DANISH TECHNOLOGICAL INSTITUTE

SpaceSite Lab

A Full Scale Moon and Mars Test and Research Facility

November 2024

Closing the Gap in Ground-Based Analogue Facilities

The vision is to establish and operate a pressure, dust and temperature controlled **full-scale Moon and Mars analogue facility** through a close collaboration between the Danish Technological Institute (DTI) and Aarhus University (AU).

DTI will lead the operation of a commercially oriented, state-of-the-art testing laboratory for **space assets and terrestrial equipment** designed to function in extreme environments, as well as providing **start-up incubation support**. AU will continue to push the boundaries of its **world-class planetary research** and leverage its renowned expertise in the field.

The feasibility study presented herein addresses key factors crucial for **informed decision-making,** including an updated gap analysis, technical requirements, terrestrial synergies, architectural design, and the estimated costs of building and operating a facility of this nature

This work is being carried out under a programme of, and funded by, the European Space Agency (ESA). The views expressed in this brief do not necessarily reflect the official opinion of ESA.

Existing Planetary Environment Facility (PEF) at Aarhus University

Challenges in Space Exploration and Outpost Development

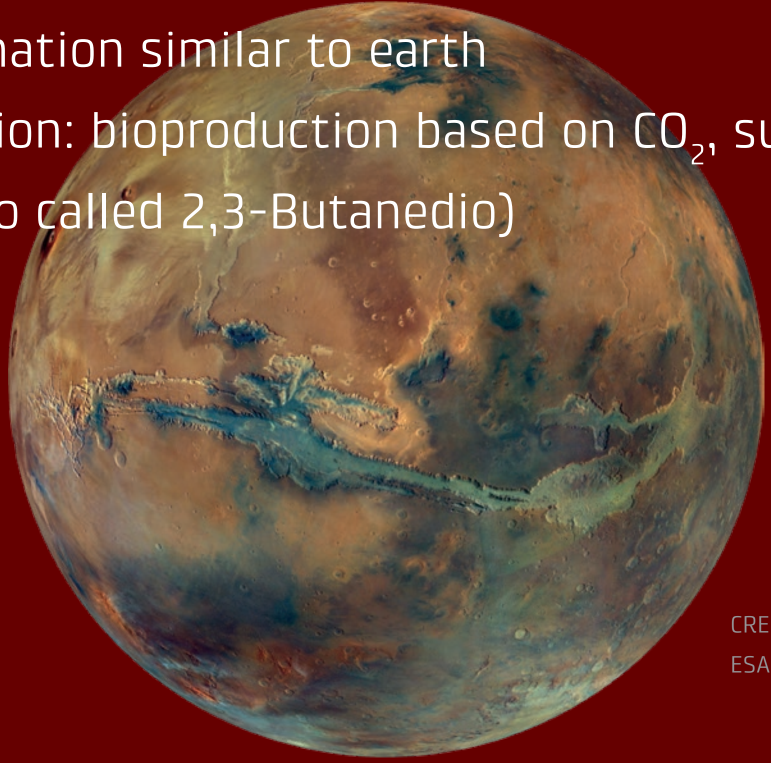
Moon

- Lunar day: 29.5 Earth days.
- Night / Day Temp.: minus -133°C, plus 121 °C
- Atmospheric pressure: 10^{-12} mbar
- Exosphere (very thin atmosphere) - He, Ar, Ne, Ammonia NH_3, Methane CH_4 and CO_2
- Lunar resources: Solar power, water (ice on the south pole), Helium-3 and minerals
- Fuel production: H_2O -> H+O through electrolysis -> finally liquefied (Methanol, Ammonia or Methane)

CREDIT
ESA/DLR/FU Berlin/G. Michael

Mars

- Martian day: 1.03 Earth days.
- Night / Day Temp.: minus -153°C, plus 20°C
- Atmospheric pressure: 6 to 7 mbar (<1% of earth)
- Atmosphere:- CO_2 (95%), molecular N (2.85%), Ar (2%)
- Natural resources: Solar power, water (hydrated minerals), geology formation similar to earth
- Fuel production: bioproduction based on CO_2, sunlight & frozen water (so called 2,3-Butanedio)



CREDIT
ESA/CESAR–M.Castillo

Key Testing Facility Gaps for Upcoming Space Missions *)

1. **Moon: Full-Scale Environmental Testing**
   Evaluate the operational performance of lunar vehicles, habitats, and large infrastructure elements under low-pressure conditions, varying temperatures, and interactions with regolith simulant.

2. **Mars: Operational Drone/Rover/Lander Testing**
   Achieve system-level verification by demonstrating reliable performance in a full-scale simulated environment. Identify areas for improvement for future Mars missions.

3. **Moon/Mars: Wind and Dust Simulation**
   Assess the resistance to long-term dust and sand exposure from both natural and man-made propellant-driven emissions under lunar and Martian conditions. Evaluate various dust mitigation strategies to enhance equipment reliability.

