
- **Housekeeping and maintenance requirements:** Dust and other contaminates float freely and are difficult to control.


MANNED RETRIEVAL MISSIONS FOR BIG AND COMPLICATED JUNK PARTS
COMPRESSING SPACEJUNK TO BUILDING BLOCKS FOR FUTURE SPACE CONSTRUCTIONS
SHUTTLE BAY
THRUST/PROPULSION FOR ORBITAL CHANGES
DRONE BAY
COLLECTING MEMBRANE
UNMANNED RETRIEVAL ORBITAL FLYERS

05

Concept Definition or: The Story of Three Space Stations

< **Sketch #01**
First sketch of an orbital platform for debris recycling during the idea gathering phase

Introduction

This chapter treats the concept definition process from the very first sketch idea, up to the formalization of the main tasks and functions of the final space station iteration. It depicts the first and second iteration of the station design, highlighting problems that had to be solved and decisions that were made, whilst elaborating on the reasoning behind these actions and the lessons learned from each iteration.

While the first two designs of the space station are complete on orbit recycling facilities, with a heavy focus on a large hangar space, the recycling process, a material cycle and the constellation of the individual components, the last iteration is an intermediate step towards such a facility. The focus shifts to provide means for the research of orbital debris and for the development of viable application strategies of this potential resource. It is altogether smaller in size, with particular attention given towards the habitability and human factor oriented aspects of the design.

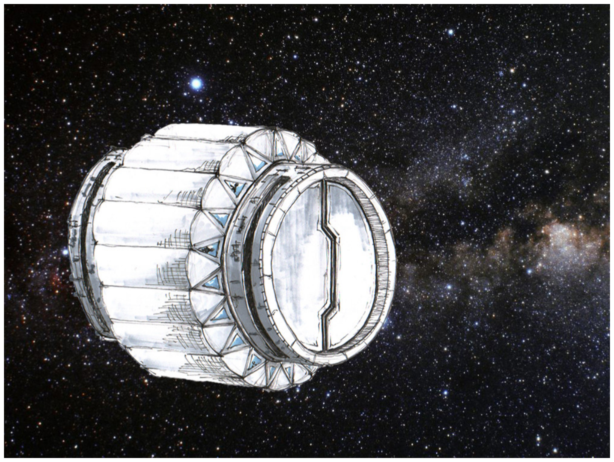
The concept definition process and design approach were strongly supported by sketching and working models of which some examples are shown.

Early Concept Idea

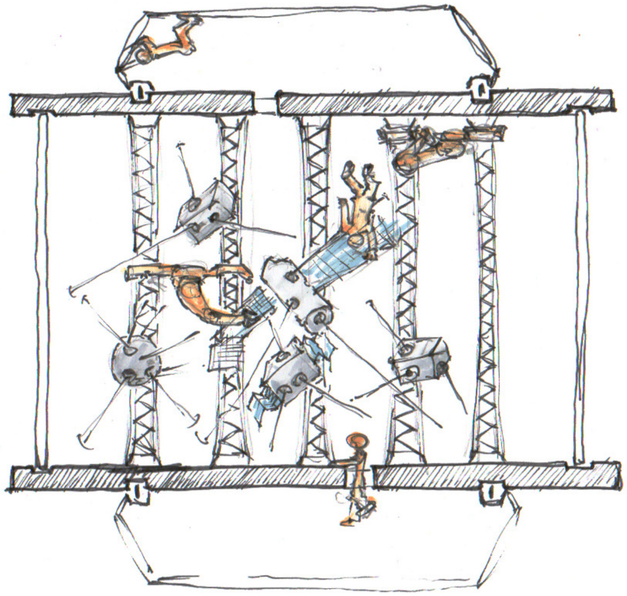
On the right hand side the early concept idea is presented in form of a space station sketch and corresponding rough sections. The station features two main components: A sealable, cylindrical, large volume, hangar surrounded by habitation and storage spaces, accommodated in a toroid inflatable. The hangar space can be used threefold:

(1) To store debris pieces and deactivated spacecraft, and to either disassemble them into raw materials or to repair and make them operational again.
(2) The possibility was entertained to utilize it for storage and mining of asteroids.
(3) Once enough debris was collected, the space could be used for assembling new spacecraft on orbit, utilizing the previously gained materials.

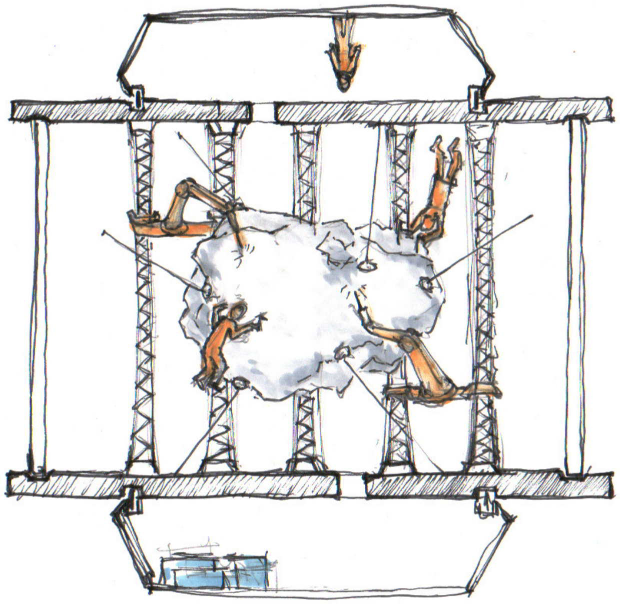
The sealable function of the hangar was intended as a precautionary measure to avoid releasing additional debris pieces, created during the disassembly process, into orbit. To assist the human crew robotic arms (RA) were intended to aid all the work processes. The hangar interior contains circumferential trusses, to which objects can be mounted, and which the RAs use for movement.



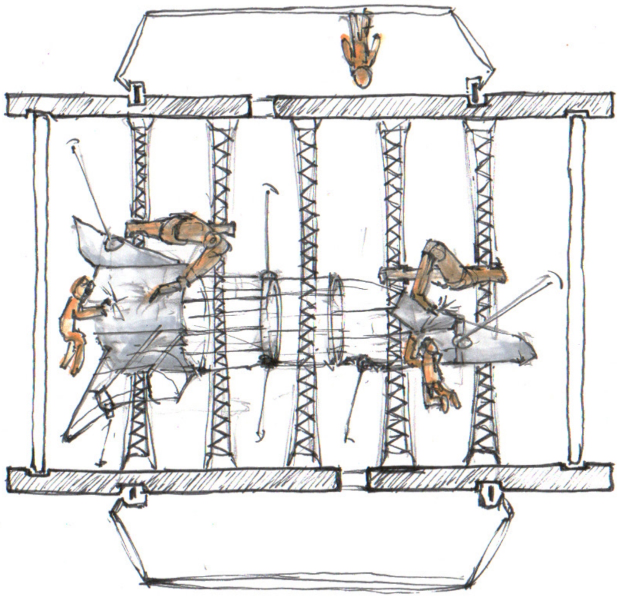
Early Concept Idea Sketches
Above: Space station sketch
Right: Corresponding section sketches depicting main functions of the early concept idea.



1. Store and disassemble debris



2. Store and mine resources from asteroids



3. Assembly of spacecraft on orbit utilizing gained resources

The Hangar Assembly Challange

One of the main tasks of the station would be to disassemble and disintegrate large debris pieces. Any such action inevitably leads to fragmentation and new debris, so it was essential to provide an enclosed space, where these jobs could be performed without further contamination of the space environment. At this point of the design process it was not concretely defined what type of debris the station would process, however, the hangar was intended to accommodate larger, unfragmented debris, since this would allow for a greater material per debris-capture ratio. Besides that, the hangar had to offer space for intermediate storage of debris as well as RA and possible human maneuverability around the workpieces. Due to current fairing size limitations, a regular hardshell module would be insufficient for this task and an inflatable module would also be problematic, due to the entrance openings limited by the diameter of the rigid endplates at either end of an inflatable. Fortunately, the company Made In Space is working on a solution that allows for the assembly of large structures on orbit called the Archinaut: A maneuverable spacecraft that utilizes additive manufacturing combined with robotic arms to create truss structures. (See page 39) Such a truss framework could be covered with either layers of textiles, lightweight honeycomb plates or very fine meshes to enclose the hangar environment.

Ideas for Hangar Assembly >
Sketches depicting potential approaches for the construction of a large scale hangar on orbit.

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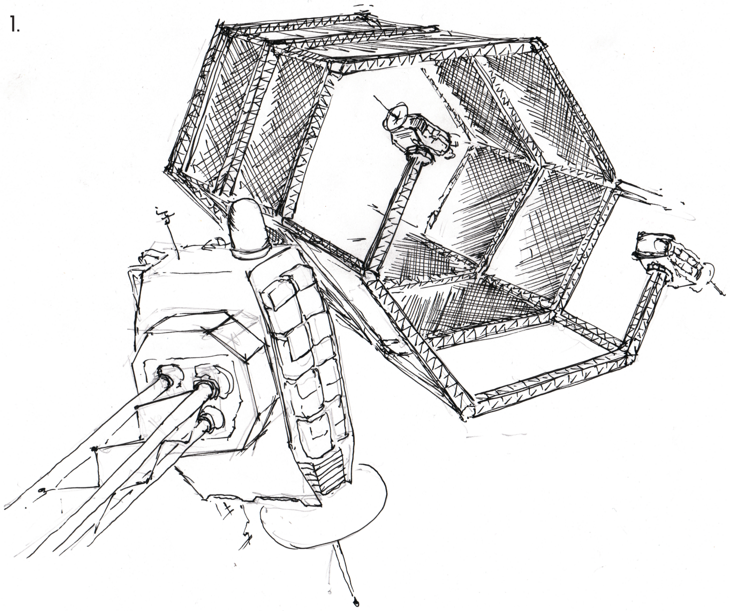

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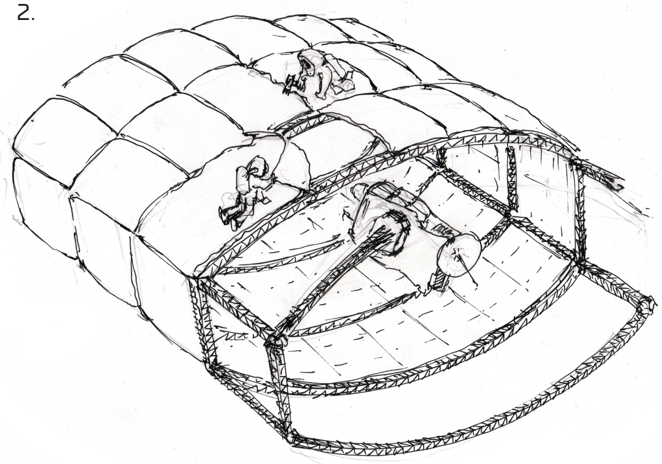

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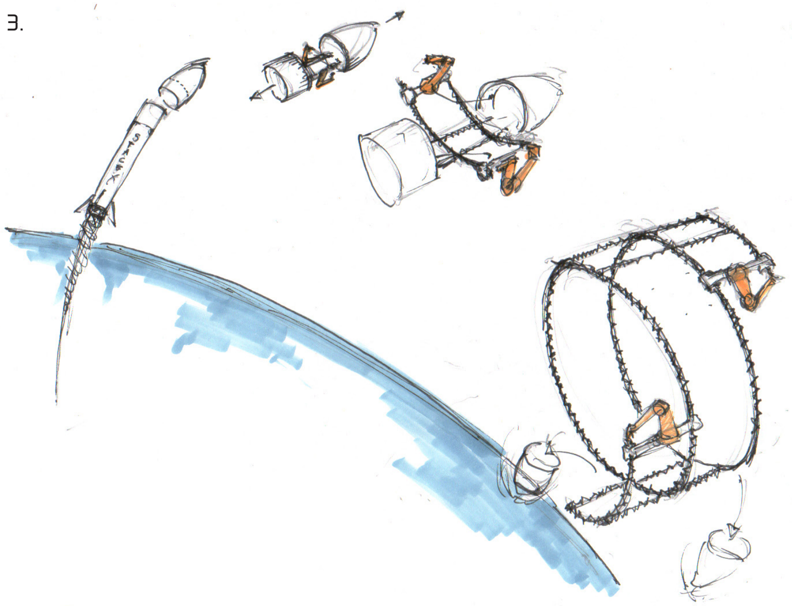


1. Archinaut constructed truss framework covered with lightweight mesh / honeycomb plate structure

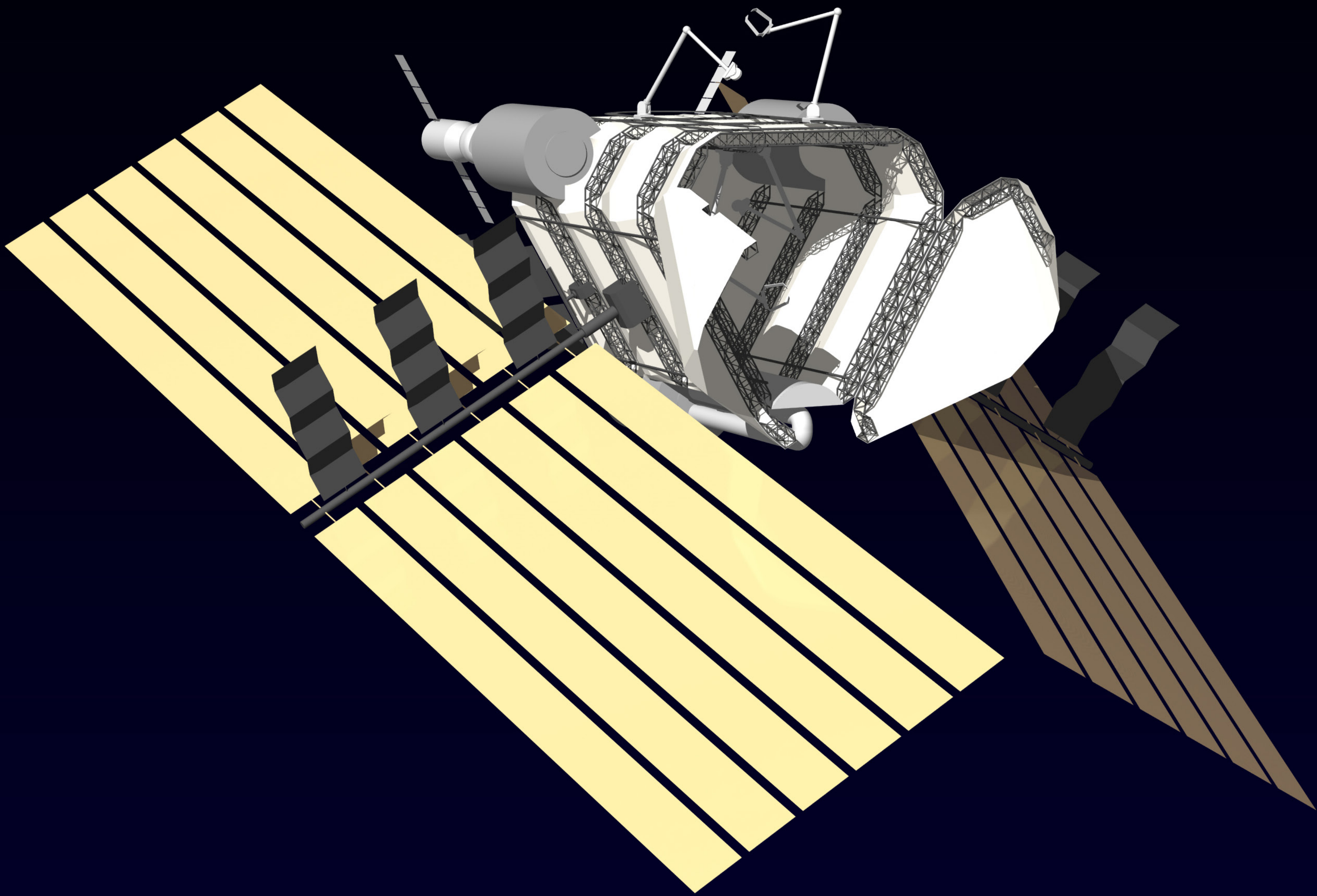
2. Archinaut constructed truss framework covered with textile layers

3. Early concept idea with two industrial robotic arms launched in in a fairing capsule subsequently welding the truss framework

First Iteration: ORDER V1

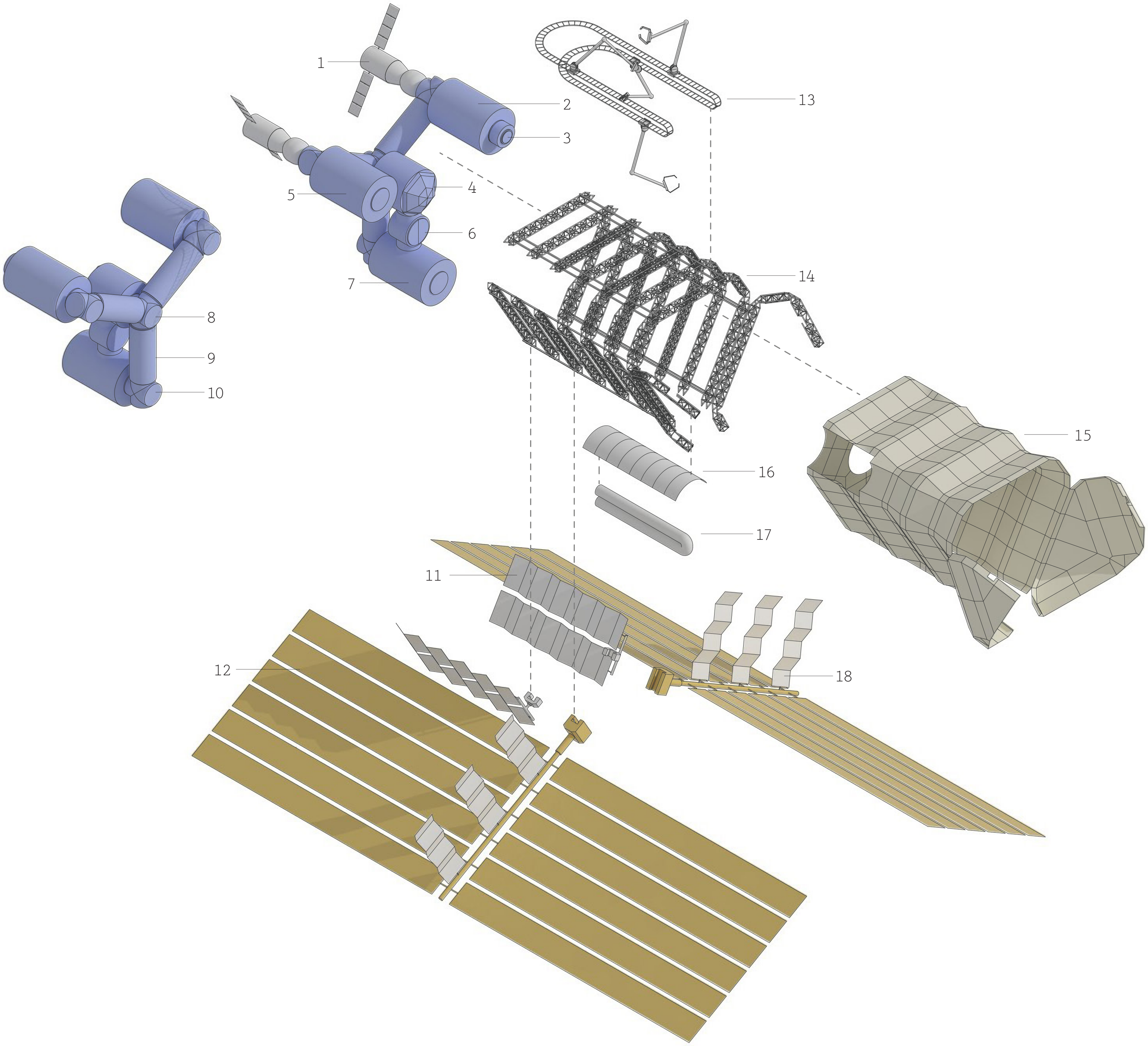
This first developed design brought together the idea of a grand hangar with approximating habitable space, and the construction method of an in-space manufactured truss framework, covered with textile layers. While in the original concept idea, the interior of the hangar was to be a shirtsleeve environment, into which astronauts could simply crossover from the habitable section, without the need to don a space suit, this approach was eventually discarded, due to the large amounts of oxygen and other gases necessary to pressurize the hangar space each time a new debris piece would be brought in. Besides, a hangar capable of containing atmospheric pressure would be an even greater challenge to construct than one that only needs to enclose debris and hinder objects from escaping into outer space. Due to this decision, it was clear that a lot of the initial debris deconstruction work would be performed by RAs. A module featuring a large array of viewing windows was oriented towards the interior of the hangar for RA control. Access between the hangar and the habitable section was provided by an airlock through which the astronauts could traverse, or through which the RAs could pass smaller chunks of debris to the pressurized section for further human-aided processing. The idea of utilizing a parabolic mirror for melting and disintegrating debris was formed during this iteration, and such a mirror with a pipeline tube is placed along one corner section of the hangar. The RAs run on a folded circular rail system and can move between hanger exterior,

ORDER V1 Space Station >
Visualization of the Space Station for Orbital Debris Recycling (ORDER).



COMPONENTS

1 Soyuz spacecraft
2 Logistics module
3 EVA Airlock
4 Robot operation module
5 Habitation module
6 Hangar airlock
7 Laboratory module
8 3-way node
9 Connecting tunnel
10 4-way node
11 Thermal radiator
12 Solar array
13 Robotic arms & guiderail
14 Truss framework
15 Textile layers
16 Parabolic mirror
17 Furnace
18 Power radiator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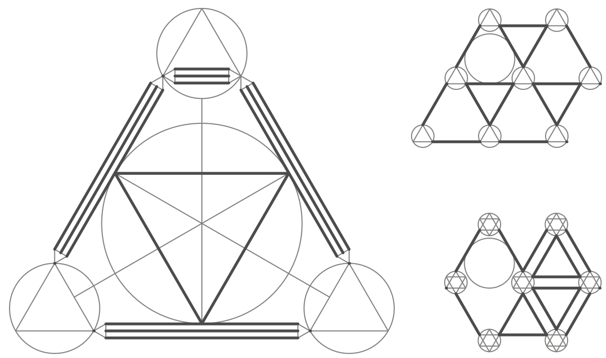
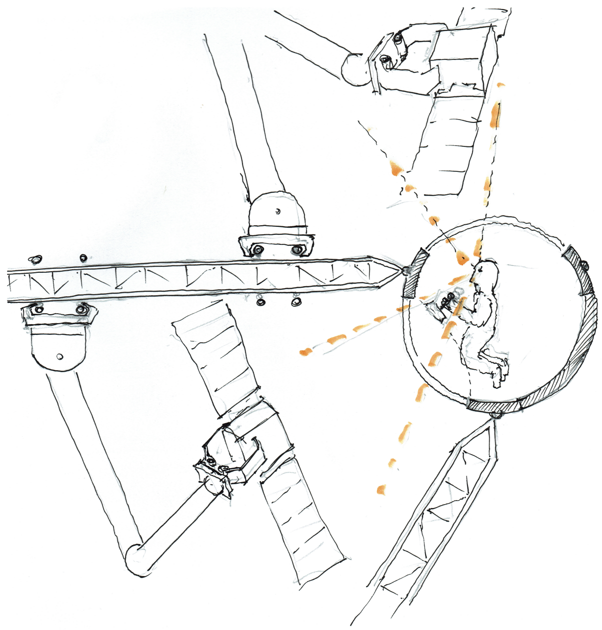
for capture, and interior, for disassembly. The hangar size is determined by an inscribed circle of 10 meters in diameter to provide sufficient space for large rocket bodies whilst ensuring enough maneuverability space around them, and to guarantee additional storage space for debris pieces that are not currently being processed. The shape and form are derived from an equilateral triangle with circles of 4.5 meters in diameter in each corner, representing the standard diameter of current aluminum shell pressurized modules. The intention was to generate a form and configuration that was suitable for expandability, if it would become necessary to grow the station in the future, by adding a larger hangar or more modules. The habitable and pressurized space consists of three main aluminum shell modules, the RA control module and an airlock connected by nodes and small diameter cylinders. However these parts were only superficially defined with little attention given to their interior. Points of focus for the next iteration design included:

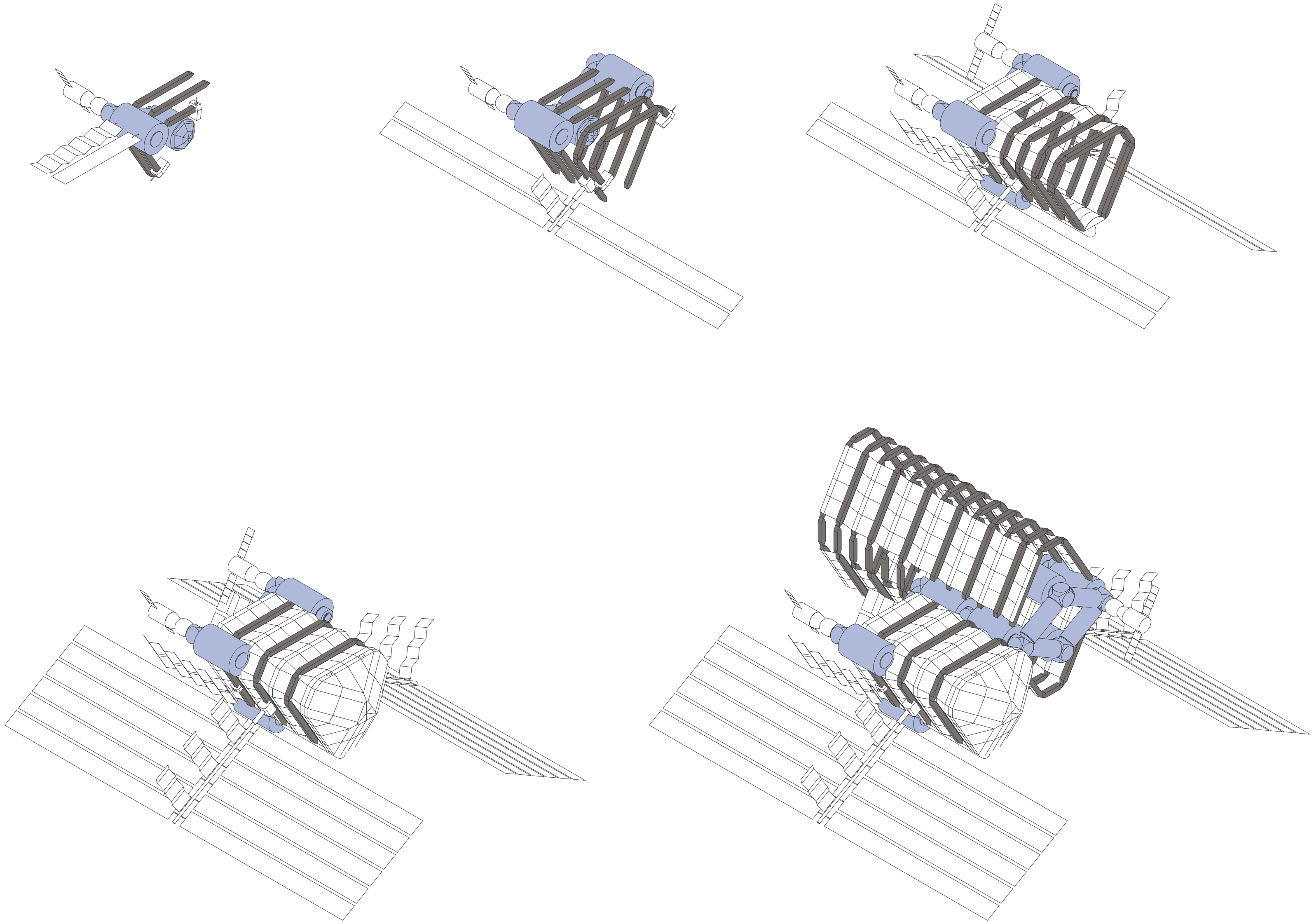
- To research how RAs move around a space station.
- To define concrete functions for the pressurized components, and get a better understanding of how much volume is necessary to accommodate them.
- To arrange the modules more efficiently, avoiding low quality connection volumes, and minimizing unnecessary costs.
- To question why and in what way the station needs to expand.



Form Definition
Shape derived with a focus on potential expandability. A 10m diameter circle is inscribed in the Hangar's interior for sufficient maneuvering space and 4.5m diameter circles at the corners representing the standard pressurized module size.



Visibility
Conceptual section sketch, depicting visibility of hangar's interior and exterior while controlling RAs and moving debris pieces.



Assembly Steps
Initial modules launched, Archinaut constructs truss framework, which is covered with textile layers. Final step is a potential expanded station containing a larger hangar.

Orbital Region & Target Debris

Since low Earth orbit (LEO), on the one hand, is most susceptible for future collisions (see page 17), and on the other, a low orbiting spacecraft is fairly protected from radiation hazards by the van Allen belts (see page 75), it was clear, pretty much from the get go, that the space station would be located in this region. What needed to be determined in the next step, is the type of debris it would collect.

Large intact debris pieces are the most likely contributor to debris proliferation (see page 17). Since the station aims to recycle the material, in addition to removing debris, it is essential that it will acquire as much mass per debris-capture, as possible. Due to these arguments, small and medium debris were disregarded and large intact debris pieces chosen as target.

