Biomorphed

Lunar Habitat Design

Computationally based Biophilic
Design for Astronaut Well-being

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Extra-/Terrestrial Architecture Graduation Studio

Maurits Roijen | 5238153

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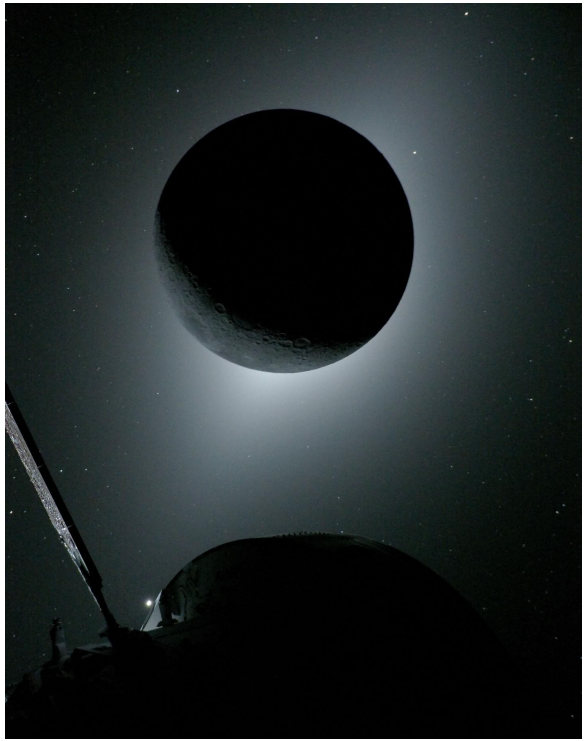
INTRODUCTION / BACKGROUND

Return to the Moon

Return to the Moon

Why is this topic relevant?

- A second space race to put humans on the Moon again
- Involving many space agencies like NASA, ESA, ROSCOSMOS, CNSA, etc.
- Aim for longer term Moon missions
- Eventually leading to colonising of the Moon and beyond



NASA. (2026, April 7). [The Moon, backlit by the Sun during a solar eclipse] [Photograph]. https://www.nasa.gov/news-release/nasas-artemis-ii-crew-beams-official-moon-flyby-photos-to-earth/

Problem Statement

Lunar habitation faces 3 main challenges

Hostile Environment

Transportation Costs

Mental Health

Problem Statement

Hostile Environment

- Abrasive lunar dust
- Moonquakes
- Micro meteorites
- Radiation
- Solar wind
- Long lunar nights
- No atmosphere
- Extreme temperature fluctuations

NASA. (1969, July 20). Astronaut Edwin E. Aldrin Jr., lunar module pilot, walks on the surface of the moon near the leg of the Lunar Module (LM) "Eagle" during the Apollo 11 extravehicular activity (EVA) [Photograph]. https://www.nasa.gov/mission/apollo-11/

Protective Habitat

The habitat should be optimised to deal with the site conditions. Especially with pressurising the habitat and dealing with radiation.

Problem Statement

Transportation Costs

- Expensive to launch rockets
- Price/kg has decreased with reusable rockets
- Building materials are heavy

In-Situ Resource Utilization (ISRU)

poses a solution by reducing the need for transporting materials from Earth.

Denko, M. (2018, November). [Photo-illustration of Mars rovers for the article "From Dust to Thrust"] [Illustration]. IEEE Spectrum. https://read.nxtbook.com/ieee/spectrum_int/spectrum_int_november_2018/from_dust_to_thrust.html

Problem Statement

Mental Health

- Stuck with the same people
- High stress environment
- Away from family and home
- Little privacy
- Confined indoors

National Aeronautics and Space Administration. (2019, May 8). Expedition 59 crew members inside the U.S. Destiny laboratory [Photograph]. https://www.nasa.gov/image-article/expedition-59-crew-members-inside-u-s-destiny-laboratory/

Biophilia

poses a solution by adding more greenery and reminding people of earth. Biophilic design can improve mental health & well-being.

Terrestrial Relevance

UN Sustainable Development Goals

- **Health & well-being** → Biophilic (human-centric design)
- **Innovation** → Design-To-Robotic-Production and 3D printing advancements
- **Sustainable cities and responsible consumption** → ISRU to reduce pollution from transport

Government of the Netherlands. (n.d.). An overview of the 17 UN Sustainable Development Goals [Infographic]. https://www.government.nl/themes/international-cooperation/united-nations/sustainable-development-goals

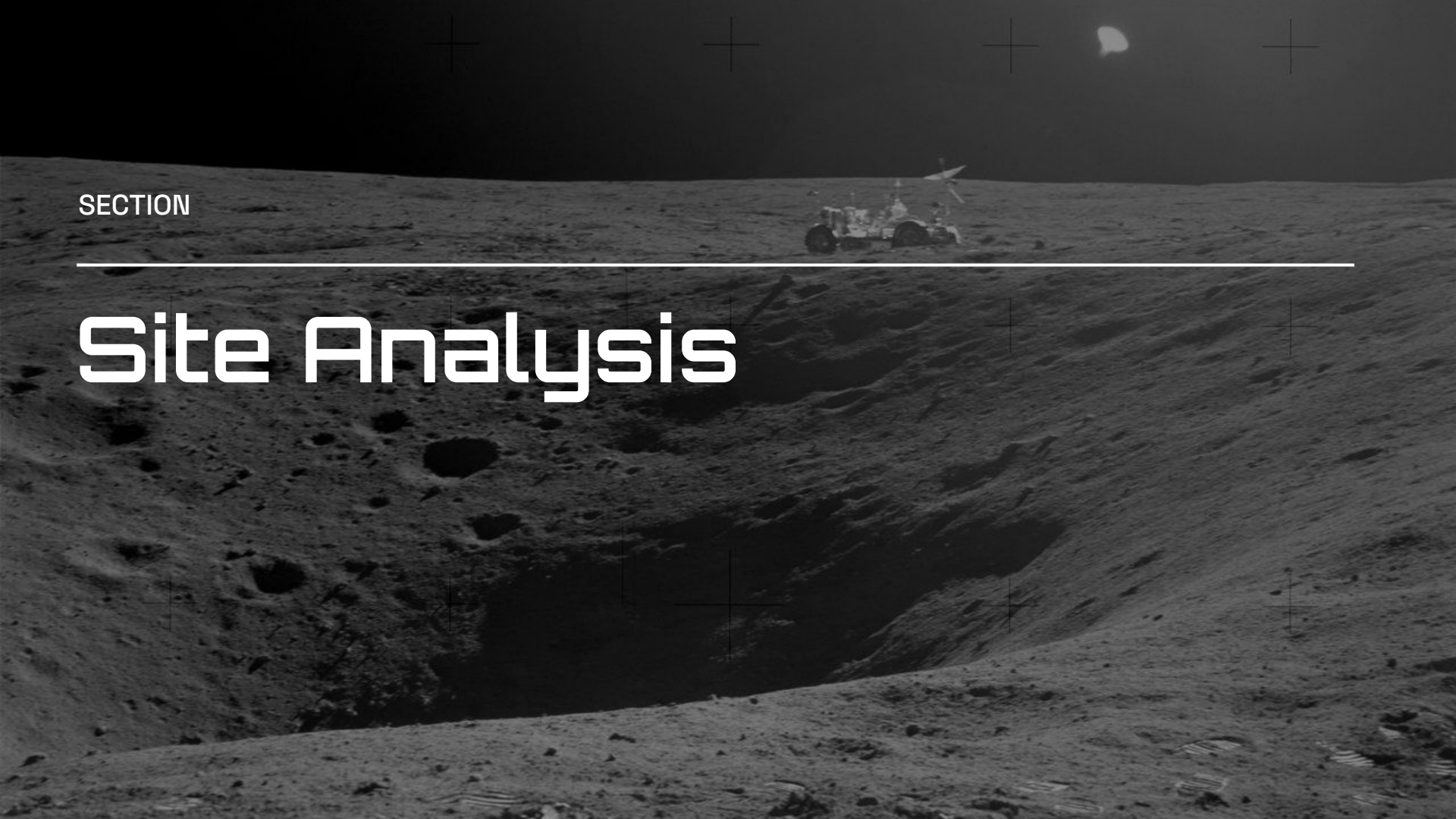
Objective

Goals

- To design a functional, safe and effective ISRU Lunar habitat
- To explore the relationship between biophilic design and 3D printing
- To create a habitat with a healthy indoor environment for mental & physical wellbeing
- To contribute to the study of future habitats designs on and off Earth

Research Question

“How can **biophilic design** principles be adapted to a lunar habitat using **ISRU 3D-printed** architecture to support astronaut **mental health** and **well-being**?”

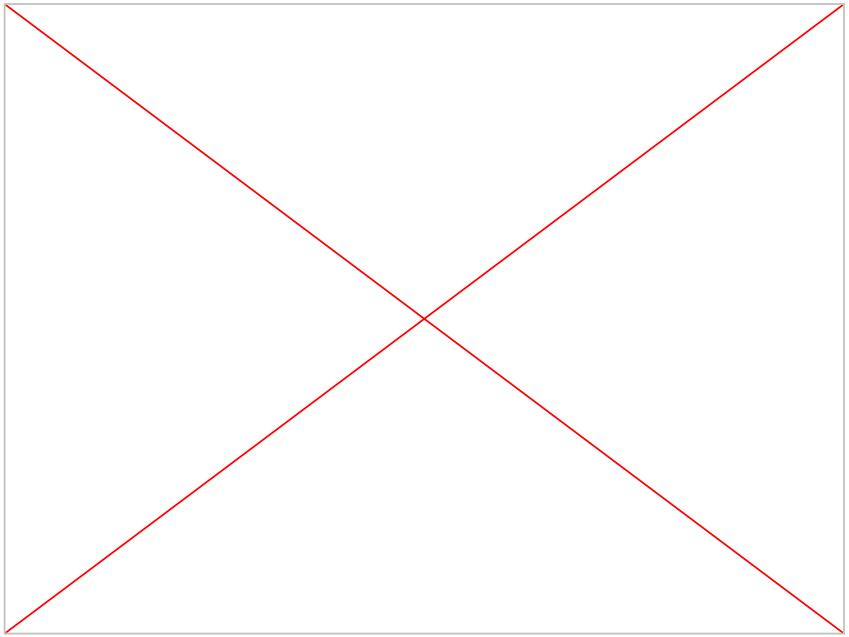


SECTION

Site Analysis

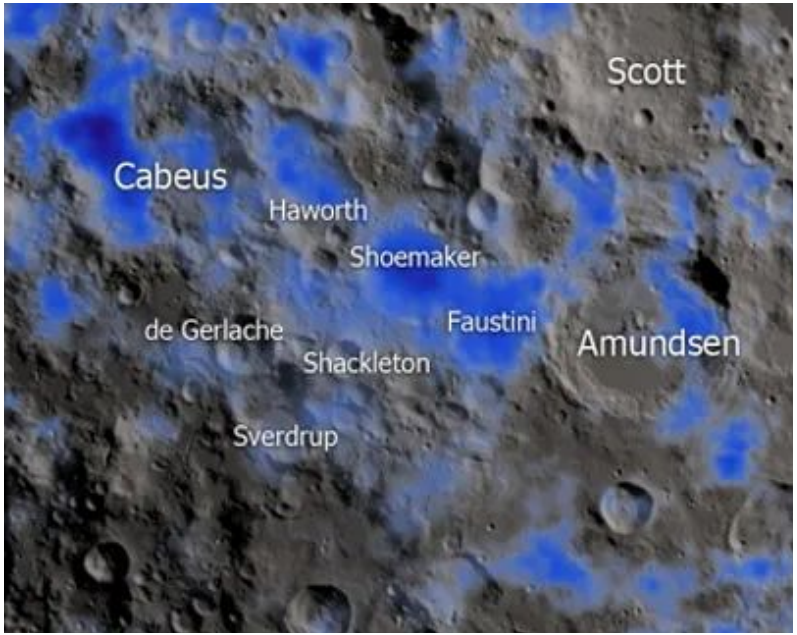
Lunar South Pole

Sunlight



Wright, E. (2022, October 5). Illumination at the moon's South Pole, 2023 to 2030 [Visualization]. NASA Scientific Visualization Studio. https://svs.gsfc.nasa.gov/4930/

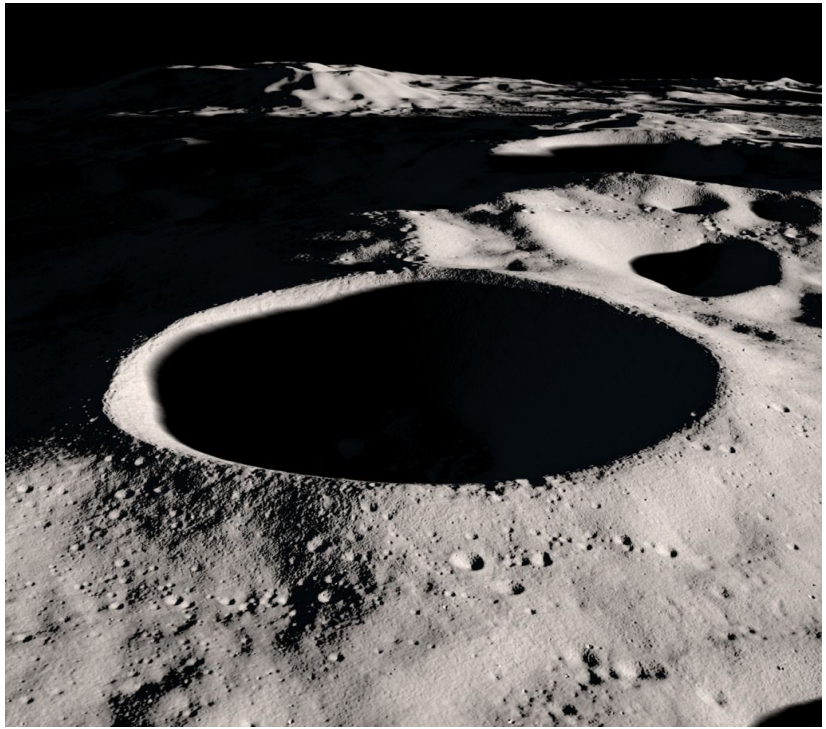
Water Ice deposits



National Aeronautics and Space Administration. (2024, January 19). LEND water south pole [Image]. NASA Science. https://science.nasa.gov/image-detail/svs-lend-20130601-580-2/

Shackleton Crater

NASA/GSFC/Arizona State University. (2022, April 20). Shackleton crater's illuminated rim & shadowed interior [Photograph]. NASA Science. https://science.nasa.gov/resource/shackleton-craters-illuminated-rim-shadowed-interior/k

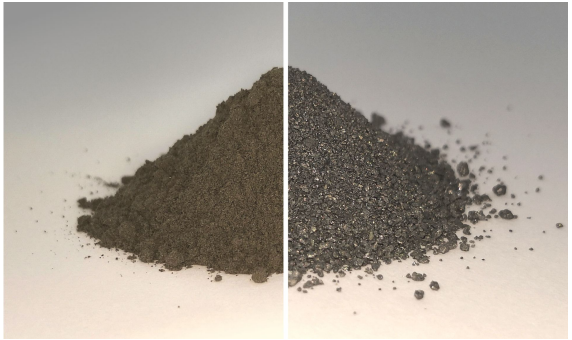


Wright, E. (2012, June 21). Visualizing Shackleton crater [Visualization]. NASA Scientific Visualization Studio. https://svs.gsfc.nasa.gov/4716k

Section

Construction & Materialisation

Extracting Materials



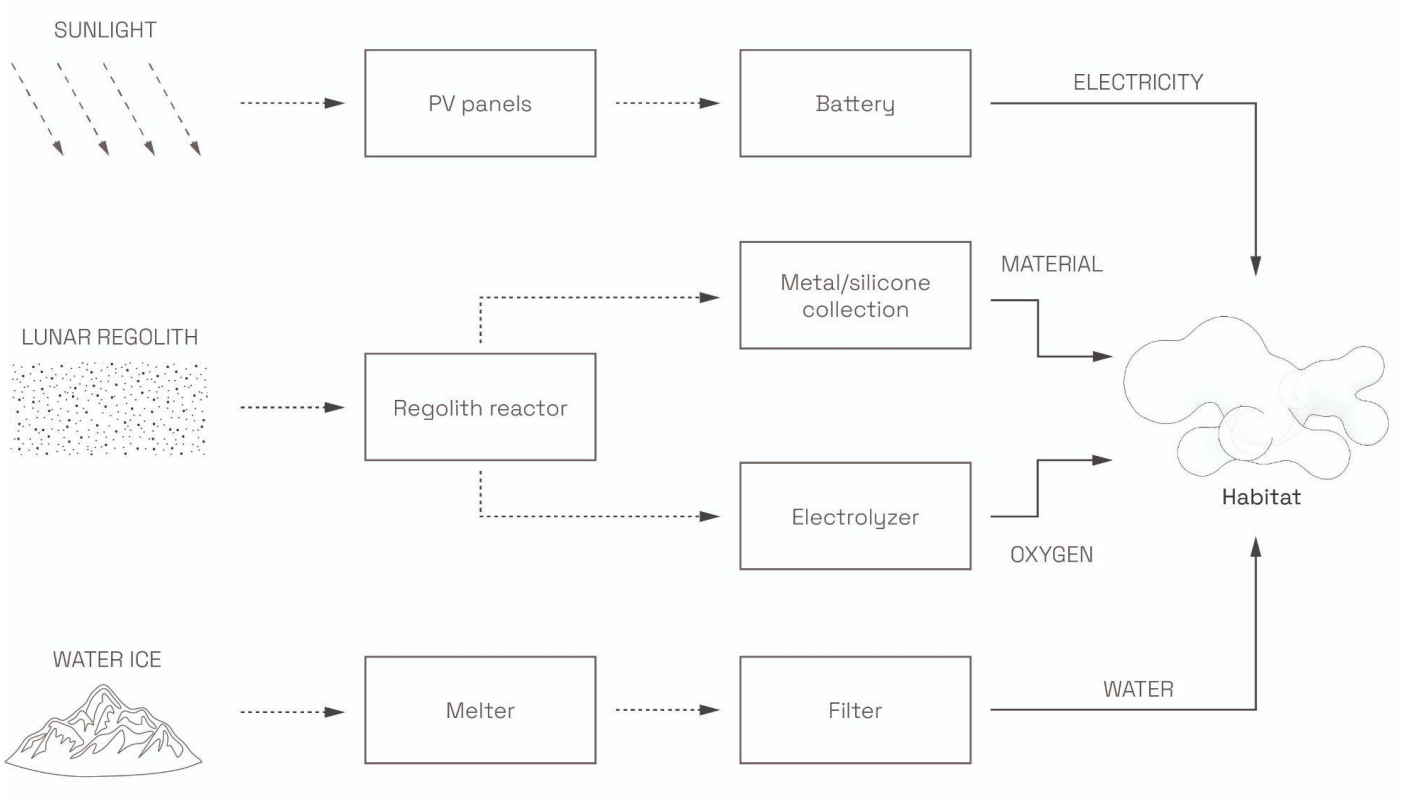
- Water (life support)
- Oxygen (life support)
- Silica (for glass)
- Metal (construction)

Lunar Regolith Composition

Element	Low-Ti Mare Soils	High-Ti Mare Soils	Highland Soils	KREEP Soils
O	60.26	60.30	60.82	60.47
Si	17.30	15.86	16.31	17.35
Al	5.56	5.70	10.66	6.48
Mg	5.53	5.70	3.84	5.39
Ca	4.44	4.60	5.92	4.43
Fe	5.85	5.29	1.90	4.47
Ti	0.66	2.01	0.17	0.62
Na	0.26	0.31	0.29	0.44
K	0.06	0.05	0.05	0.19
Mn	0.08	0.07	0.03	0.06