4. **Moon/Mars: Entry, Descent and Landing (EDL) Testing**
   A facility designed to test and analyze the effects of dust and regolith turbulence on landers under lunar and Martian conditions, including the validation of fluid dynamics simulation tools.

5. **Mars/Moon: Operational In-Situ Resource Utilization (ISRU) Testing**
   A facility equipped with ample simulant materials, a deep well, and sufficient space to test ISRU equipment under realistic environmental conditions.

Proposed Configuration for Dusty Thermal Vacuum Chamber:

- large scale (Ø30 meter, 7 meter high)
- low pressure (earth atmosheric to 10^{-4} mbar)
- temperature control (-80°C to +100°C)
- realistically mobilizing dust/sand (natural/human-generated)
- ISRU well (3m deep)

These specifications rectify critical gaps identified in analyses conducted by space agencies.

*) Synthesis of various GAP analysis reports, ESA and NASA

Ground Based Facility Comparison Update

Facility		Scale m3 Full Scale	TVAC*)	Dust**)	Regolith
ESRIC Dusty Thermal Vacuum Chamber, Luxembourg	ESA	10	YES	YES	YES
University of Glasgow, Glasgow UK	ESA	12	YES	No	YES
COMEX hydrosphere, Marseille FR	ESA	20	YES	No	YES
KICT Dirty Thermal Vacuum Chamber, Korean	KASA	50	YES	No	YES
Planetary Environment Facility (PEF), Aarhus University DK	ESA	42	YES	YES	YES
LUNA, European Astronaut Centre (EAC), Cologne GE	ESA	3000	No	No	YES
Large Space Simulator (LSS), Noordwijk NL	ESA	2300	YES	No	No
NASA's Glenn Research Center Space Environments Complex (SEC), Ohio US	NASA	27000	YES	No	No
Proposed Large Scale Mars and Moon, Aarhus, DK	ESA	5000	YES	YES	YES

Existing and Planned Analogue Facilities for Mars and the Moon.
The Proposed Aarhus Facility adresses the gap for Large-Scale Dusty Windy Thermal Vacuum Chamber (DWTVC >5000 m3)

*) Thermal Vacuum Chamber
**) Mobilized dust with realistic velocity distribution only available in Aarhus, DK

Advancing Technology Readiness Level for Space Assets

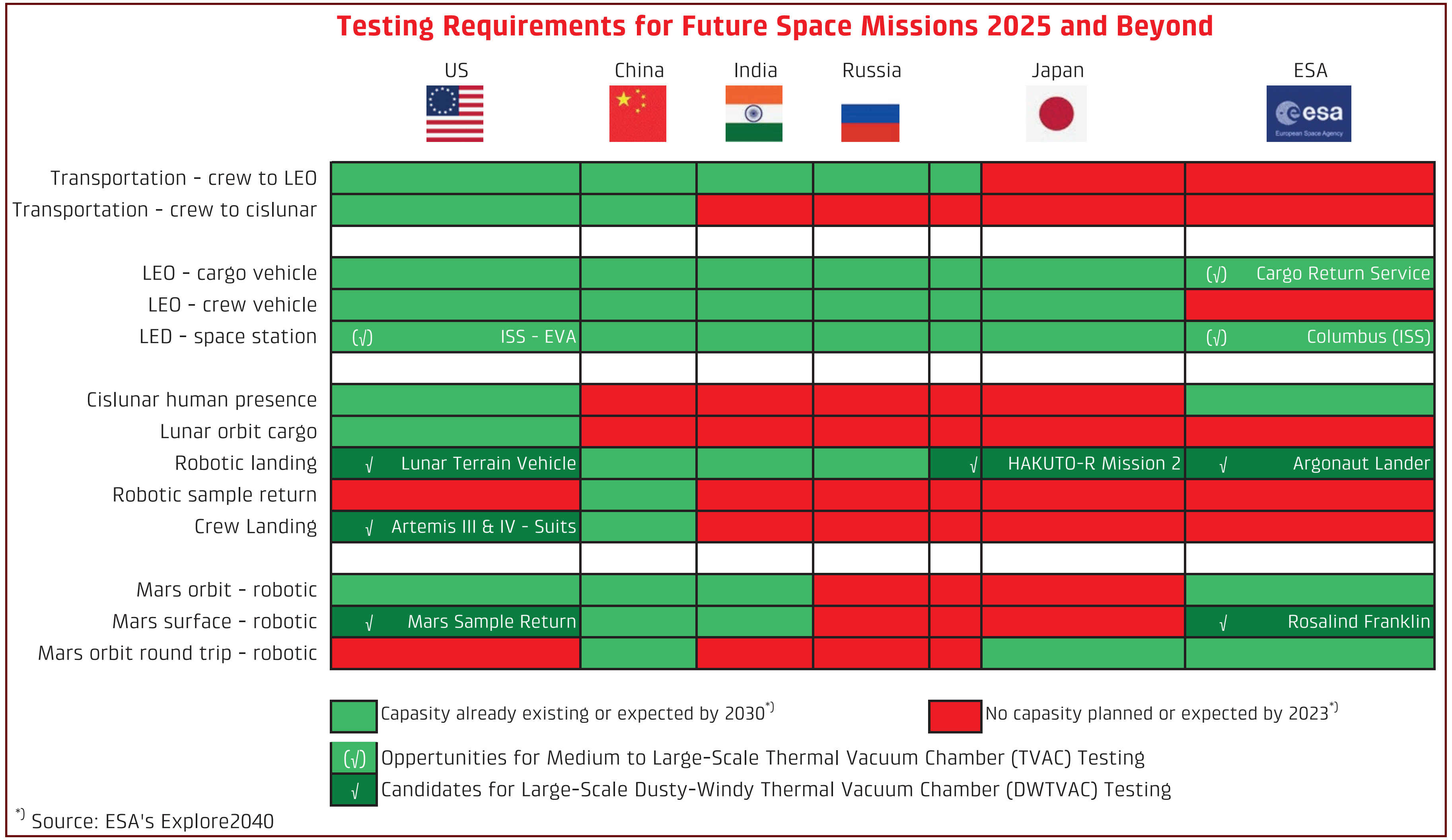
The figure outlines testing requirements for space missions by 2025 and beyond.