Large intact debris can be separated into two categories: Rocket bodies and deactivated or retired spacecraft (satellites). Even though satellites are generally made up of more valuable materials, they pose a lot of challenges for capturing and recycling. Firstly, they are fragile; any attempt to capture or propel them could cause a breakup of components like solar arrays or antennae. Secondly, most satellites are unique and mission specific, which makes it difficult to design an efficient recycling process, due to size, mass, component and material variations. Thirdly, they contain highly developed technologies protected by property claims of the associated nations. Rocket bodies,

Selected Target Rocekt Bodies
Kosmos 3M and Zenit 2 second stage dimensions.
Kosmos 3M was identified by multiple studies as an optimal benchmark target for ADR test, due to its large numbers in similar orbital regions.

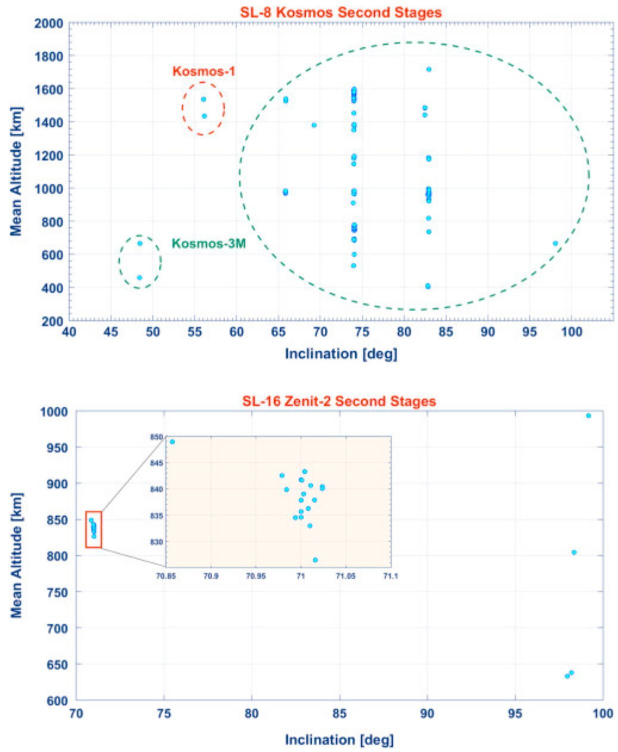
on the other hand, are built sturdy and are meant to endure huge amounts of structural stress. There are a lot of similar rocket types, making them an ideal target for benchmark missions in order to develop and refine capture and de-orbiting methods. Furthermore they consist mainly of aluminum and steel which are very well recyclable materials, and finally they have less critical technologies, easing the probability of complications through property claims (see page 26). Rocket bodies make up 42% of the abandoned intact objects in space and 57% of the abandoned mass.[1]

In an optimal ADR scenario, objects with the highest probability of contributing to future debris population growth would be removed first. One way to determine such objects is with the equation given by Liou, based on an object's mass and collision probability at a specified time.[2] The disadvantage of this approach is the often very different orbital properties of the determined objects. This could be a viable procedure for multiple spacecrafts with single de-orbiting missions, but in the case of a space station that is supposed to continuously capture and process debris, or in the case of any multi-target de-orbiting spacecraft, the propellant and energy requirements for radical orbit changes are exceedingly high. It is more efficient to select an orbital region that offers multiple large debris targets in need of removal.

1 Anselmo & Pardini, 2016
2 Liou et al., 2006, 2009, 2010

Such regions have been identified by various studies.[3] Anselmo has ranked upper rocket stages in orbit based on a normalized and dimensionless ranking index. The 290 Kosmos 3M (SL-8) second stages and the 22 Zenit 2 (SL-16) second stages in LEO make the top of the list. They represent a total mass of 416.150kg and 198.000kg respectively. The SL-8 Kosmos stages are distributed at altitudes between 400-1800km in two inclination bands of approximately 74° and 83° The Sl-16 Zenit 2 stages are located between 800-850 km altitude at an inclination of about 71°. The Kosmos 3M rocket bodies are also recommended by a different study as an optimal benchmark target.[4] Additionally their spread throughout almost the whole bandwidth of LEO altitudes suggests a more efficient collision prevention.

The Kosmos 3m second stage has a 2,4m diameter, a 6,5m length and a dry weight of approximately 1,44 tons.[5] The Zenit 2 second stage has a 3.9m diameter, a 10,4m length and a dry weight of approximately 8.9tons.[6] These two rocket body types were selected to be collected and processed by the space station.



Kosmos 3m and Zenit 2 RB Orbital Regions
Spread of the second stage rocketbodies depicted by orbital inclination and altitude.
Credit: Anselmo & Pardini, 2016

3 Liou, 2011, Van der Pas et al., 2014, Anselmo & Pardini, 2016
4 Bonnal et al., 2013
5 Space Launch Report, Kosmos 3M Data Sheet, 2005
6 Space Launch Report, Zenit Data Sheet, 2017

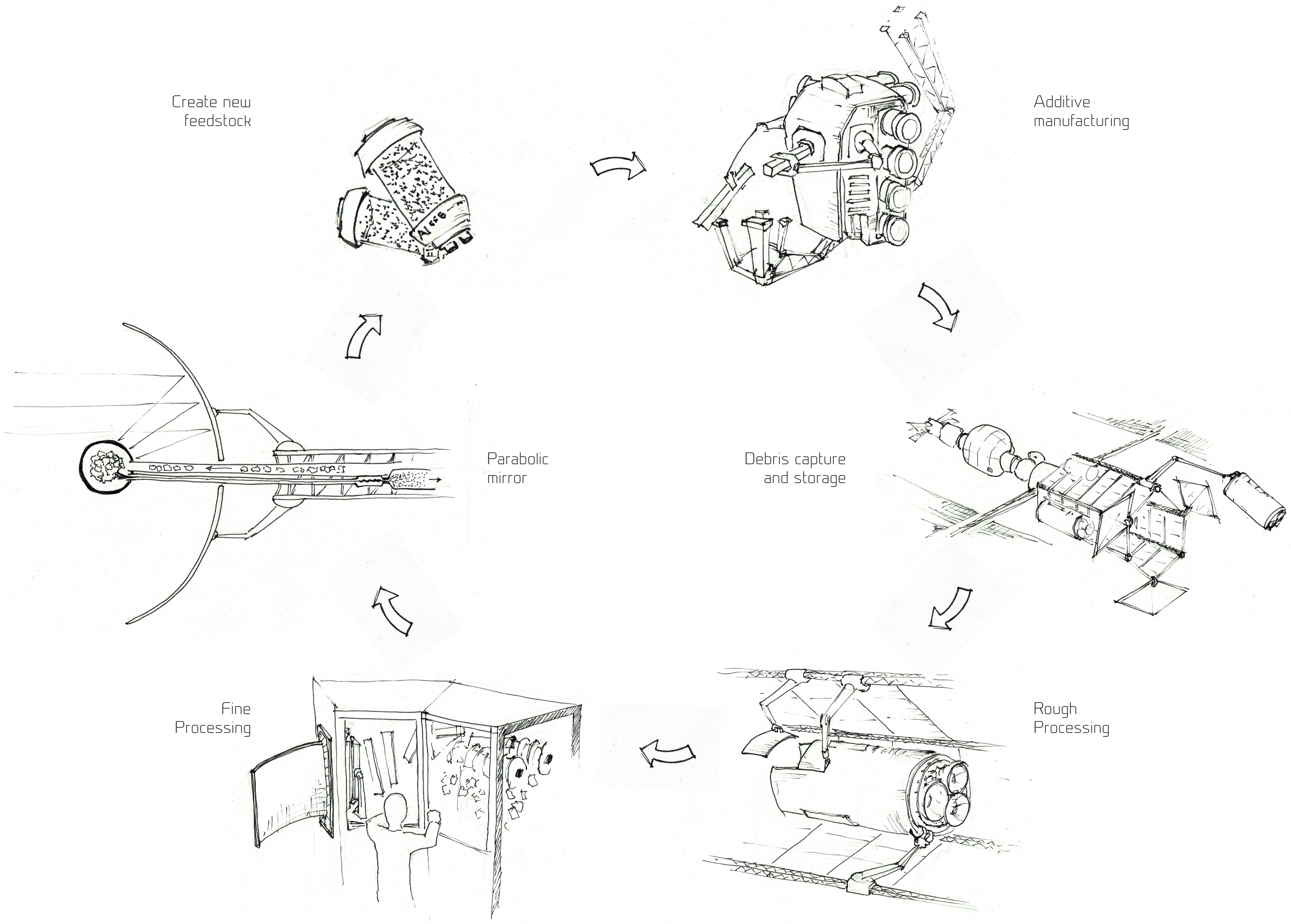
The Recycling Process

Since it was determined that the station will target two types of rocket bodies, the preliminary recycling efforts were focused on metal processing, with the possibility of expanding the facility to handle different types of debris later on.

The upper stages are captured, relieved of any excess fuel or other hazardous material, brought to the station and stored on the external surfaces of the hangar before being moved inside. Only one rocket body at a time is processed inside the hangar. Here it is cut and disassembled by the RAs into pieces small enough to pass through the airlock connecting the hangar interior with the pressurized work module. The inner surfaces of the hangar are used to store these disassembled components and cut pieces before they are transferred inside the module. Both the exterior and interior storage possibilities serve as a failsafe to help achieve a continuous flow of the capture and recycling process. If the RAs inside the Hangar are behind schedule on processing, the station can still achieve its goal of removing 5-10 large debris pieces from orbit per year, by storing them externally. Similarly, if there are any complications leading to a delay inside the work module, the RAs can still continue disassembling further rocket bodies. Since the rocket bodies are limited to two types, the crew and ground personnel is intended to develop command code strands and learning algorithms for the RAs and to tweak and refine them with every upper stage processed. The goal is to create a fully automated disassembly program for each rocket body type, minimizing the need for manual RA control to exceptional situations.

In the work module, the crew inspects, cleans and feeds the cut up pieces into shearing and shredding machinery. The resulting metal chips and flakes are guided into cylindrical furnaces at the station's extremities, heated by parabolic mirrors and energy from the station's solar arrays. This is done by pressurized pipelines connecting the module with the furnaces. Once the temperature inside the furnace reaches the specific melting points of the various metals (aluminum alloy: 463-671 C°, aluminum: 660 C°, steel-carbon: 1425-1540 C°, steel-stainless: 1510C°, titanium: 1670C°), they are sucked out of the furnace through a recoil line, this automatically leads to the separation and sorting of the metals. Finally, the metals are pulverized and filled into special containers, creating feedstock for either the Archinaut robots or the on board 3D-Printers. This establishes a material cycle and will provide the station with the possibility to either self-expand so that it may accommodate the removal of more debris pieces or the removal and processing of new debris pieces like satellites, or generally enable the in-space production of new spacecraft.

Intended Material Cycle >
Archinaut assembles truss framework of hangar to enable disintegration. Materials fine processed and melted in parabolic mirror furnaces to create new feedstock for Archinaut and on board additive manufacturing facilities.


Create new
feedstock
Additive
manufacturing
Parabolic
mirror
Debris capture
and storage
Fine
Processing
Rough
Processing

Second Iteration: ORDER V2

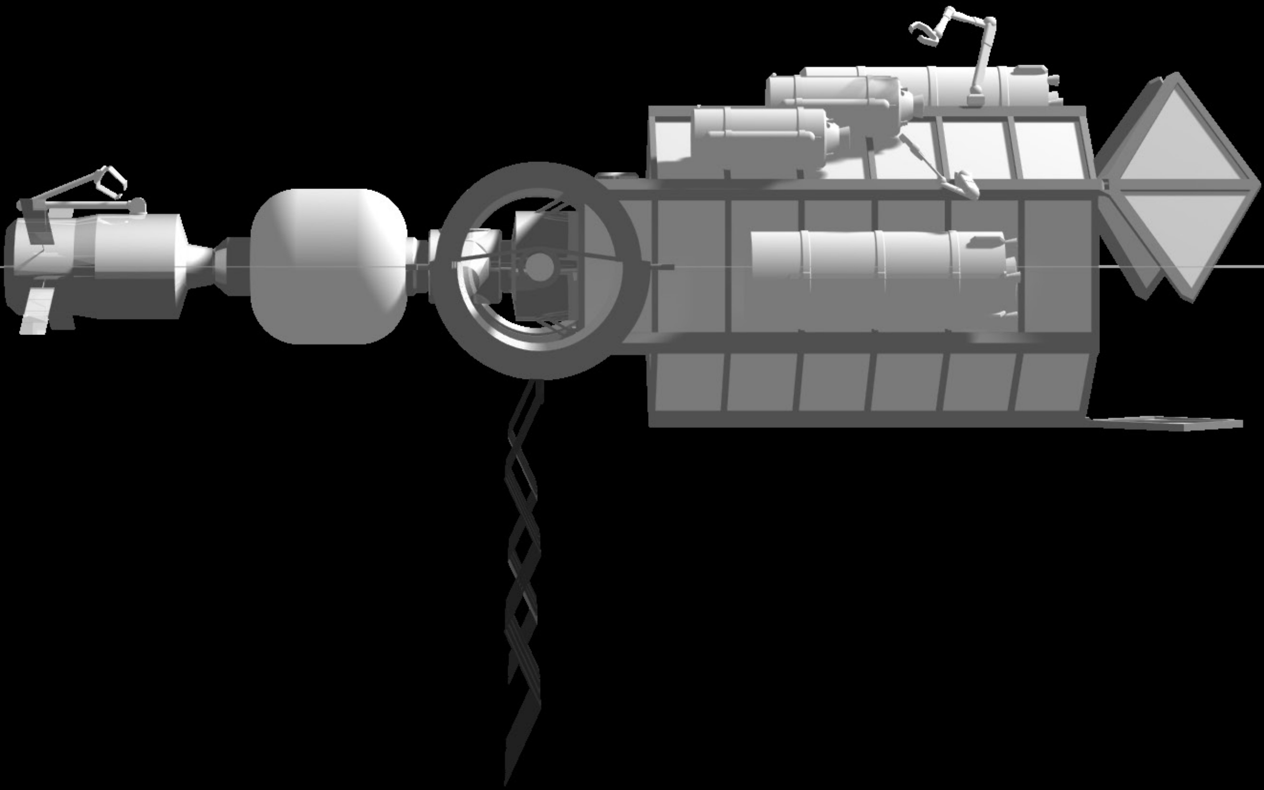
To summarize the concept development at this point: The ORDER (Orbital Debris Recycling) Space Station is located in the LEO regime, at an altitude of 400-600km and an inclination of 71°-74°. It captures Kosmos 3M and Zenit 2 second stages and aims to remove 5-10 objects from their orbit per year. It processes and recycles the metals in the rocket bodies and generates feedstock for in space 3D-printers. The salvaged material is subsequently used to expand the station or to help construct new spacecraft like a second generation ORDER space station. Its main architectural components are described in the following paragraphs:

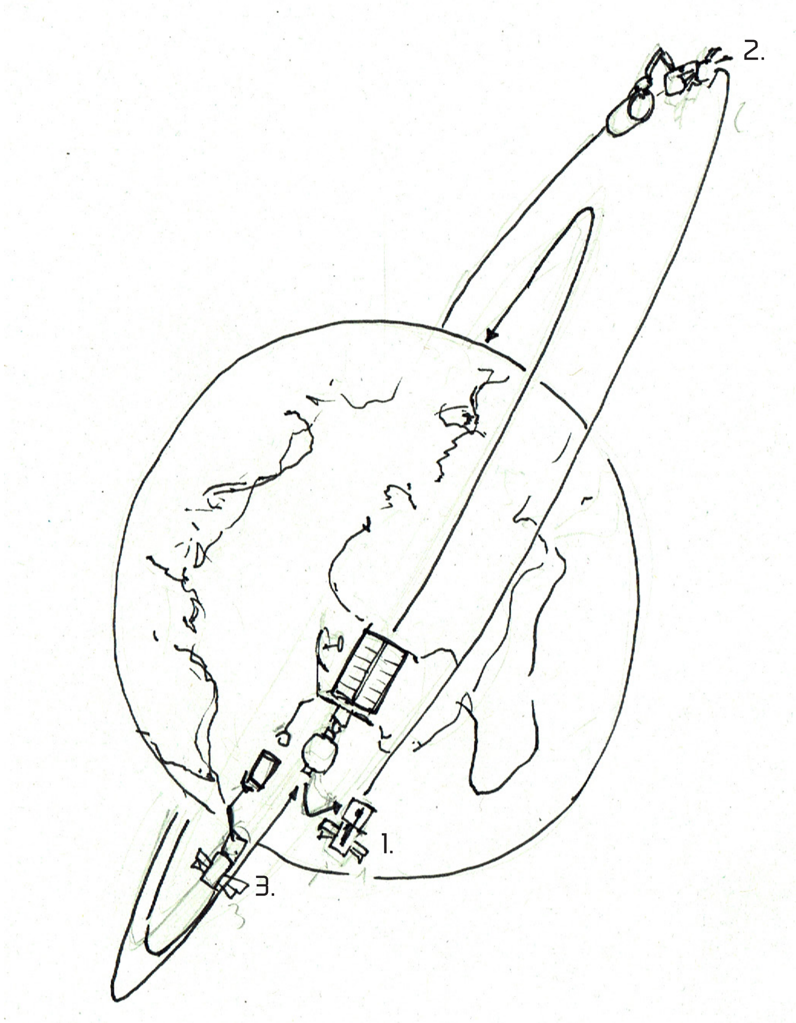
A **hangar**, consisting of a truss network, assembled by Archinaut spacecraft and covered in honeycomb aluminum plates by RAs. It is used for rough disassembling and storing of the intact rocket bodies on its exterior and disassembled debris pieces on its interior

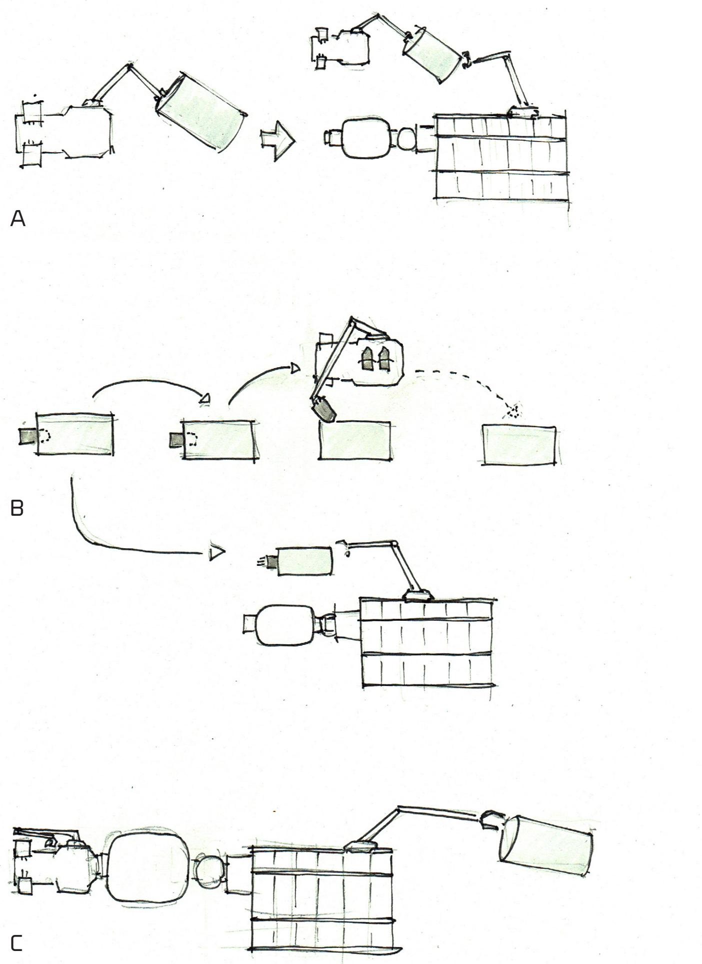
A cylindrical, aluminum shell, **work module**, 4.5 meters in diameter and 6.5 meters long, containing a processing section for inspection and shredding of the previously disassembled debris pieces, and a workshop section for RA repairs and tool-head refurbishment. It features an ISS like **cupola** attached to the nadir side of the module granting oversight of the hangars interior and housing the RA controls. An **airlock** connects the hangar interior with the work module and grants a third exit to the exterior of the space station for EVAs.

Two **Cylindrical furnaces** at the stations extremities,

ORDER V2 Space Station >
Elevation visualization of the Space Station for Orbital Debris Recycling (ORDER).







1. The ATV spacecraft modified with an robotic arm detaches from the ORDER space station and executes an orbital transfer.

2. The ATV rendezvous with the target rocket body and captures it.

3. The ATV performs an orbital change returning to the ORDER space station with the rocket body and passes it to one of the station's robotic arms.

A: The stations modified ATV detaches, rendezvous and captures target rocket body, and returns it to the ORDER space station.

B: The ATV is equipped with thruster deorbiting kits. It rendezvous with multiple target rocket bodies, and attaches a TDK to them. The rocket bodies then return to the station autonomously.

C: The ORDER space station captures rocket bodies in its altitude range utilizing a robotic arm.

< **Capturing Debris**
Sketches for capture sequence and capture options of the station.

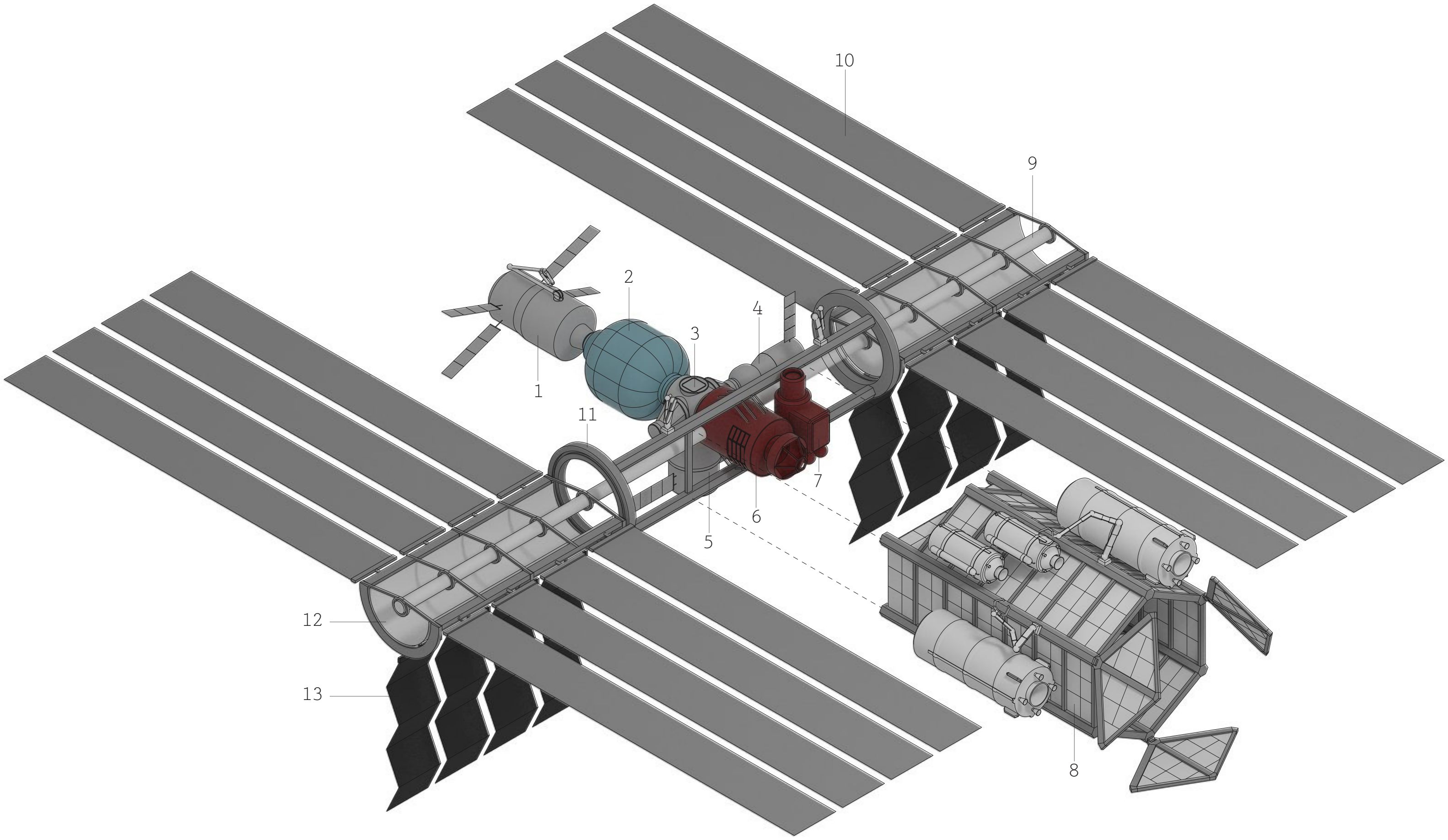
fed and emptied by a pressurized pipeline system running from the work module and heated by **parabolic mirrors** and the energy generated from the **solar array** network.

An inflatable **habitation module**, based on the size of the Bigelow Sundancer module (see page 55), that can accommodate a crew of 2-4, offers a safe haven for solar storms and high radiation events, two customizable private quarters, room for sports and leisure activities, a galley and table for gathering, food consumption and conferencing. Further, the module offers storage space for supplies and crates of 3D printer feedstock.

The stations configuration features a modified ATV spacecraft, enhanced with a RA, that detaches itself from the station, to either capture rocket bodies at higher altitudes and bring them back to the station, or attaches TDKs to the rocket bodies, so they can return to the space station autonomously. Rocket bodies in the altitude range of the space station are captured by the station's RAs.