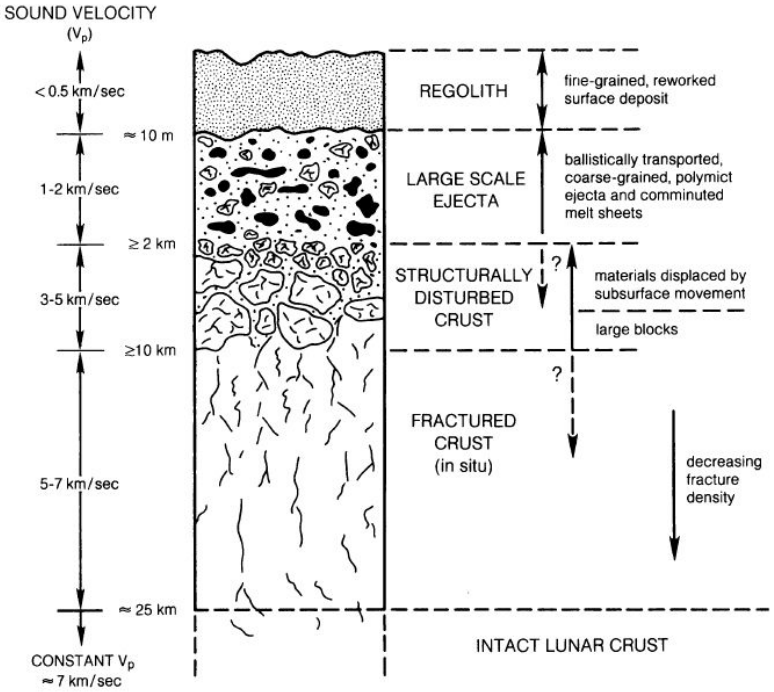
Sarantos, M., Killen, R. M., Glenar, D. A., & Stubbs, T. J. (2012). Assumed composition of the lunar regolith and variation across soil types a [Table]. ResearchGate. https://www.researchgate.net/figure/Assumed-Composition-of-the-Lunar-Regolith-and-Variation-Across-Soil-Types-a_tbl1_258661774

Sanders, G. (2025). Progress review NASA lunar ISRU [PDF]. NASA Technical Reports Server. https://ntrs.nasa.gov/api/citations/20250003730/downloads/Progress%20Review%20NASA%20Lunar%20ISRU_Sanders.pdf


SUNLIGHT
PV panels
Battery
ELECTRICITY
MATERIAL
Metal/silicone collection
LUNAR REGOLITH
Regolith reactor
Habitat
Electrolyzer
OXYGEN
WATER ICE
Melter
Filter
WATER

3D Printing

- Using the top layer of regolith
- Easy to mine with robots
- Need a way to ‘print’ the dust without additives

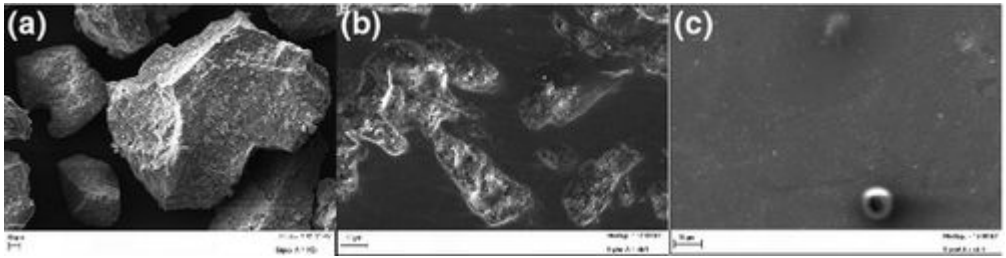


Heiken, G. H., Vaniman, D. T., & French, B. M. (Eds.). (1991). Lunar sourcebook: A user's guide to the moon. Cambridge University Press.

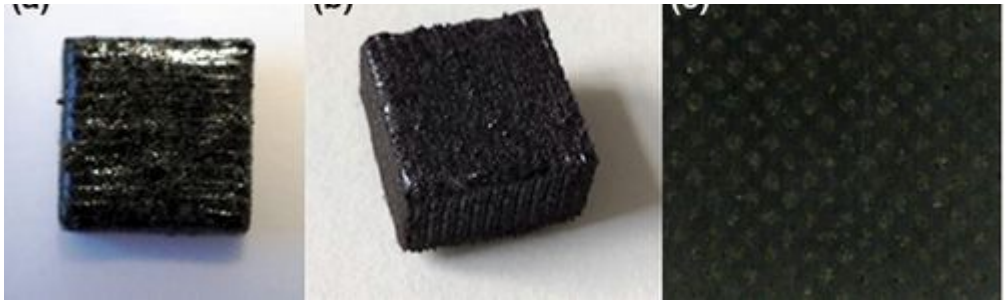
3D Printing

Selective Laser Melting (SLM)

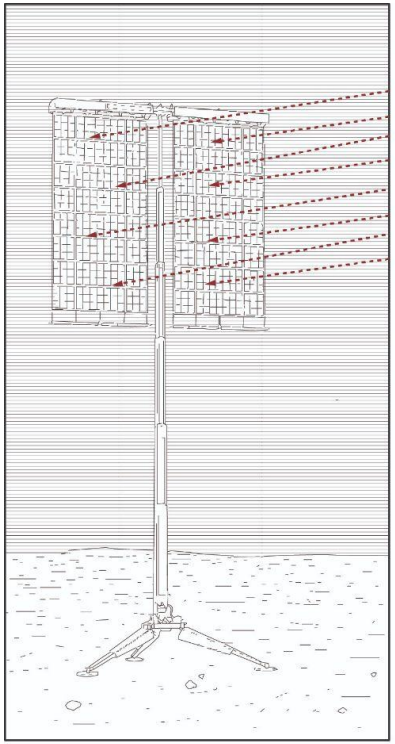
- Melts regolith into a glass-like solid
- No additives required
- Energy-intensive
  - 1500 degrees celsius
- Less porous than SLS so better structural integrity



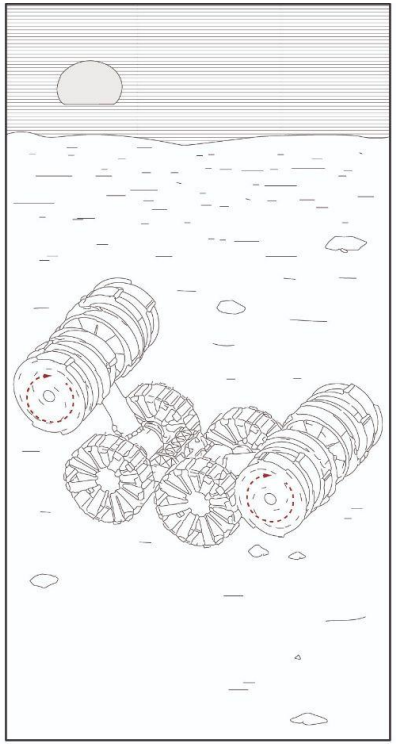
Powder **Sintered** **Melted**



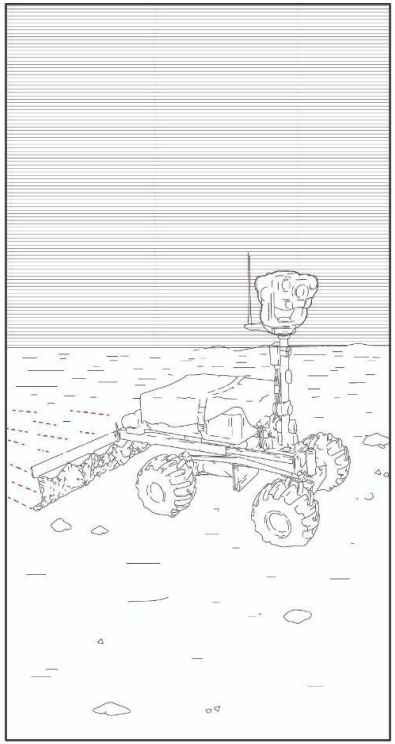
Fateri, M., & Gebhardt, A. (2015). Process parameters development of selective laser melting of lunar regolith for on-site manufacturing applications. International Journal of Applied Ceramic Technology, 12(1), 46–52. https://doi.org/10.1111/ijac.12326



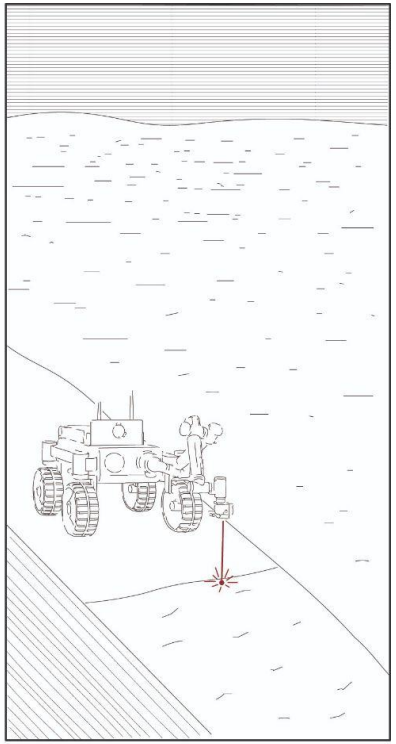
Collecting Solar Energy



Mining & Processing Regolith



Flattening Regolith



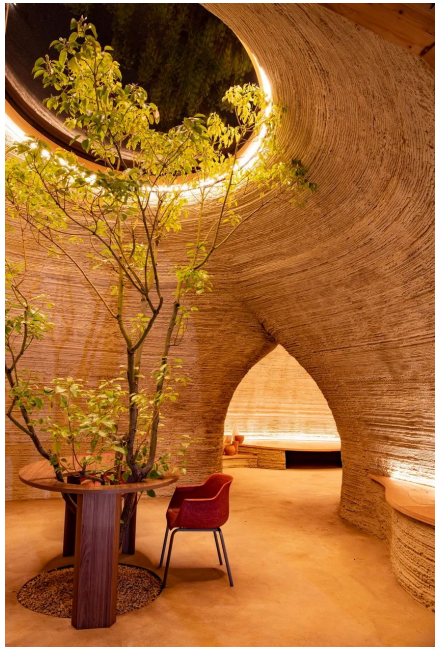
Melting The Regolith With Lasers

3D Printing

Case Study

TECLA by Mario Cucinella Architects

- Used material extrusion not SLM
- Organic shapes
- Custom unique texture on the exterior
- Integrated strip lighting
- Compressive dome shape



Mario Cucinella Architects. (2020). *TECLA: The first eco-sustainable housing prototype 3D printed from raw earth.* https://www.mcarchitects.it/en/projects/tecla-technology-and-clay

Section

Mental Health & Well-being

Missions in Space

- Stuck with the same people
- High stress environment
- Away from family and home
- Little privacy
- Monotonous environment

Sick Building Syndrome

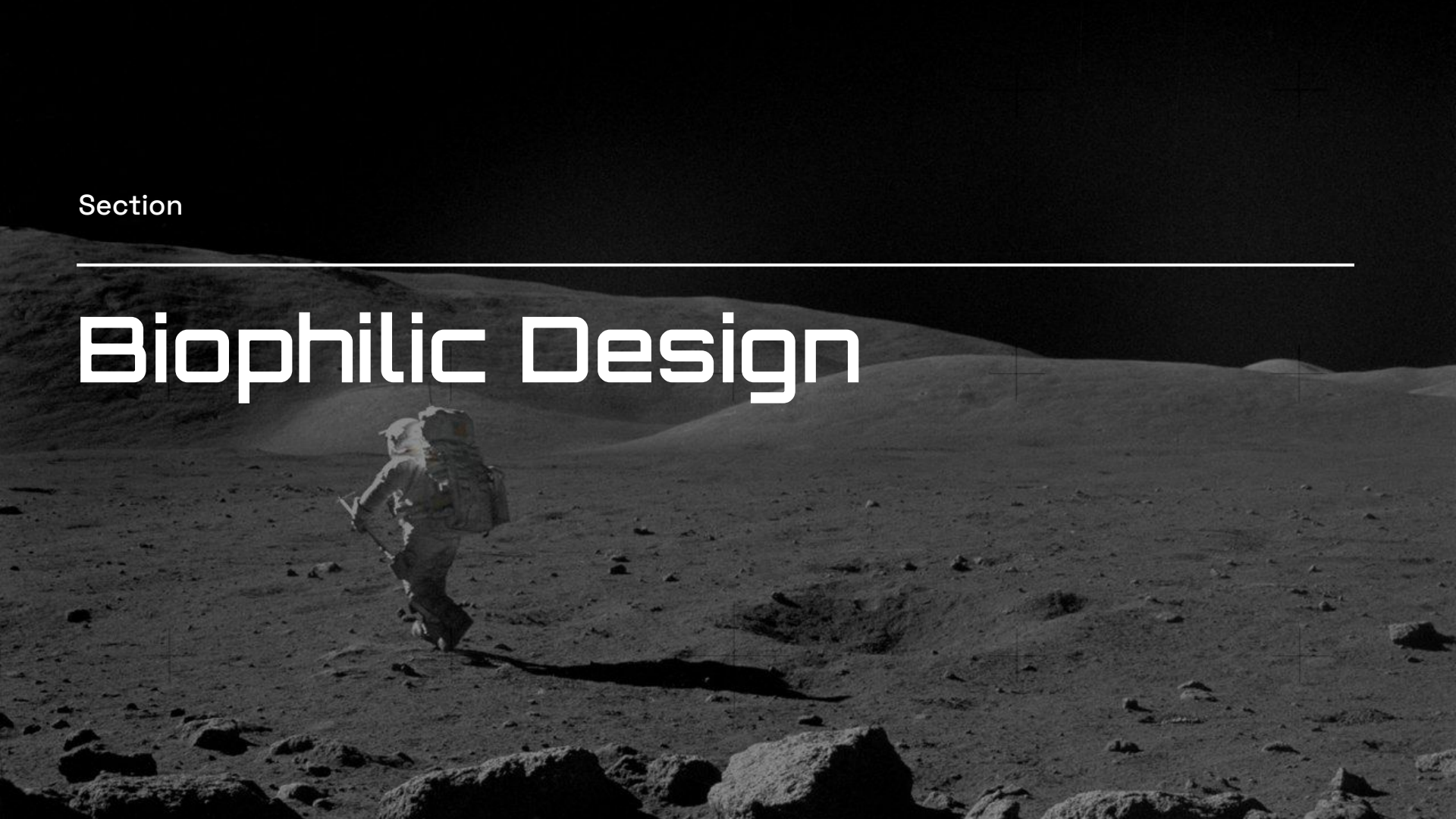
- Improper, harsh lighting
- Thermal/humidity discomfort
- Bad acoustic quality → noise
- Bad air quality

Biophilic Design Interventions Should Respond through:

- ❑ Non-monotonous, dynamic spaces
- ❑ Separation between public & private spaces → ability to retreat
- ❑ Lighting comfort
- ❑ Acoustic comfort
- ❑ Thermal comfort
- ❑ Good air quality

Section

Biophilic Design



Biophilic Design

Definition

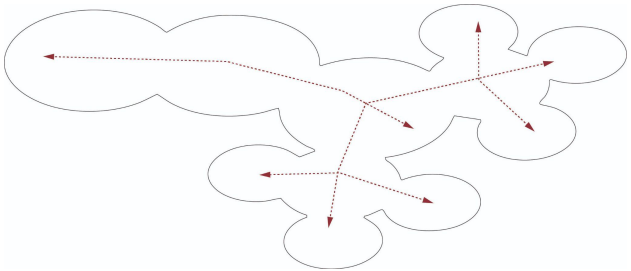
An approach to architecture and interior design that **connects people with nature** within built environments, using **natural elements, forms, and processes** to **improve human health**, well-being, and productivity, stemming from our innate **love for nature**

Computational Systems

At the building level **biophilic design** comes through **2 main design systems**

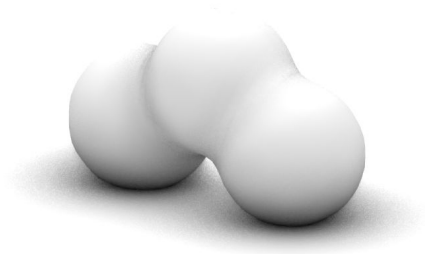
Lindemayers L-System

A mathematical system that describes plant growth and allows us to model it.



Metaballs

A modelling technique involving spheres to create **organic looking shapes.**

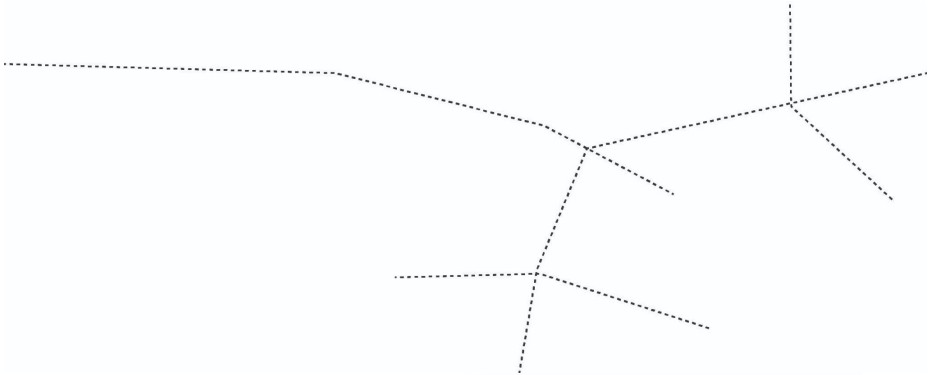



Nature
L-system

L-System

Why L-System?