It covers the complete range of space activities, from transportation and operations in Low Earth Orbit (LEO) and cislunar presence to lunar and Mars exploration missions.

Green areas represent existing or planned capacities in the respective countries or regions.

Red areas indicate no planned capabilities by 2030.

Checkmarks highlight significant opportunities for European ground testing facilities.



Key opportunities exist within the Argonaut and Artemis lunar programs, as well as in robotic missions like Mars Sample Return and Rosalind Franklin.

Business opportunities will also exist in traditional outer space testing, such as outgassing, thermal vacuum testing, and artificial sunlight testing.

It's also important to mention testing scientific instruments that don't necessarily require a large facility but can leverage the capabilities of a large-scale facility.

And thence we came forth to see the stars again - From The Divine Comedy.

We are honored by the European Space Agency's (ESA) trust in DTI to address gaps in ground-based testing facilities and envision a European center capable of full-scale testing of space assets under operational conditions. The SpaceSite Lab initiative is vital in a decisive moment for the space industry, facing the challenges of achieving a sustainable and commercially viable future for human and robotic space exploration. Our commitment to the advancement of these technologies is steadfast.

In a time of unprecedented planetary challenges, bold initiatives are essential. The SpaceSite Lab may also prove to be the crucible and integrative playground for technological solutions that may monitor and support the implementation of countermeasures to the climatic crisis. DTI is committed to advancing the space industry's transition toward sustainability and commercial viability.

Thanks to our partnership with Aarhus University and the visionary designs by Bjarke Ingels and his team, we have the pleasure to present an ambitious and innovative concept. We invite the space community to collaborate with us in realizing this transformative facility. Together, we can shape the future of space exploration at a crucial moment.

As one of Europe's leading Research and Technology Organizations, DTI fully endorses and supports this initiative.

Juan Farré, President and CEO
Danish Technological Institute

Terrestrial Synergies

SpaceSite Lab.

Applied Research

Meteorology: Conduct simulations and studies of various weather phenomena.

Aeronautics: Recreate wind and temperature conditions to test instruments designed for high-altitude balloons, drones, and scaled wind turbine blades.

Materials: Test advanced materials for tribology, 3D printing, and printed electronics, i.e with locally recyclable resources.

A Large-Scale Dusty-Windy Thermal Vacuum Chamber offers advanced climate control features

Its unique characteristics exceed industrial standards

Scale
Ø30m, 7m high

Vacuum
Air pressure to 10^{-4} mbar

Temperature
Cooling elements minus 80°C to 100°C

Humidity
Range of 50%-90%RH

Air
Enclosure

Light
Adjustable LED panels

Wind
Tunnel 5 x 3 meter, speed 0.1 to ~30m/s

> New clients can be served with a large dusty climate chamber mimicking real life scenarios.
>
> *Stig Koust, ph.d, Business Manager, DTI, Air and Sensor Technology*

Large Climate Chamber

Arctic Research: Simulate operational situations under extreme arctic conditions.

Meteorological Equipment: Perform testing and calibration on large-scale weather monitoring installations.

Utilizing the Closed Chamber as a Large Test Room

- **Environmental Studies:** Measure aerosol emissions from vehicles (cars, buses) and heating appliances (stoves, etc.).
- **Protective Gear Evaluation:** Assess the effectiveness of tents in maintaining an airtight environment.
- **Ventilation Systems:** Test and evaluate the performance of large ventilation systems.
- **Agricultural Studies:** Examine the response of plants and crops to specific atmospheric conditions and articificial sunlight.

ARCHITECTUAL DESIGN

BIG , BJARKE INGELS GROUP

BIG - Bjarke Ingels Group is a leader in architectural design, with expertise extending to space architecture projects. Their proposal for the new Mars and Moon Test and Research Facility underlines the identity and flexibility of a genuine workshop.