COMPONENTS

1 Modified ATV with robotic arm
2 Habitation module
3 6-way node
4 Soyuz spacecraft
5 Dragon cargo
6 Work module
7 Airlock
8 Hangar
9 Material pipeline
10 Solar array
11 Rotator
12 Parabolic mirror
13 Radiator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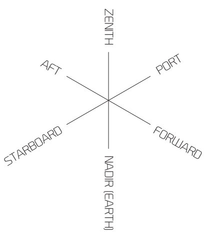
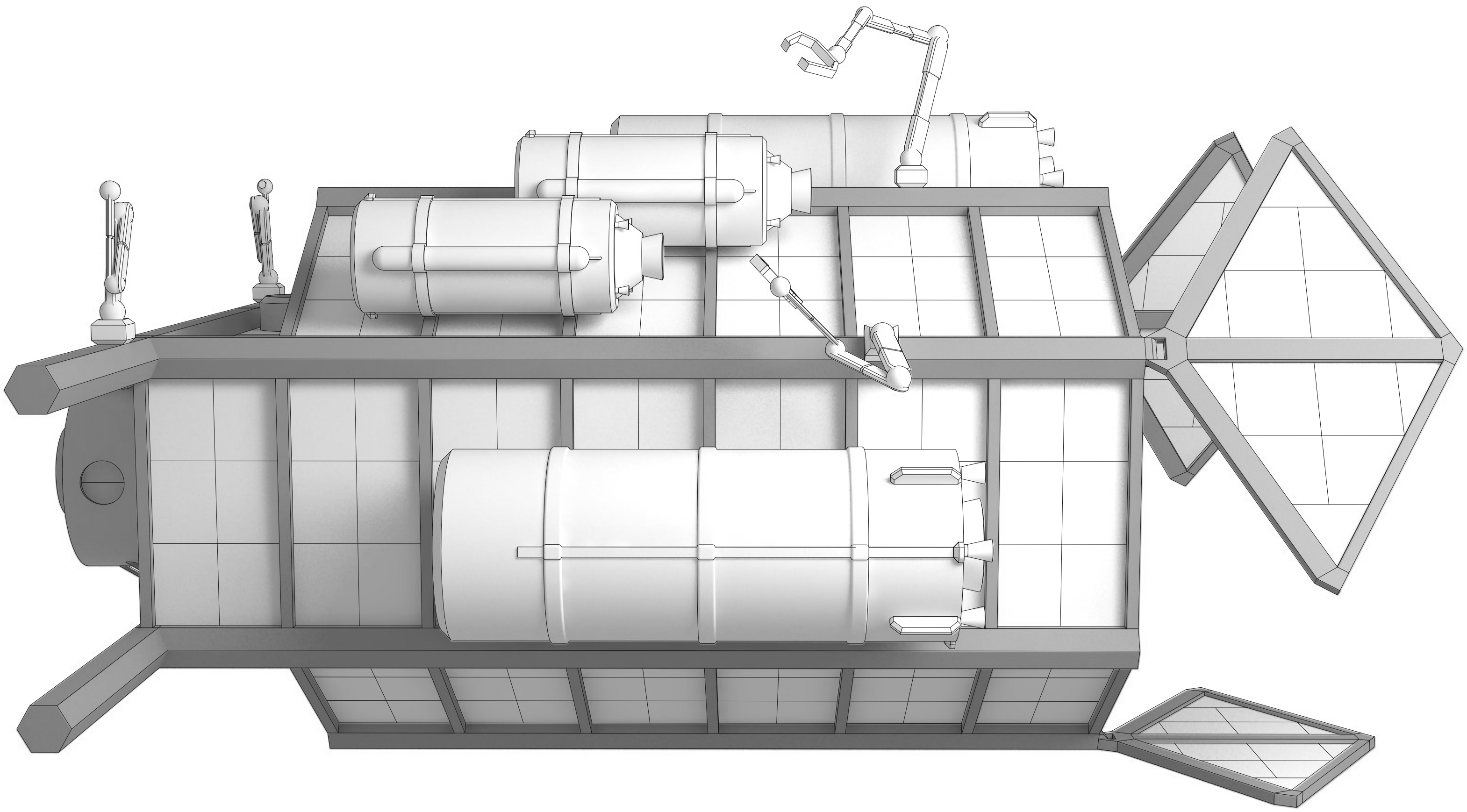
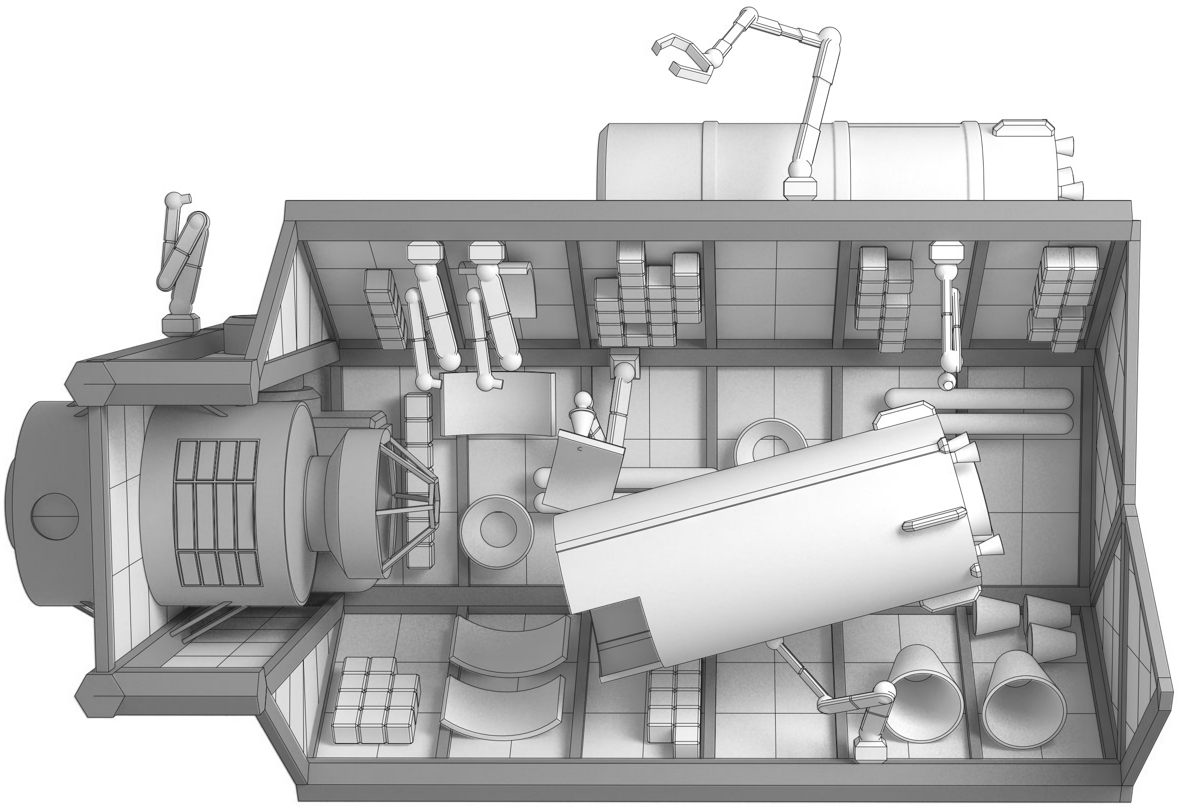
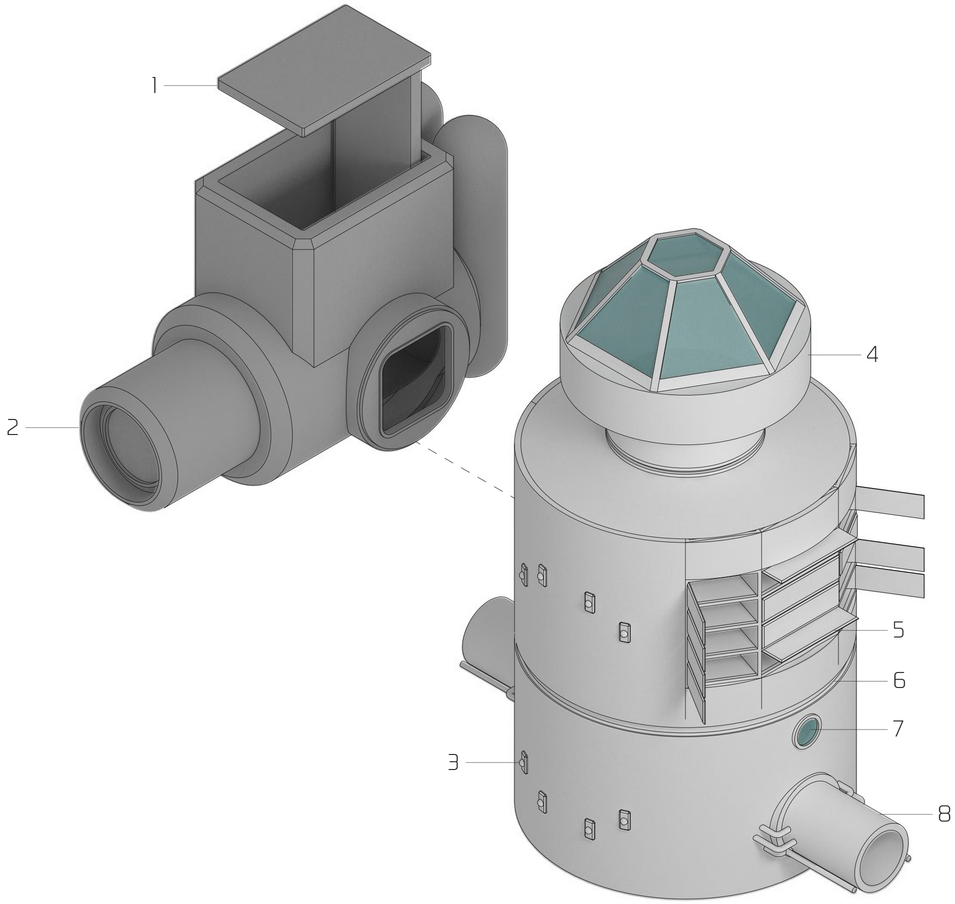

ZENITH
AFT
PORT
STARBOARD
FORWARD
NADIR (EARTH)



Hangar Exterior
Exterior surfaces utilized to store captured rocket bodies in order to guarantee unhindered removal of at least 5 large debris pieces per year.

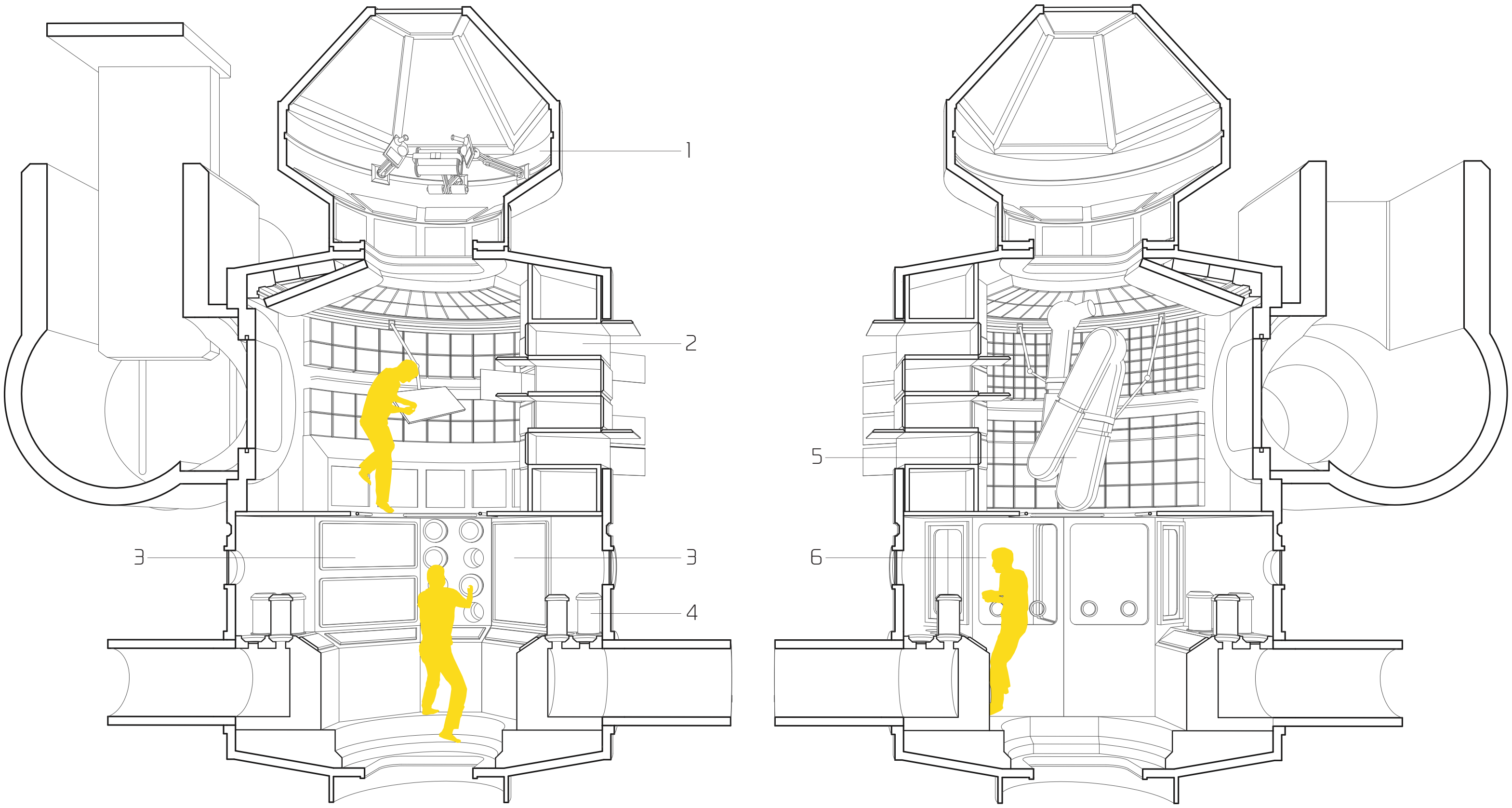


Hangar Interior
Only one rocket body at a time is processed inside the closed hangar. The interior walls are used for storage of disintegrated parts before they are passed on for fine processing to the station's pressurized section.



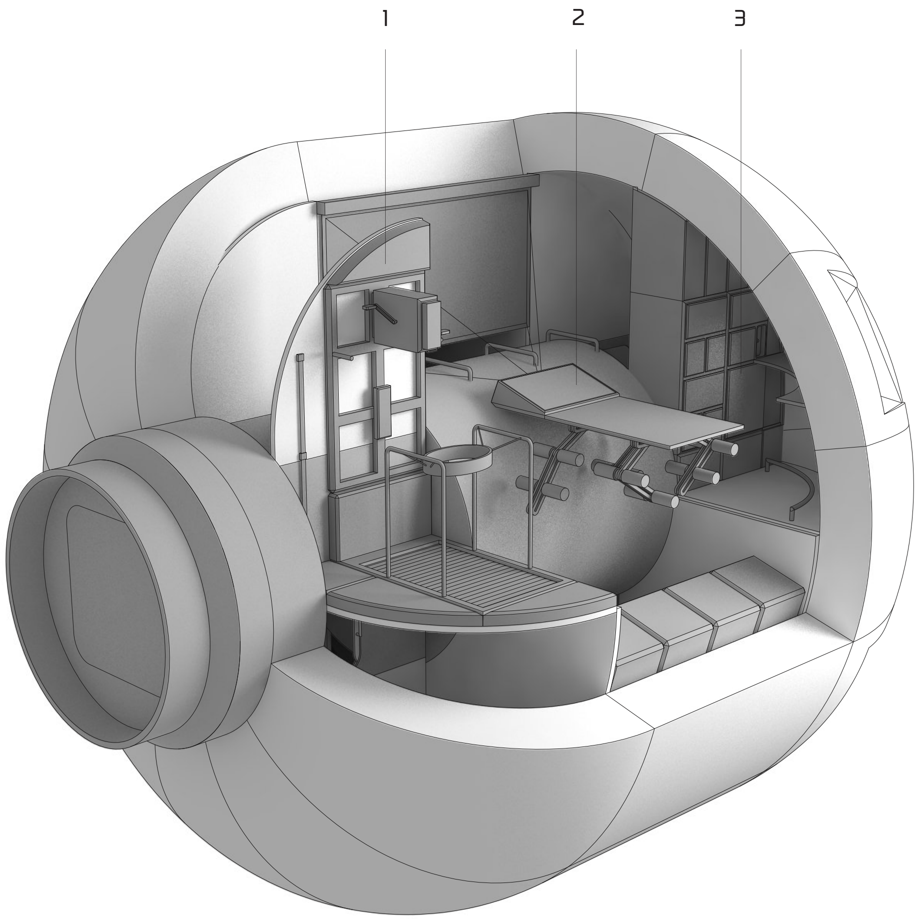
Work Module & Airlock
Isometric view of the work module, the RA control cupola and the 3-way airlock.

1 Airlock loading bay (hangar)
2 Airlock exit (external)
3 Truss grapple fixture
4 RA control cupola
5 RA toolhead exchange
6 Groove for hangar isolation
7 Window to material processing
8 Material pipeline (to parabolic mirror)

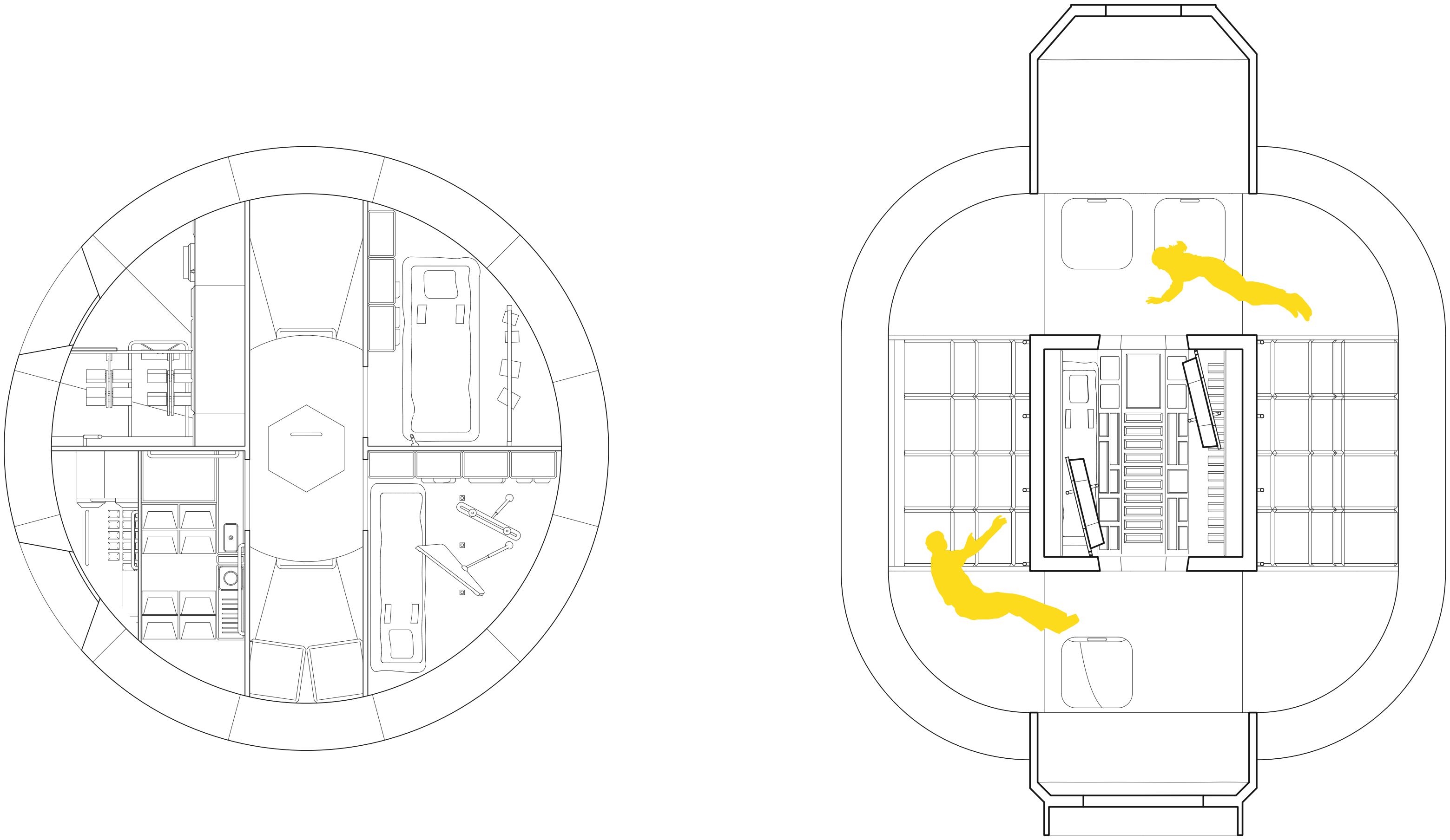


1 RA control cupola
2 RA toolhead exchange
3 Additive manufacturing
4 Containers for processed feedstock
5 Repair workshop
6 Material Processing

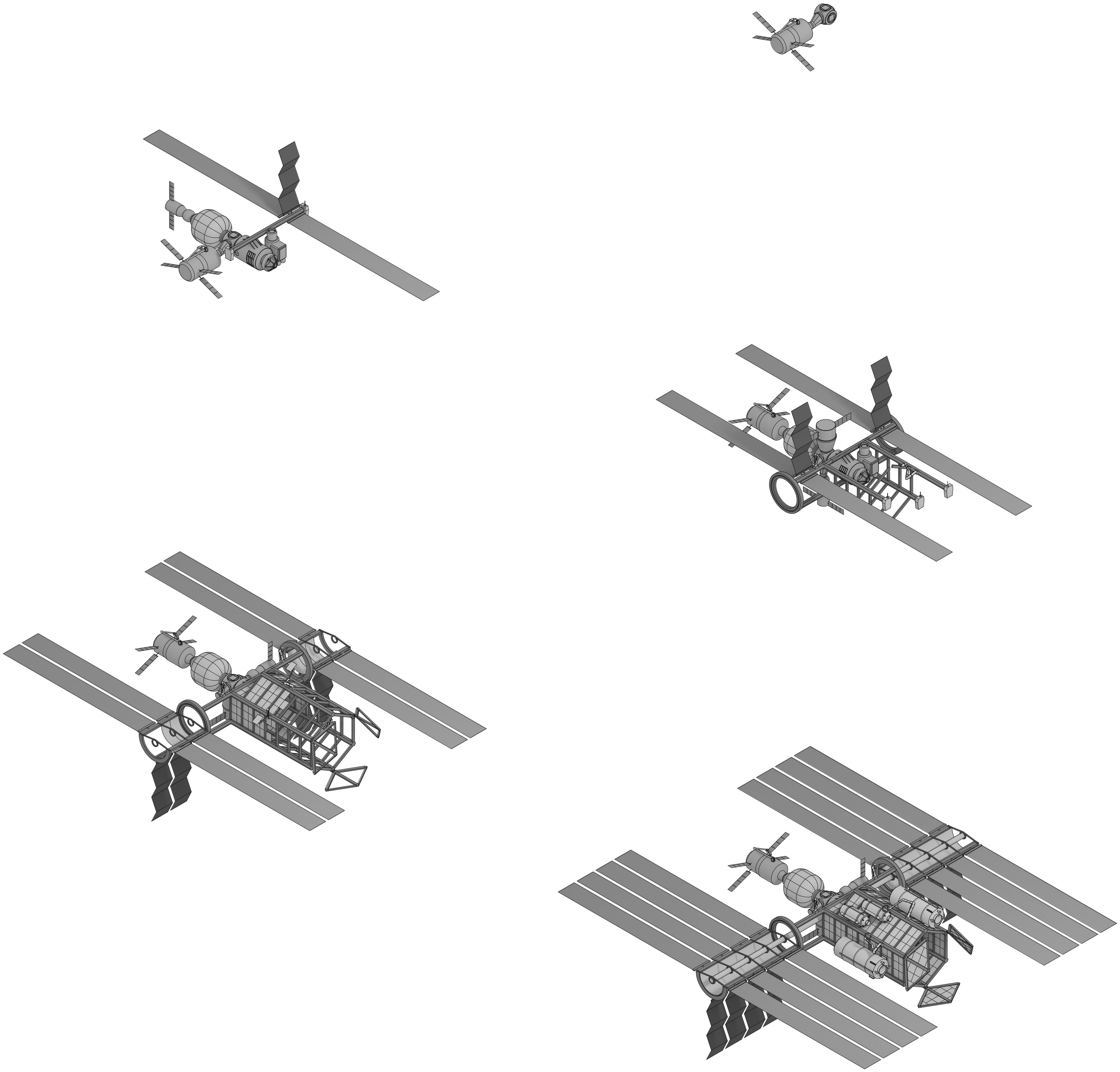
Work Module Interior
Three dimensional section showing the interior layout of the work module.

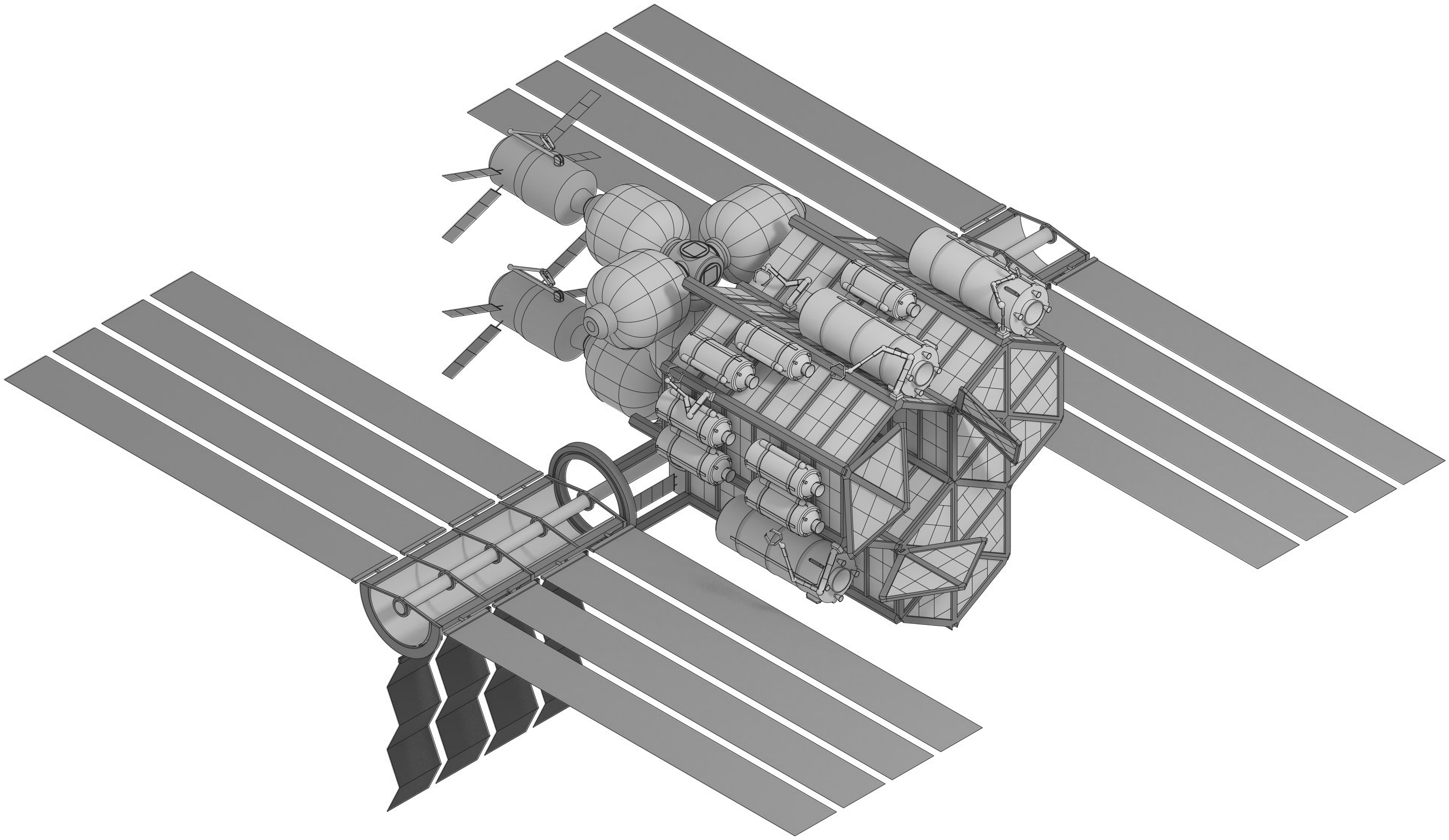


Habitation Module
Cutaway visualization showing sports (1), dining (2), and galley (3)area.



Habitation Module Plans
Floor plan of private area and section through the module.



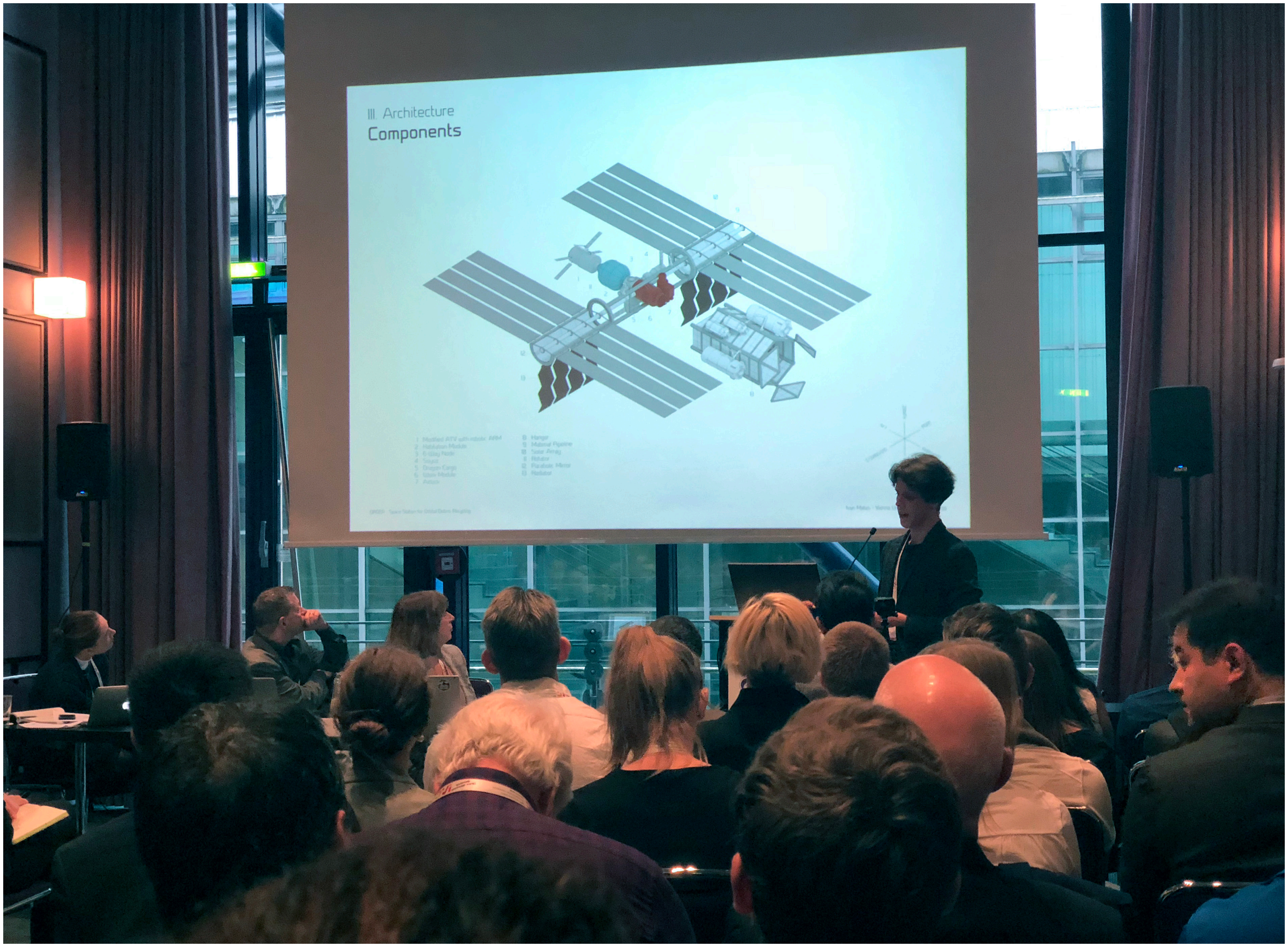


Assembly & Expandability
Steps of assembly, culminating in a potential expanded constellation of the ORDER space station, utilizing the gained material to construct additional hangars for processing of alternate kinds of debris or for orbital spacecraft manufacturing.

Presentation at IAC and Feedback

This iteration of the space station was presented at the Space Architecture panel of the 2018 International Astronautical Congress (IAC) in Bremen. The reception was positive and sparked a lot of feedback after the presentation and during the peer review of the conference-paper in the following months. While the idea was appreciated that the station utilized the gained material to expand and add additional hangars, it was criticized that it required a large amount of material launched from earth in the first place, to construct the initial hangar on orbit, while it was unclear if the added hangars would really be necessary, or bring a substantial benefit to the station. This demanded a rethinking of the possible applications for the recycled material and to question if some material could be gained through an alternative method, to be utilized for the construction of an initial hangar. Further the recycling process and material cycle were seen as ambitious and creative but not completely feasible and in need of more research. It was also pointed out that a station of this magnitude would have a substantial propellant requirement to maintain orbit as it is, and changes in altitude to rendezvous and capture rocket bodies on its own would be uneconomic.