1. Biomimicry → mimic plant growth
2. Modular design
    a. Building can grow and branch out in the future
3. Efficient pathing
    a. L-system branches create pathing for humans and LSS
4. Spatial Hierarchy
5. Compartmentalization (safety)



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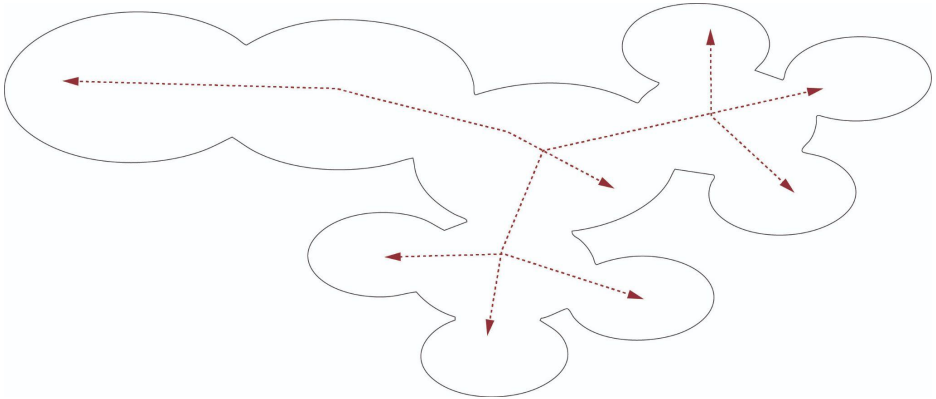

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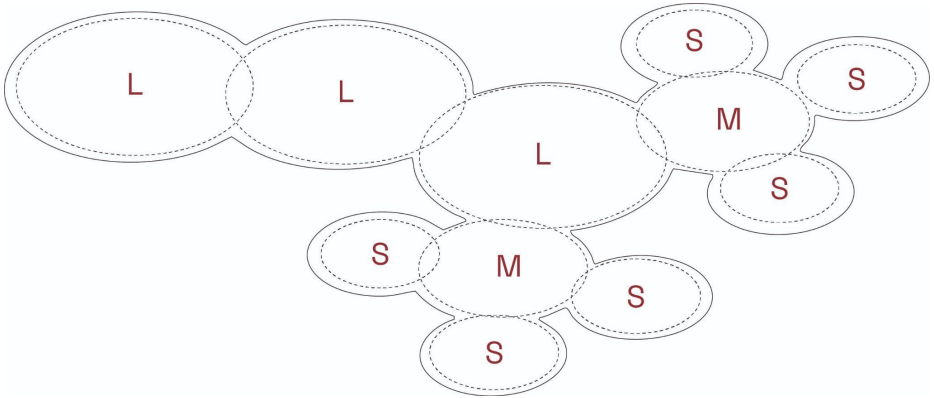

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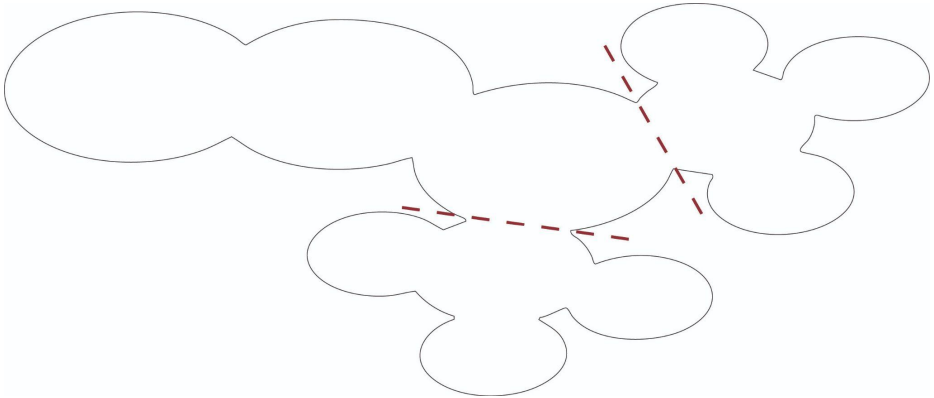
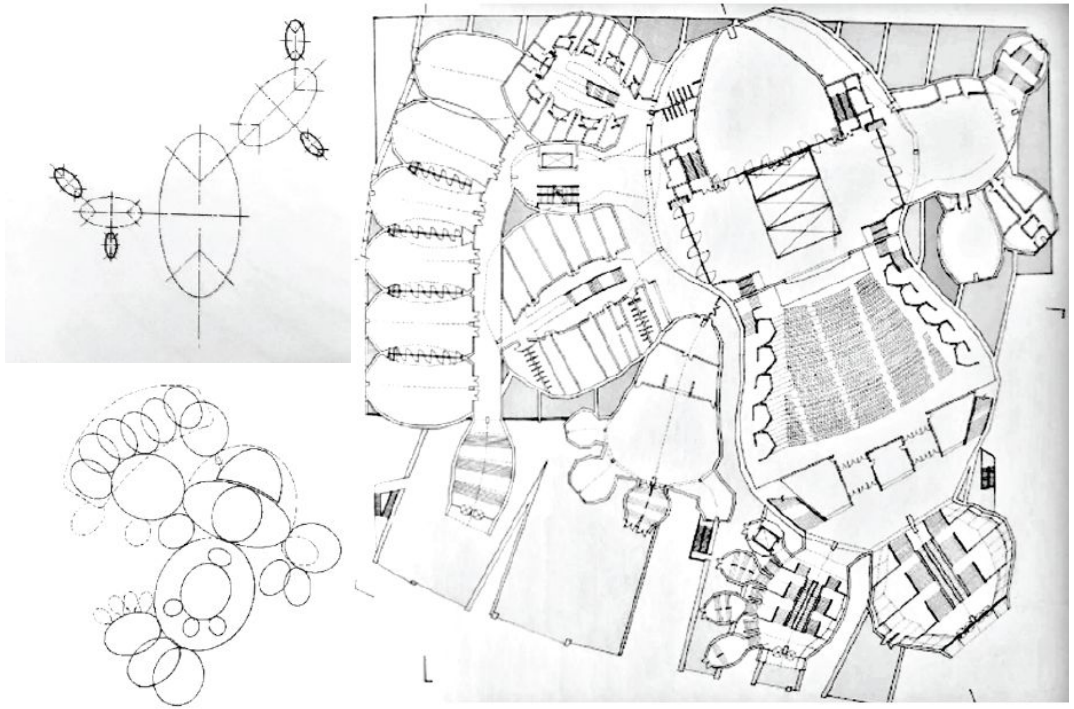


L-System

Case Study

Cardiff Bay Opera House by Greg Lynn

- Precedent for designing with L-systems
- Uses the L-system to define the floorplan
- Clear spatial hierarchy through size differences



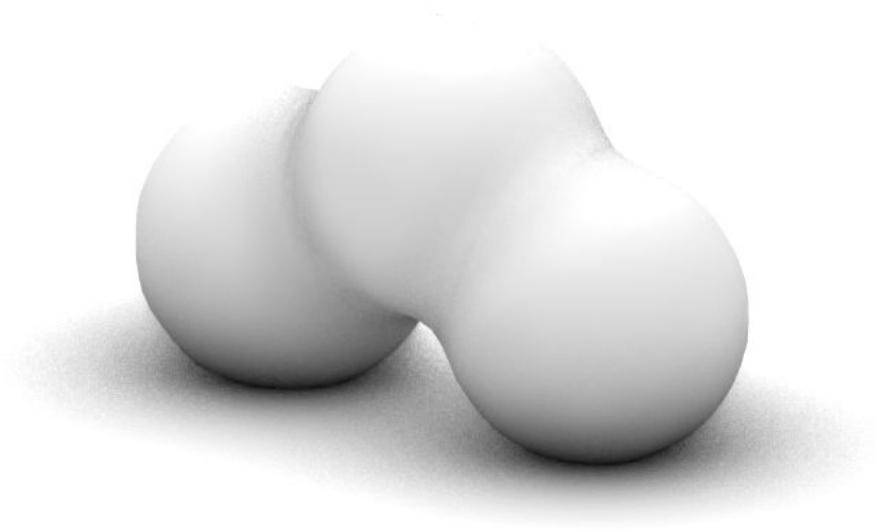
Lynn, G. (1999). Animate form. Princeton Architectural Press.


Nature
Metaballs

Metaballs

Why Metaballs?

1. 3D printing allows us to step away from more typical orthogonal architectural designs
2. Easy way to achieve an organic look
3. Spheres are ideal shapes when dealing with pressure
4. Domes work well in compression, ideal for 3D printing



Metaballs

Why Metaballs?

1. 3D printing allows us to step away from traditional blocky looks you find on Earth at the moment
2. Easy way to achieve a dynamic organic form
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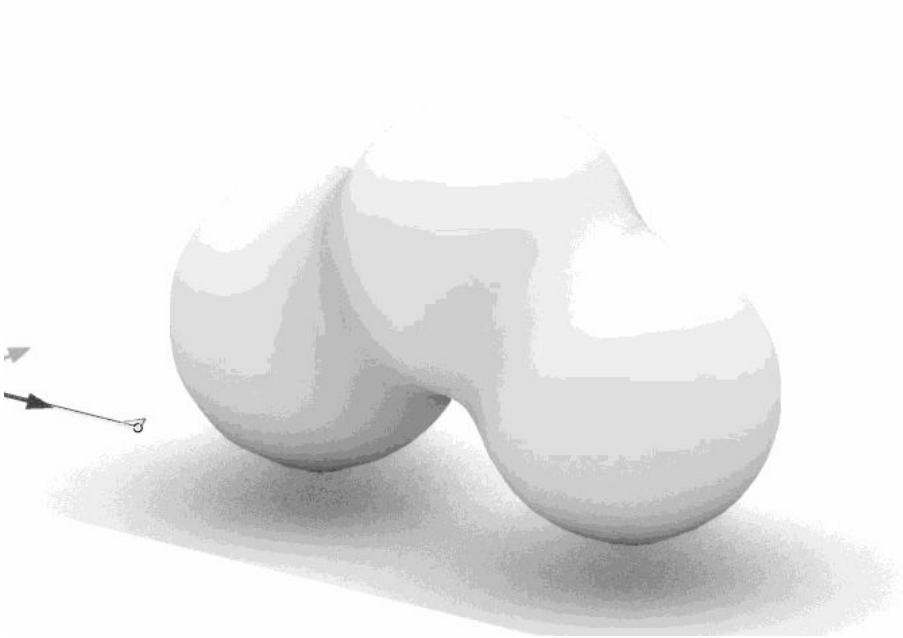

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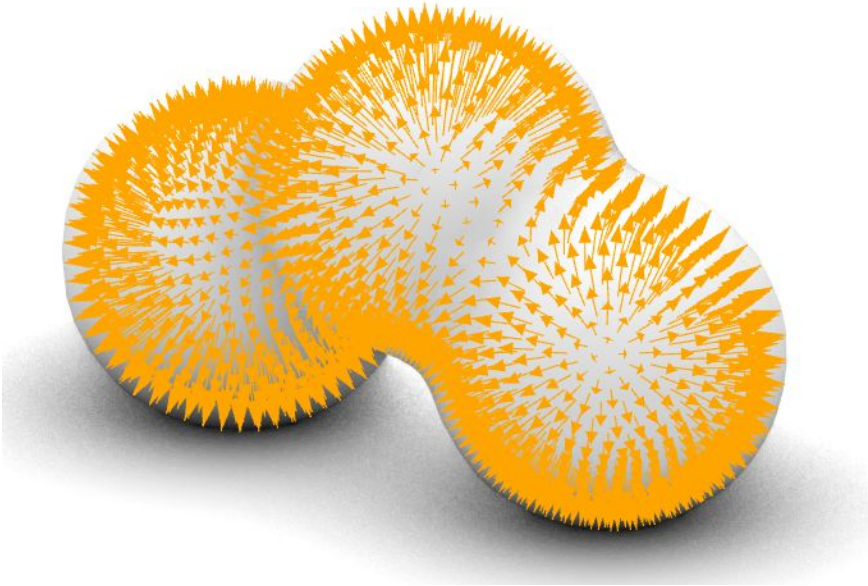

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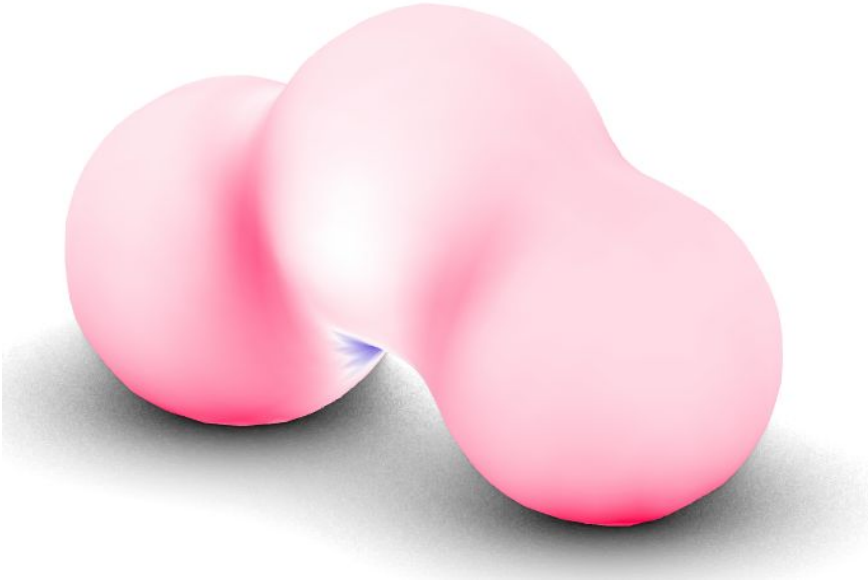


Section

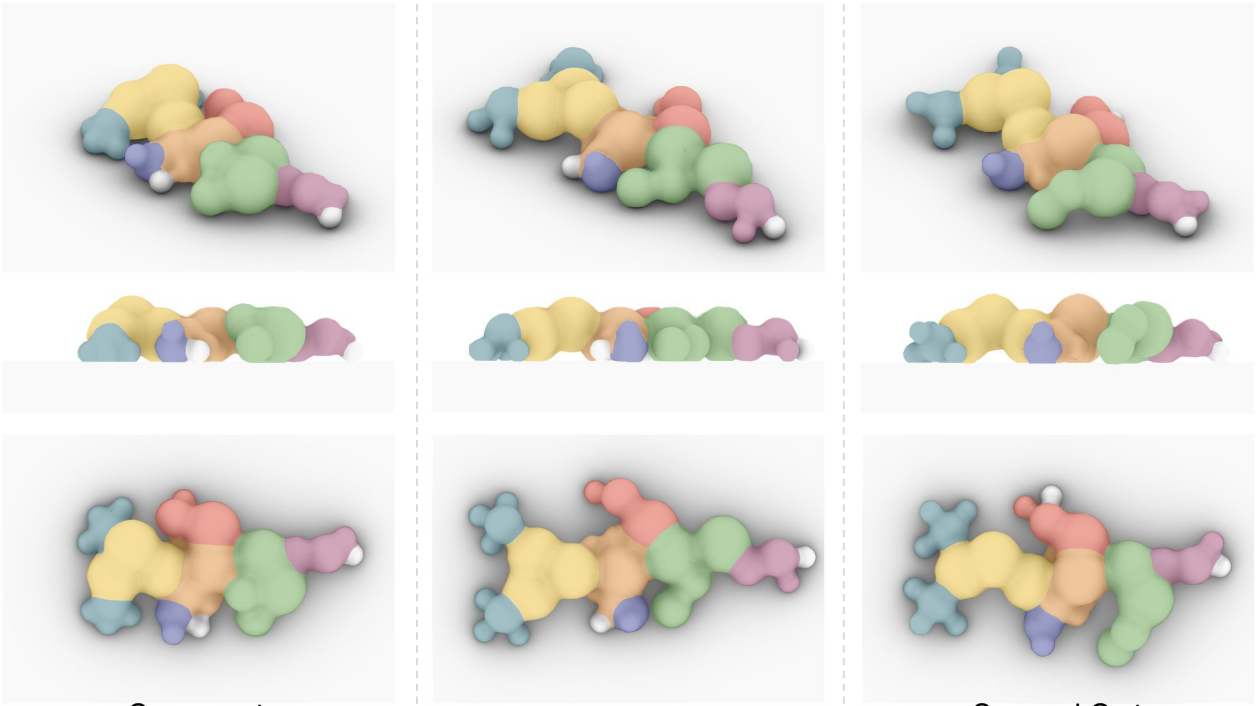
Programme

Long-Term Research Mission For A Crew Of 6

TYPOLOGY		SIZE							ACTIVITY			PRIVACY			EXTERIOR	
PROGRAMME	ROOM	AREA 1 Person (m2)	Max. Capacity	MIN. AREA (m2)	Number of rooms	Total floor area (m2)	% OF HABITAT	MIN. HEIGHT (m)	CATEGORY	CROSS-FUNCTION	Details	CAPACITY	VISIBILITY	ACOUSTICS	ACCESS	VIEW
Dirty Zone	Airlock (EVA Prep)	8	3	24	2	48	600.00%	3	Support	/		Small groups (2-3)	Enclos...	Neutral	Yes	No
	Lunar Soil Lab	12	2	24	1	24	300.00%	3	Work	/		Large groups (4-6)	Enclos...	Neutral	No	No
	Geology Lab	12	2	24	1	24	300.00%	3	Work	/		Large groups (4-6)	Enclos...	Neutral	No	No
	System Mainetenance	8	1	8	1	8	100.00%	3	Support	/		Small groups (2-3)	Enclos...	Neutral	No	No
	Storage (outdoor equipement)	4	3	12	1	12	150.00%	3	Support	/		Storage	Enclos...	Neutral	Yes	No
Core Utility Zone	Life Support Systems	8	1	8	1	8	100.00%	3	Support	/		Small groups (2-3)	Enclos...	Sound ...	No	No
	Systems Maintenance	8	1	8	1	8	100.00%	3	Support	/		Small groups (2-3)	Enclos...	Sound ...	No	No
	Storage (food, water, oxygen)	8	3	24	1	24	300.00%	3	Support	/		Storage	Enclos...	Neutral	No	No
	Bathrooms	5	1	5	3	15	187.50%	3	Support	/		Individual	Enclos...	Sound ...	No	No
Personal/Quite Zone	Private quarters	8	1	8	6	48	600.00%	3	Personal	/		Individual	Enclos...	Sound ...	No	No
Social Zone	Kitchen	2	6	12	1	12	150.00%	6	Social	/		Small groups (2-3)	Open	Neutral	No	No
	Dining Room	3	6	18	1	18	225.00%	6	Social	/		Large groups (4-6)	Open	Neutral	No	Yes
	Living Room	4	6	24	1	24	300.00%	6	Social	/		Large groups (4-6)	Open	Neutral	No	Yes
	Social Space	4	6	24	1	24	300.00%	6	Social	/		Large groups (4-6)	Open	Neutral	No	Yes
Work Zone	Research Labs	10	4	40	2	80	1000.00%	3	Work	/		Large groups (4-6)	Hybrid	Neutral	No	No
	Agricultural Lab	10	4	40	1	40	500.00%	3	Work	/		Large groups (4-6)	Hybrid	Neutral	No	No
Command Zone	Command & Control	4	6	24	1	24	300.00%	3	Work	Support		Small groups (2-3)	Hybrid	Sound ...	No	Yes
	Radio Room	4	2	8	1	8	100.00%	3	Work	Support		Small groups (2-3)	Hybrid	Sound ...	No	No
Health Zone	Gym	8	6	48	1	48	600.00%	6	Social	/		Large groups (4-6)	Open	Neutral	No	No
	Meditation Room	8	1	8	1	8	100.00%	3	Personal	/		Individual	Enclos...	Sound ...	No	Yes
	Medical Bay	10	2	20	1	20	250.00%	3	Personal	Support		Small groups (2-3)	Enclos...	Sound ...	No	No