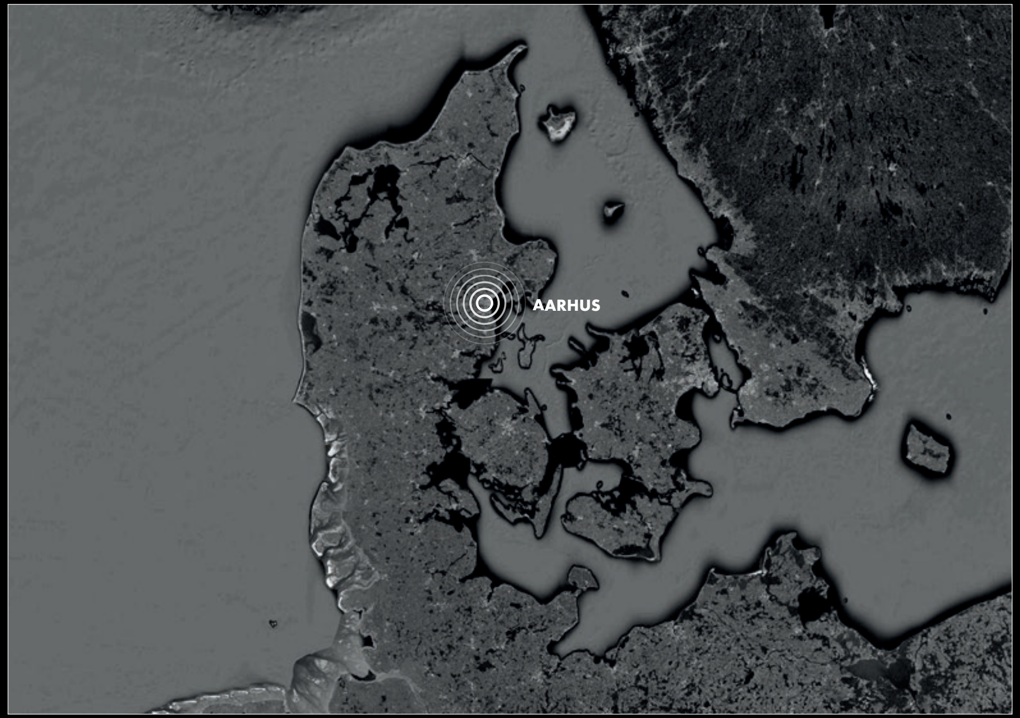
A **Greenhouse Hangar** features a structure that allows natural light to flood the space, creating a large, flexible, non-heated work area surrounding the **Vacuum Chamber**. This design mirrors the workspace environment typically found in space or flight-related hangars. The hangar is organized with sliding door entrances of appropriate sizes to facilitate movement and access.

All office-related activities, such as meeting rooms, computer workstations, restrooms, and tech areas, are centralized within an **Office Tower**. This tower provides an overview of the entire facility. BIG proposes developing the Office Tower as a lightweight wood structure.

Positioned like a house within a house inside the greenhouse, this design potentially reduces the need for extensive insulation, eliminates the need for water membranes in detailing, and does away with drainage requirements.

The Greenhouse Hangar is constructed using glass and steel with large skylight openings to ensure natural ventilation. As the structure is unheated, the working areas around the Vacuum Chamber are shielded from wind, rain, and snow, but the temperature varies with the Danish seasons.

The materials selected for the project are chosen for their durability and ability to withstand daily wear and use without demanding frequent maintenance. This ensures a flexible and long-lasting workshop environment for the Mars and Moon Test and Research Facility