Presentation at the IAC 2018 >
Author presenting the ORDER space station at the space architecture panel of the International Astronautical Congress 2018 in Bremen.
Foto Credit: Tom Rousek

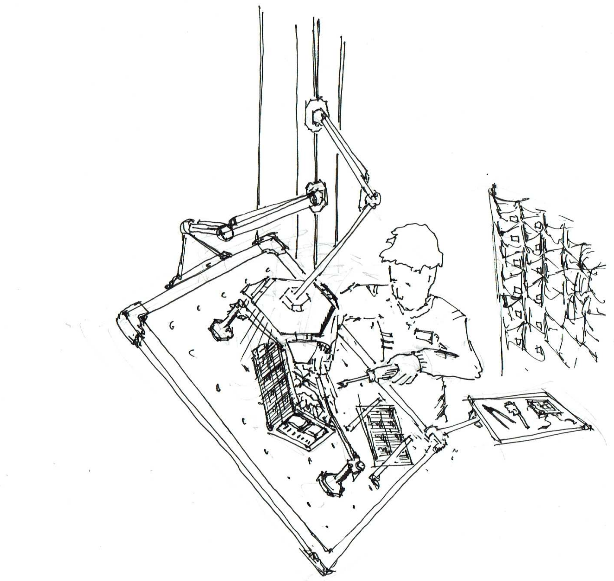

III. Architecture
Components

Adaptation of Concept

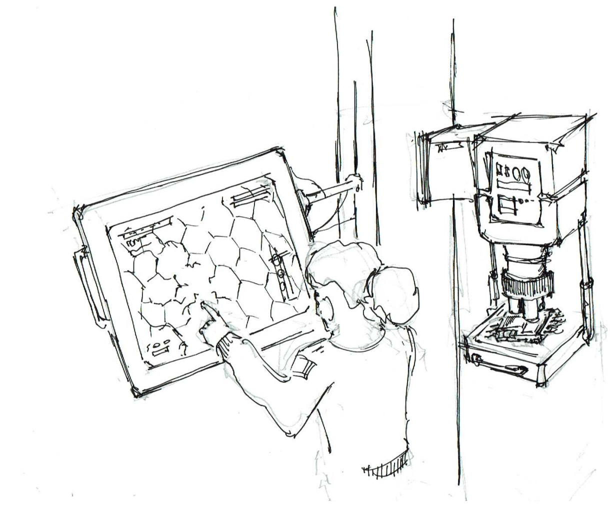
The feedback for the second iteration prompted a re-evaluation of the station's main functions and components. To find the best possible application for space debris as a resource, it became evident, that further research of and experience with actual debris was necessary.

Therefore, the next iteration of the space station would form an intermediate step to the before presented on orbit recycling facility. It would still acquire the previously defined Kosmos 3M rocket bodies, but in notedly reduced numbers. The main difference would be the waving of the large hangar component. It would be replaced by a compact shredder into which the rocket bodies or other debris could be fed and roughly disintegrated step by step. The other main focus points of the station would be the research of the debris material condition, development of fine processing steps and feedstock generation. Further, debris would not only be disintegrated but also disassembled and stripped for components. Smaller, defunct satellites could also be brought in for repairs and upgrades and subsequently be re-launched from the station. Additionally, the station could assemble and launch ADR spacecraft from orbit while simultaneously refining the technology. Finally, the station could perform scientific experiments and earth observation as is currently done on the soon to be privatized ISS. The main goal of the station would be to find the best and most efficient uses of the orbital debris resource in order to see if a large facility for recycling is viable or if some other scenario would develop.

Disassemble & Repair

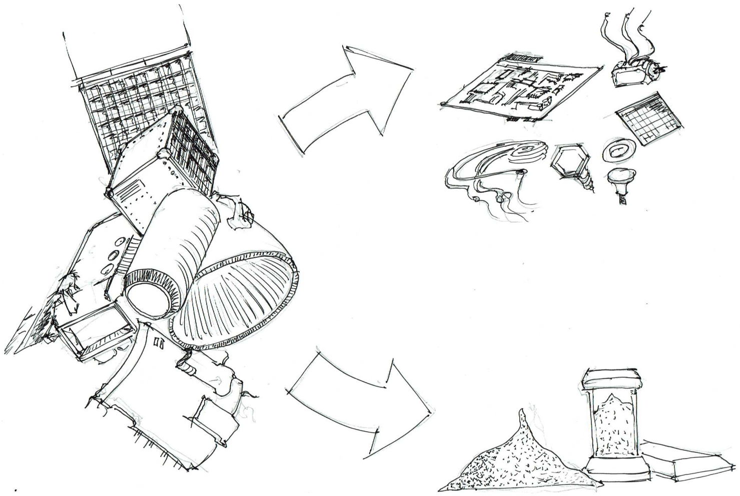


Material condition research

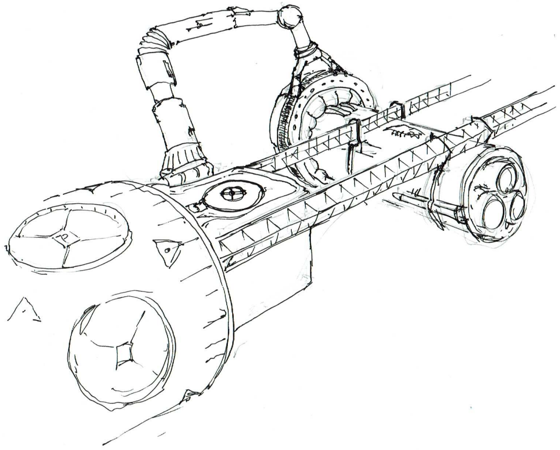


Re-thought Functions of Third Iteration
Sketches depicting the intended functional focus of the third iteration.

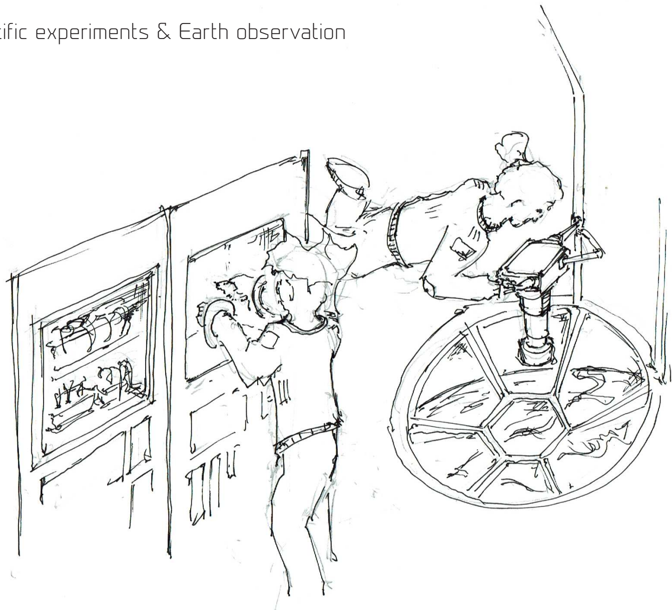
Salvage valuable components / Process raw materials



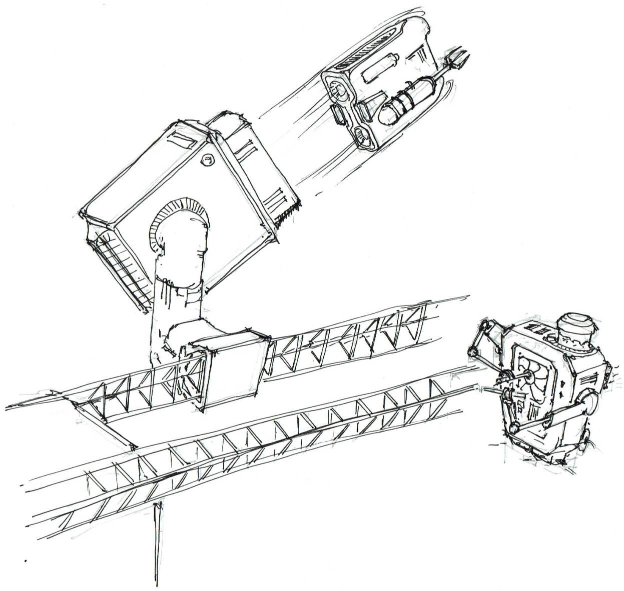
RA operated compact shredder / Eliminate necessity for hangar

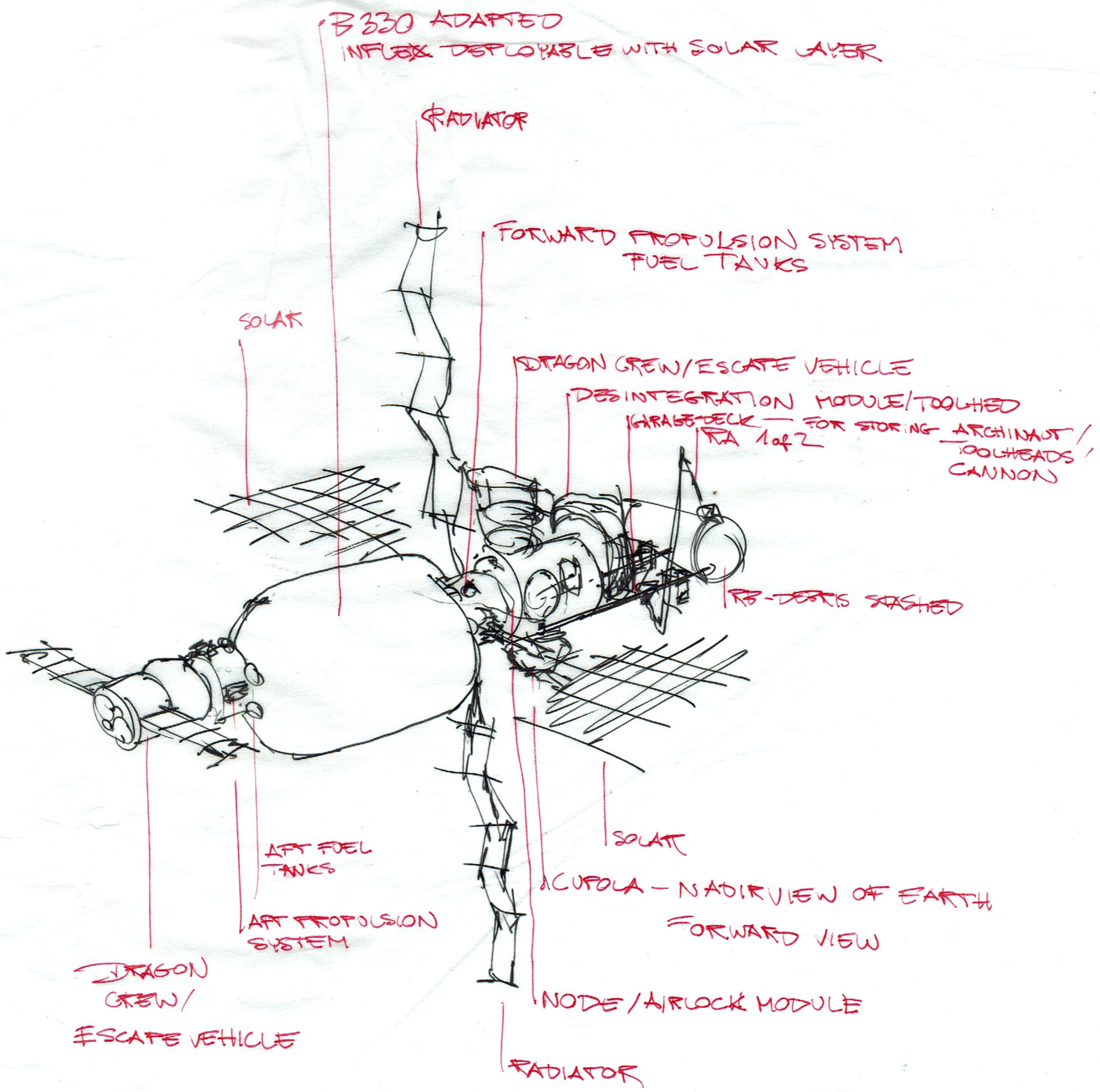


Scientific experiments & Earth observation

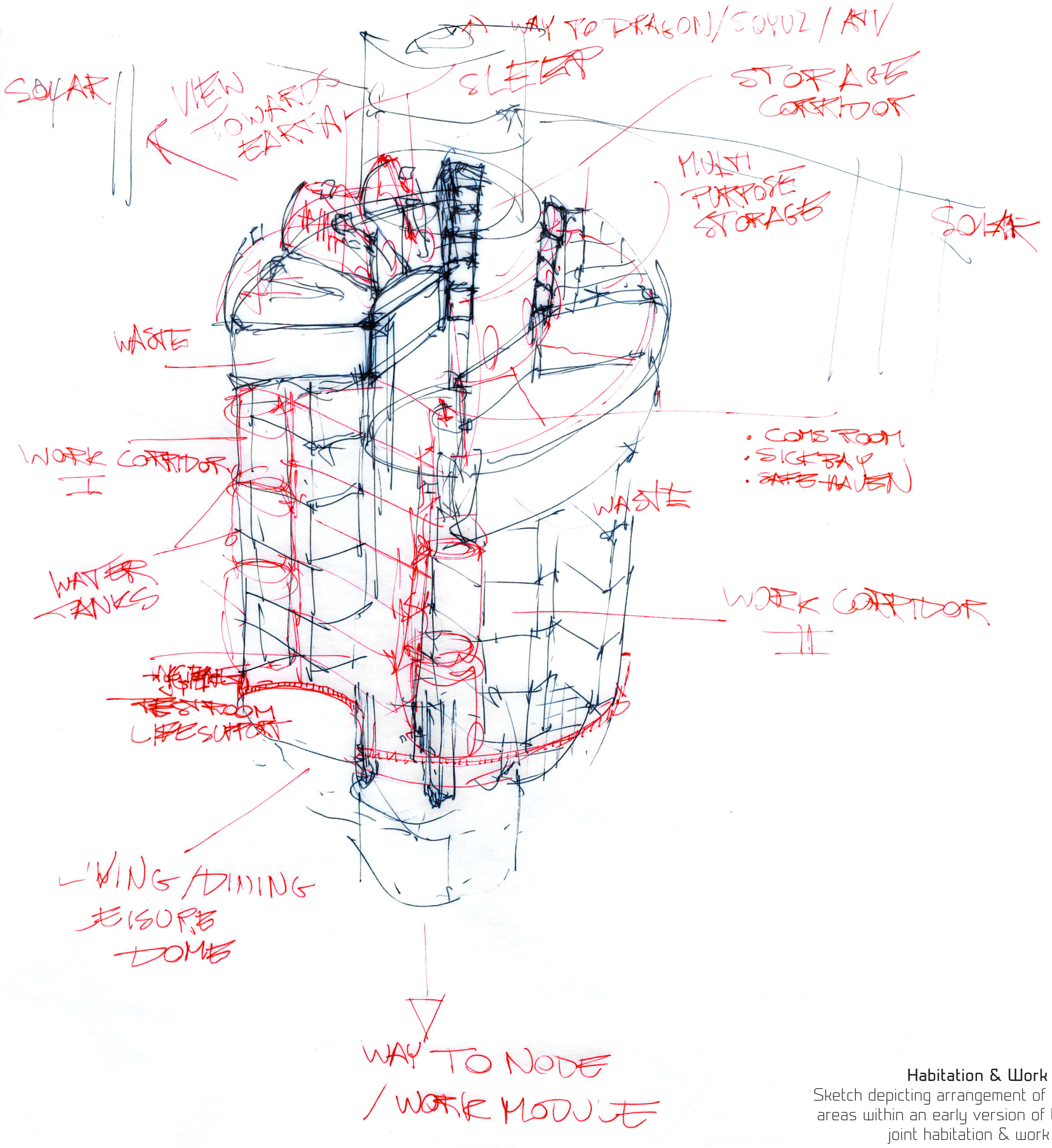


Launch satellites, ADR spacecraft & TDKs

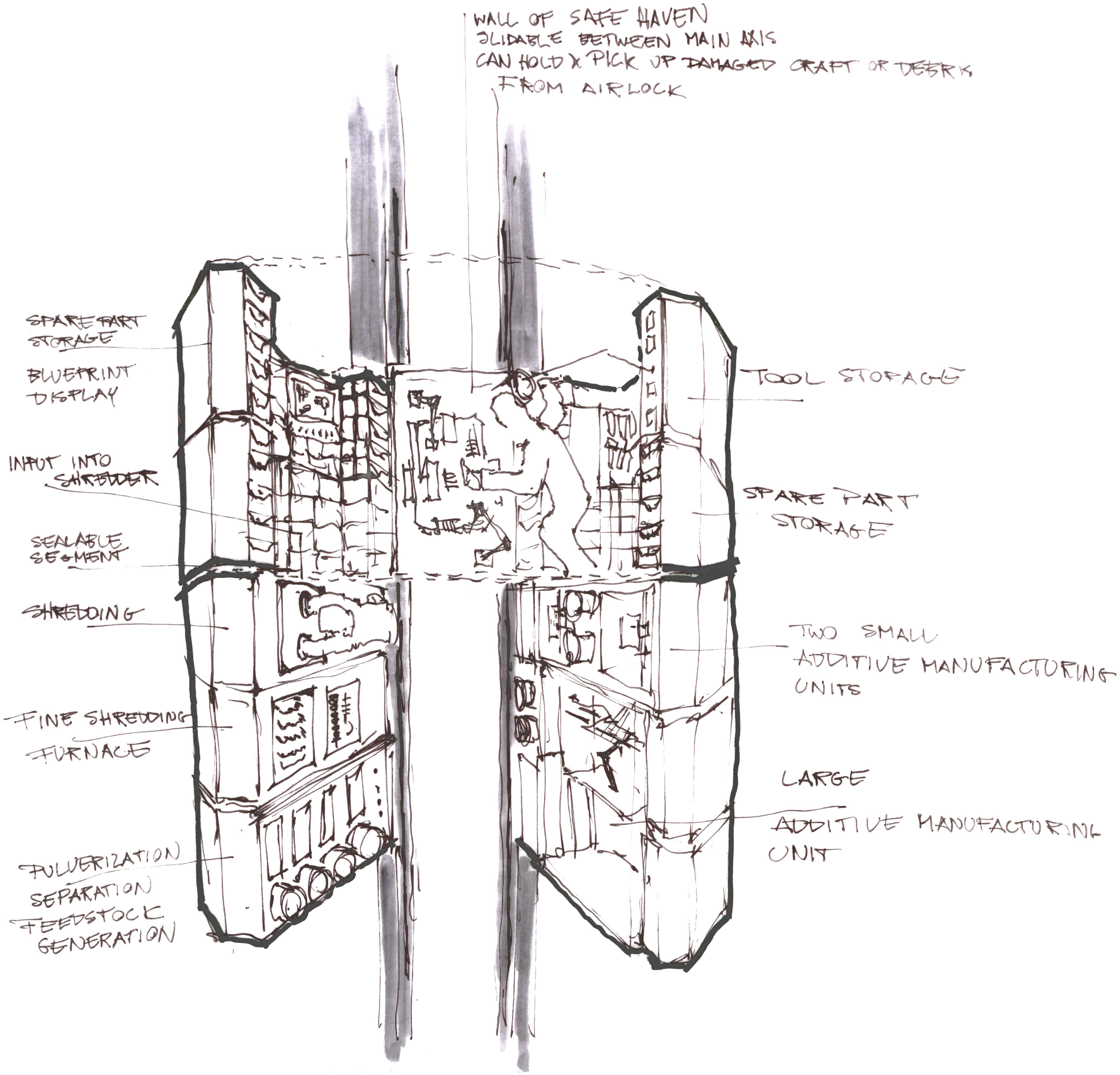




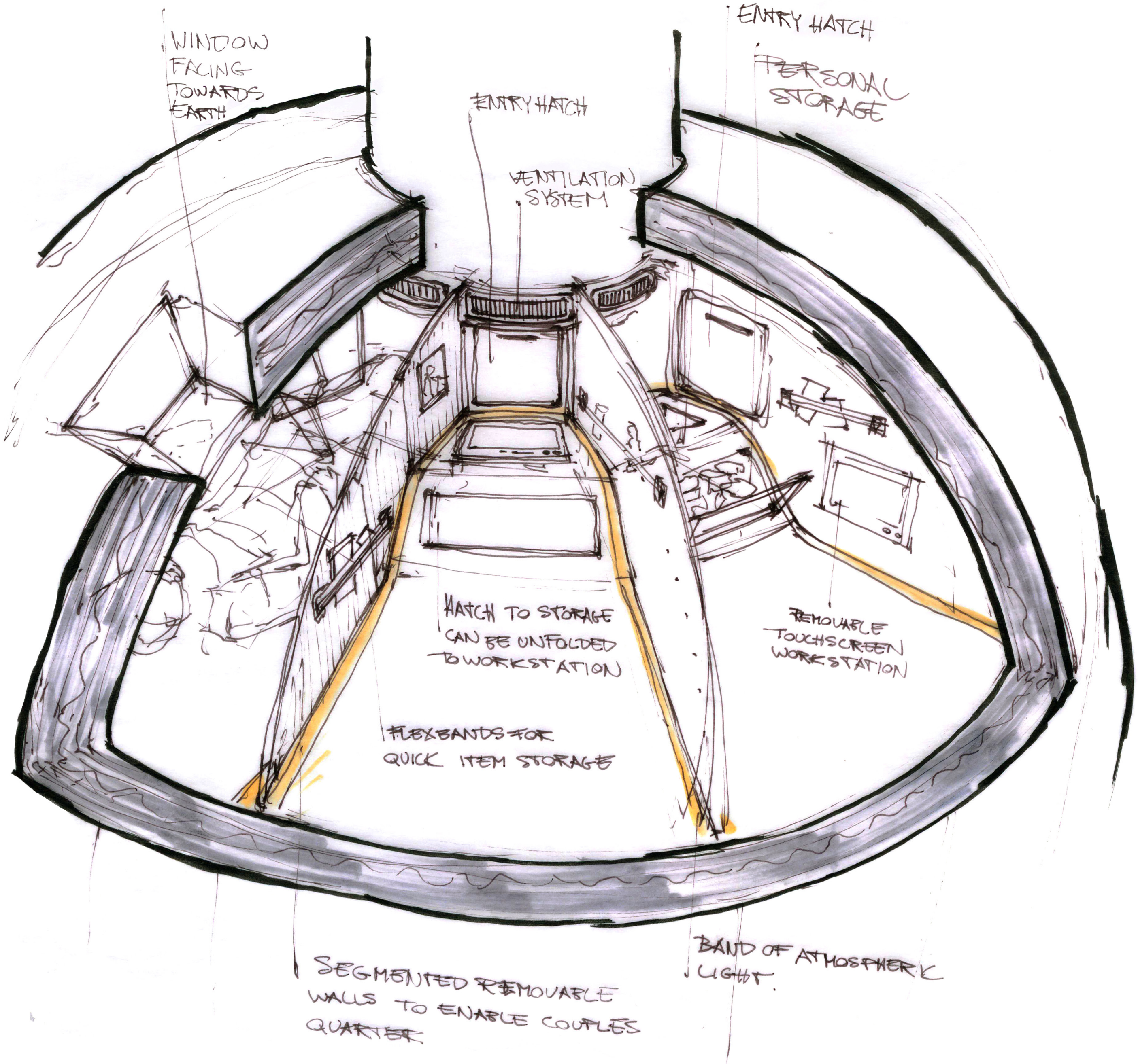
Components
Sketch depicting arrangement of the next iterations reduced components.



Habitation & Work Module
Sketch depicting arrangement of function areas within an early version of the new joint habitation & work module.

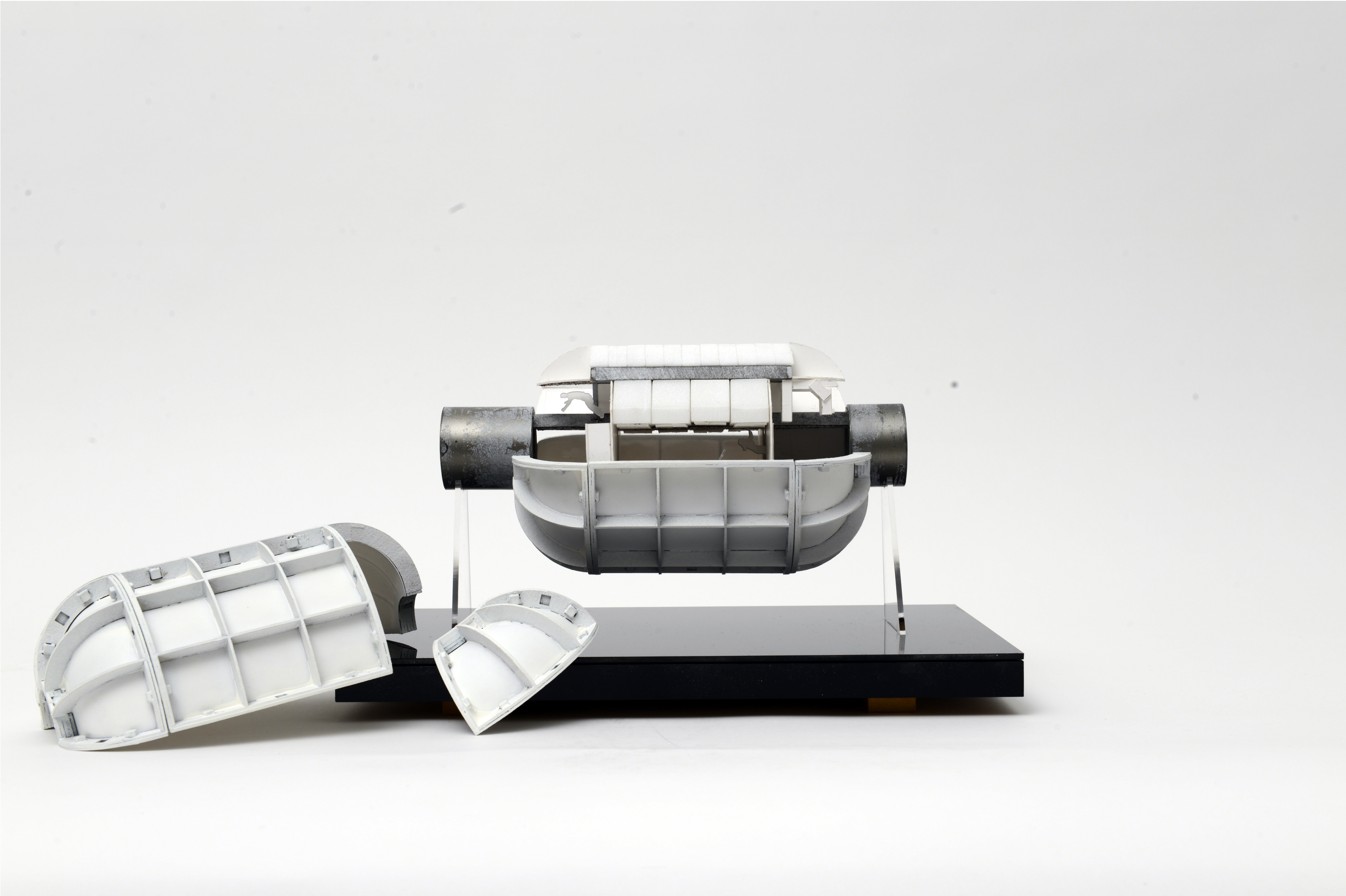


Debris Processing Corridor
Early arrangement sketch of the processing area within the new habitation & work module, utilizing ISPR racks.

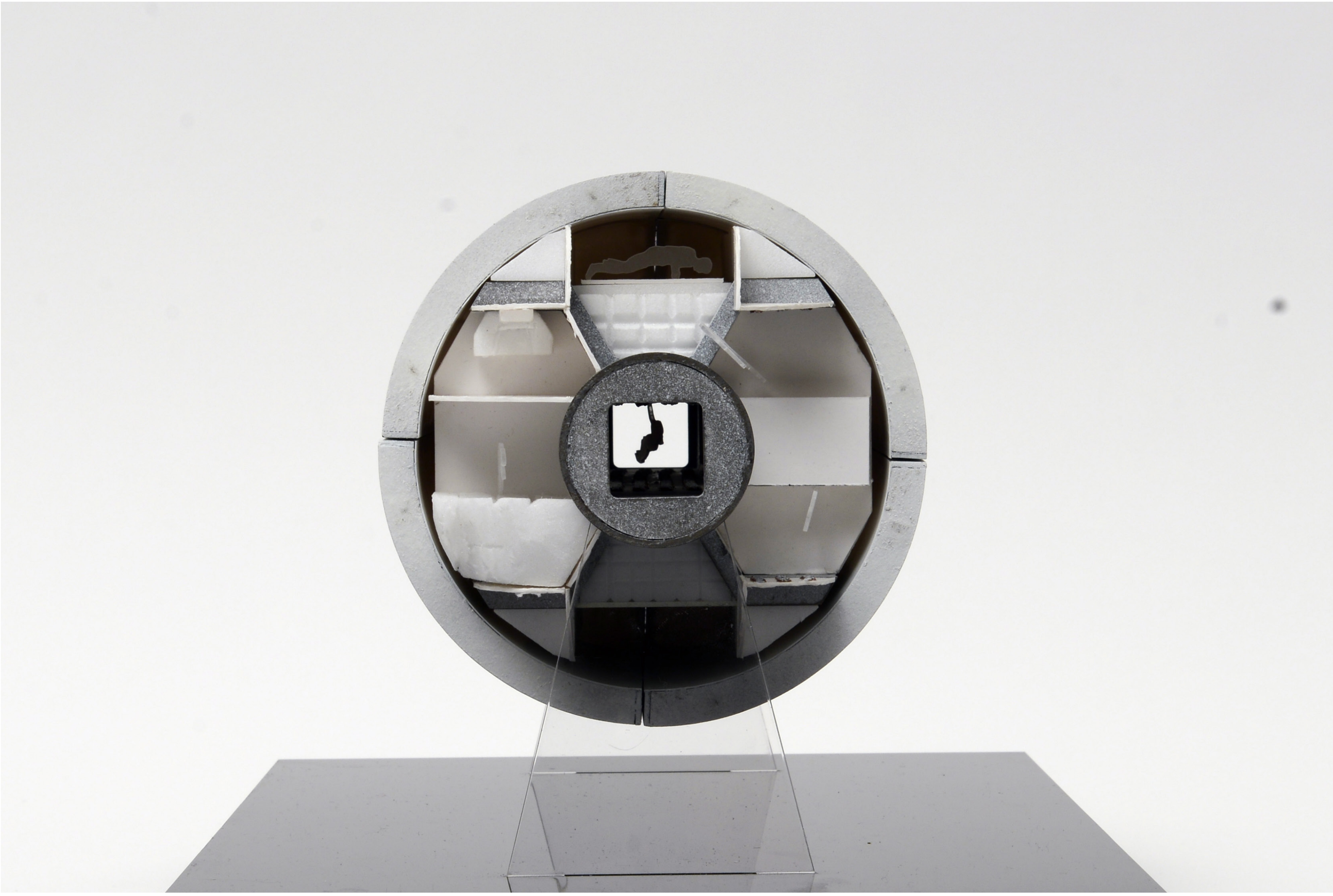


Private Quarters Sketch
Early cutaway sketch of a private quarter arrangement variation within the new habitation & work module.