Programme

V1 V2 V3



Compact
Low Branching

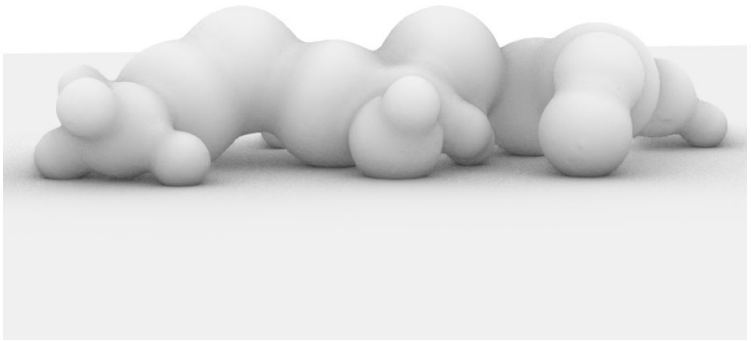
Spread Out
Clearer Branching

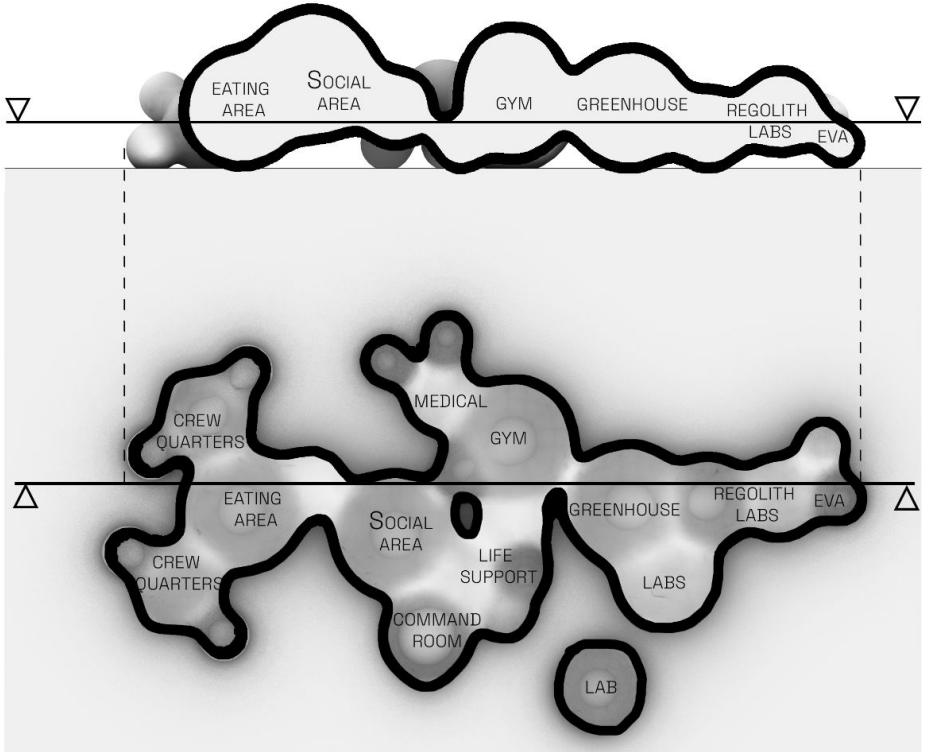
Programme

Distribution

- Clear separation between working area and leisure area

- Centrally placed LSS





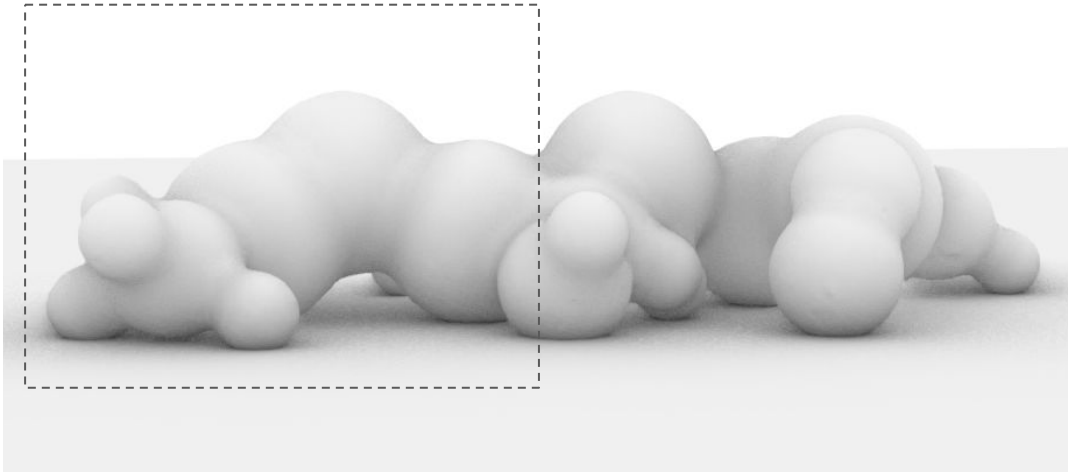
Section

Proof of Concept

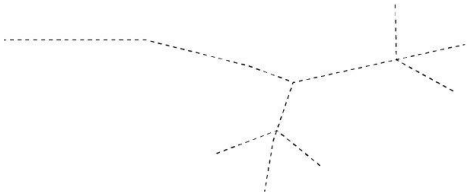
Fragment

Chosen Fragment

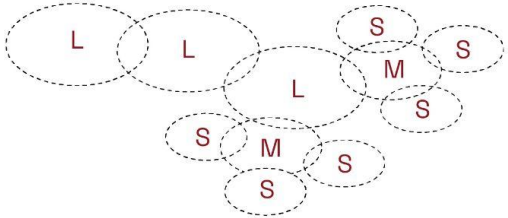
- Crew sleeping and social area
- Proof of concept
- Biophilic design framework can be extrapolated to the larger habitat



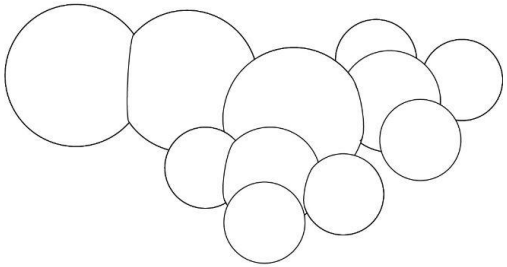
Concept



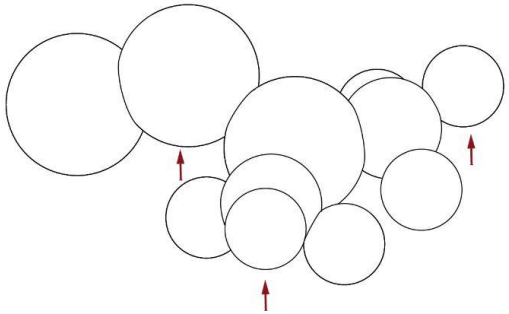
L-System



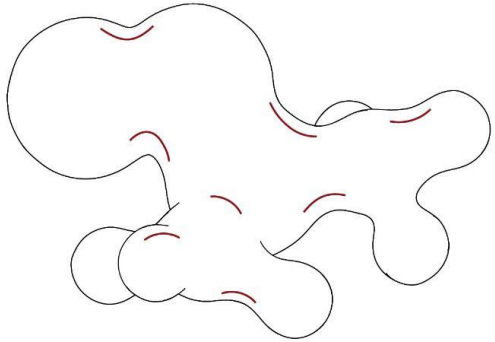
Bubble Diagrams



Volume

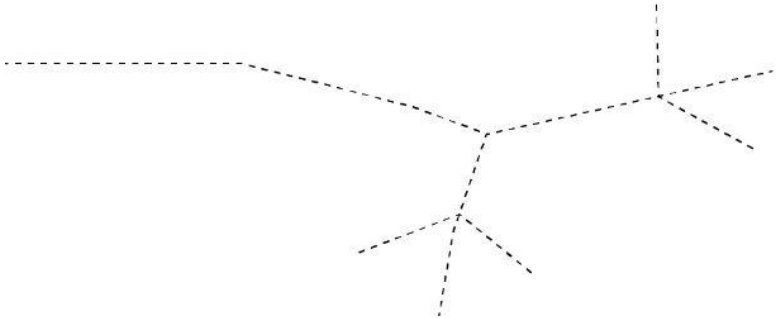


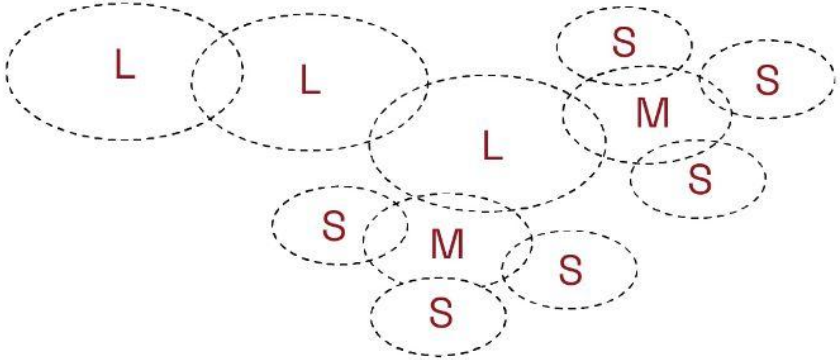
Dynamic Height Changes



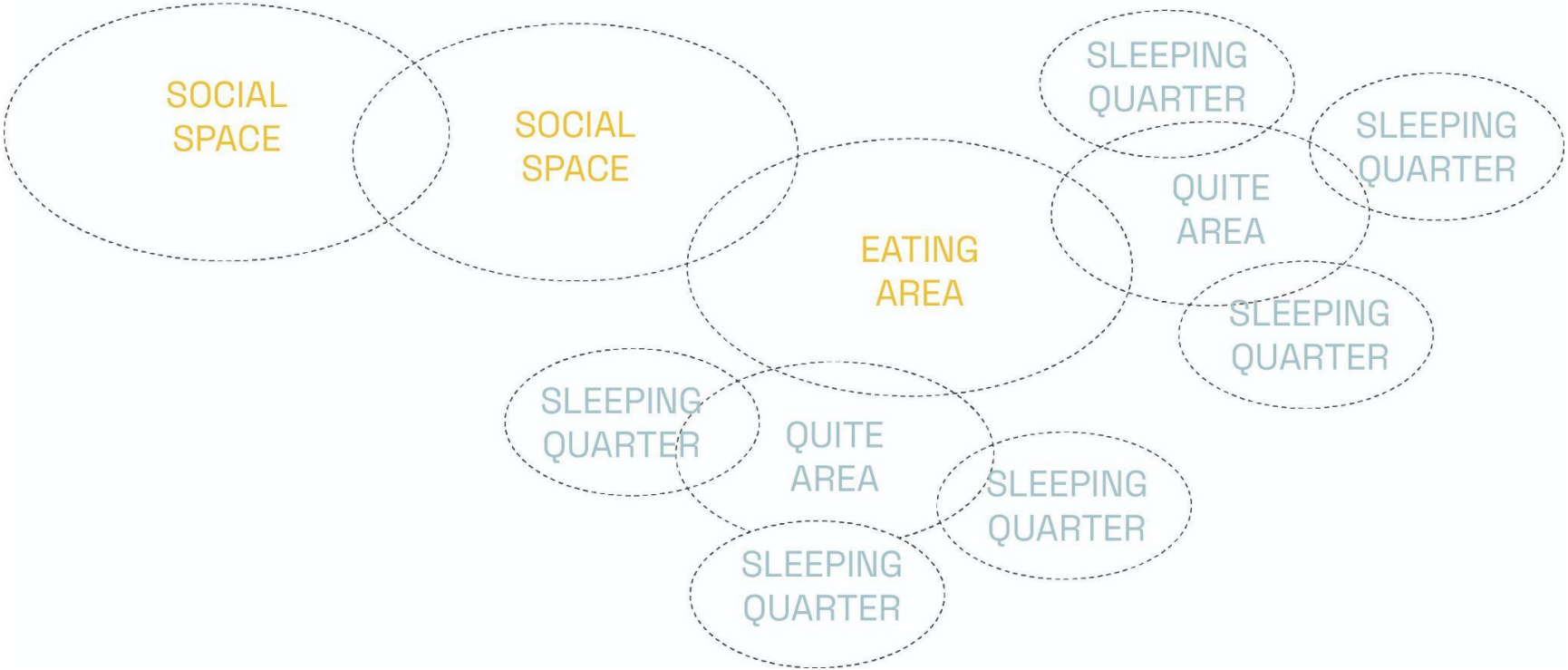
Creating Smooth Metaballs

L-System

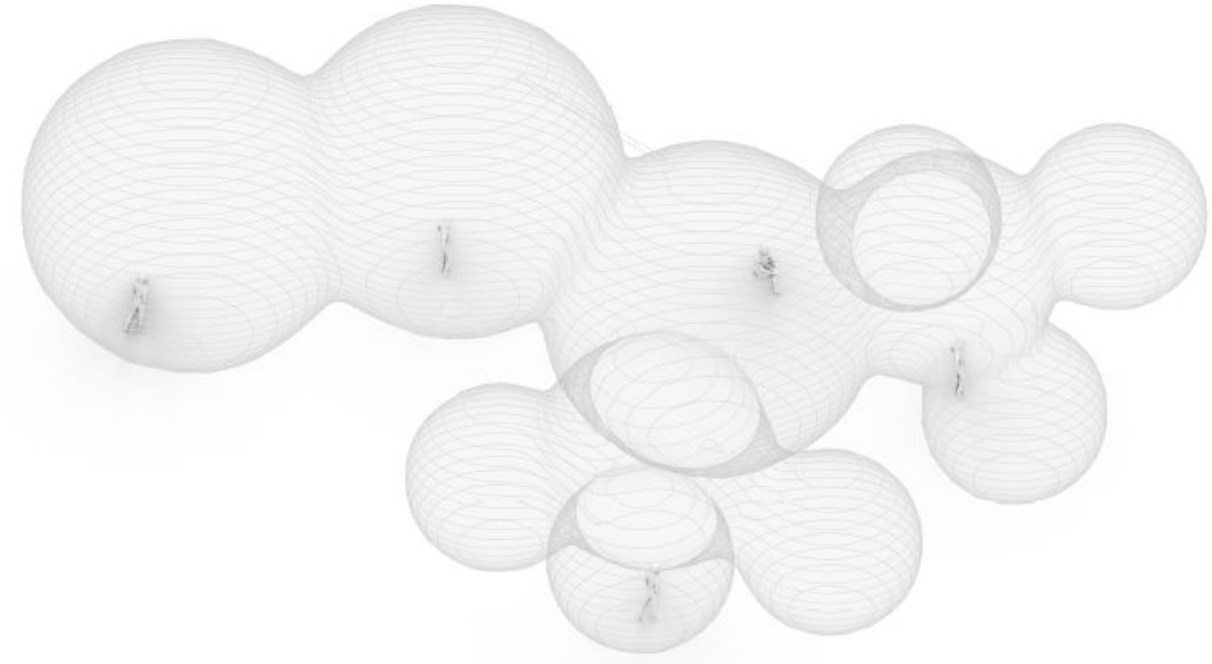




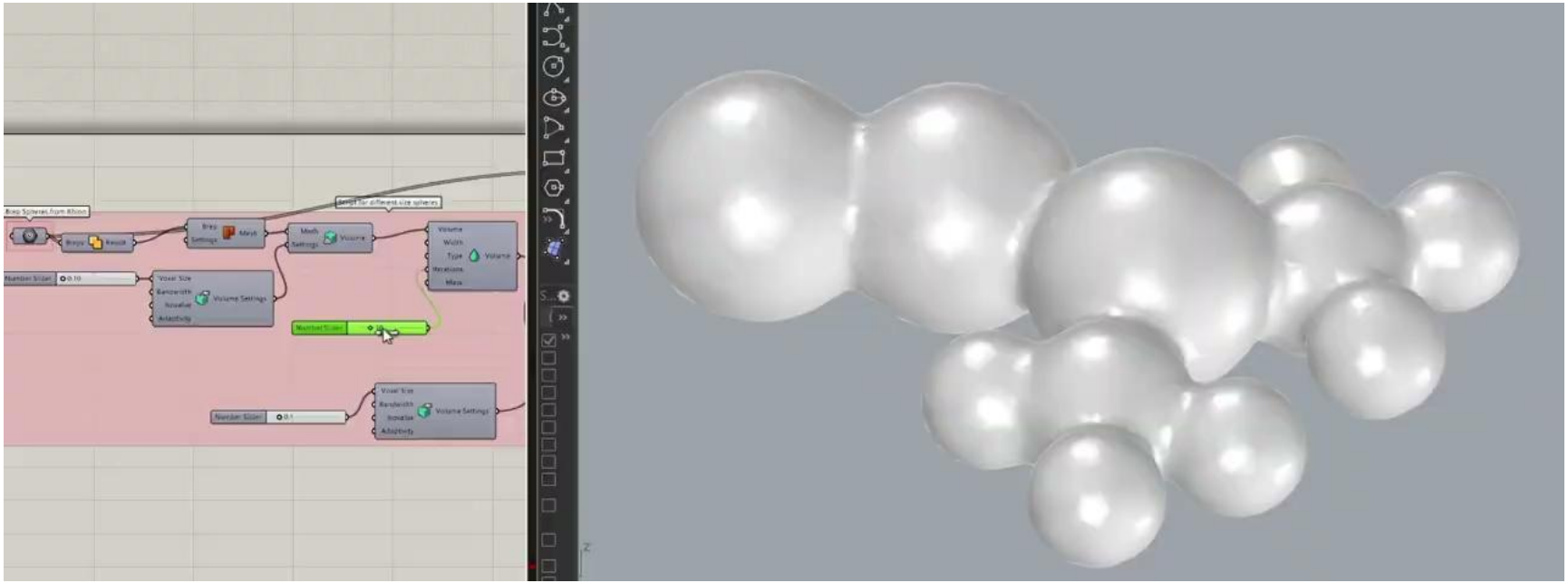
Bubble Diagram



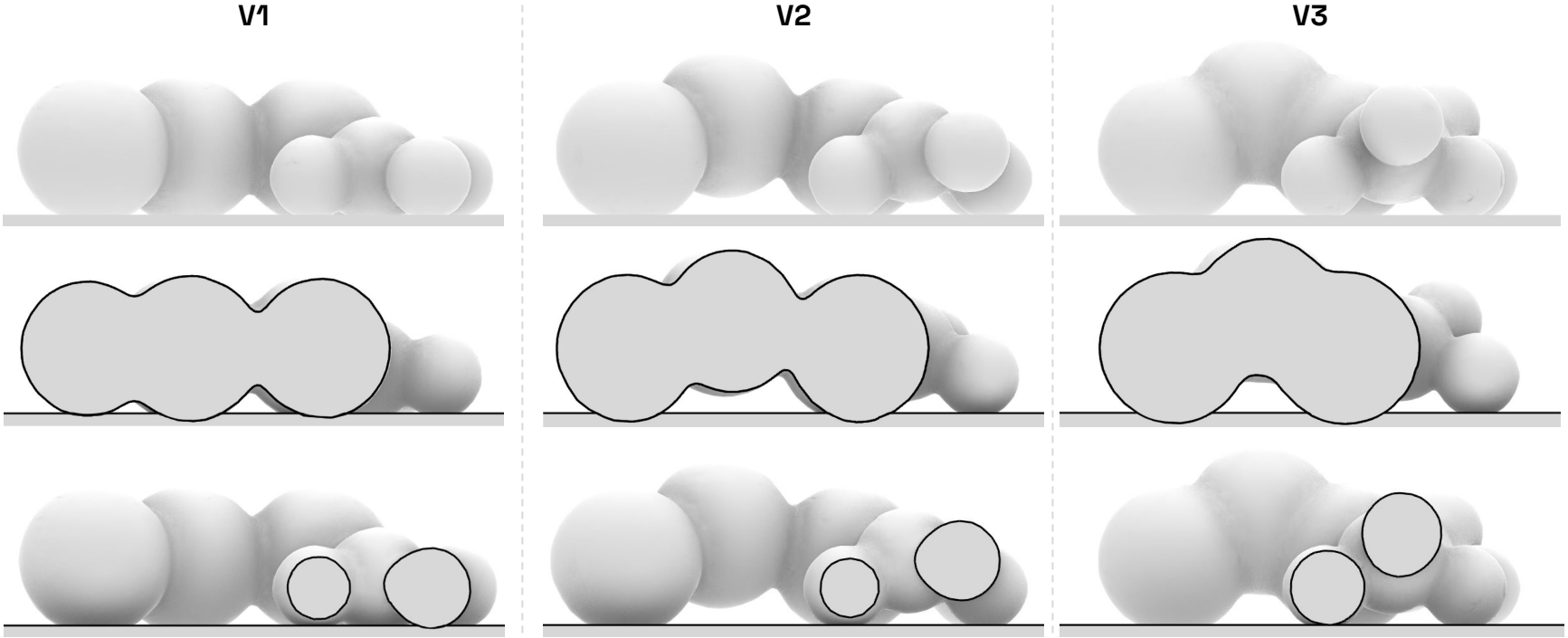
Bubble diagram → metaball volumes



Grasshopper Metaball Script



Metaball Adjustments



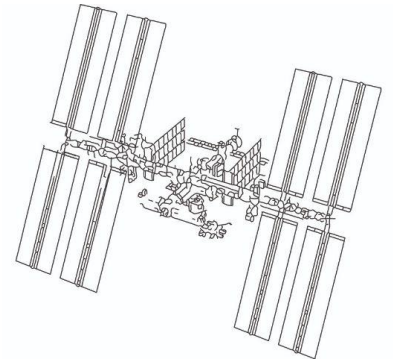
Fragment

Structural Optimisation

Envelope Thickness

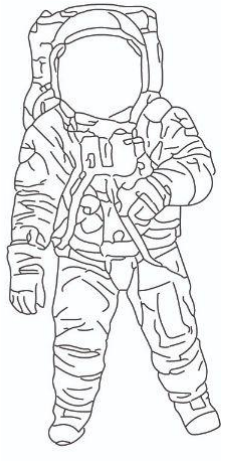
Radiation Exposure

EARTH
2.4 mSv/year



ISS
182.5 mSv/year

MOON
110 - 380 mSv/year



ESA Career MAX
1000 mSv

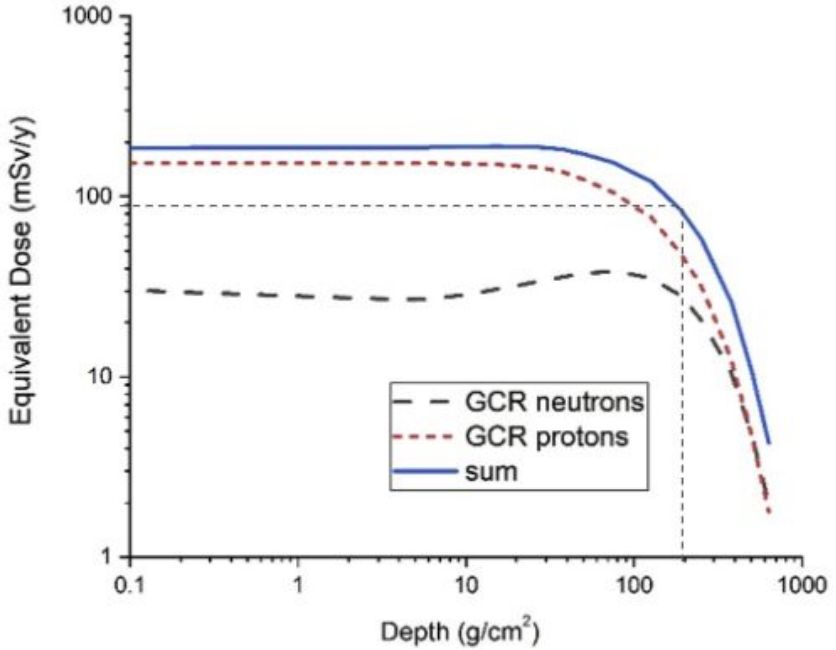
Envelope Thickness

Radiation protection

- ALARA Principle
  (As Low As Reasonably Achievable)
- To reduce cancer and ARS risk
- Aim for around half of the exposure you would get on the ISS