DENMARK

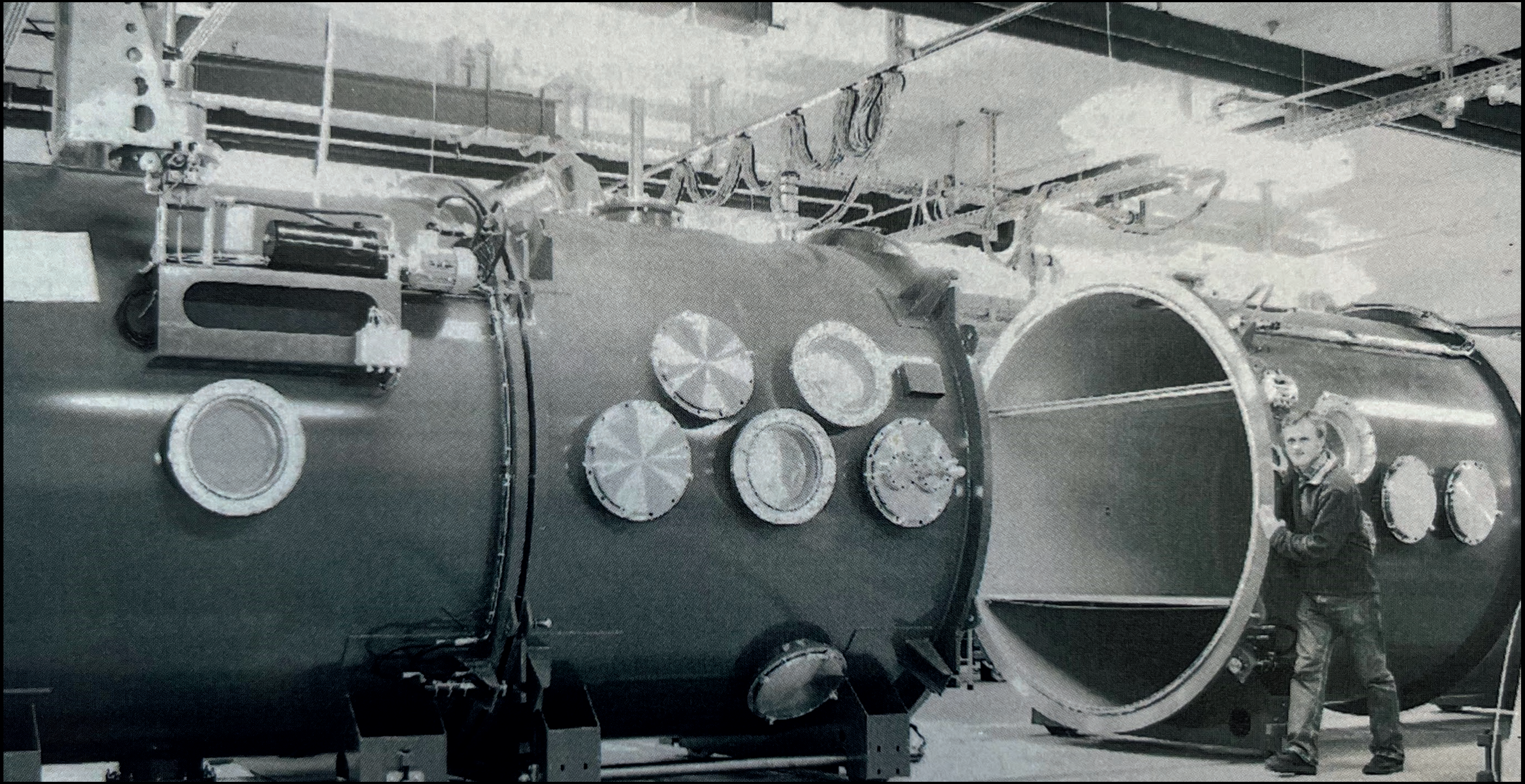
AARHUS

LOCATED IN THE INTERSECTION OF E45 AARHUS NORTH

PROJECT LOCATION

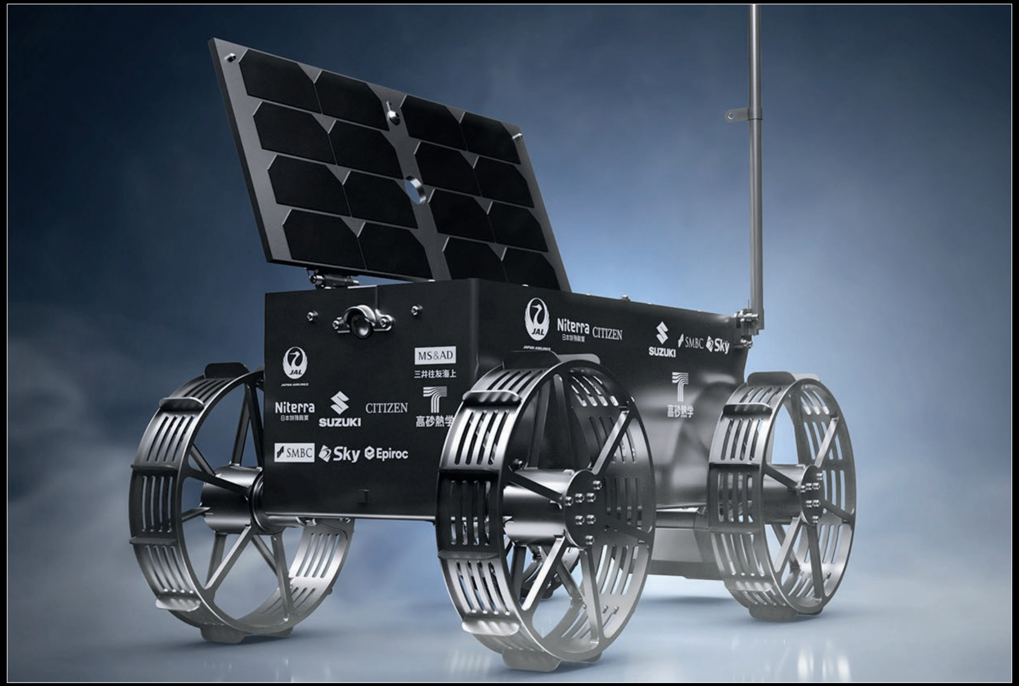