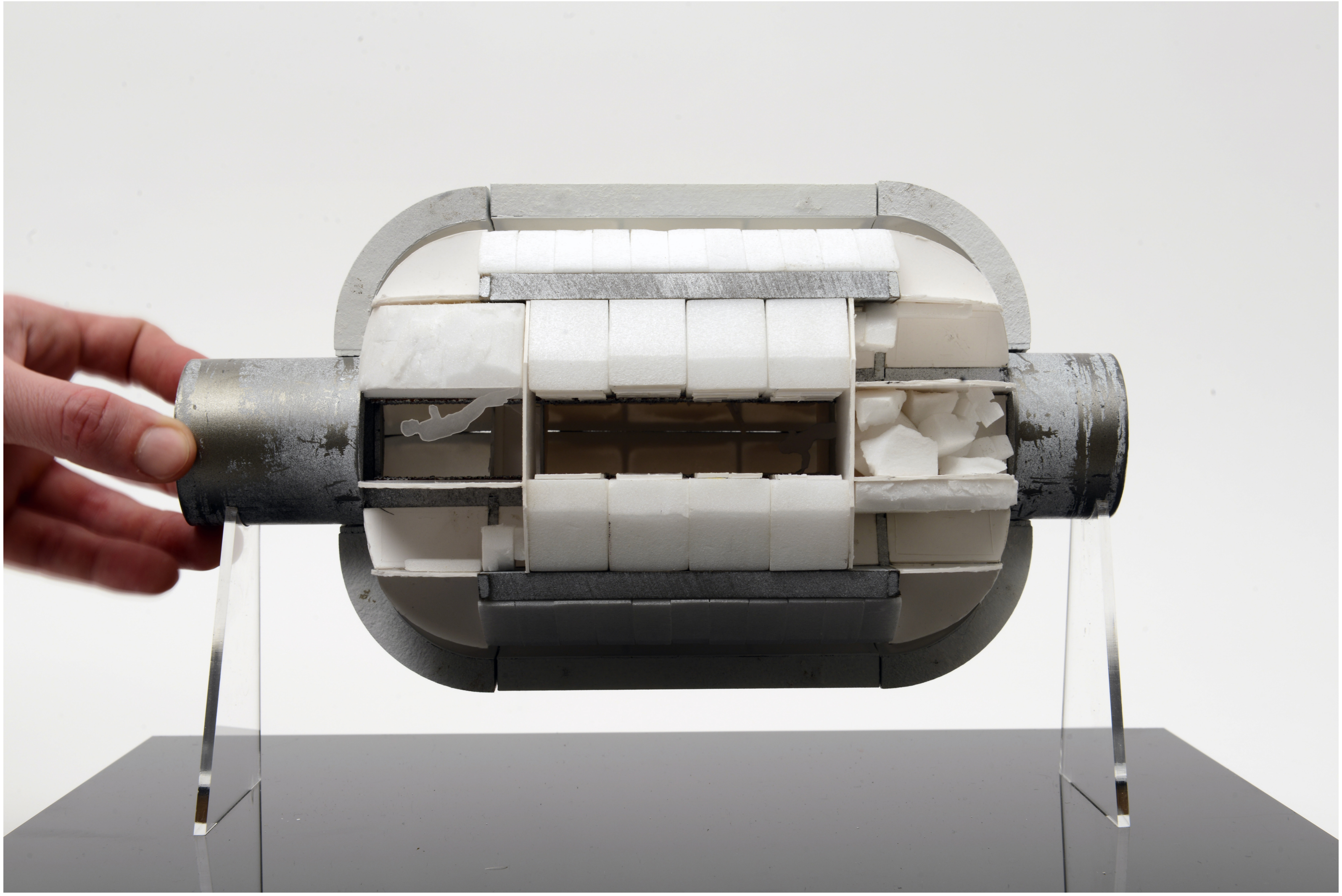
Working Model
Model of the new habitation & work module
for the station's third iteration.
Foto Credit: Niklas Heiss



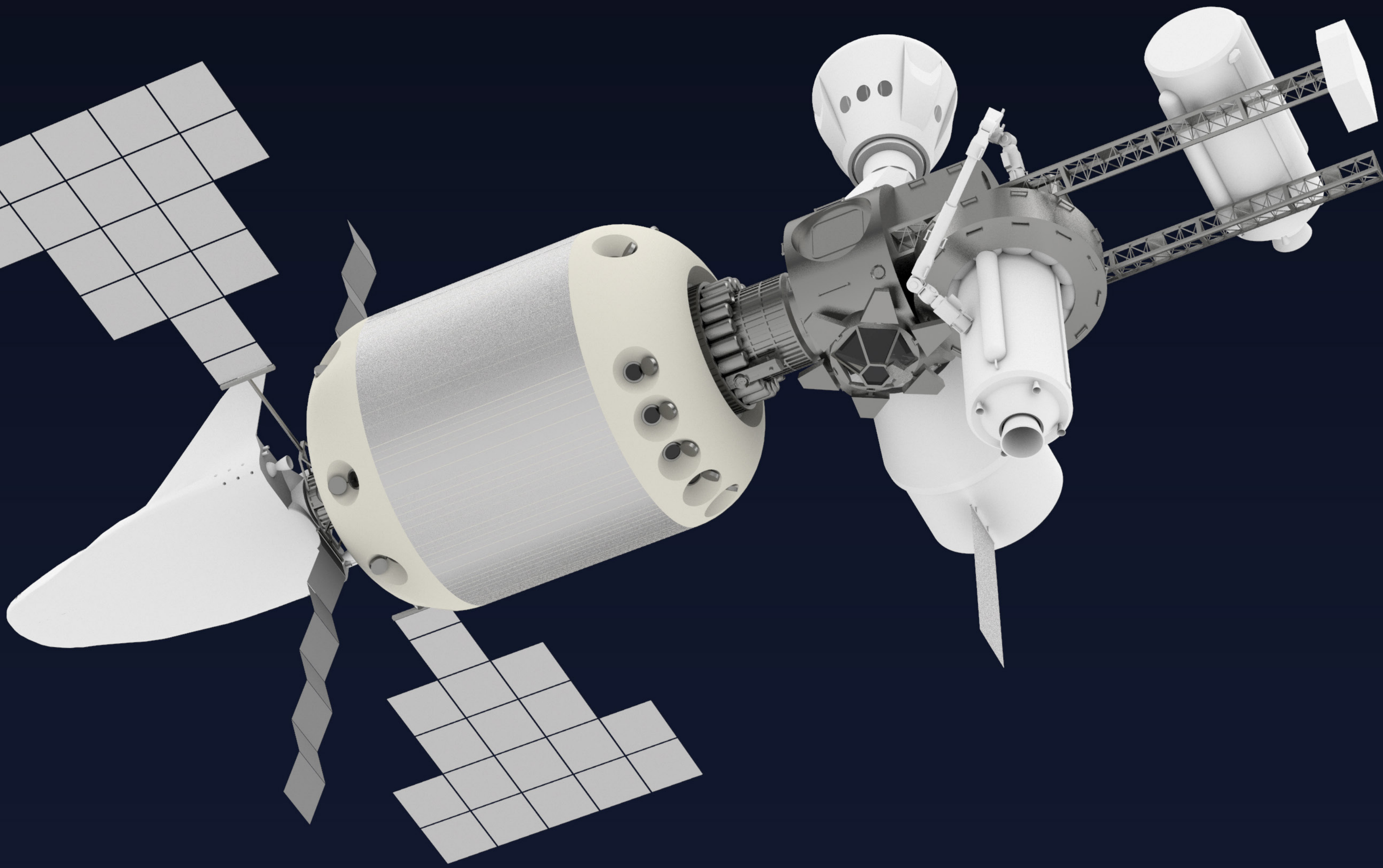
Working Model
Shell parts can be magnetically attached and detached to examine interior space quality. Multiple interior variations were built.
Foto Credit: Niklas Heiss



Working Model
Cross section presenting an early version of the social area.
Foto Credit: Niklas Heiss



Working Model
Longitudinal section with a view through the early version of the work corridors containing ISPR sized racks.
Foto Credit: Niklas Heiss



06 Final Design: Third Iteration

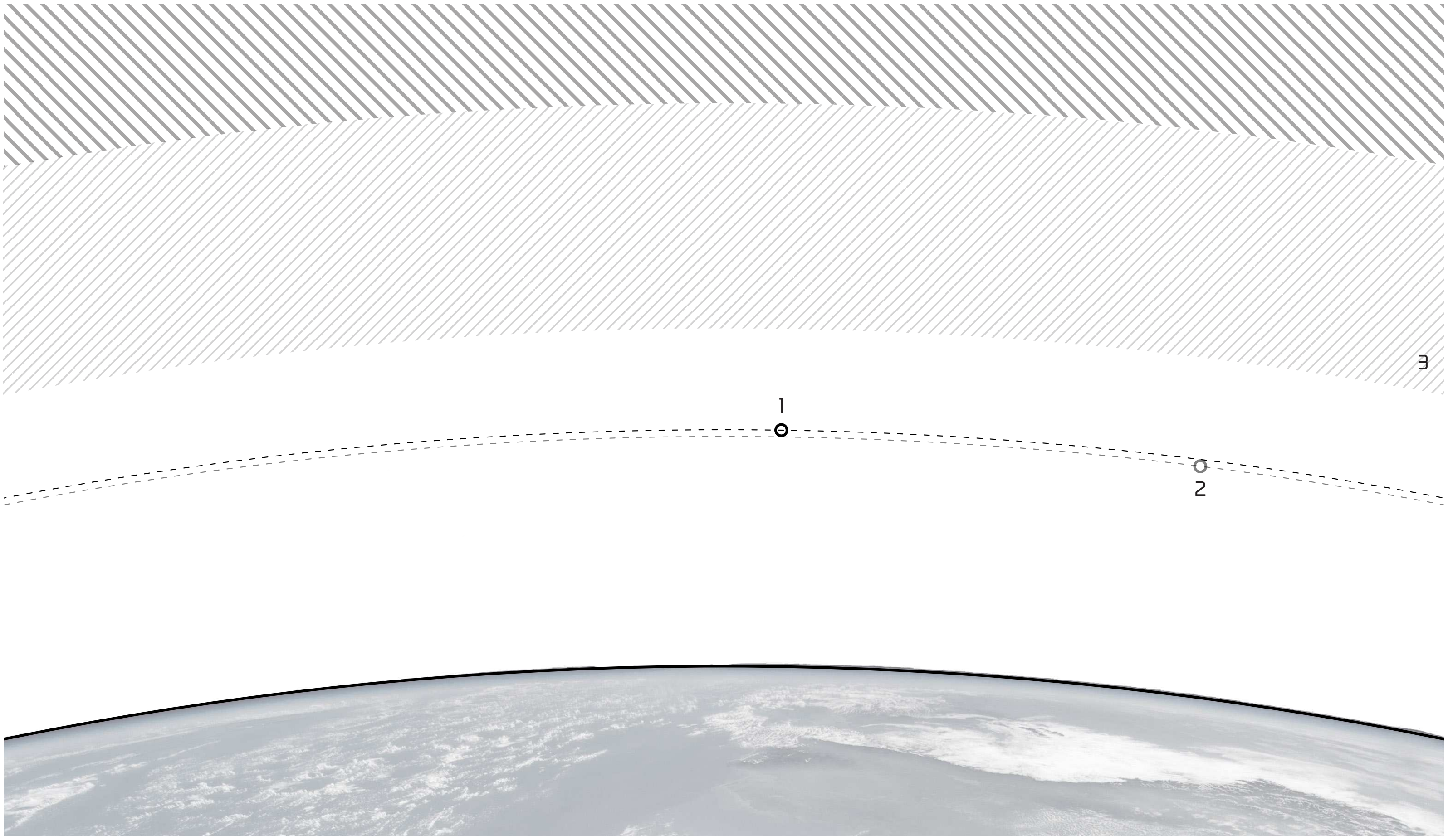
< **Space Station R3-Debris**
Space station for Research concerning Resource utilization and Recycling of Debris, viewed from below.

Introduction

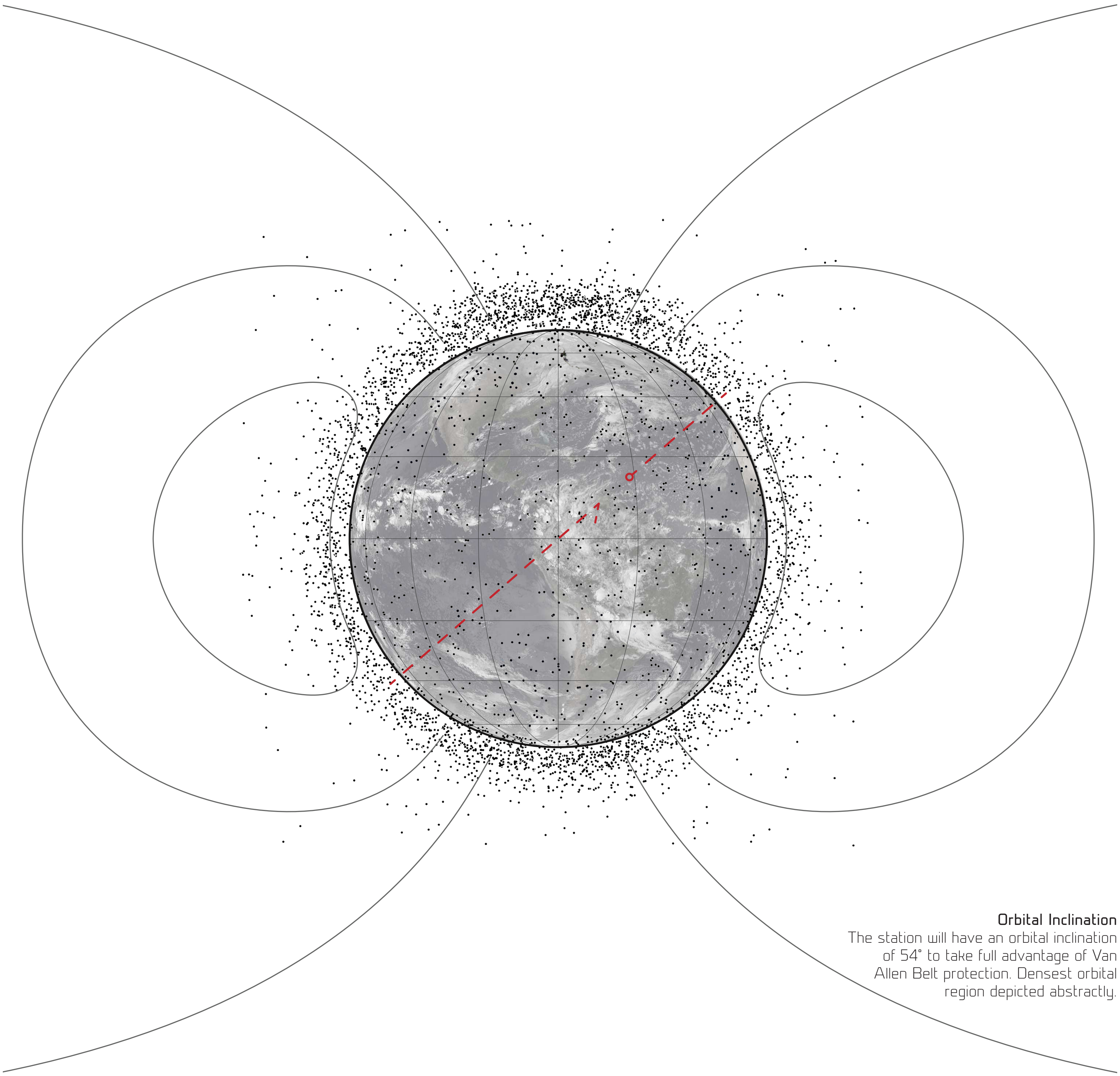
This chapter depicts the third iteration, the final design of the Space Station named R3-Debris (Research concerning Resource utilization and Recycling of Debris). Its main components are a joint habitation and work inflatable module, based on the dimensions of the BA-330 (see page 58), and a node and airlock module, equipped with a compact shredder (replacing the large hangar for rough processing) and a cupola for Ra control and Earth observation.

The station regularly houses a crew of 4 on 6-12 month missions, and can accommodate up to 8 people during crew exchange periods. Its main goal is the research of orbital debris, its material properties and utilization possibilities, as well as the development of ADR methods.

During the design process a particular attention was attributed to the joint habitation and work module, which is presented in a more elaborate detail. The main architectural focus was placed on habitability and an adequate distribution of the functions within the module. It is divided into a private, work and social section, whereas the former is specifically placed in the most quiet part of the space station constellation, to ensure maximal tranquillity for the crew during resting periods. The module is further equipped with a sealed environment material processing and workshop segment, two ISPR sized rack corridors for exchangeable experiments, a storage corridor, an additive manufacturing facility, a social hub, hygiene and sport facilities, as well as a greenhouse.



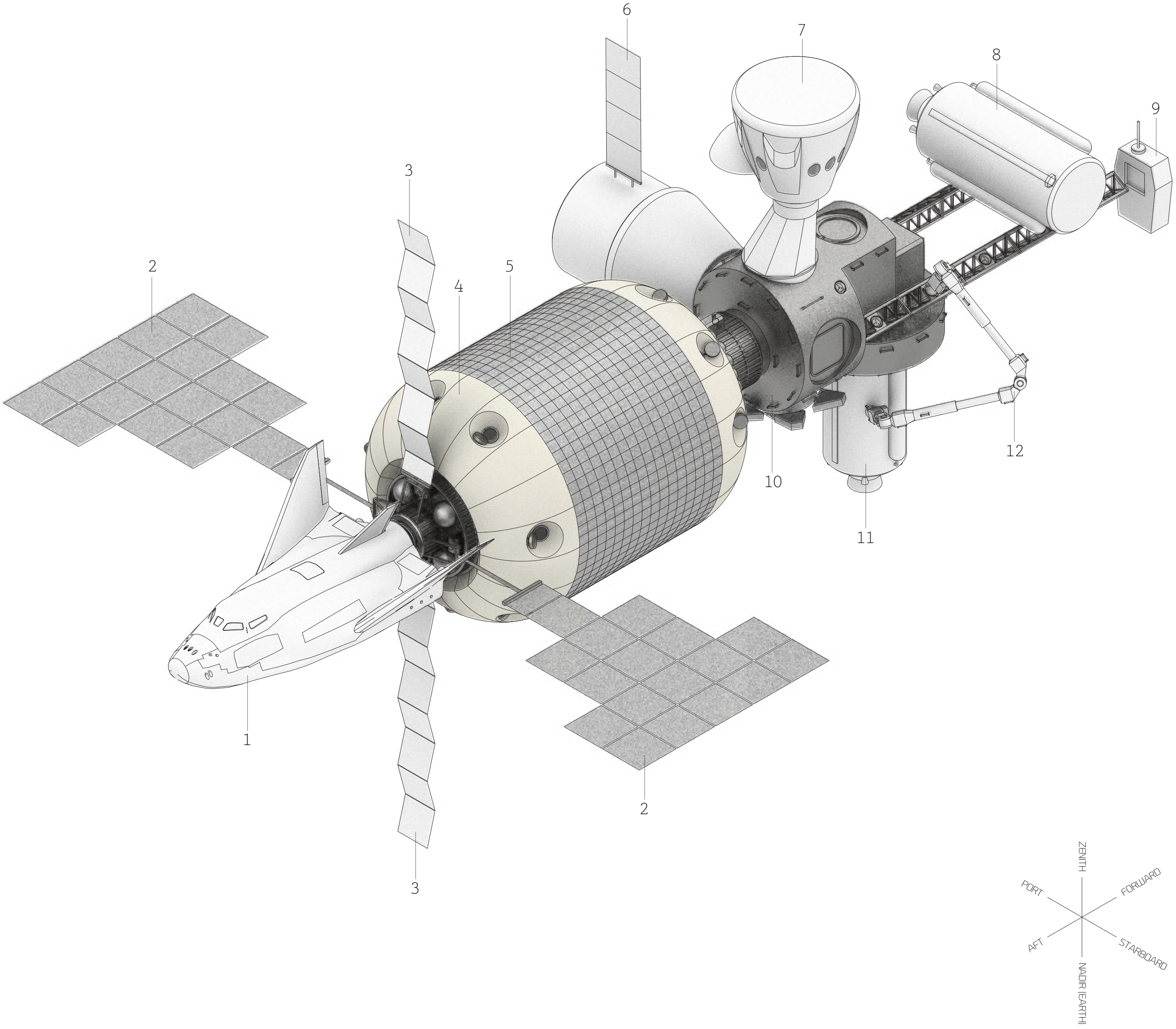
Orbital Location
The station will be orbiting at an altitude of aprox. 420 km (**1**). The ISS (**2**), for comparison, orbits at aprox. 400km altitude. Both stations are protected from radiation by the Van Allen Belts (**3**)



Orbital Inclination
The station will have an orbital inclination of 54° to take full advantage of Van Allen Belt protection. Densest orbital region depicted abstractly.

COMPONENTS

1 Dreamchaser
2 Solar array
3 Radiators
4 Habitation & work module
5 Solar panels on inflatable layer
6 Dragon cargo
7 Dragon crew
8 Stored rocket body
9 Archinaut
10 Node, airlock & shredding module
11 Rocket body being processed
12 Robotic arm



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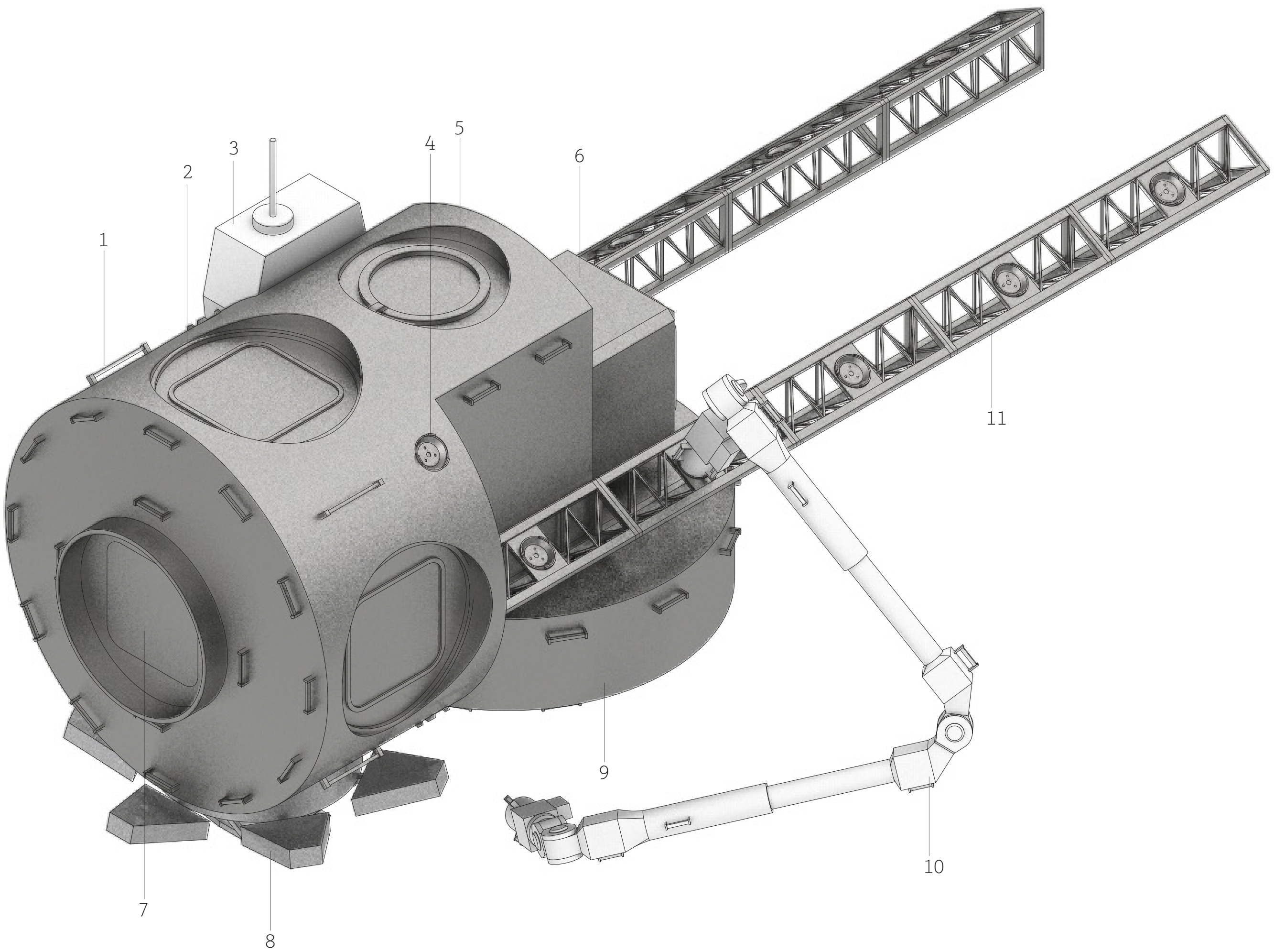
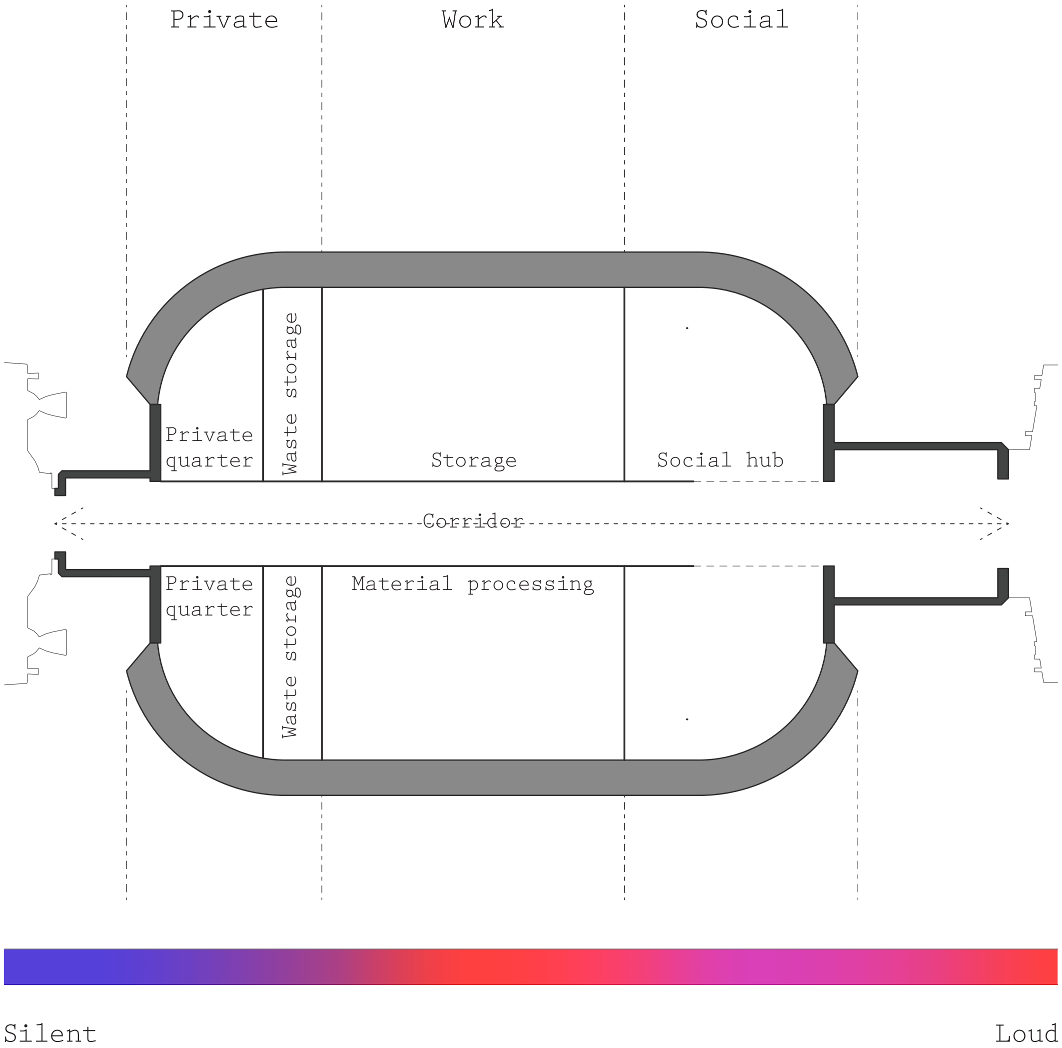
ZENITH
PORT
FORWARD
AFT
STARBOARD
NADIR (EARTH)