90 mSv/year → ~ 200 g/cm^2

→ **800 mm of regolith shielding**



Equivalent dose in the lunar environment for different thicknesses of regolith shielding (Adapted from Meurisse et al., 2020)

Gravitational Force

Design V1 - Force of Gravity

Max Compression
0.00869 < 9.250 kN/cm^2

Max Tension
0.00236 < 0.925

Structure performs well in low gravity

Overengineered thanks to the thickness required for radiation protection

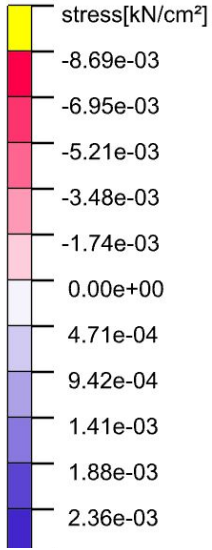
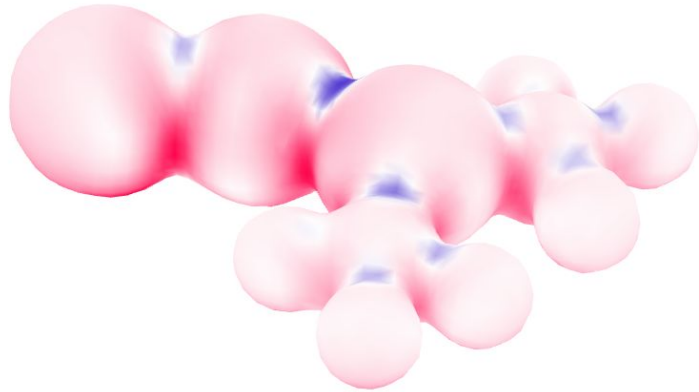


TABLE 4 Compression strength of samples solidified at different target temperatures.

Target temperature (°C)	1300	1400	1500
Compressive strength (MPa)	27.4 ± 2.6	118.2 ± 2.9	125.1 ± 18.4
Initial failure strength (MPa)	15.6 ± 7.0	65.5 ± 2.1	92.5 ± 16.3



Forces: Gravity

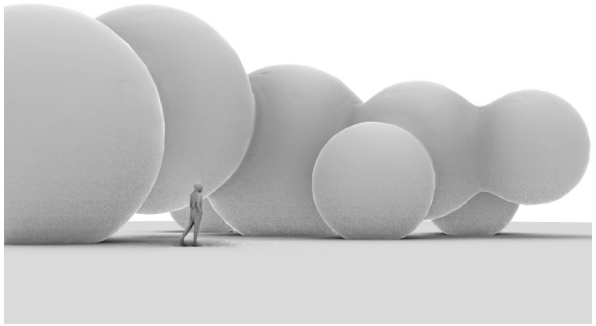
https://www.researchgate.net/publication/390602870_Melting_and_solidifying_behavior_of_lunar_regolith_simulant_under_a_vacuum_environment

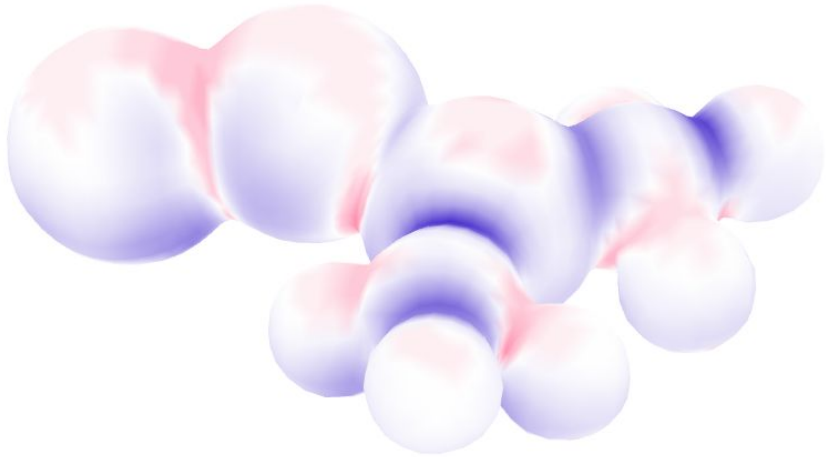
Gravitational Force

Design V2 - Cantilevers

Raising the metaballs

→ More variable interior facilitating jumpy lunar movement

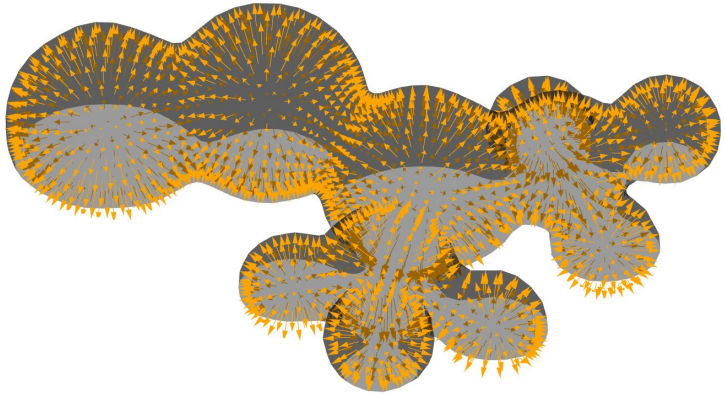


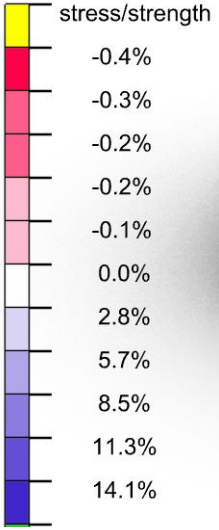


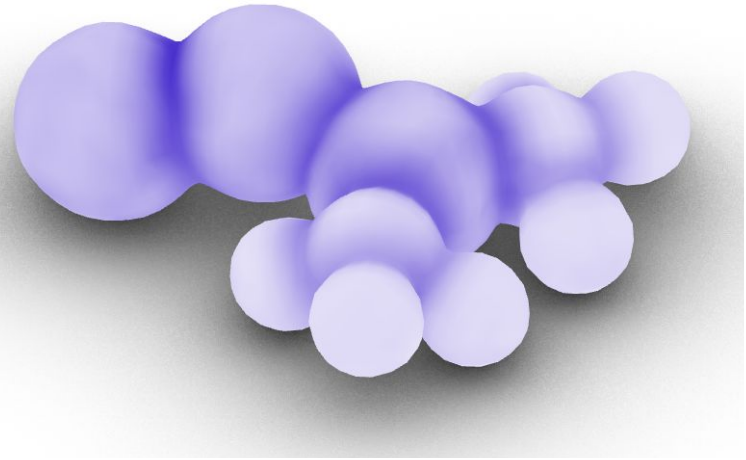
Forces: Gravity

Atmospheric Pressure

Design V2 - Pressurised







Air pressure pushes the shell out

Peak tension 1.7% → 14.1%

Forces: Pressure

Final Structure

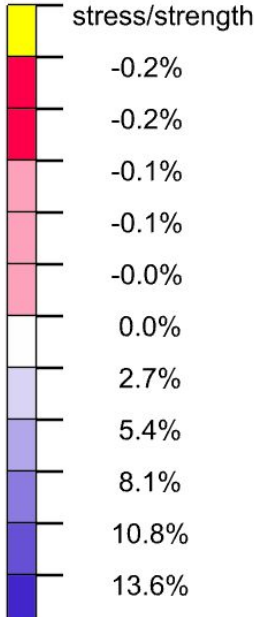
Design V3 - Metaball smoothing

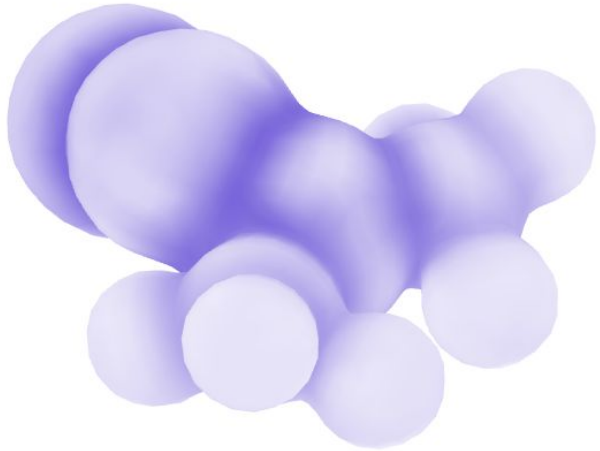
Metaballs are moved closer together and blended

→ More efficient load path to the ground

→ ‘necks’ are reduced

→ Reduce peak stress in the hotspots





Forces: Gravity + Pressure

Fragment

Porosity

Window Type Exploration

Round

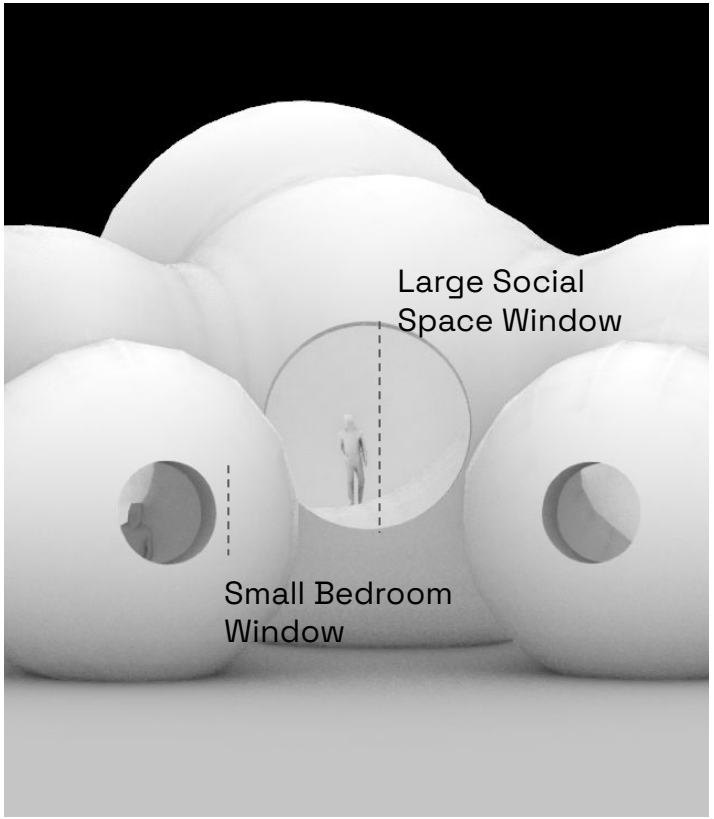
Metaball

Porosity

Porosity levels

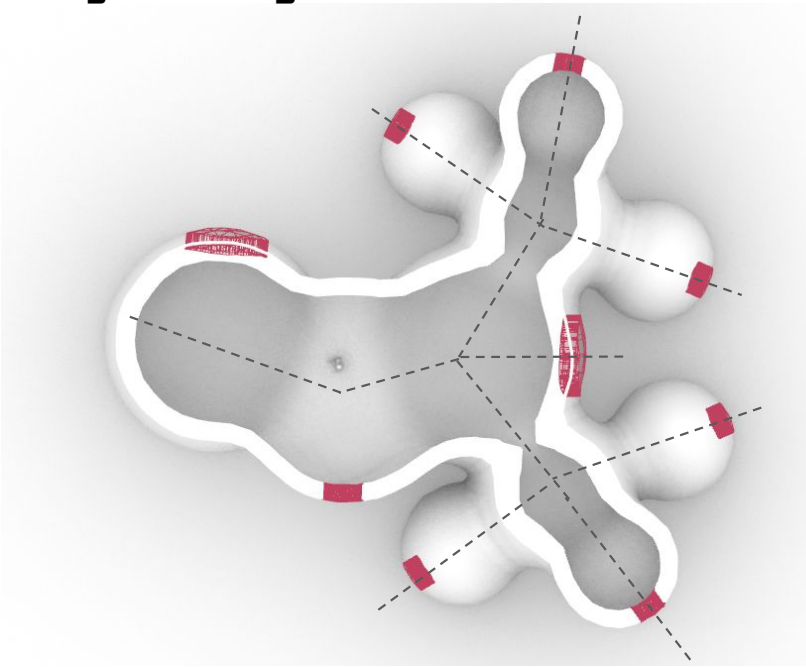
	Function	Porosity Demand
	Private Quarters	Low-Medium
	Transition Space	No-Low
	Kitchen/dining room	High
	Social Space	Medium
	Living Room	High

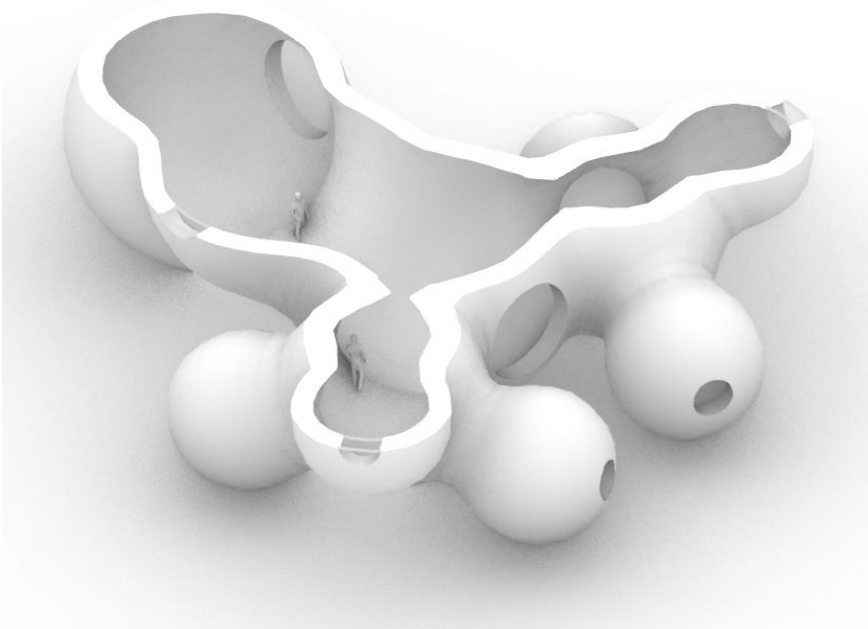
- Dependent on function
- Private vs Public