AARHUS DENMARK

SITE CONDITION TODAY
AARHUS DENMARK



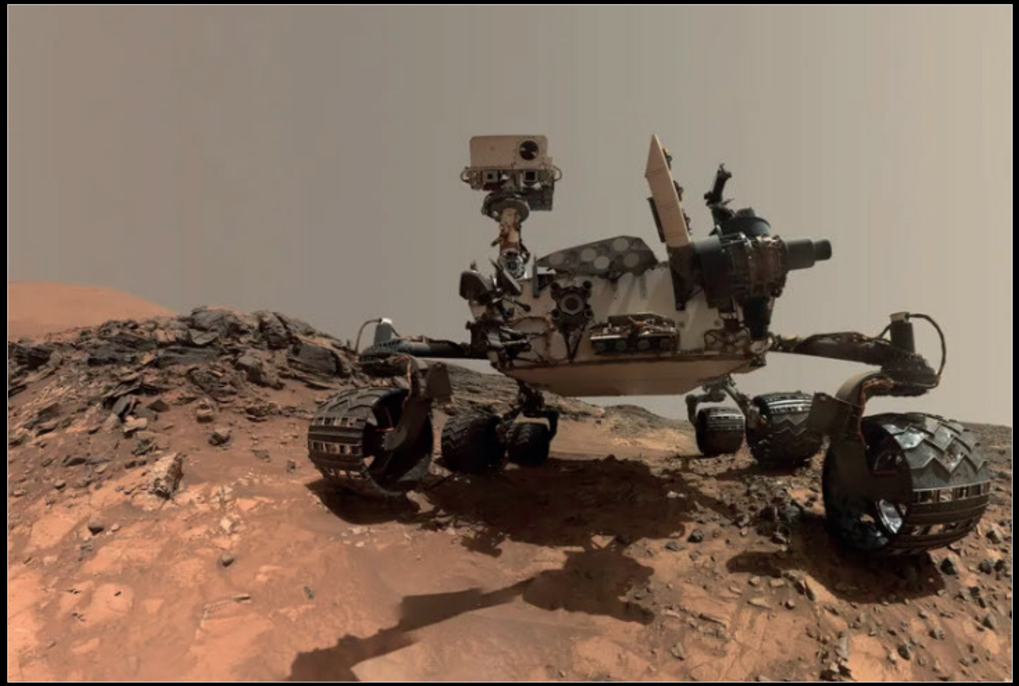
DUSTY-WINDY THERMAL VACUUM CHAMBER AT AU (AARHUS UNIVERSITY)