COMPONENTS

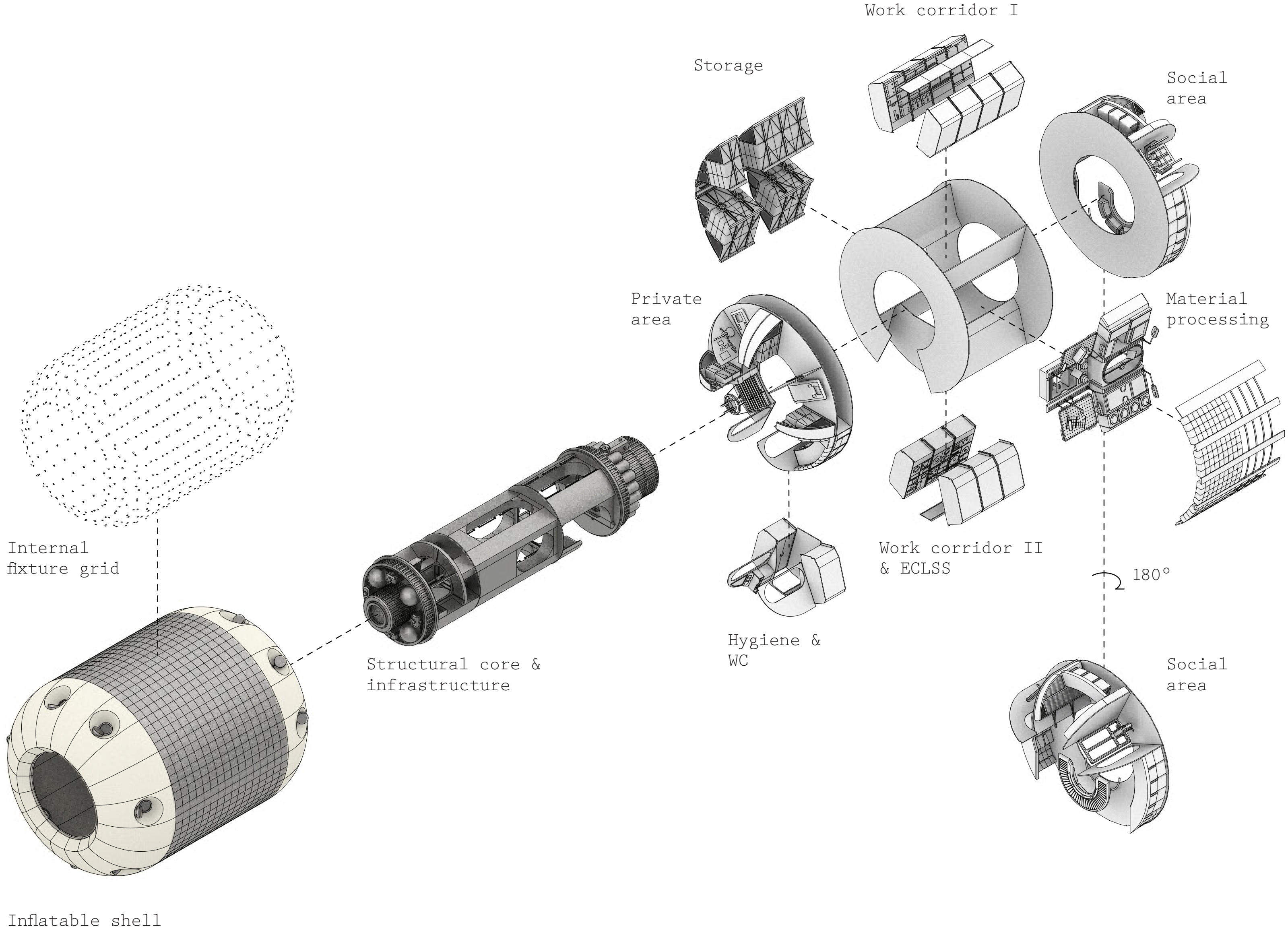
1 Handrail
2 Common berthing mechanism
3 Archinaut (parked)
4 Grapple fixture (RA movement)
5 Airlock EVA exit
6 Scientific airlock
7 CBM connected to habitation & work module
8 Cupola for RA control and Earth observation
9 Rough processing shredder
10 Robotic arm
11 Truss framework for debris storage



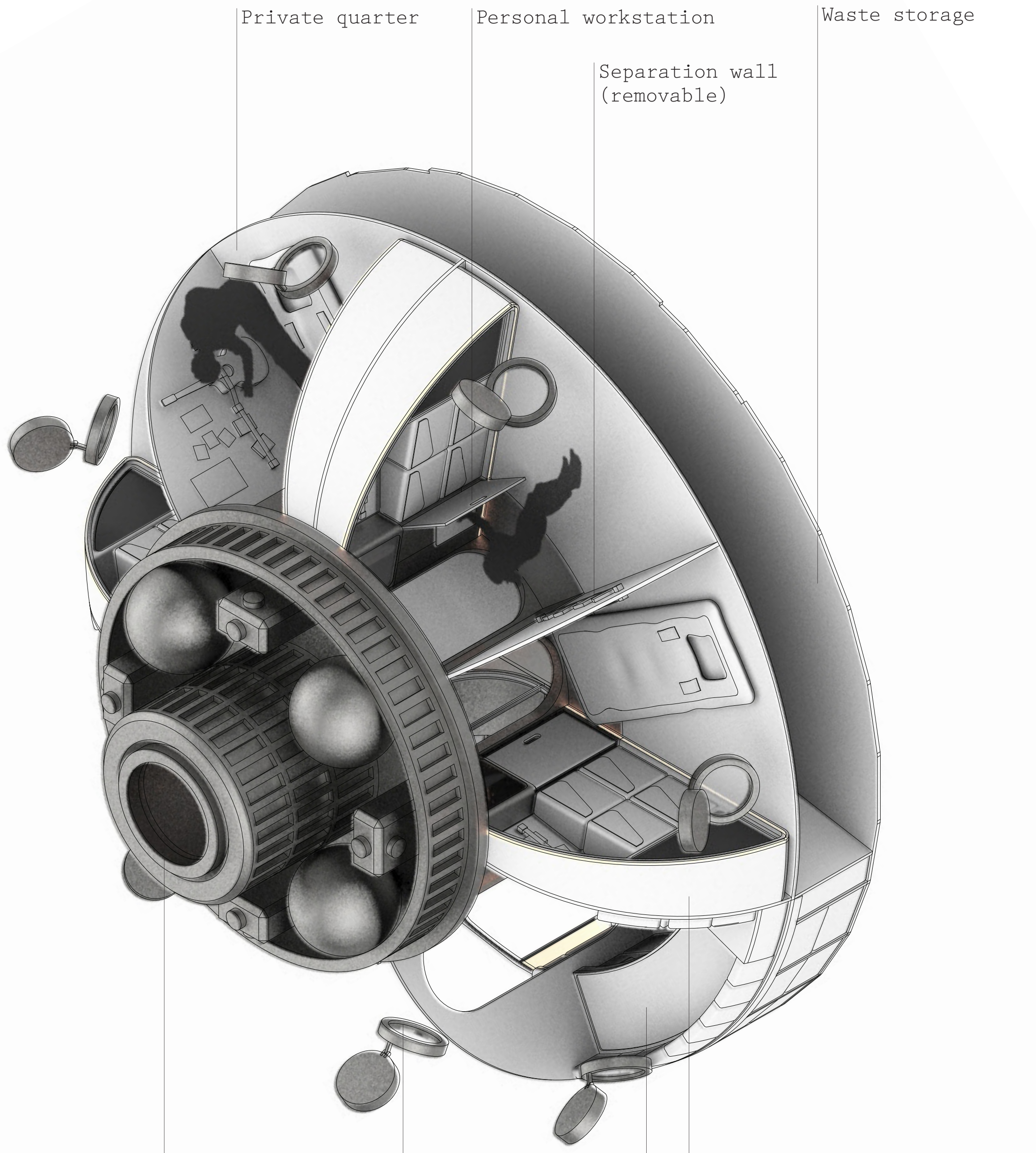
Node, Airlock & Shredding Module
The module provides a harbor for an Archinaut spacecraft, as well as a storage truss for captured debris. It features an airlock with an EVA and science exit, a cupola, for RA control and Earth observation, and a rough processing shredder that can be fed with debris pieces by the RA.



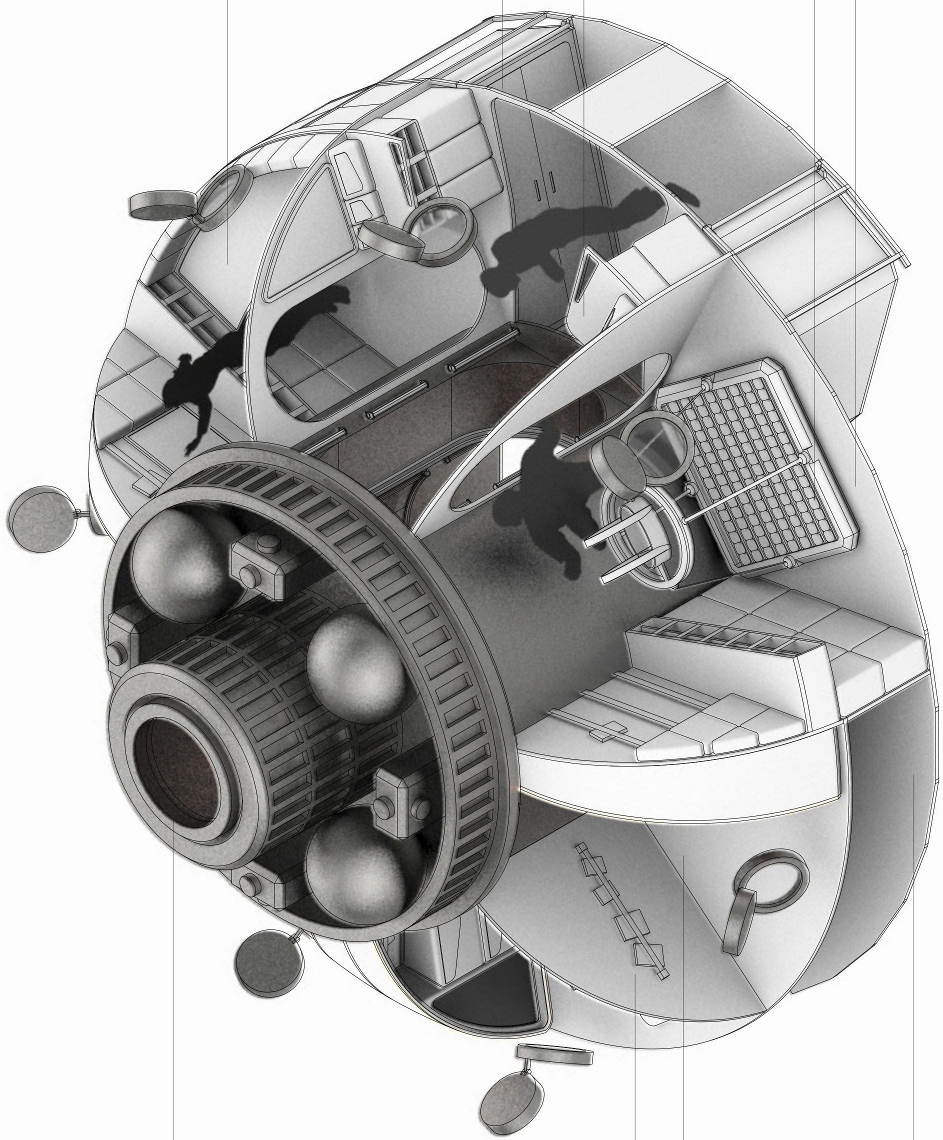
Zoning of Habitation & Work Module
The module is divided into a private, work, and social area. The private quarters are placed at the silent aft end of the module and separated by the waste storage compartment from the noisy work area. All areas are accessible by a central corridor.



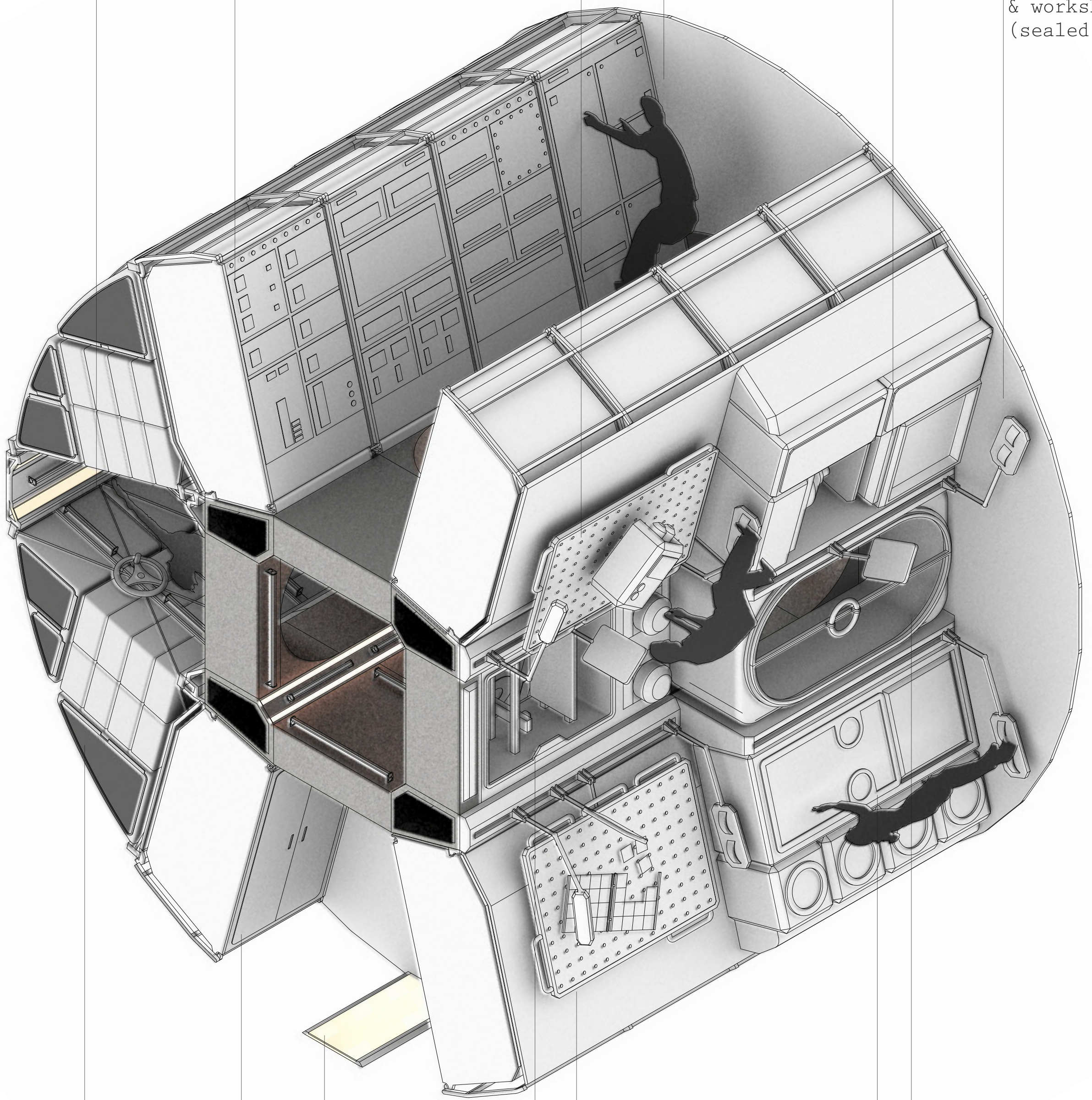
Habitation & Work Module Exploded View
The Inflatable shell is fixed to the forward and aft endplates of the core element, which takes the structural stresses during launch and contains the infrastructure of the module. The private and social areas are positioned in the dome-shaped ends of the module with the work area in between.



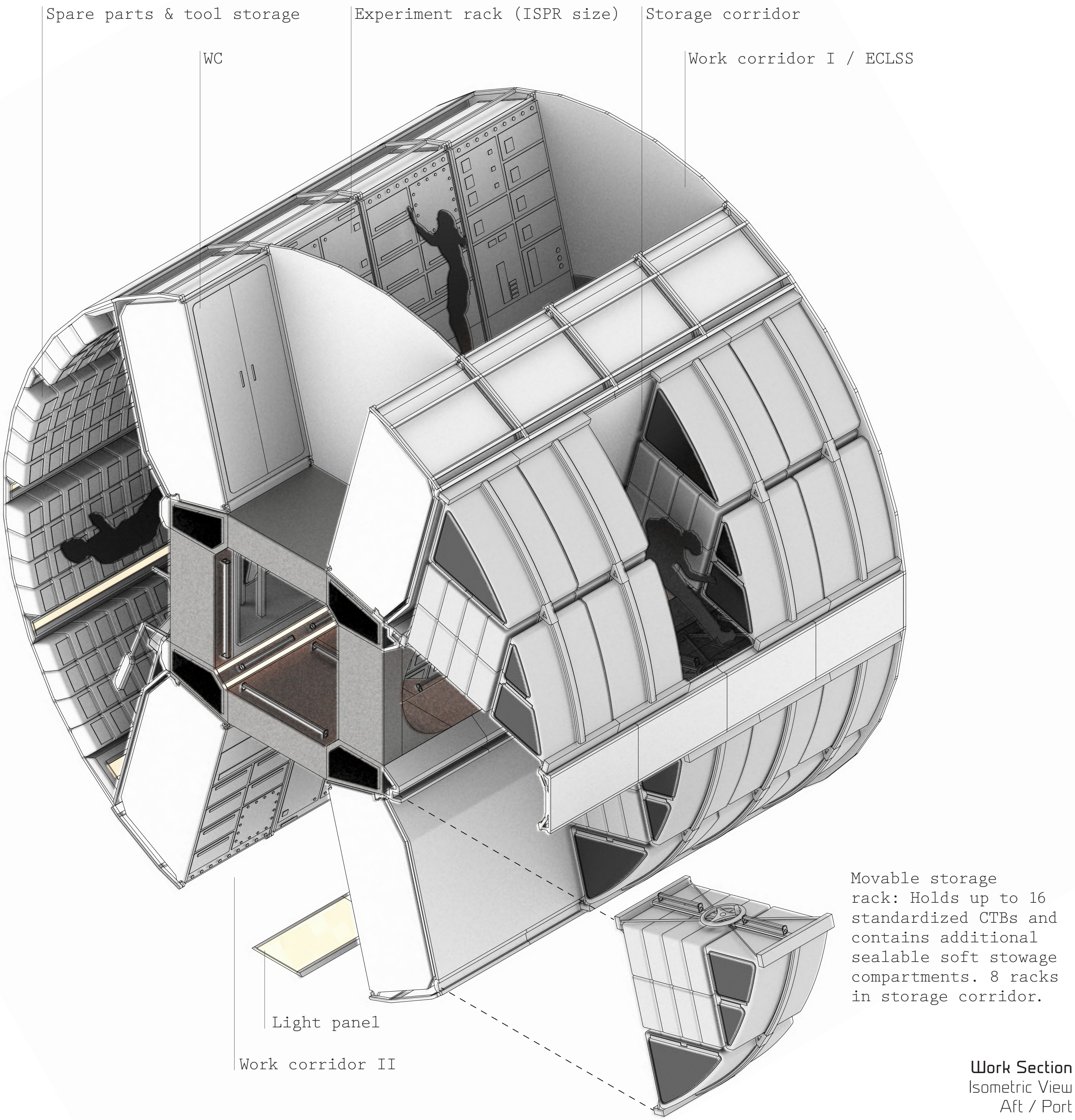
Private Section
Isometric View
Aft / Starboard



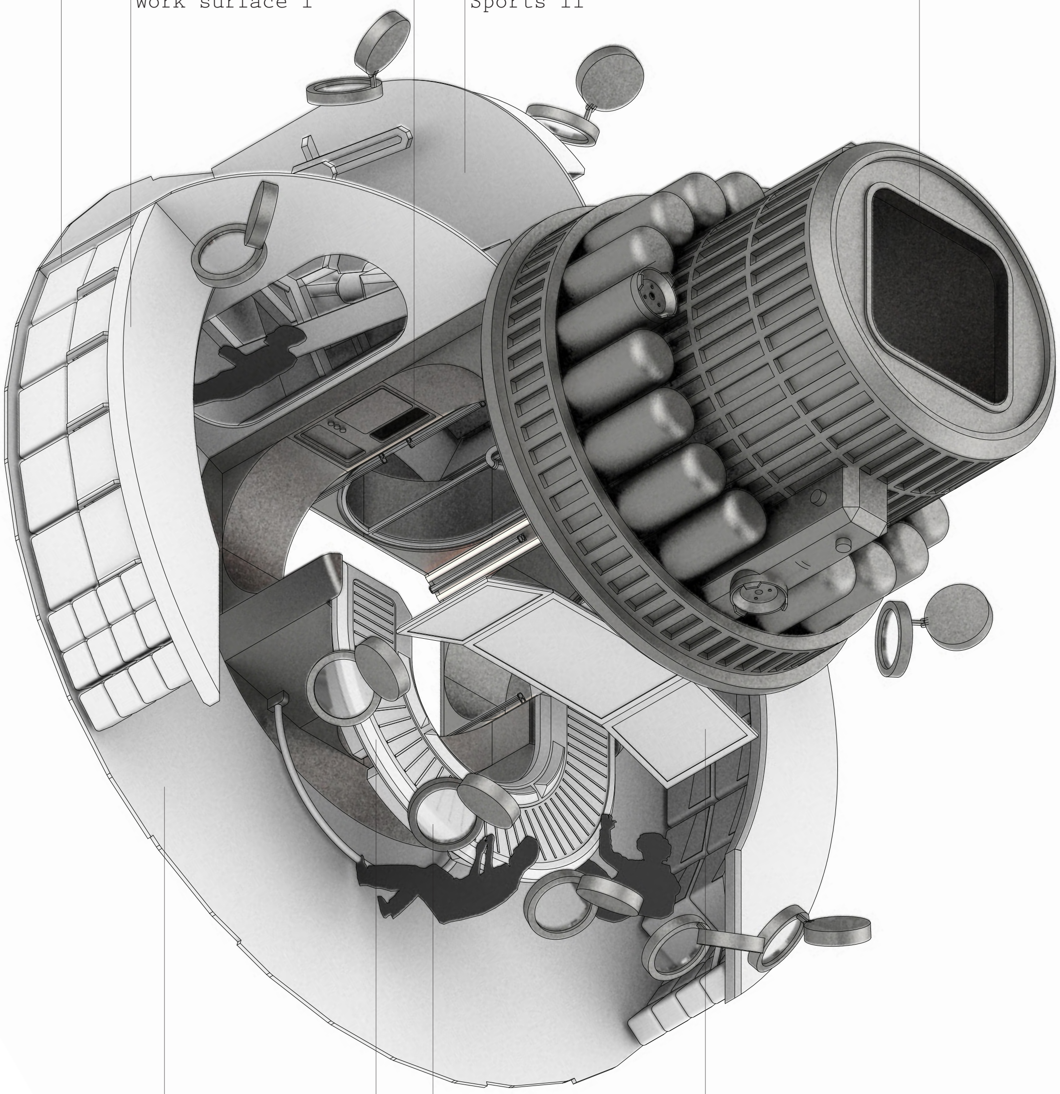
Private Section
Isometric View
Aft / Port



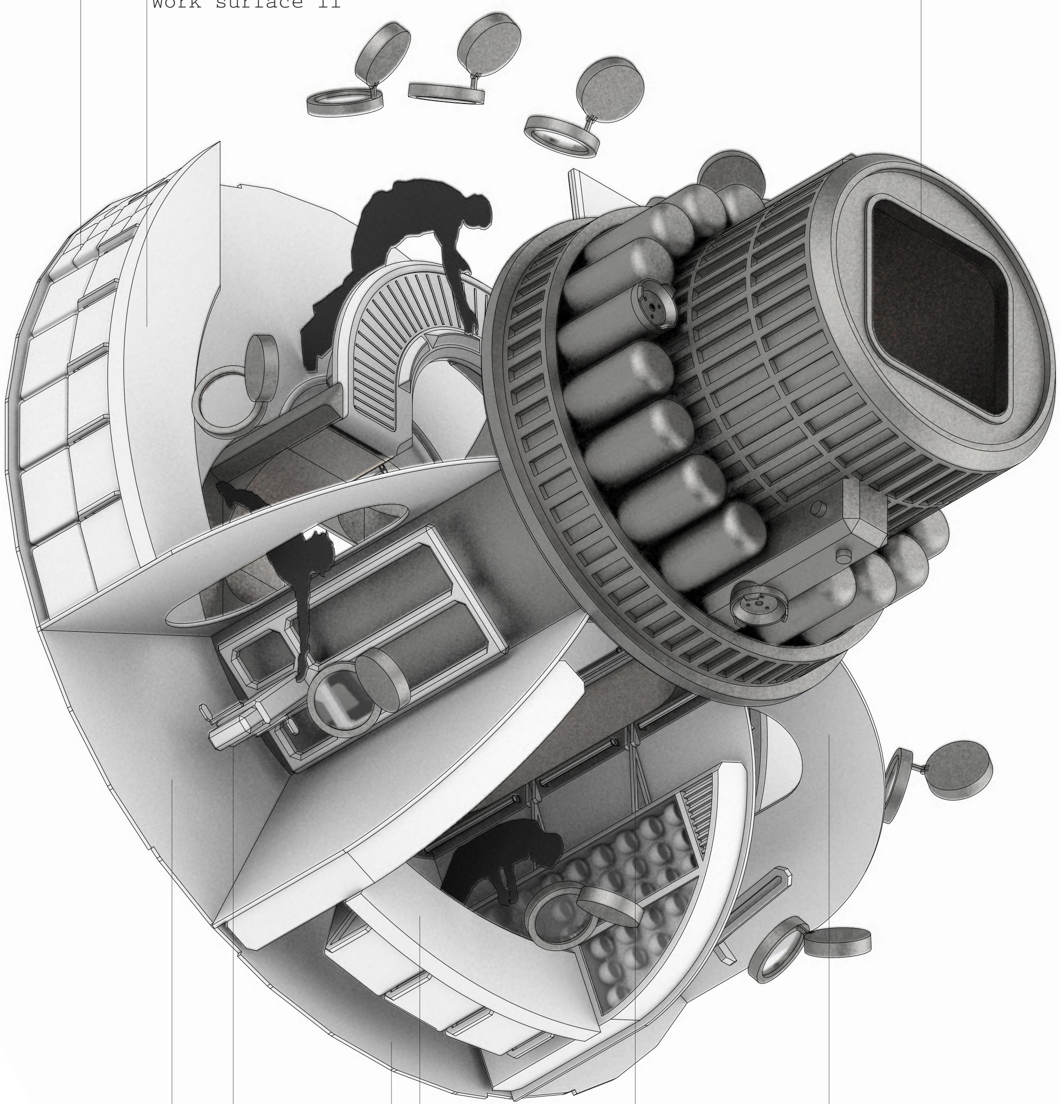
Work Section
Isometric View
Aft / Starboard