Porosity

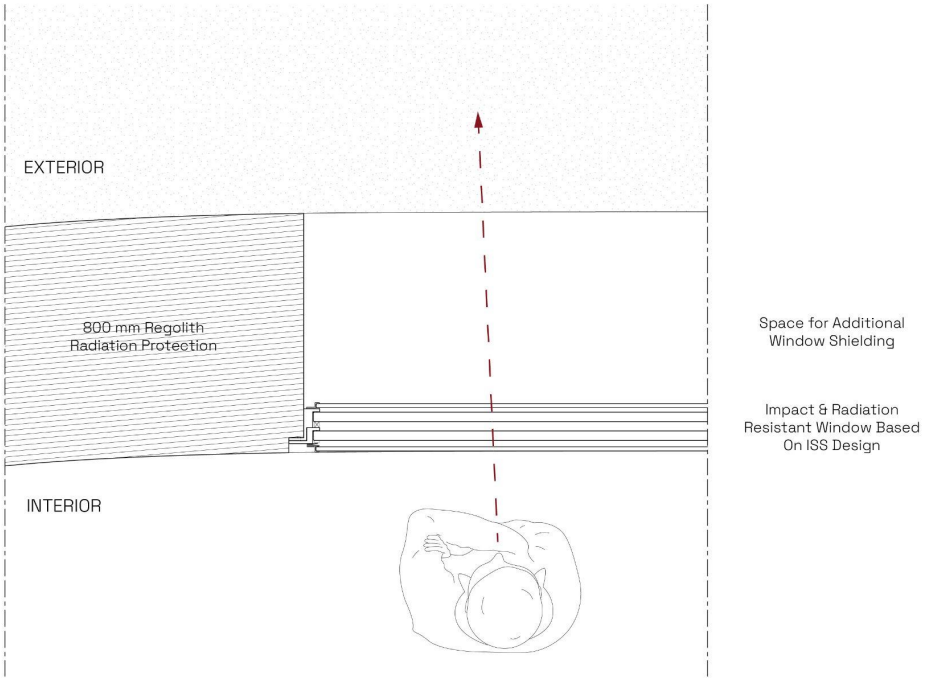
L-system Logic

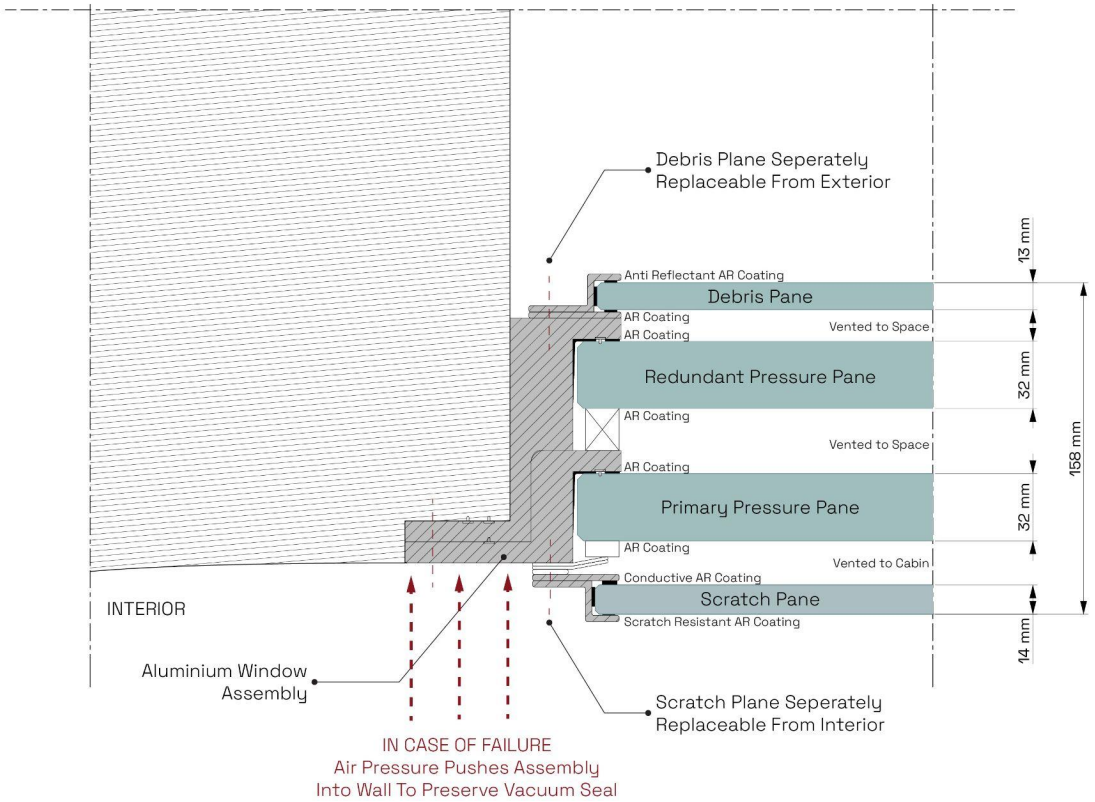




Window Detail

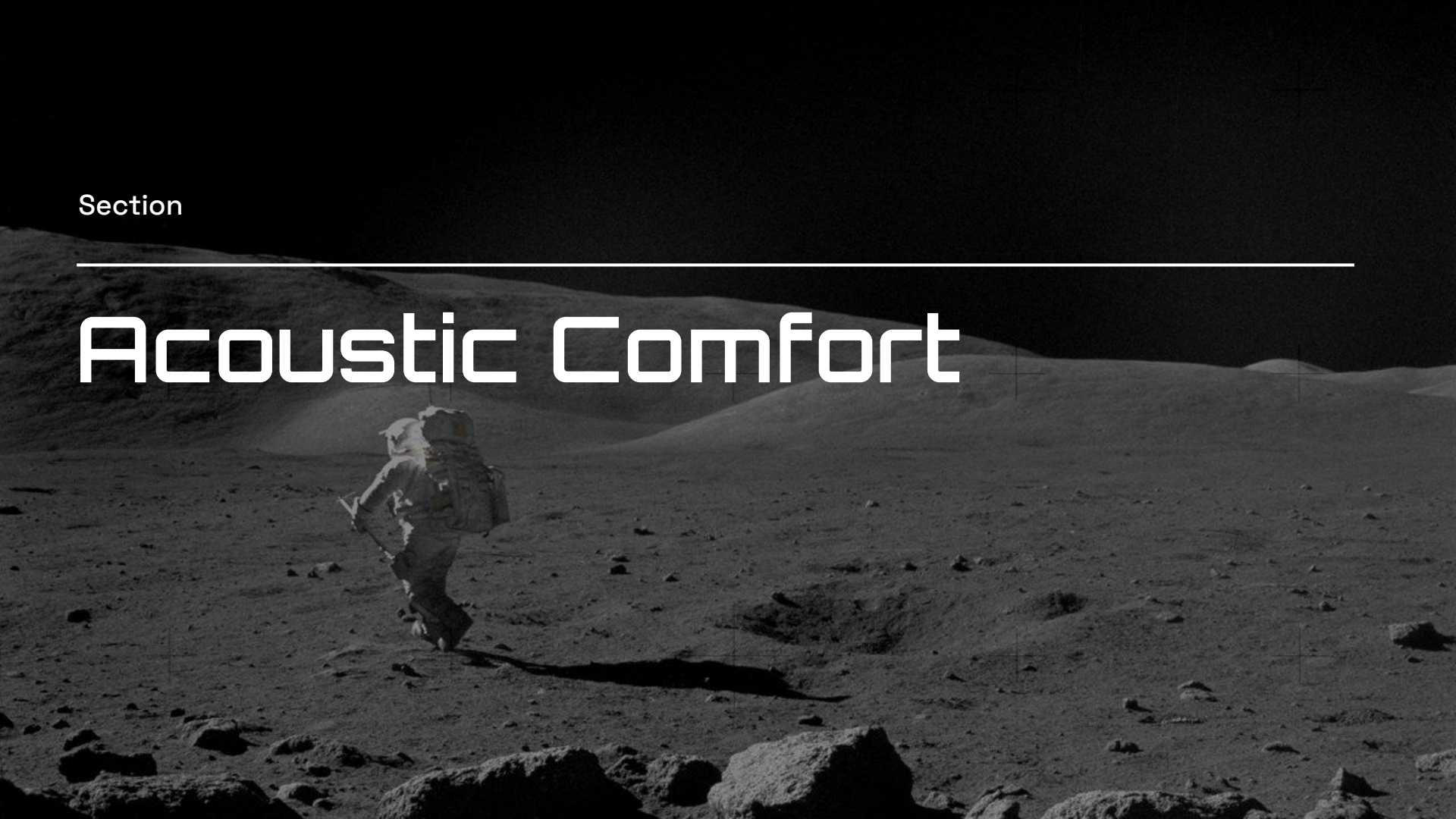
- Flush with the wall
- Space for additional radiation shielding
- Views of the Lunar landscape




Debris Plane Seperately
Replaceable From Exterior
Anti Reflectant AR Coating
Debris Pane
AR Coating
AR Coating
Vented to Space
Redundant Pressure Pane
AR Coating
Vented to Space
AR Coating
Primary Pressure Pane
AR Coating
Vented to Cabin
Conductive AR Coating
Scratch Pane
Scratch Resistant AR Coating
13 mm
32 mm
32 mm
14 mm
158 mm
INTERIOR
Aluminium Window
Assembly
Scratch Plane Seperately
Replaceable From Interior
IN CASE OF FAILURE
Air Pressure Pushes Assembly
Into Wall To Preserve Vacuum Seal

Section

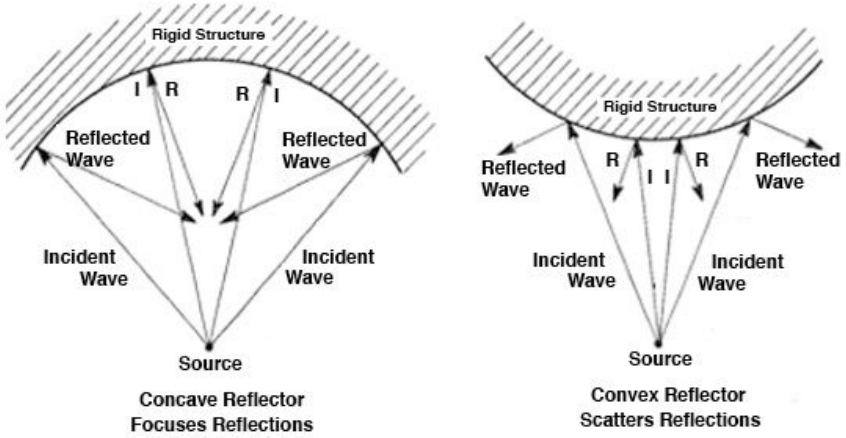
Acoustic Comfort

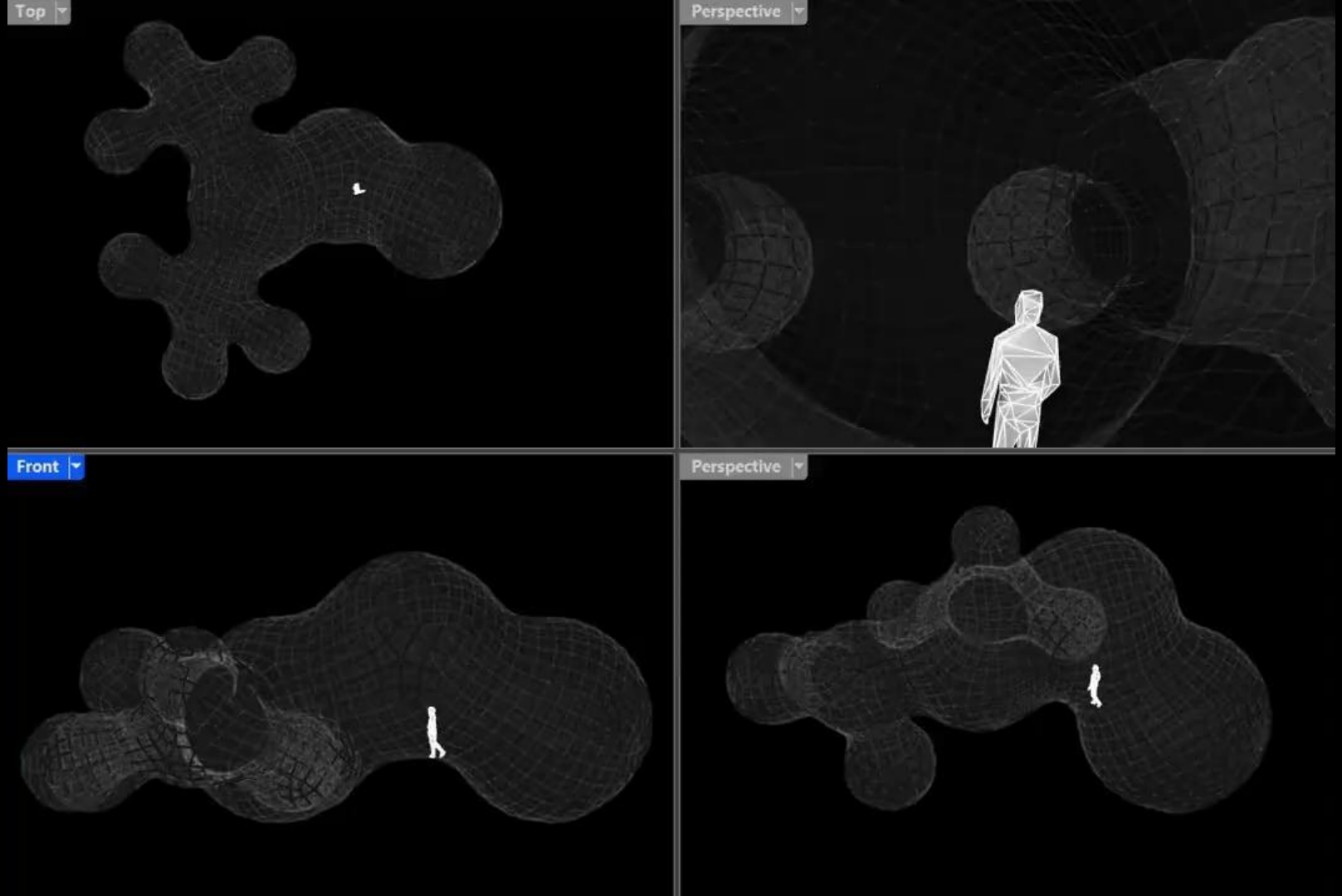


Acoustics

Metaball echo

- Concave shape of the metaball causes sound waves to bounce back
- Lots of echo
- Unpleasant acoustics with smooth walls




Top
Perspective
Front
Perspective

Acoustics

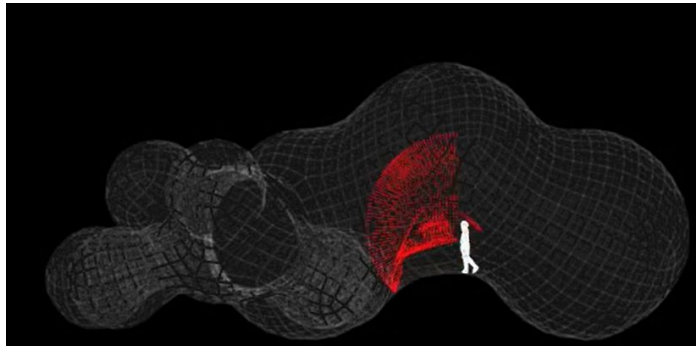
Simulation

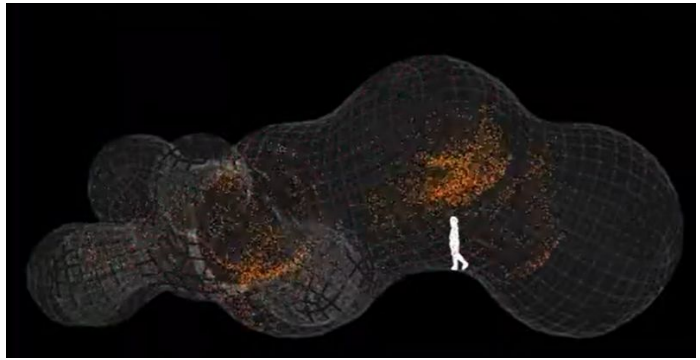
- Concave shape reflects and concentrates sound back to user

- High reverberation time (echo)

- Low speech intelligibility

NEED TO SCATTER SOUND INTO DIFFERENT DIRECTIONS AND ABSORB MORE

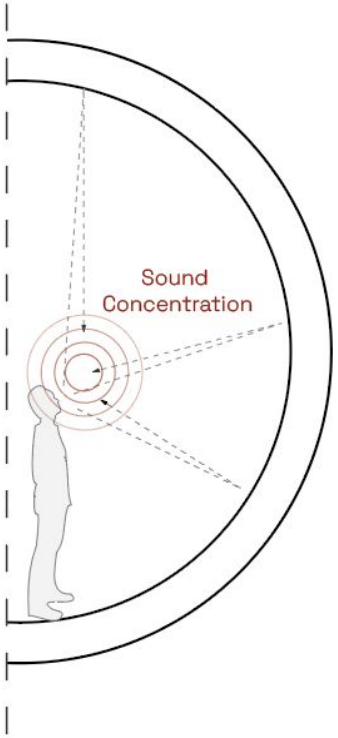


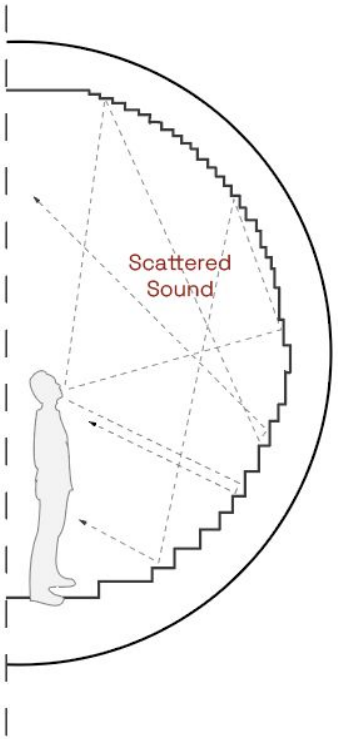


Acoustic Pattern

Scattering

- Breaking up the surface
- Increase reflections
- Reduce concentration of sound





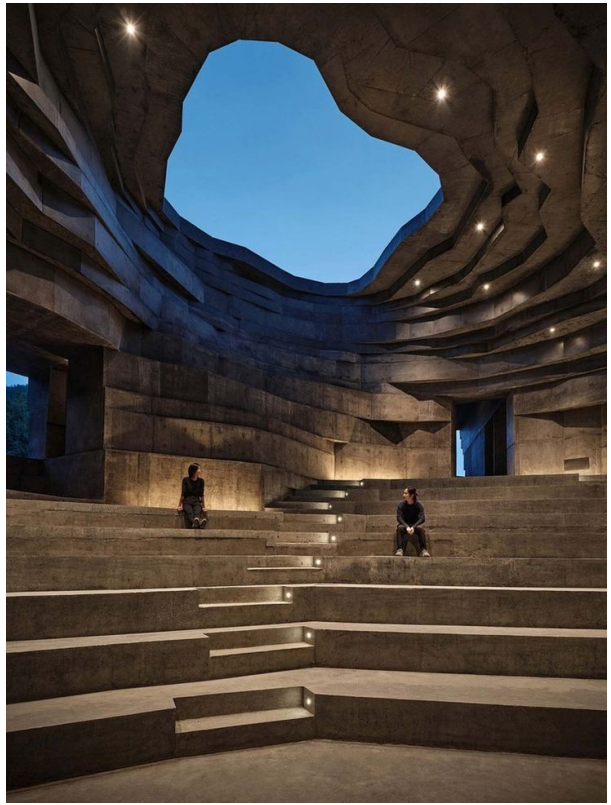
Nature

Rock Formations

Case Study

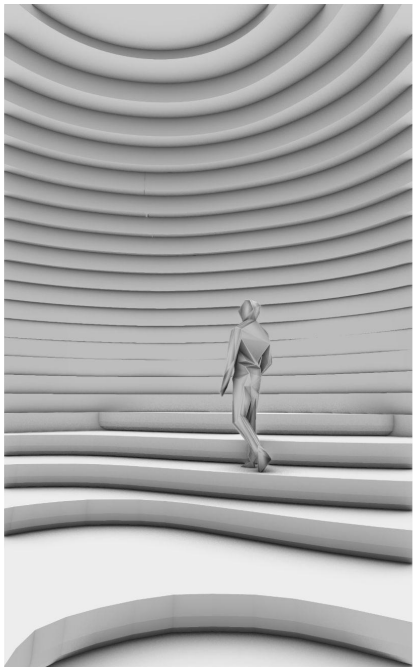
Chapel of Sound - OPEN Architecture

- Varying heights and widths
- Functional terracing
- Mimics natural rock formations

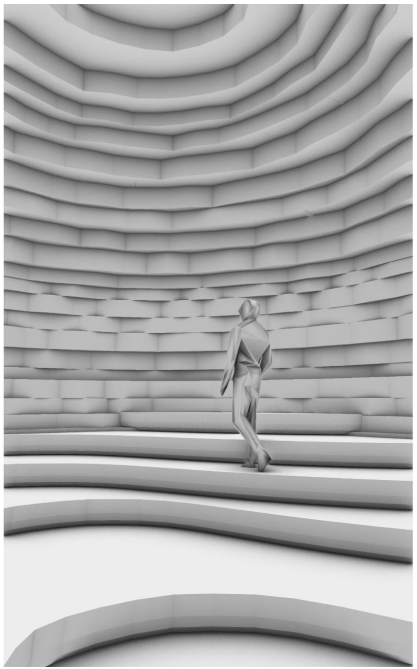


OPEN Architecture. (2024). Chapel of Sound [Photograph]. Divisare. https://images.divisare.com//images/c_limit,f_auto,h_2000,q_auto,w_3000/v1722846688/6e942a2e-b25c-4049-ba67-fbe6d4033832/open-architecture-chapel-of-sound.jpg

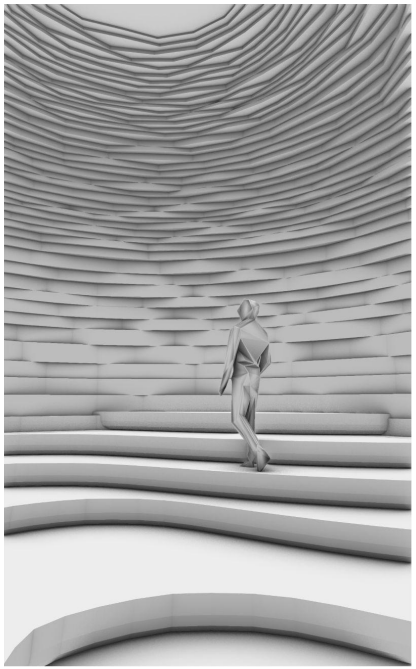
Wall Pattern



Large Massing



Varied Heights

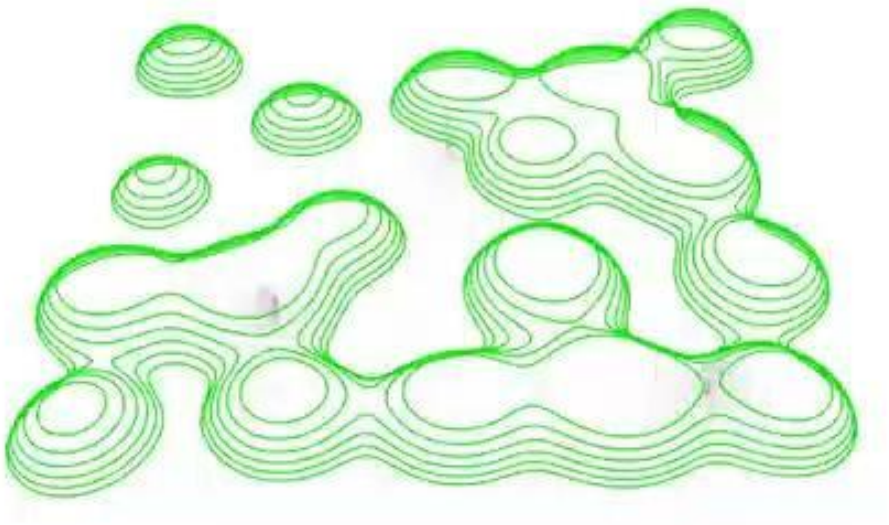


Option
Reduced for printability

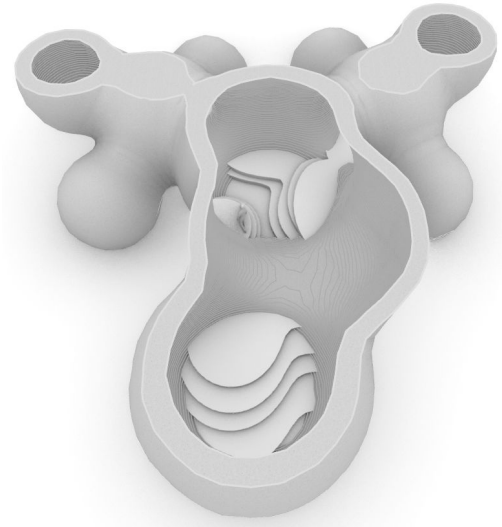
Terracing

Creating useable floor spaces

- Random point generation
- Creates 2D metaballs
- Offset and extrudes for terracing