MOON LANDER
APEX 1.0 ISPACE

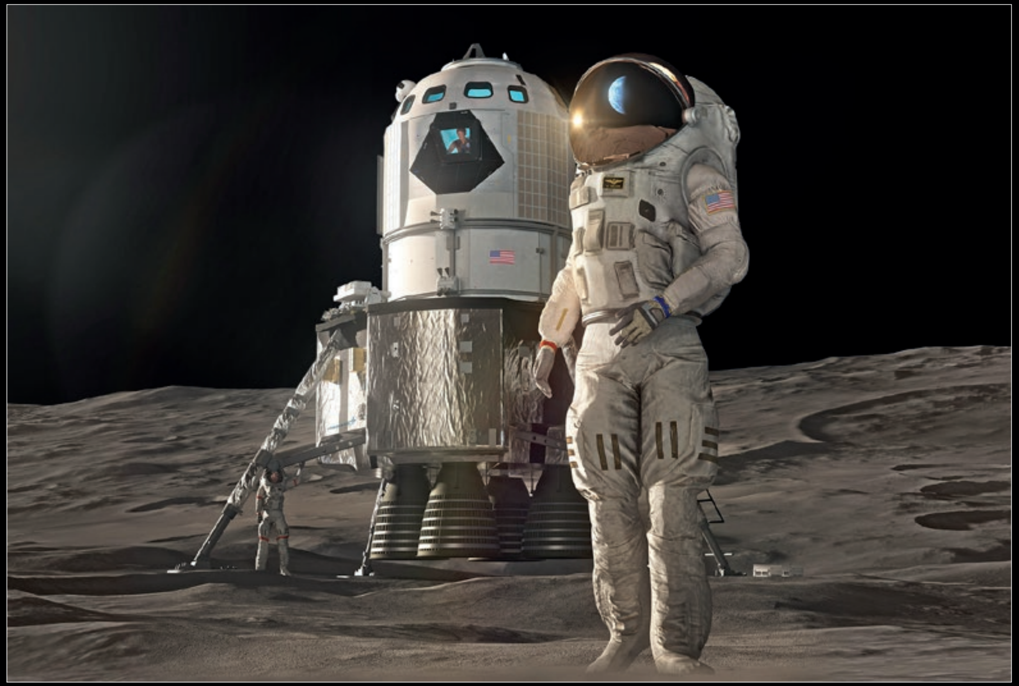


MOON ROVER
M1 ISPACE

MOON ROVER
HiveR NEURO SPACE



MARS ROVER
PERSEVERANCE NASA

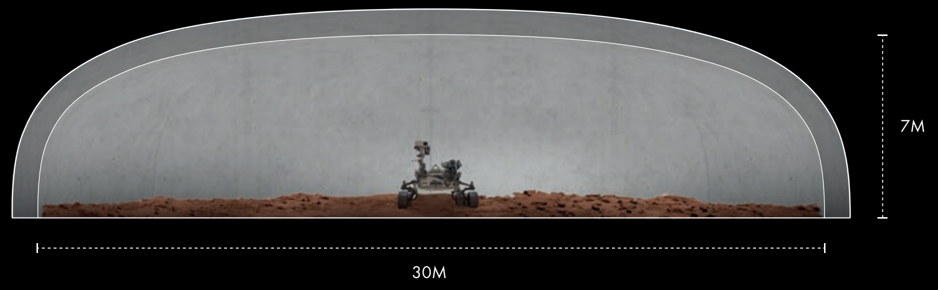


EVA, SUITS FOR EXTRAVEHICULAR ACTIVITY
LUNAR MARTIAN LANDER

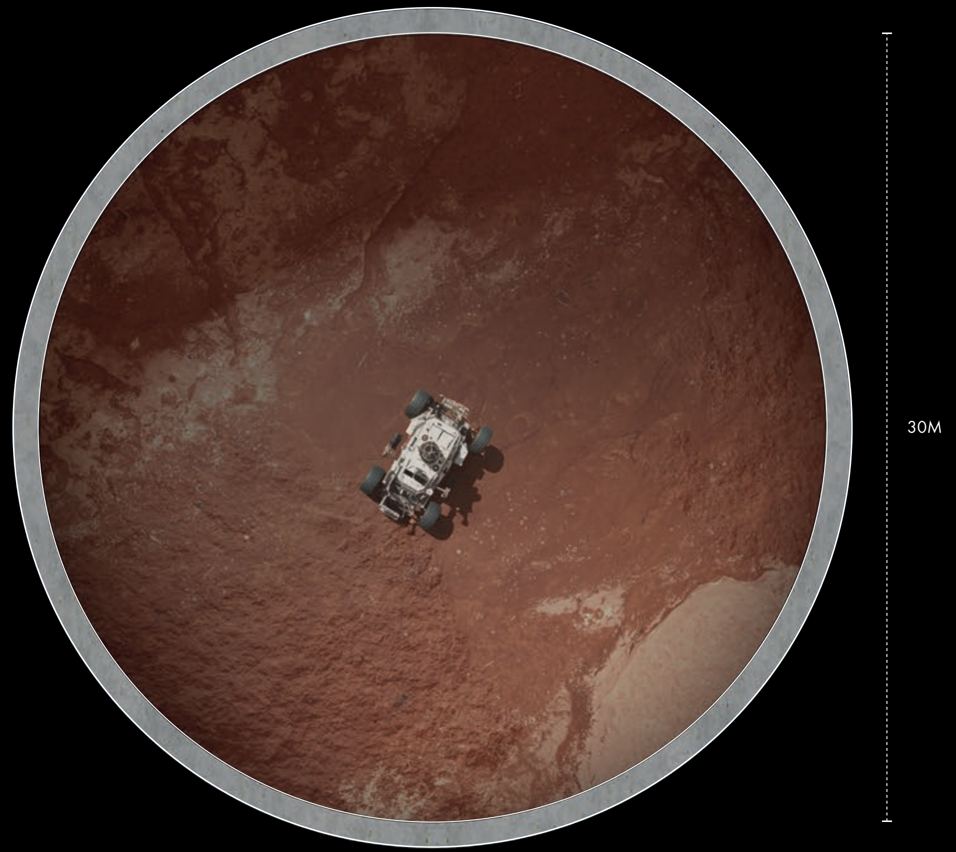
TESTING REAL SCALE MARS OR LUNAR HABITATS, LANDED MISSIONS
ODYSSEUS SPACECRAFT, LUNAR SUFACE LANDING BY THE U.S, 2023