Work Section
Isometric View
Aft / Port

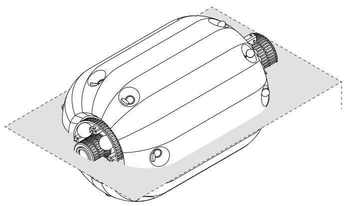


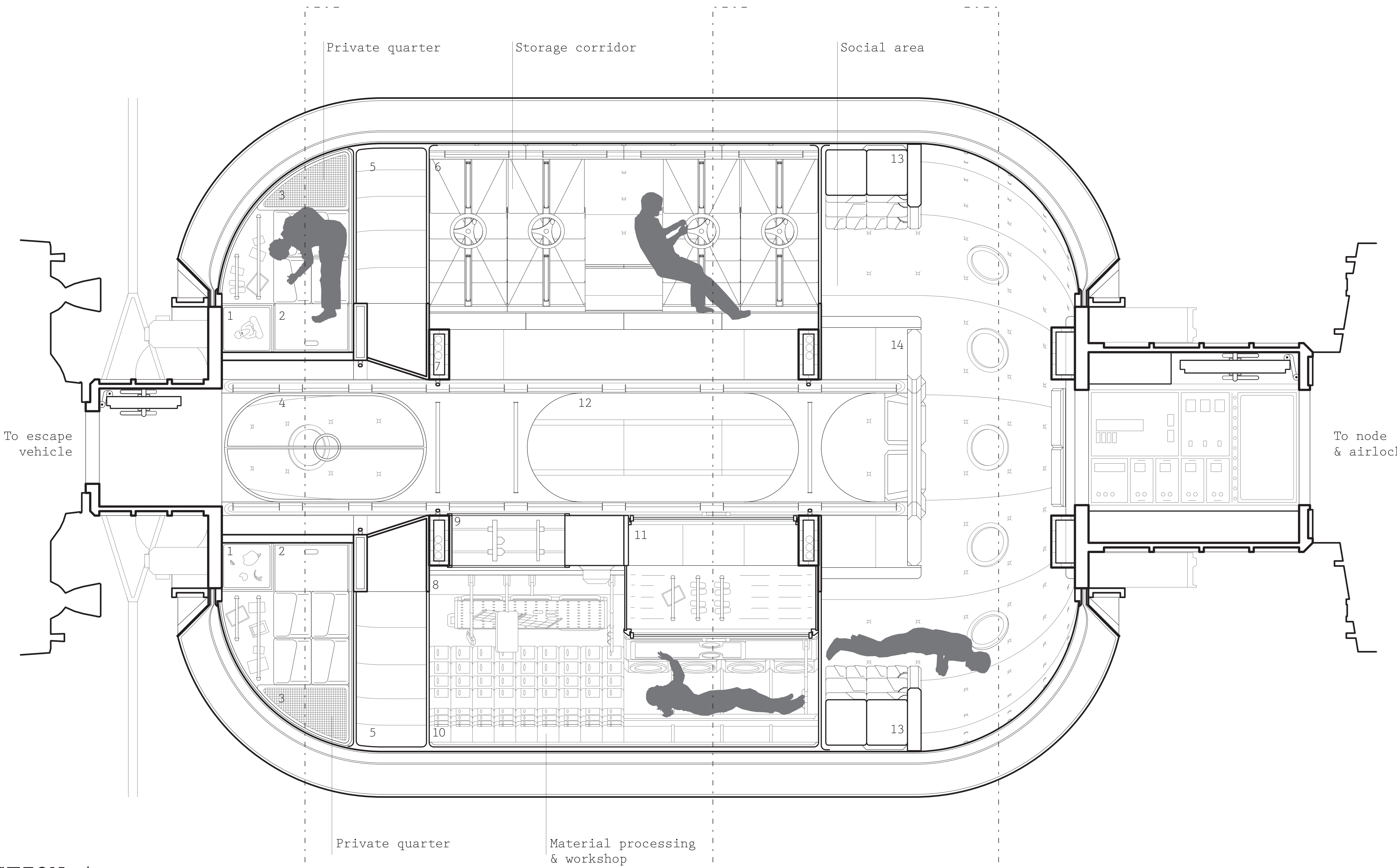
Social Section
Isometric View
Forward / Starboard



Social Section
Isometric View
Forward / Port

1 Personal storage display
2 Deployable workstation
3 Sleeping bag stowage
4 To hygiene, medical bay & sports I
5 Waste storage
6 Movable storage rack
7 Infrastructure cross connection
8 Work & repair station
9 Additive manufacturing
10 Spare parts & tool storage
11 Transition room
12 To work corridor I
13 Joint work & project surface
14 Dining & conferencing table





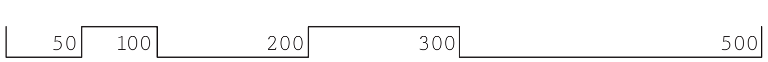
SECTION A

Scale 1:50

Floorplan Private

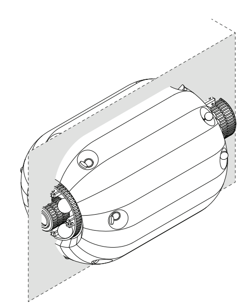
Floorplan Work

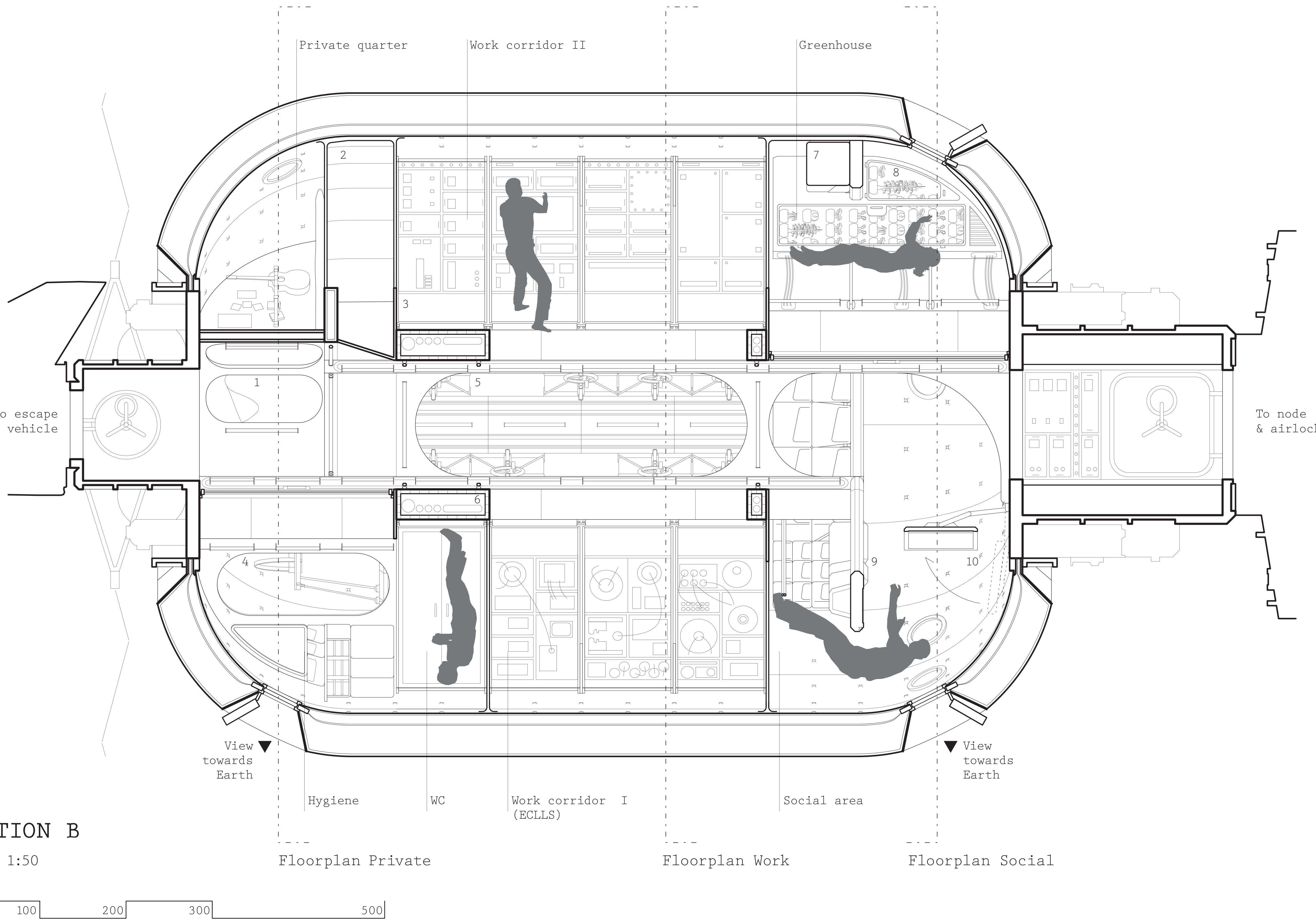
Floorplan Social



06 Final Design

1 To private quarter
2 Waste storage
3 Experiment rack (ISPR size)
4 To sports I
5 To storage corridor
6 Infrastructure cross connection
7 Storage and work surface
8 Hydroponics cabinet
9 Dining & conference table
10 Deployable conference screen



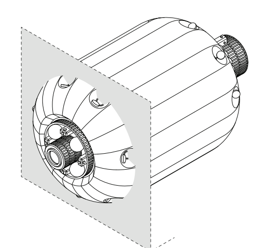


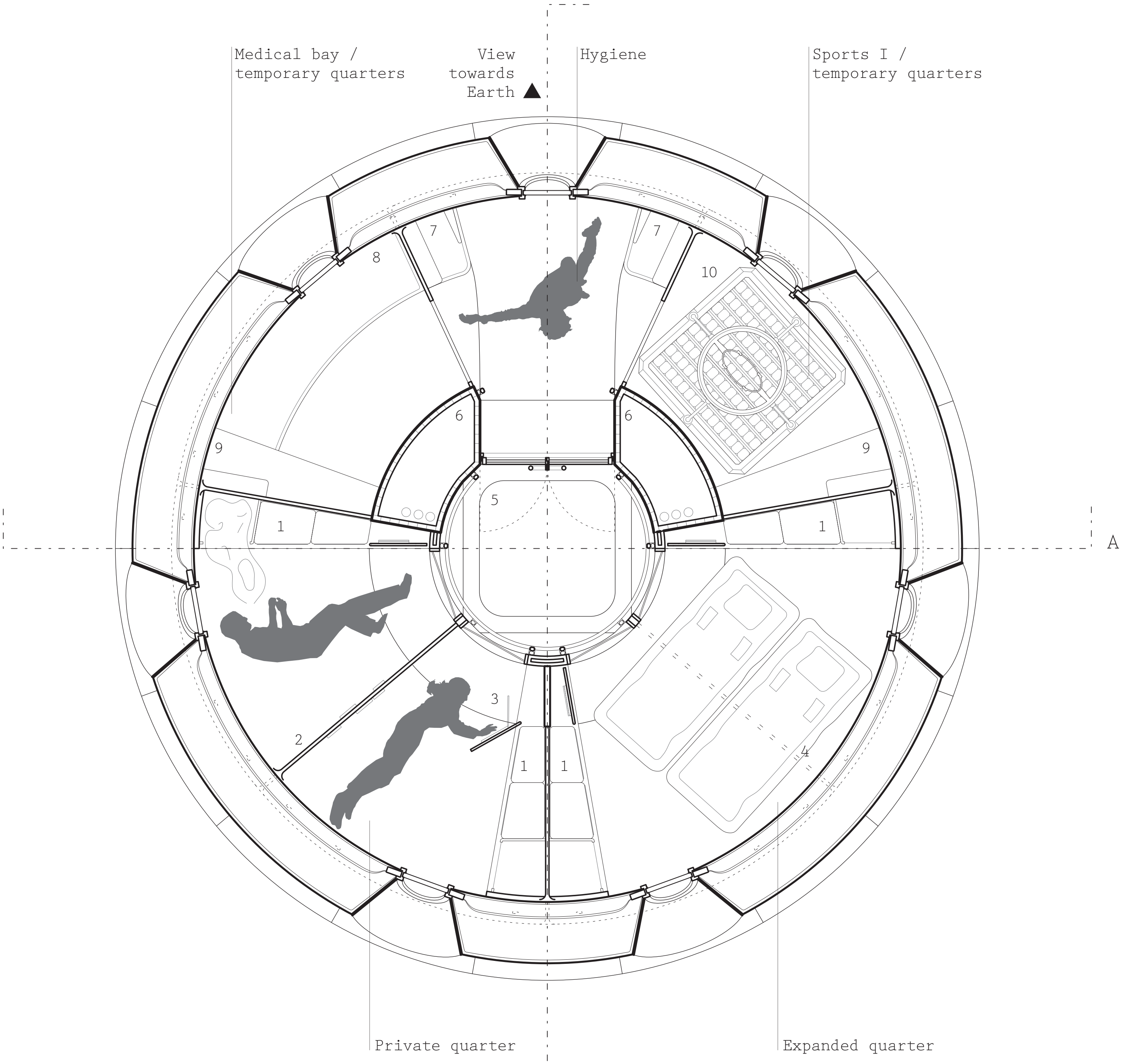
SECTION B

Scale 1:50

06 Final Design

1 Personal storage element
2 Separation wall (removable)
3 Deployable workstation
4 Removed separation wall
5 To connecting corridor / node & airlock
6 Water tank / infrastructure
7 Personal hygiene
8 Medical bay bedside
9 Work surface
10 360° Treadmill





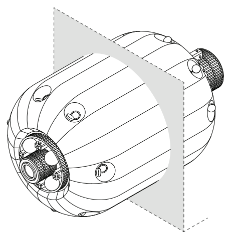
FLOORPLAN PRIVATE

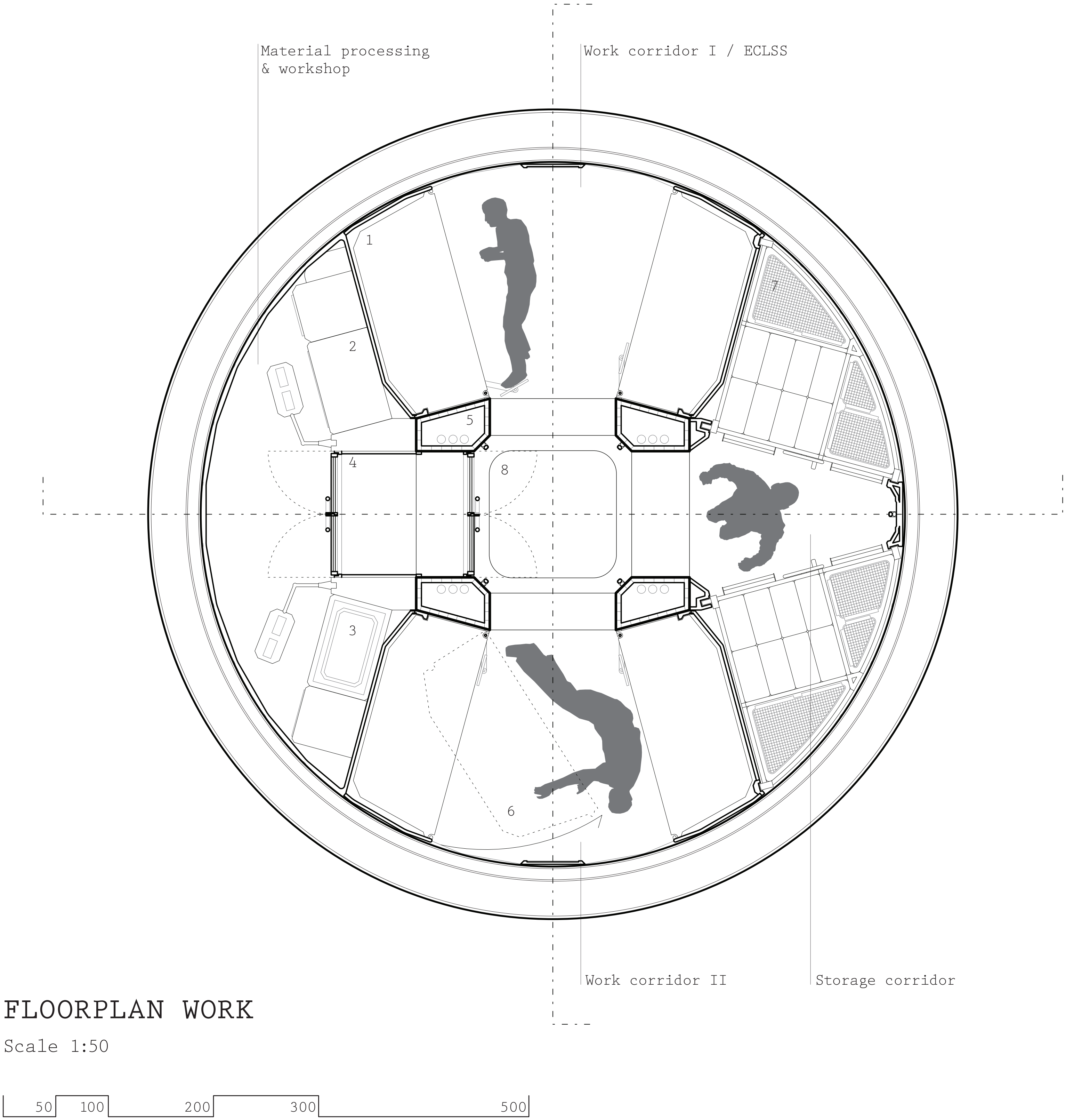
B

Scale 1:50

50 100 200 300 500

1 Experiment rack (ISPR size)
2 Material processing facility
3 Material research / microscope
4 Transition room
5 Infrastructure
6 ISPR being exchanged
7 Movable storage rack
8 To social area / node & airlock

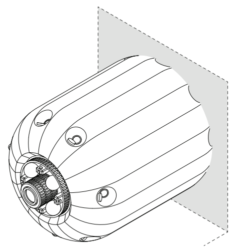


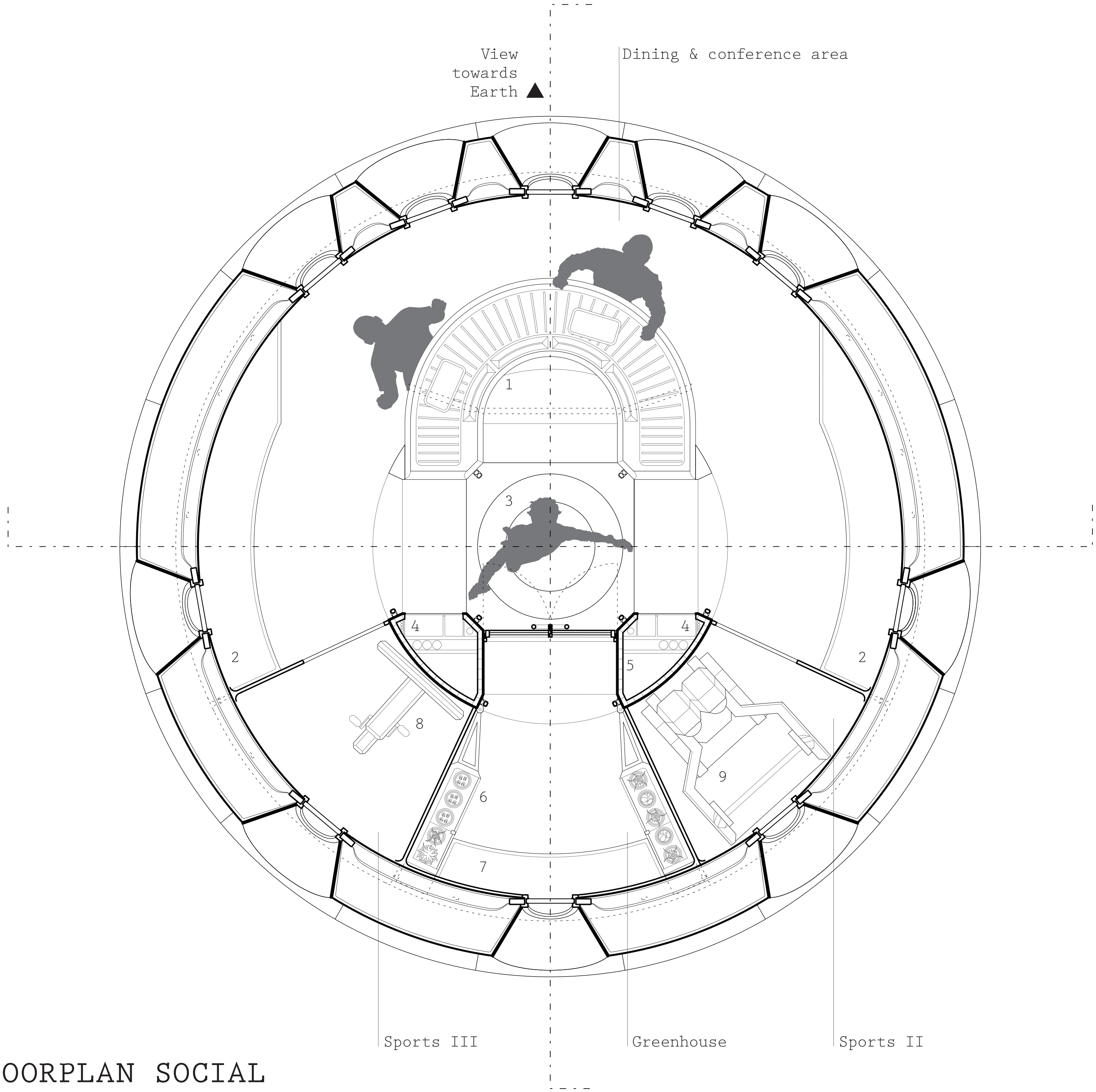


FLOORPLAN WORK

Scale 1:50

1 Dining & conferencing table
2 Joint work & project surface
3 To connecting corridor / escape vehicle
4 Hygiene & food heating
5 Water tank / infrastructure
6 Hydroponics cabinet
7 Work surface
8 Ergometer
9 Advanced resistive exercise device