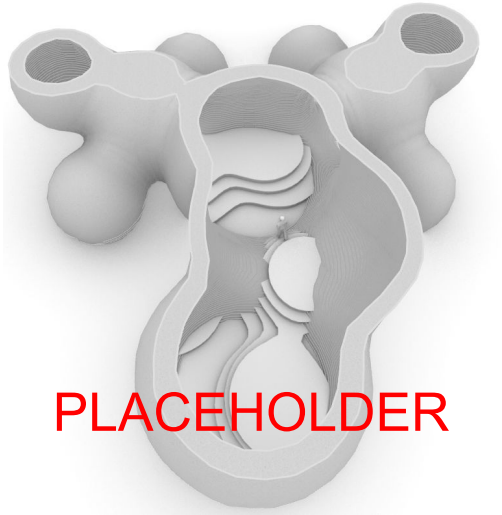


Terracing study



GOOD: Back room has different defines zones

BAD: Does not interact with the building geometry and the flat plateaus are too small to be functional



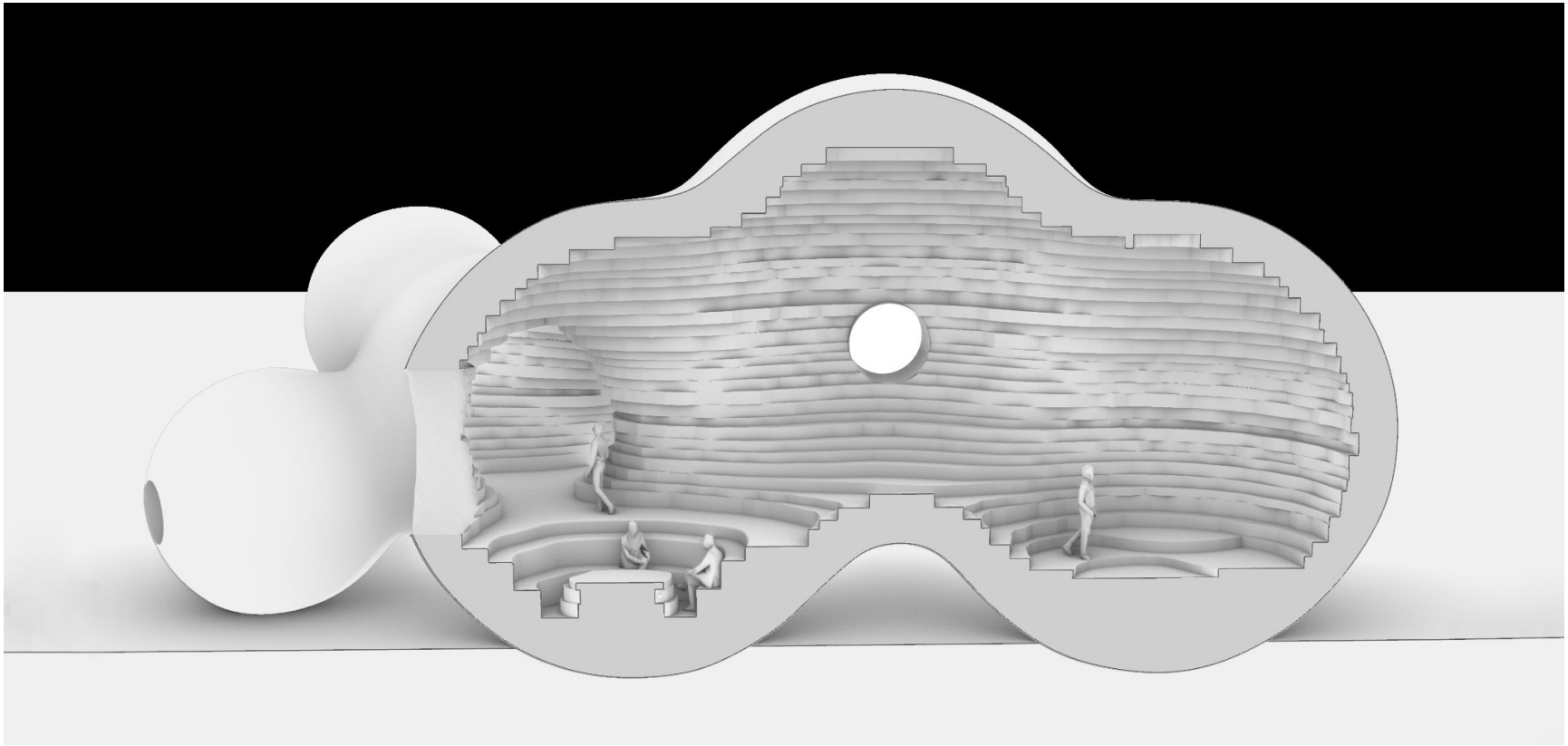
GOOD: High number of level changes and defined zones, clear metaballs

BAD: ‘dead zones’ where there is a random gap between terrace and wall

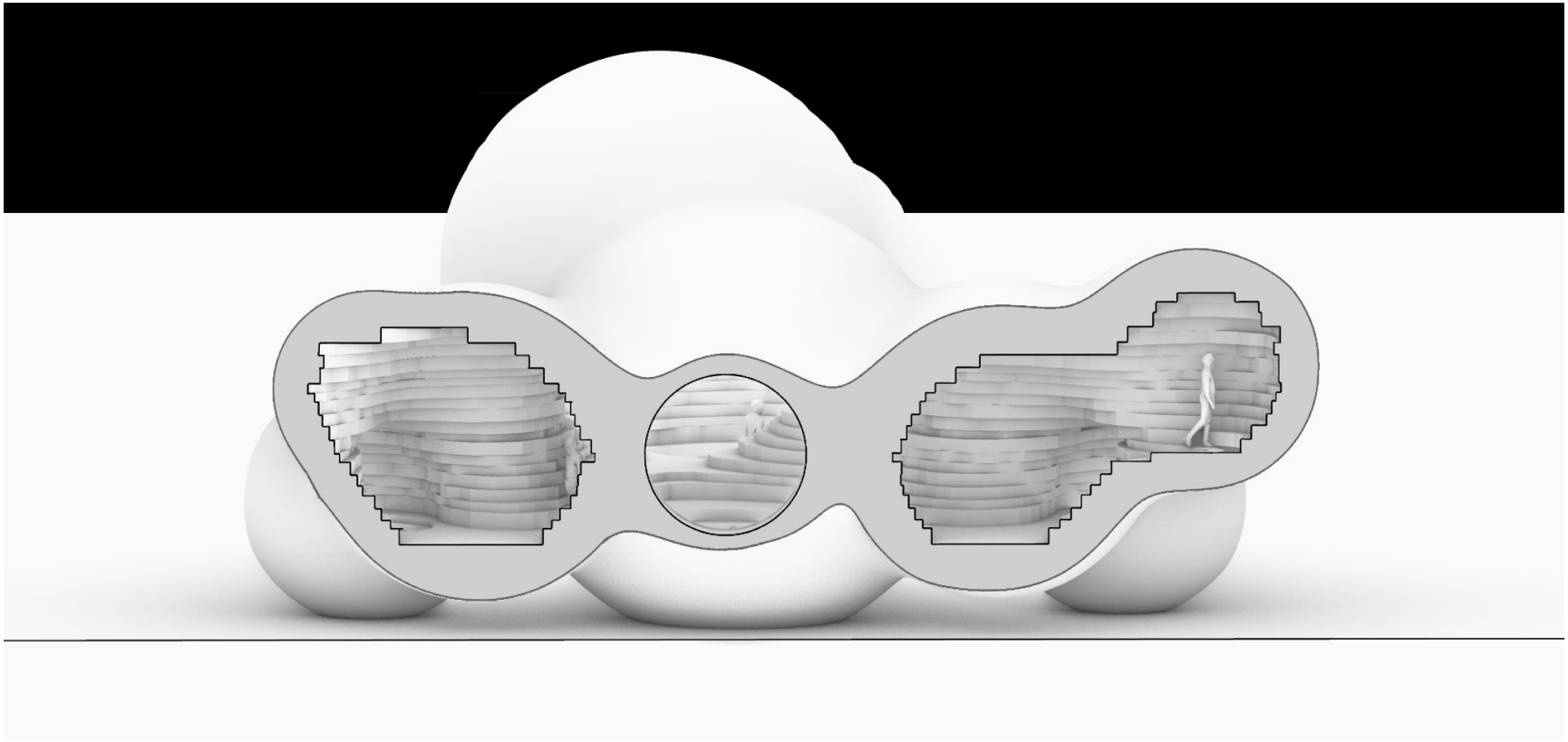
GOOD: Logical pathing, terracing builds up in height and then goes back down into a pit

BAD: Front stairs are too big, reducing the usable space

Section



Section



Interior

Lighting Comfort

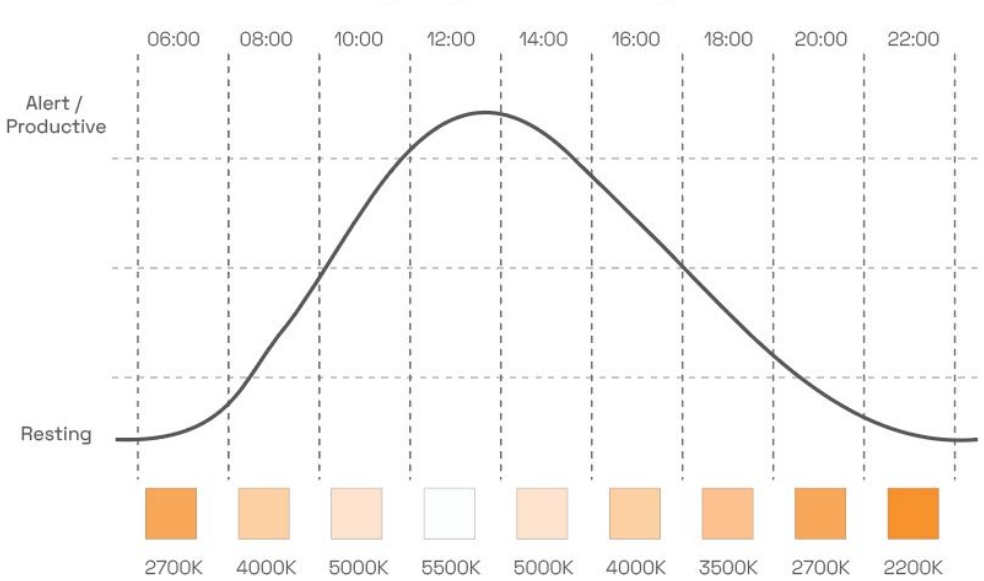
Circadian Rhythm

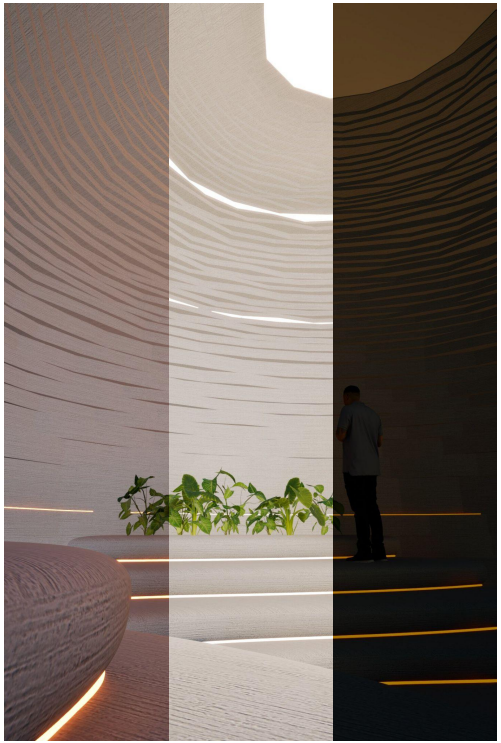
Mimicking natural light

- Maintaining the biological clock
- Improve productivity
- Improve sleep
- Improve cognitive performance

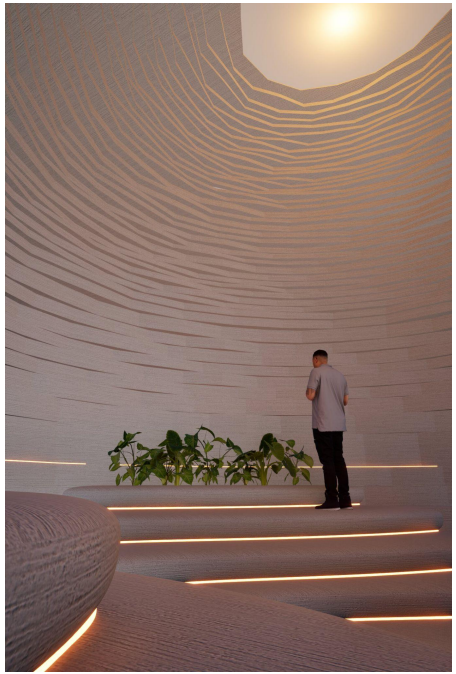
Circadian Rhythm

Mimicking natural light

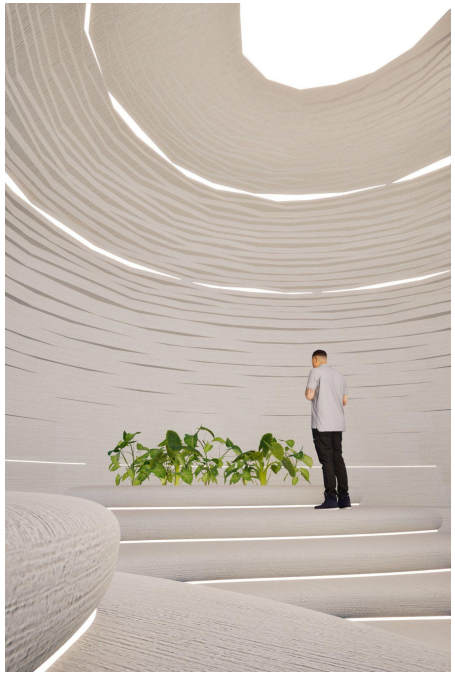




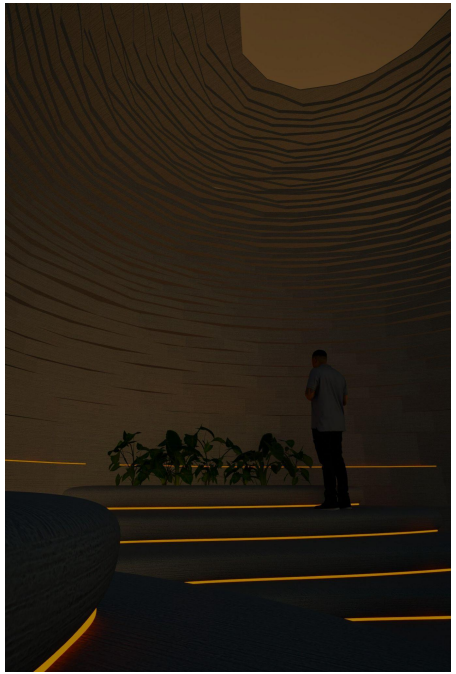
Circadian Rhythm



Morning



Noon

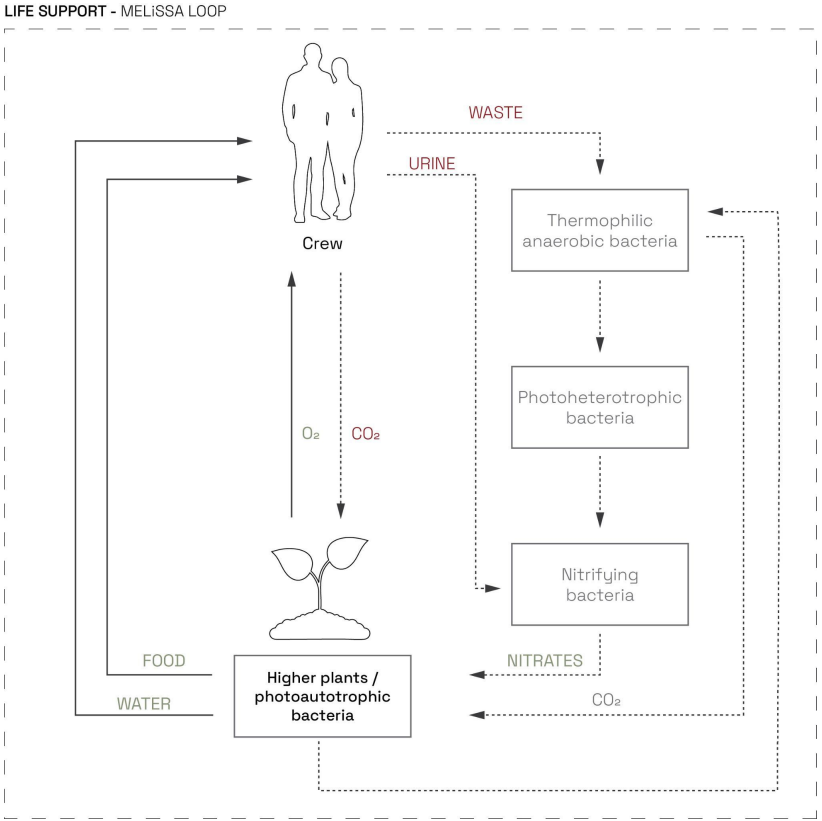


Night

Section

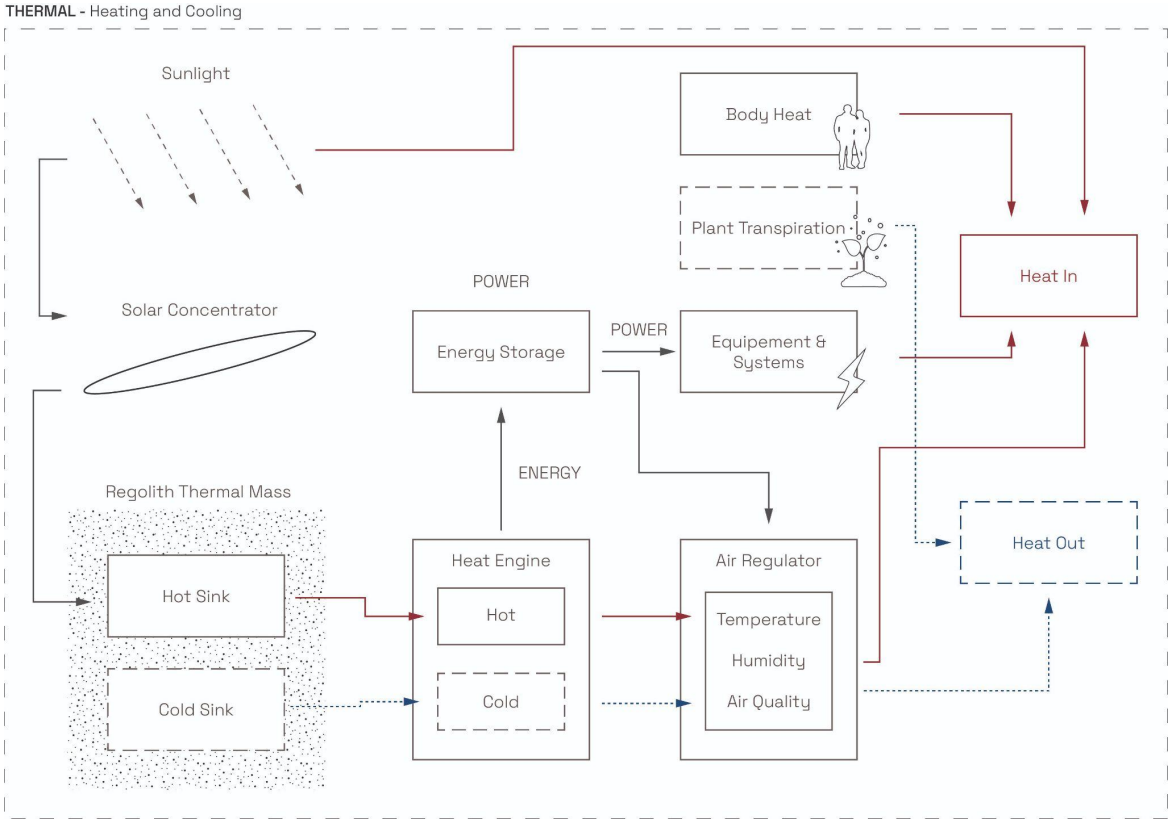
Life Support Systems

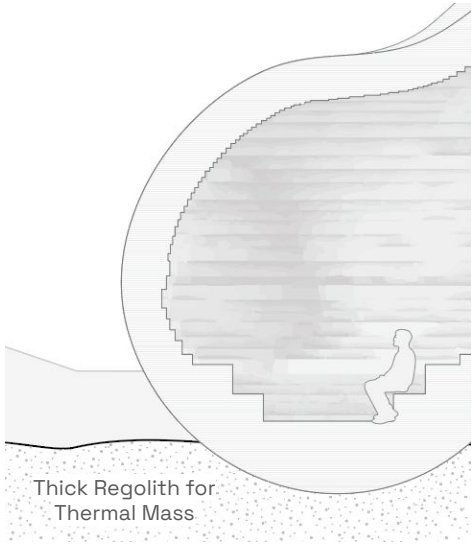
MELiSSA Loop



System based on:
European Space Agency. (n.d.). Closed loop compartments. https://www.esa.int/Enabling_Support/Space_Engineering_Technology/Melissa/Closed_Loop_Compartments

Thermal Regulation





System based on:
European Space Agency. (2017, March 17). How to keep warm on the Moon. https://www.esa.int/Enabling_Support/Preparing_for_the_Future/Discovery_and_Preparation/How_to_keep_warm_on_the_Moon

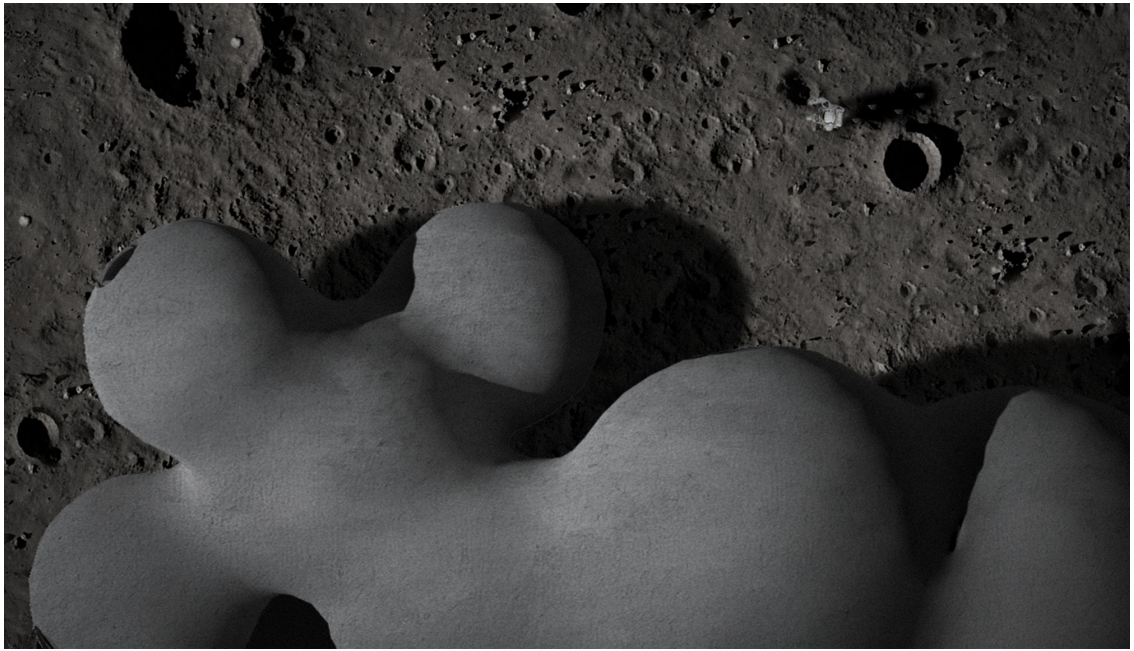
SECTION

Conclusion

Concept Summary

Design Steps

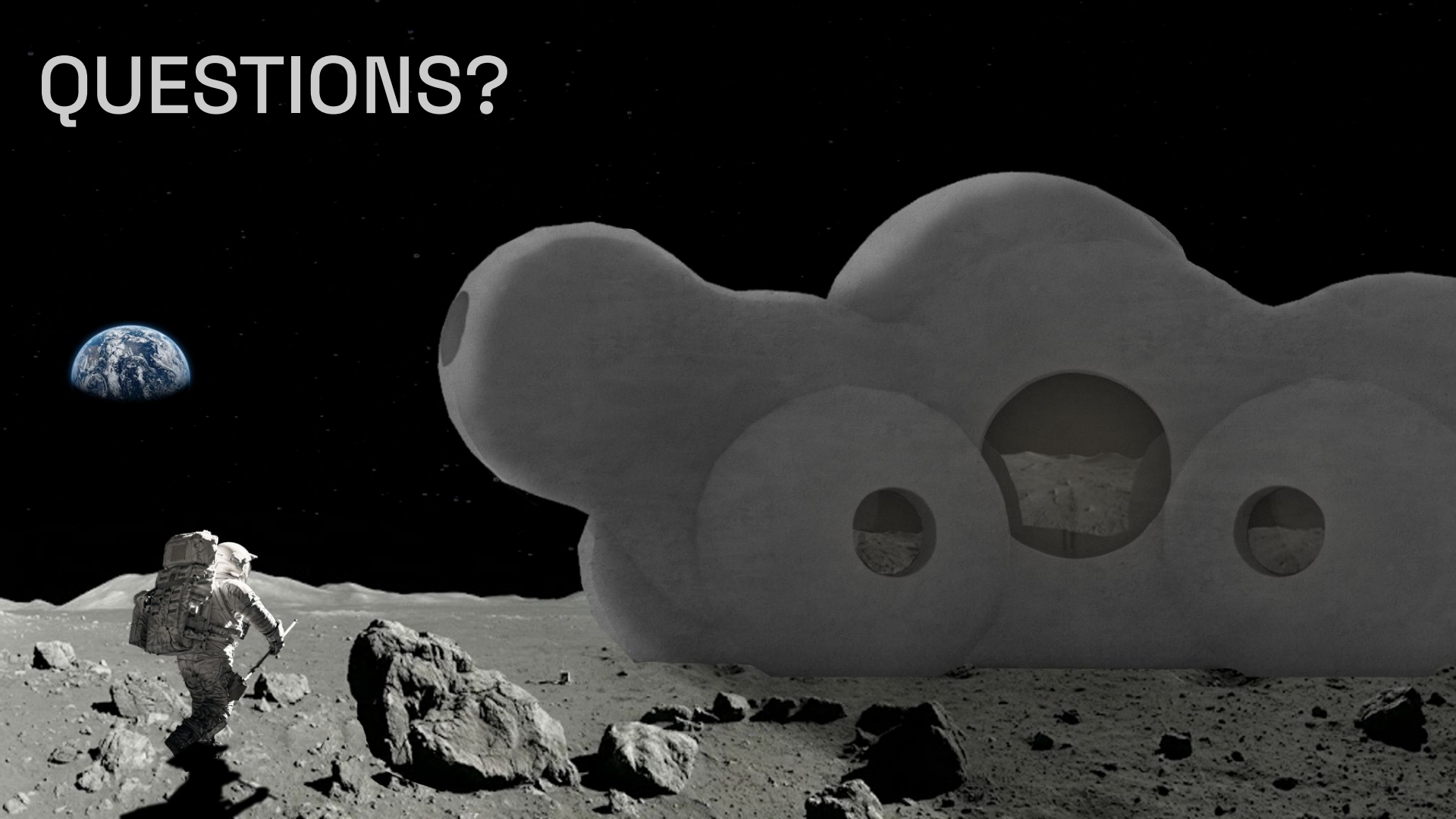
1. L-system
2. Functional Distribution
3. Metaballs
4. Structure Optimization
5. Porosity
6. Interior



RQ Response

Mental & Physical Health	Design Response
☑️ Protection from lunar environment	- Pressurised + radiation shielding
☑️ Non-monotonous, dynamic spaces	- Metaball morphology
☑️ Separation between public & private spaces → ability to retreat	- L-system spatial hierarchy
☑️ Lighting comfort	- Circadian lighting
☑️ Acoustic comfort	- Rock-like wall texturing
☑️ Thermal comfort	- Thermal mass
☑️ Good air quality	- Plants integrated in LSS

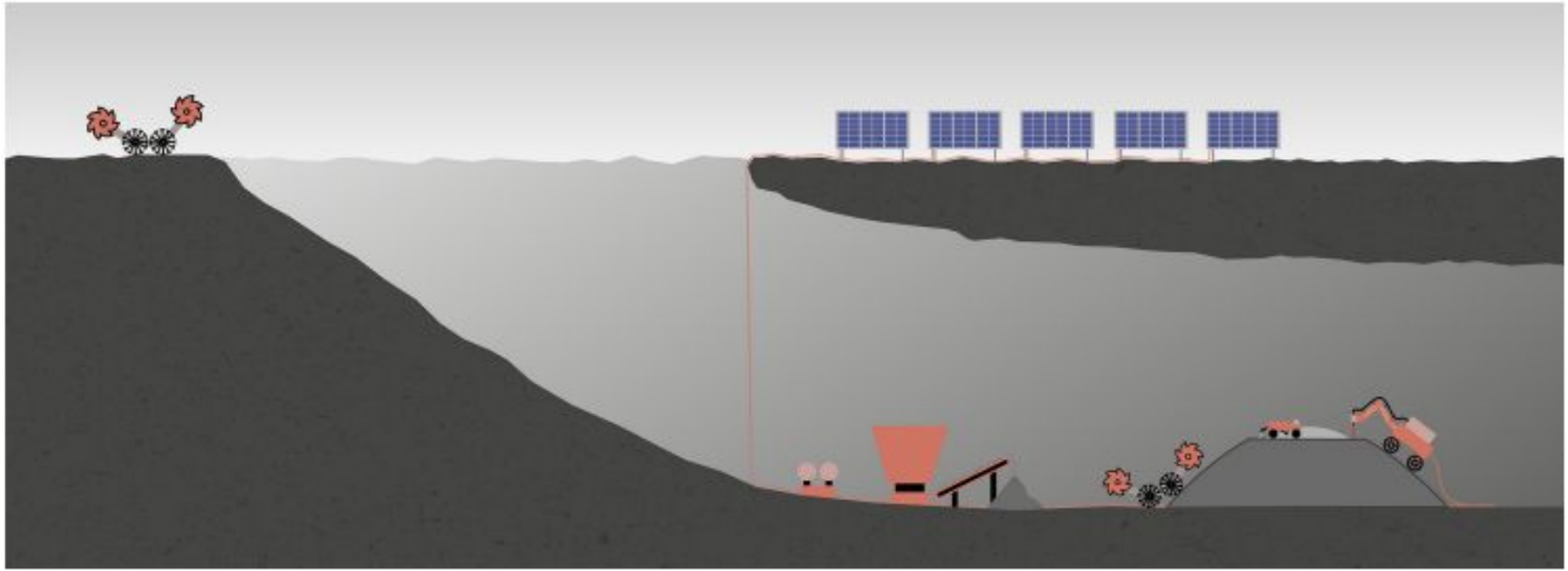
QUESTIONS?



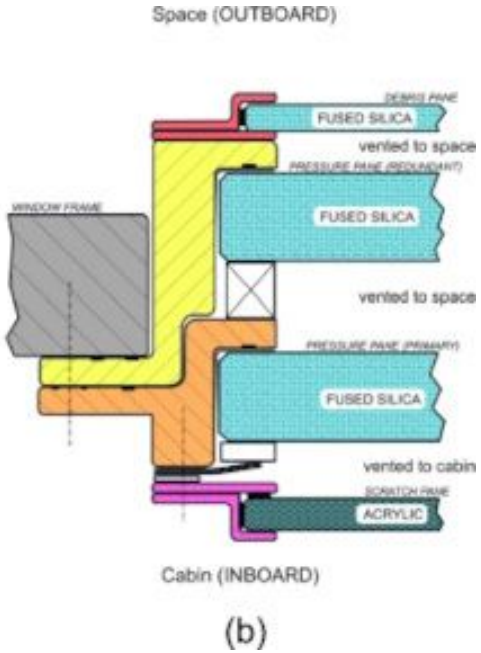
SECTION

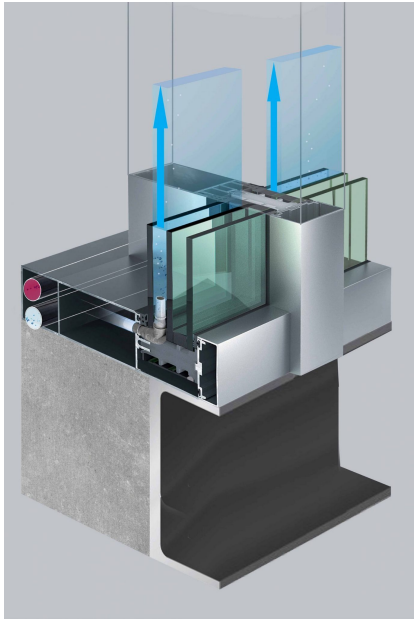
Appendix (extra slides)

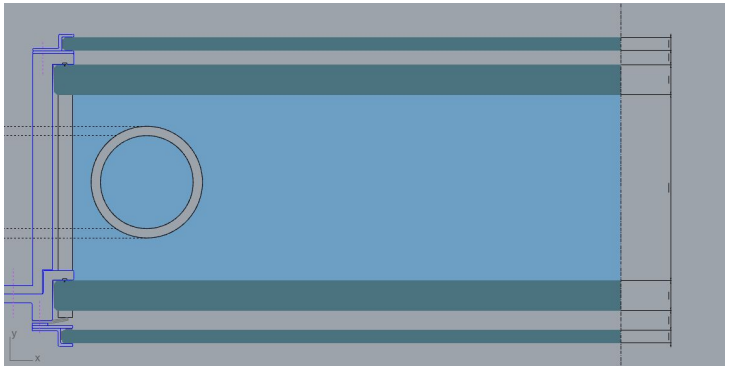
JIP Construction Method



Window Shielding

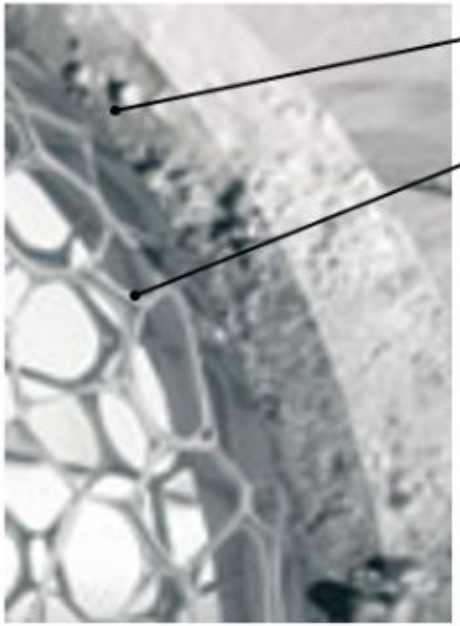






Regolith Accretion

Vertical Salt Deposit Growth System
GEOtube Tower (2009), Faulders Studio, Dubai



Cheibas et. al., Towards Additive Manufactured Off-Earth Habitats with Functionally Graded Multi-materials, p. 84

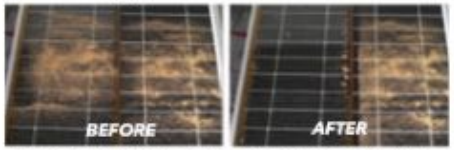
Regolith

- Accretion with electrostatic, sintered with laser heat

Aluminum Metallic Structure

- Medium to conduct electricity
- 3d-printed

Technology reference



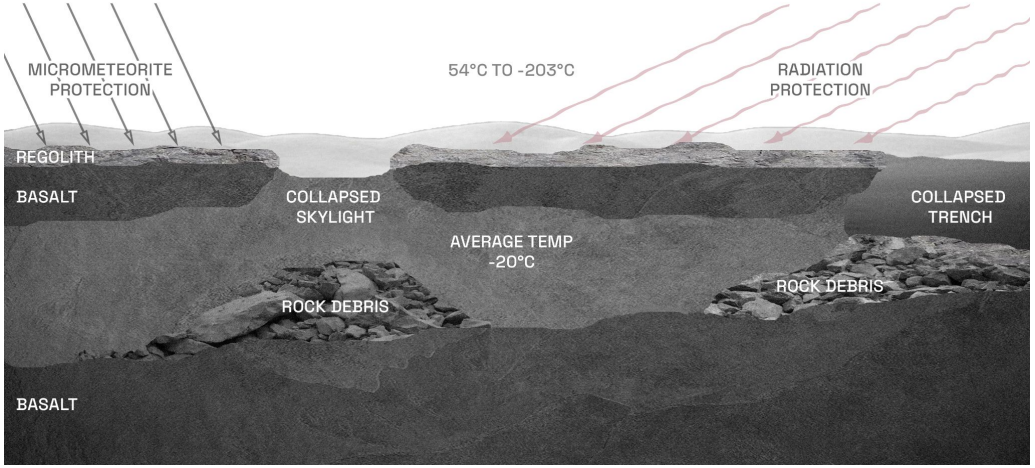
Electrostatic cleaning system for sand removal from solar panels (2015), H. Kawamoto & T. Shibata

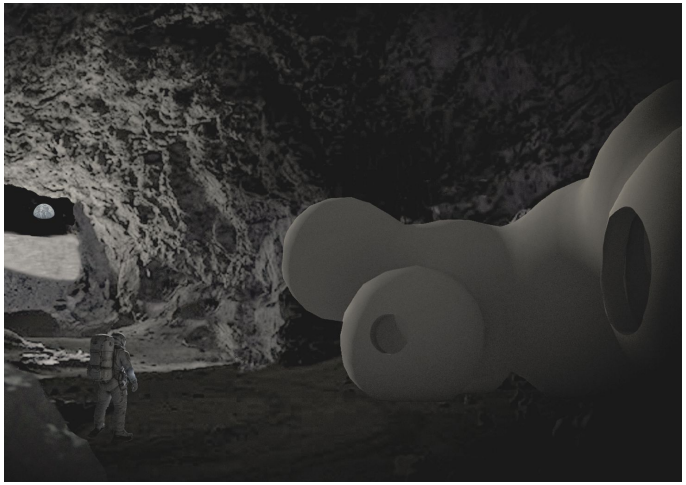
- Current technology: use electrostatic to **repel** regolith
- Reverse principle: use electrostatic to **attract** regolith

*based on in class discussion with expert

10

Lava Tube


MICROMETEORITE PROTECTION
54°C TO -203°C
RADIATION PROTECTION
REGOLITH
BASALT
COLLAPSED SKYLIGHT
AVERAGE TEMP -20°C
COLLAPSED TRENCH
ROCK DEBRIS
ROCK DEBRIS
BASALT



Old Interior Render