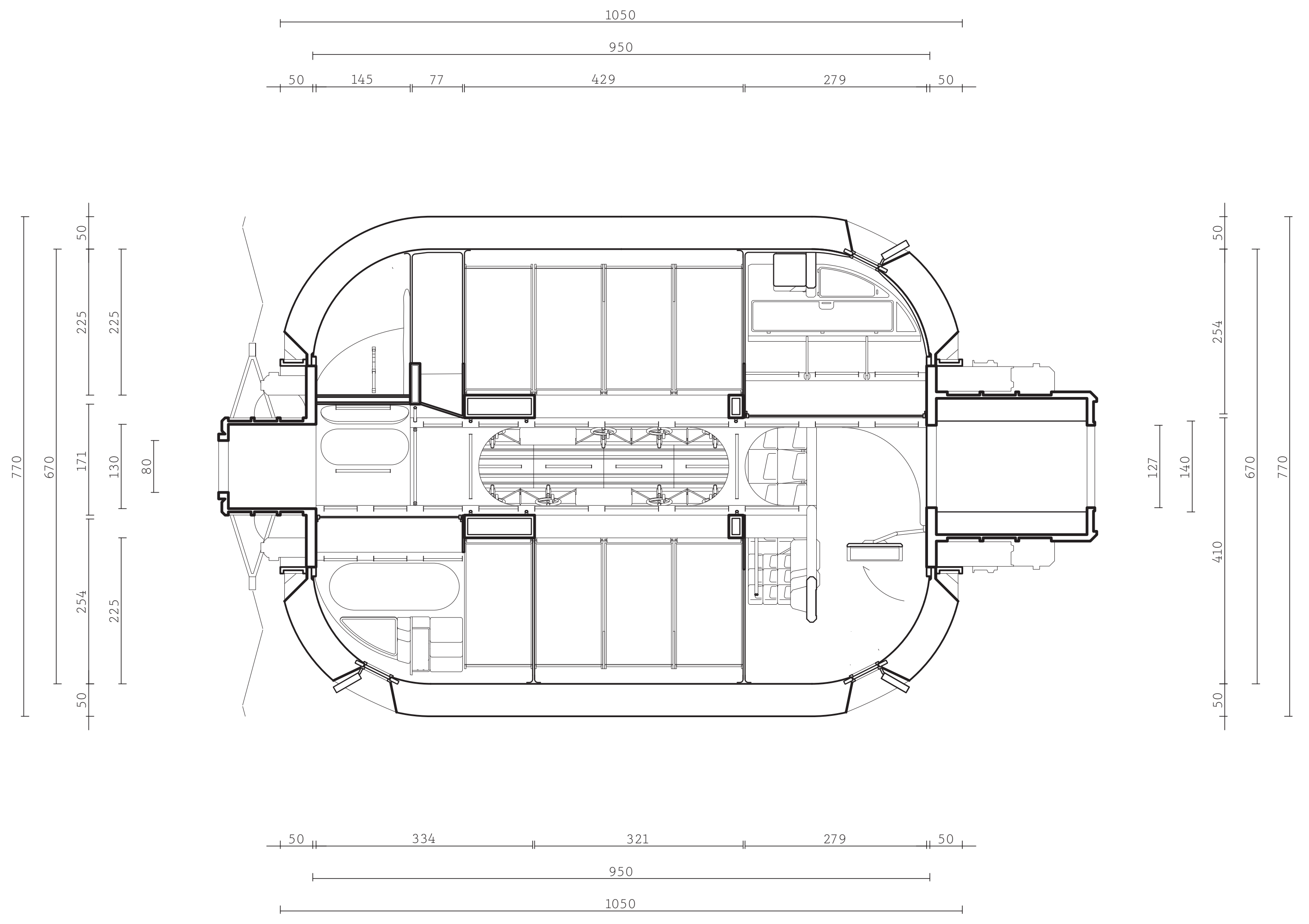


FLOORPLAN SOCIAL

Scale 1:50

Summary of Volumes & Dimensions

Location	Volume	Habitable
Private Section		
Medical Bay	7,65 m³	5,32 m³
Sports I	7,65 m³	6,72 m³
Personal Hygiene & WC	15,36 m³	10,95 m³
Private Quarter x 4	4,71 m³	3,78 m³
Waste Storage	13,18 m³	-
Work Section		
Work Corridor I	24,25 m³	12,52 m³
Work Corridor II	32,41 m³	16,73 m³
Material Processing & Workshop	31,86 m³	23,97 m³
Storage Corridor	31,01 m³	14,04 m³
Social Section		
Social Area	49,53 m³	43,47 m³
Greenhouse	10,23 m³	8,12 m³
Sports II	7,05 m³	6,89 m³
Sports III	7,05 m³	6,71 m³
Other		
Connecting Corridor	27,51 m³	27,51 m³
Aft Entry	1,59 m³	-
Forward Entry	4,53 m³	4,53 m³
Total	**289,7 m³**	**202,6 m³**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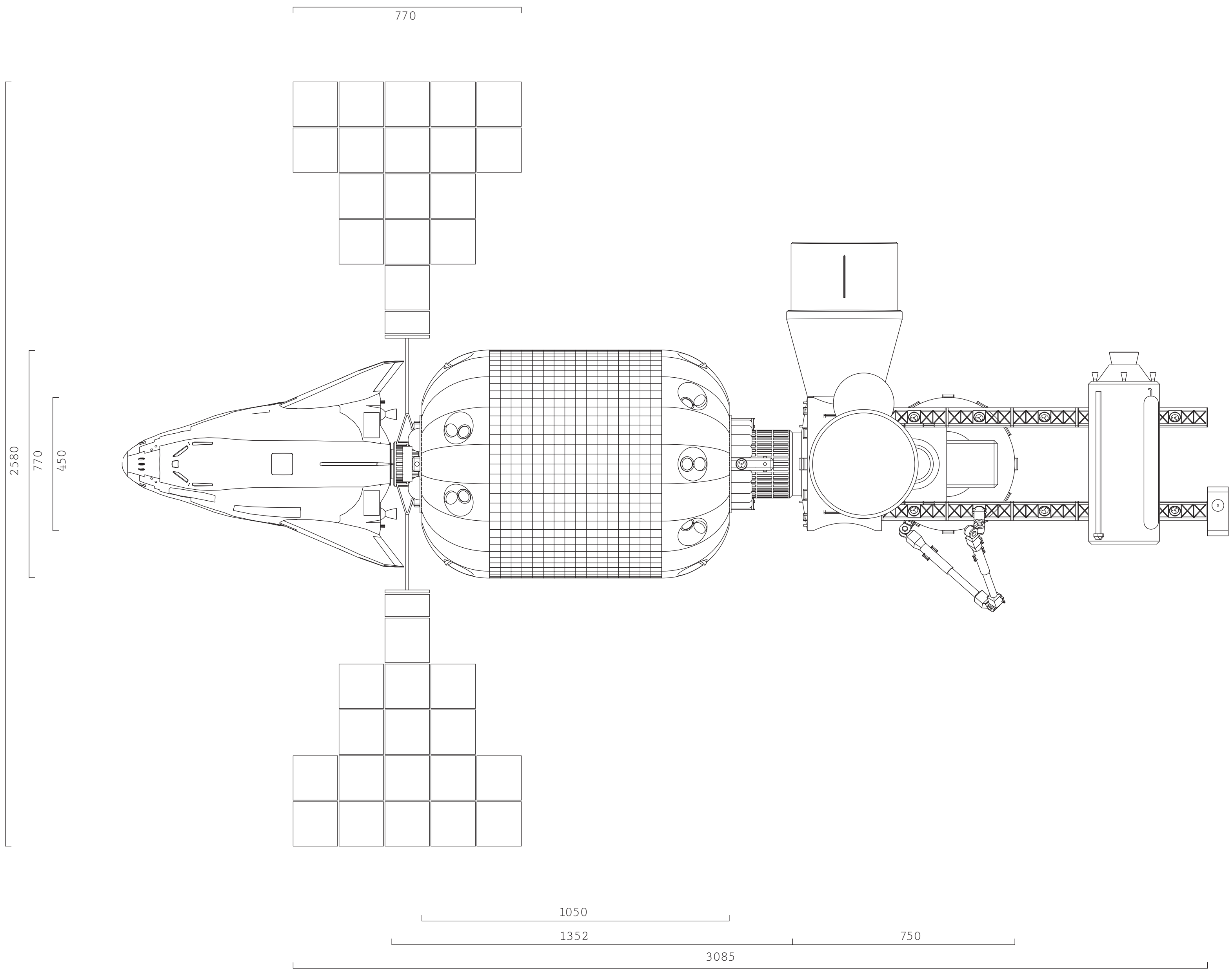
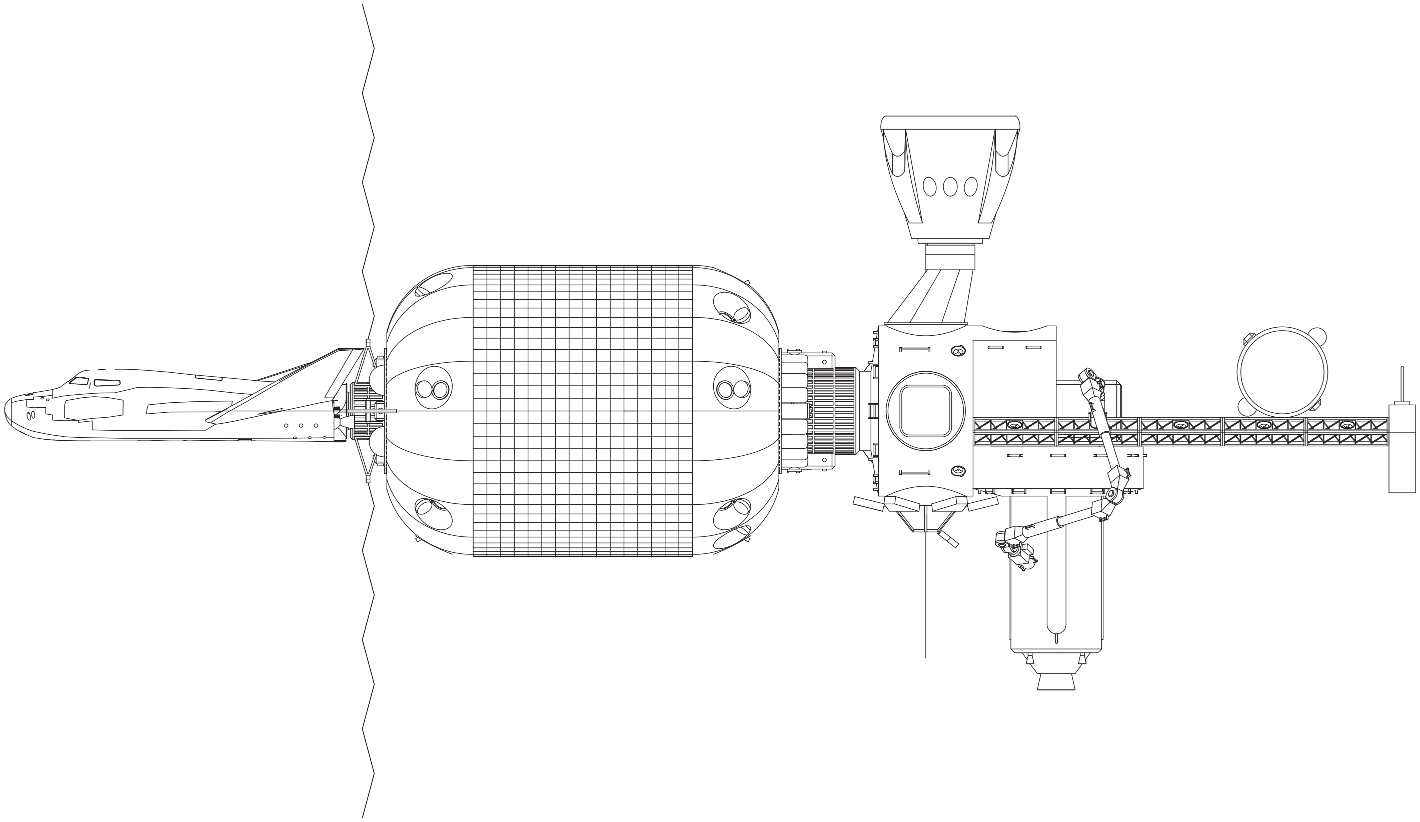
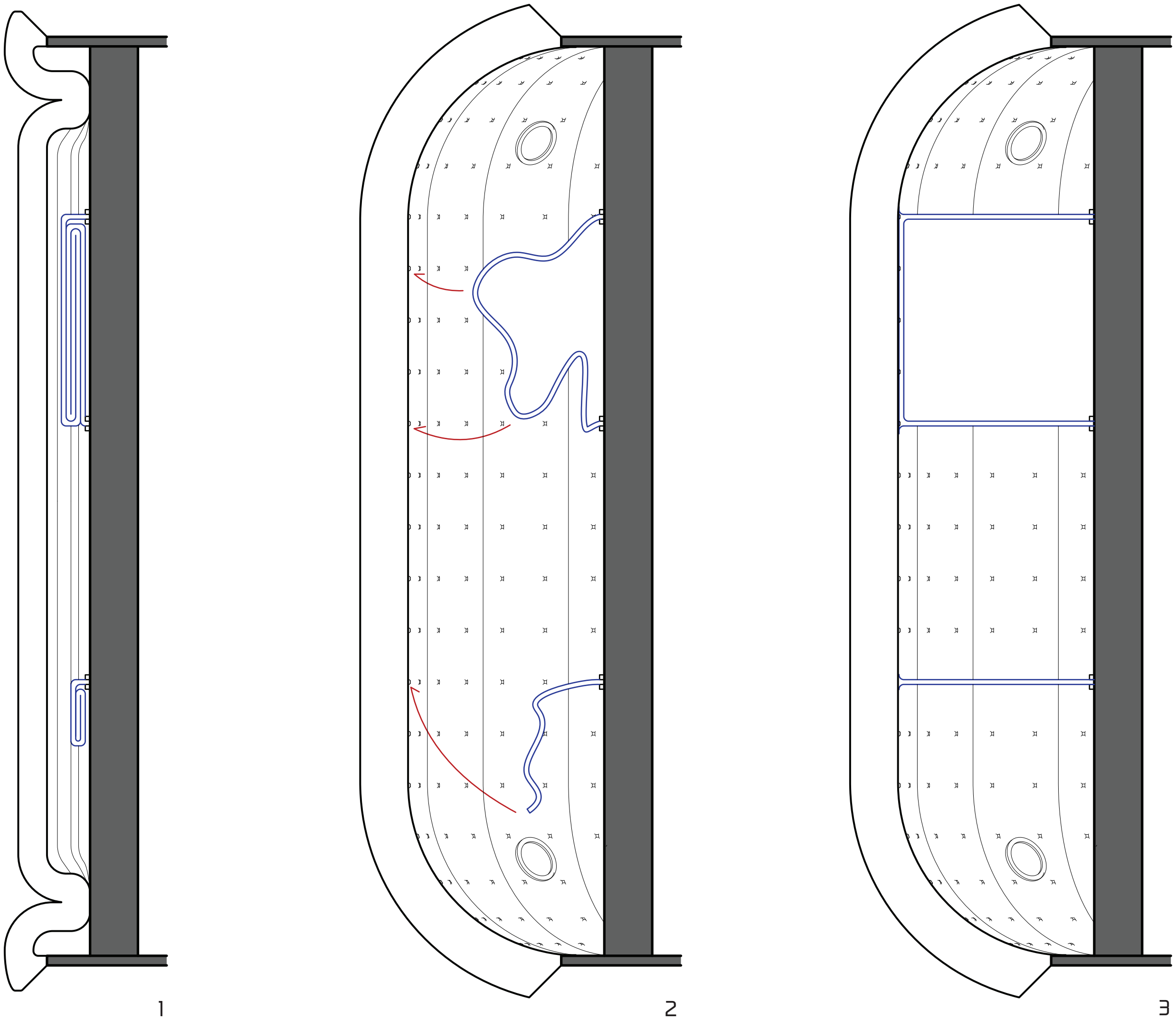


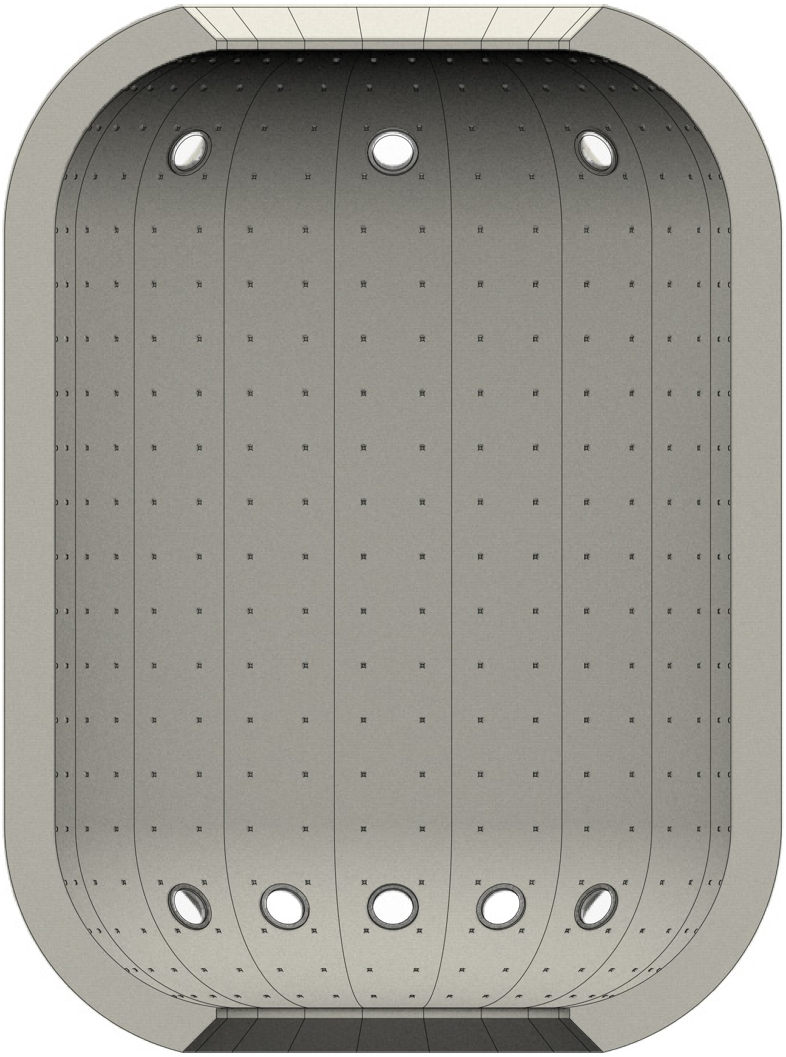
Top View
Scale 1:200



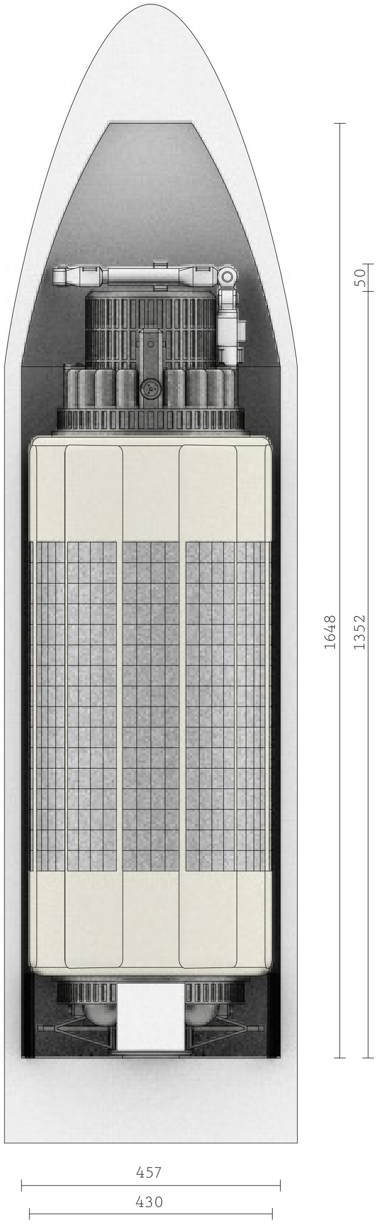
Elevation Starboard
Scale 1:200



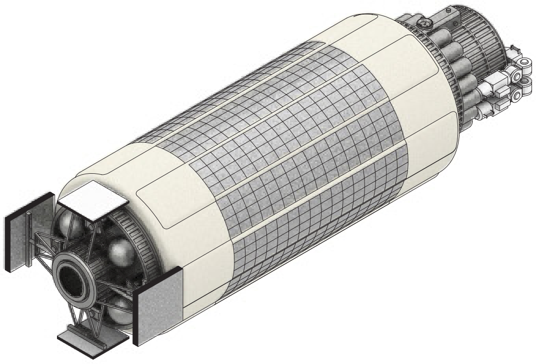
Separation Walls and Sealed Compartments
In the launch configuration the separation walls and sealed compartments are folded to the structural core (**1**). Once the shell is inflated, they are unfolded (**2**) and affixed to the fixture grid on the shell's interior (**3**).



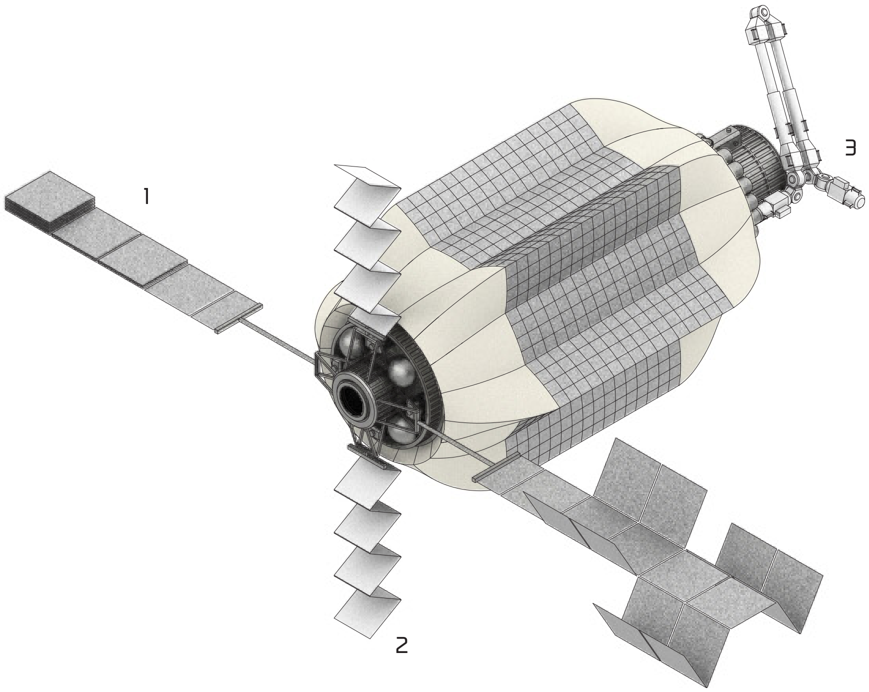
Internal Fixture Grid
The inner layer of the inflatable shell features a three dimensional fixture grid. Besides affixing the modules separation walls and sealed compartments, it can be used to attach, restraints, lights, screens structural elements and other modular items as required.



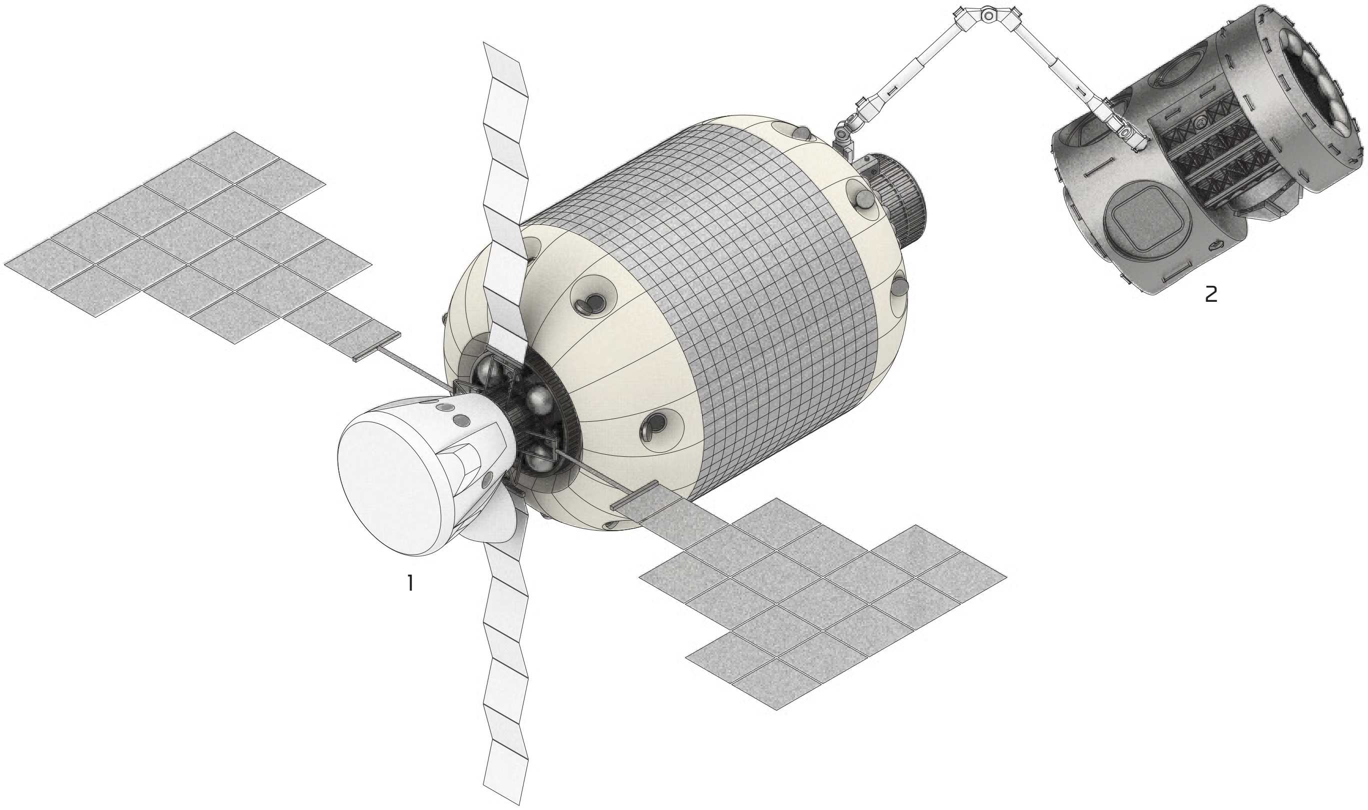
Launch Constellation
The folded habitation & work module with an attached RA, inside the Atlas V fairing.



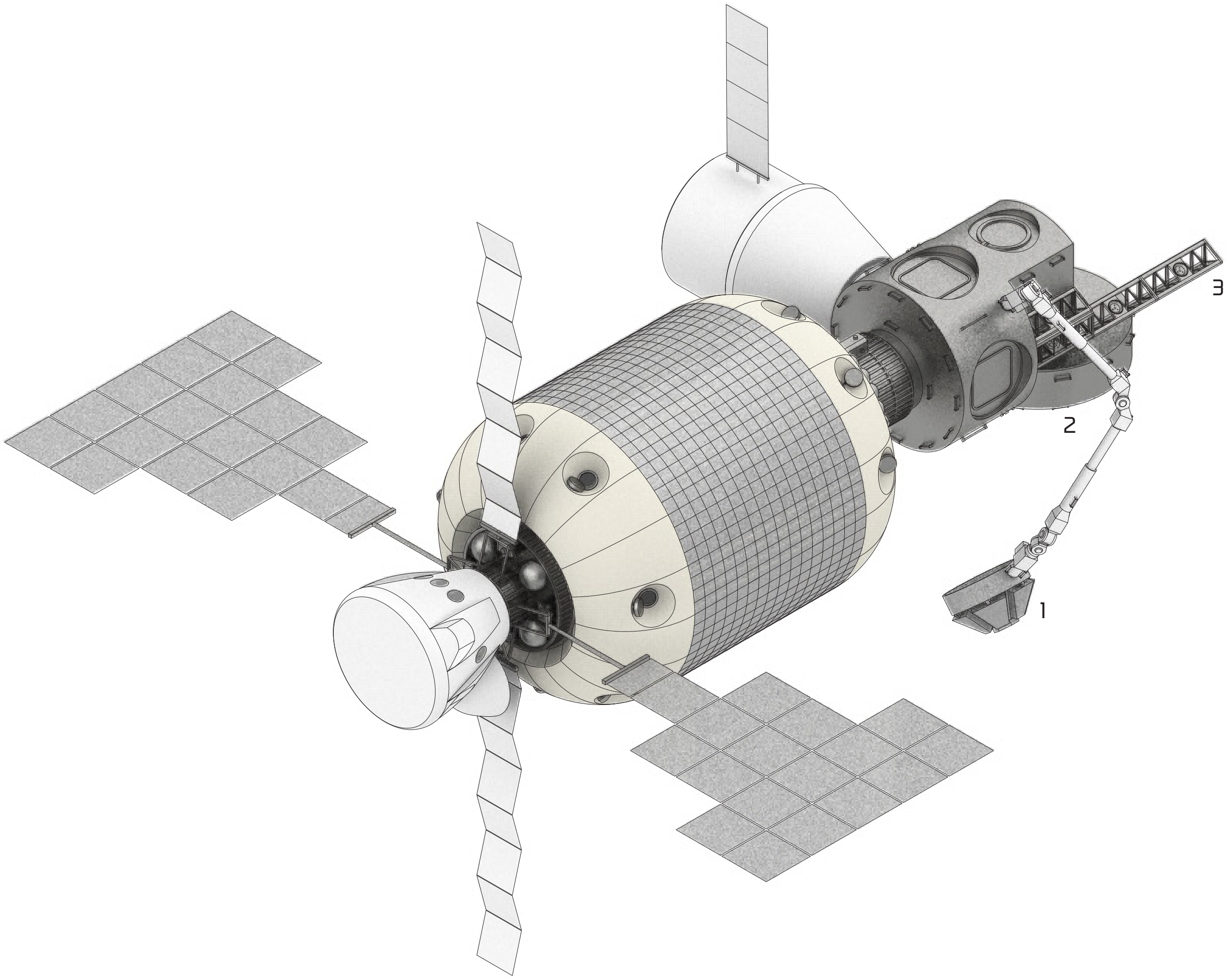
Assembly - 1
The folded habitation & work module is launched into orbit with an RA attached.



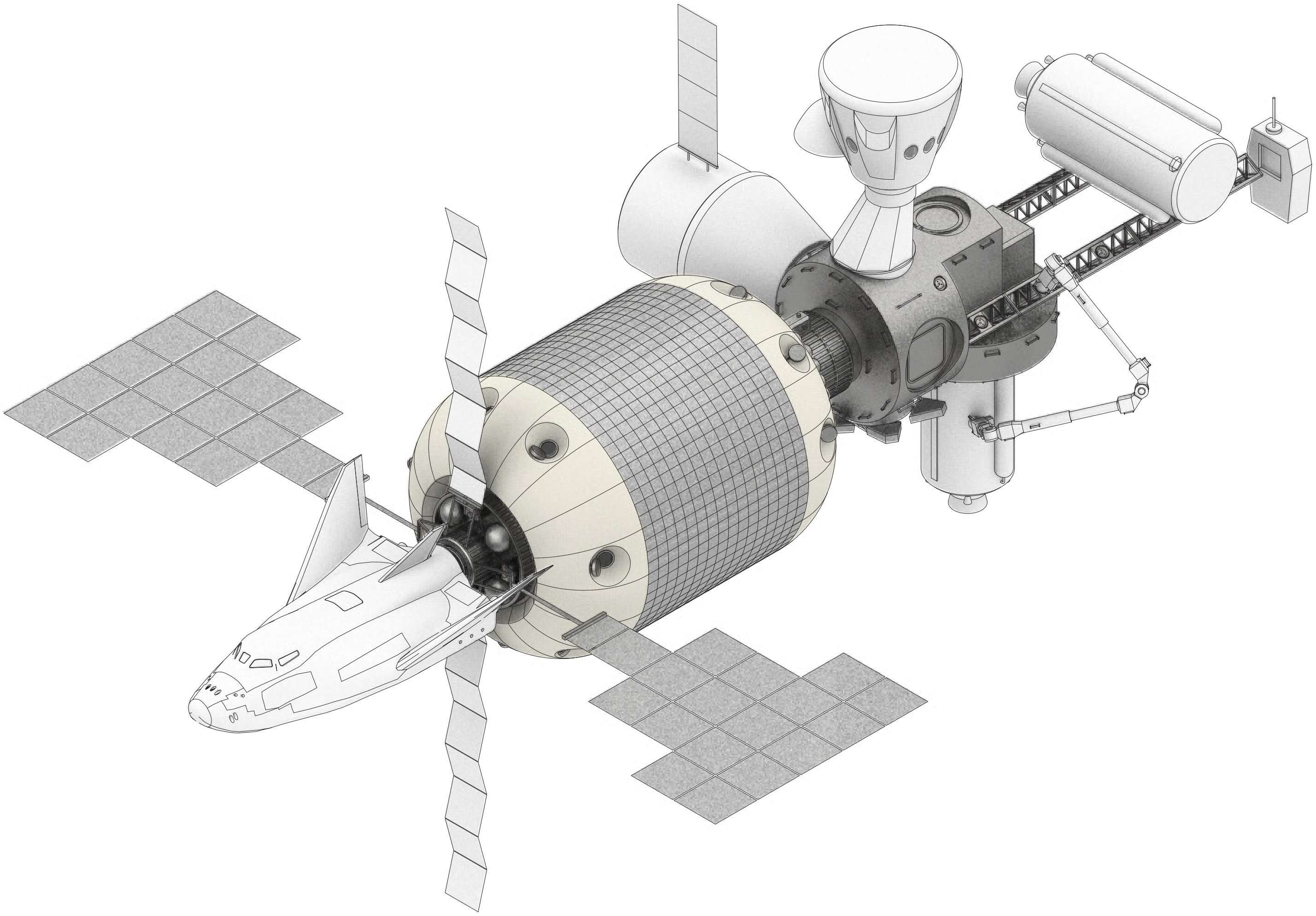
Assembly - 2
The module starts unfolding and inflating, the solar array (**1**), radiators (**2**) and RA (**3**) are deployed.



Assembly - 3
Crew boards inflated module (**1**) to commence interior outfitting. The node and airlock module is launched in its compact state and captured by the RA (**2**).



Assembly - 4
After berthing the node and airlock module to the inflatable modules forward side, the RA grabs the cupola (**1**). Subsequently, the shredder element can fold downward (**2**) and the scientific airlock expand. The truss modules start being connected by the RA (**3**).



Assembly - 5
After receiving cargo deliveries for the interior instruments and racks, the station is fully operational.

Conclusion

Orbital debris poses a significant threat to all current and future space missions and its number is constantly growing. Steps have to be taken to actively remove large debris pieces from orbit in order to ensure a stable environment. Fortunately, debris removal technologies are making huge leaps, and the first successful deployment of a throw-net in space has been demonstrated during the development period of this diploma thesis. However, it is still unclear when these technologies will be implemented and the removal process will begin. Up to now, the FCC (Federal Communications Commission) has received requests for over 17.000 satellites launches in the next ten years (We now have around 2000 active satellites in orbit). Considering the number of space launches is literally sky rocketing, it is unclear whether the estimated removal of 5 large debris pieces per year is sufficient to maintain a stable debris environment, or if more drastic steps have to be taken.

Unfortunately, as of now, there are little plans to utilize orbital debris as a resource. The conceptual approach, presented in this work, was generating feedstock for in space additive manufacturing from spent rocket stages. However, the cost of conceiving and maintaining an on orbit recycling facility capable of such a task are admittedly high, and also make little sense before technologies for processing and concepts for utilization of the gained material are devised.

For this reason, the main focus of the space station, treated in this thesis, shifted from recycling to research of orbital debris in its final version. The design provides the necessary infrastructure to store, disintegrate, disassemble or repair debris, and to examine its material properties. As a consequence of this concept adaptation, the size of the station got reduced. This triggered designing a more detailed interior layout of the station's inflatable module with an emphasis on functionality as well as habitability. One of the biggest challenges was the lack of gravity which allowed the utilization of the complete volume and required a three dimensional design approach, relying on models and sketches.

Inflatable modules provide a larger volume and have equal or better radiation and MMOD protection properties than the currently used honeycomb aluminum shell variants. They also present opportunities for greater architectural innovation, due to this larger volume and the independence of their deployed shape from launcher vehicle fairing sizes. For this diploma work, an existing inflatable module concept was adapted and its interior completely redesigned. Yet it would be interesting to explore the possibilities of shapes and volumes that can be created with altering the inflatable shell itself.

Further Publications by Author

ORDER: Space Station for Orbital Debris Recycling
Conference Paper IAC 2018

R3-Debris: Space Station for Research concerning Recource utilization and Recycling of Debris
Conference Paper ICES 2020

Acronyms & Abbreviations

ADR	Active Debris Removal
AES	Advanced Exploration Systems
AIAA	American Institute of Aerospace and Aeronautics
ALM	Apollo Lunar Module
AMF	Additive Manufacturing Facility
ATV	Automated Transfer Vehicle
BEAM	Bigelow Expandable Activity Module
CBM	Common Berthing Mechanism
(M)CTB	(Multipurpose) Cargo Transport Bag
ECLSS	Environmental Control and Life Support System
EDT	Electrodynamic Tether
ERA	European Robotic Arm
ESA	European Space Agency
ESAS	Exploration Systems Architecture Study
EVA	Extra Vehicular Activity
FCC	Federal Communication Commission
GEO	Geostationary Equatorial Orbit
HTV	H-II Transfer Vehicle
IAC	International Astronautical Congress
IADC	Inter-Agency space Debris Coordination Committee
IBS	Ion Beam Shepherd
InFlex	Intelligent Flexible
IRMA	In Space Robotic Manufacturing and Assembly
ISRU	In Situ Resource Utilization
ISS	International Space Station
JERMS	Japanese Experimental Remote Manipulating System
JSC	Johnson Space Center
LEGEND	LEO-to-GEO Environment Debris Model
LEO	Low Earth Orbit
MEO	Medium Earth Orbit
MIS	Made In Space
MLI	Multilayered Insulation
MMOD	Micrometeoroid and Orbital Debris
MSS	Mobile Servicing System
NACA	National Advisory Committee for Aeronautics
NASA	National Aeronautics and Space Administration
NBP	Neutral Body Posture
PMD	Post Mission Disposal
RA	Robotic Arm
SLS	Space Launch System
SSN	Space Surveillance Network
TDK	Thruster Deorbiting Kit
UCS	Union of Concerned Scientists
ULA	United Launch Alliance
UNOOSA	United Nations Office for Outer Space Affairs

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