EXAMPLES OF LARGE SCALE TEST OBJECTS

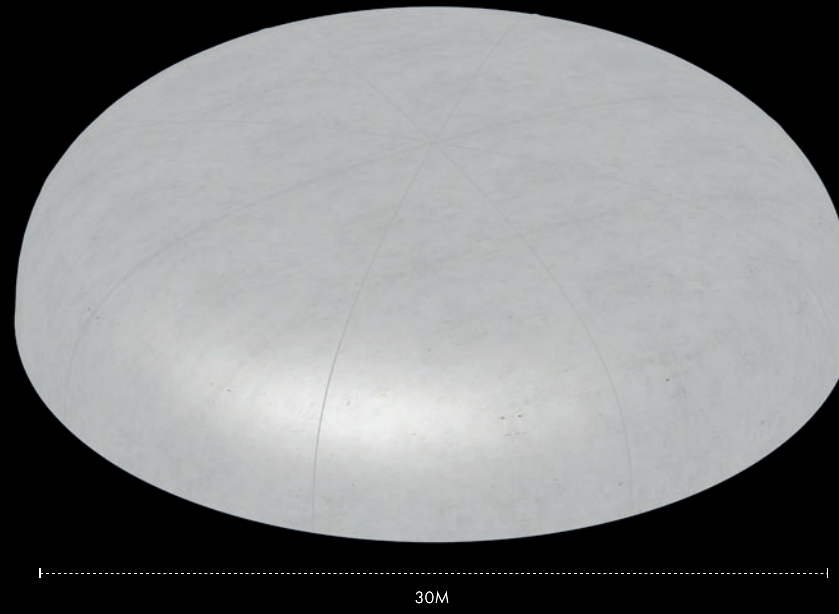
VACUUM CHAMBER



SECTION



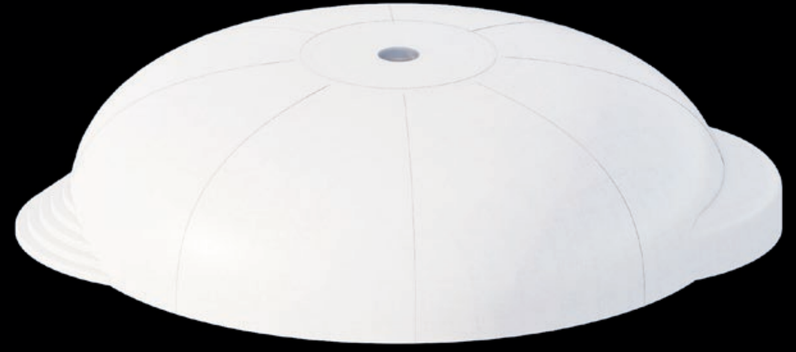
PLAN



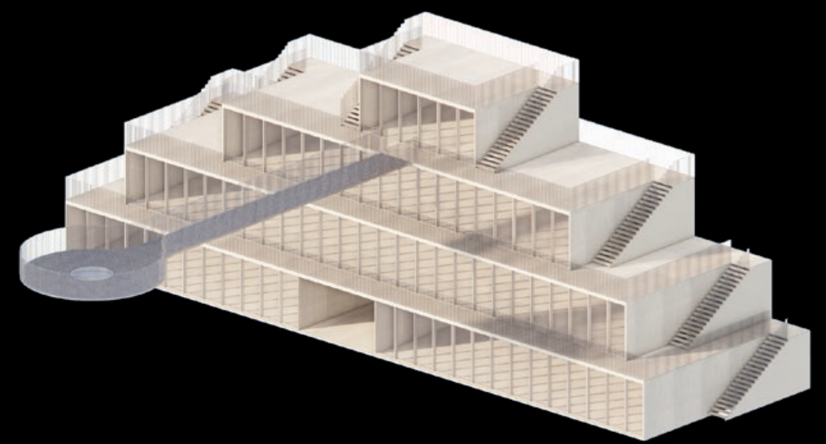
AXO

VACUUM CHAMBER

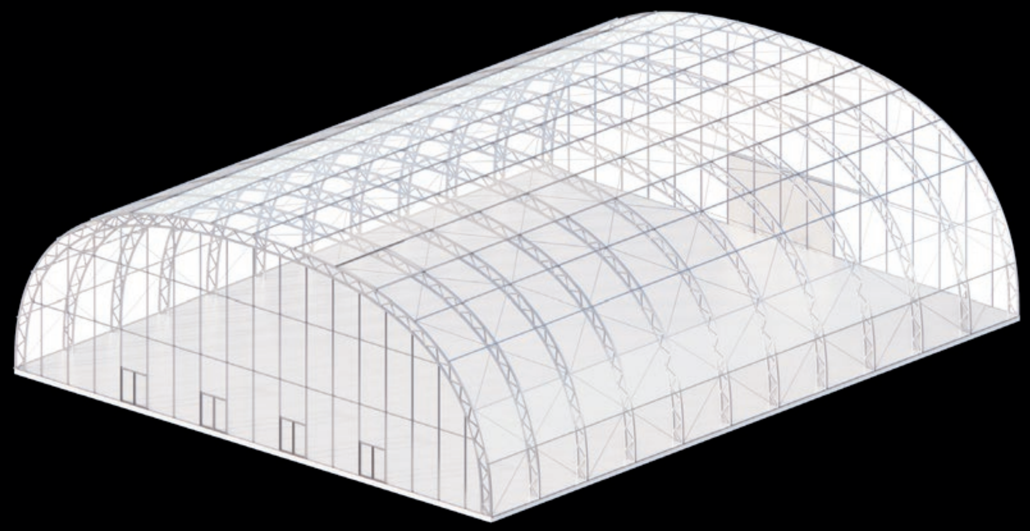
GEOMETRY REQUIREMENTS



1. VACUUM CHAMBER



3. OFFICE TOWER / BOH



5. GREENHOUSE HANGAR

THREE BUILDING COMPONENTS

PROGRAM SPECIFIC

ELEVATION

EAST FACADE




HOUSES WITHIN GREENHOUSES

EXISTING REFERENCES

LECTURE CORNER

VACUUM CHAMBER EXTERIOR

ELEVATED TERRACE / OFFICE CORRIDOR

OFFICE / BOH

OFFICE TOWER

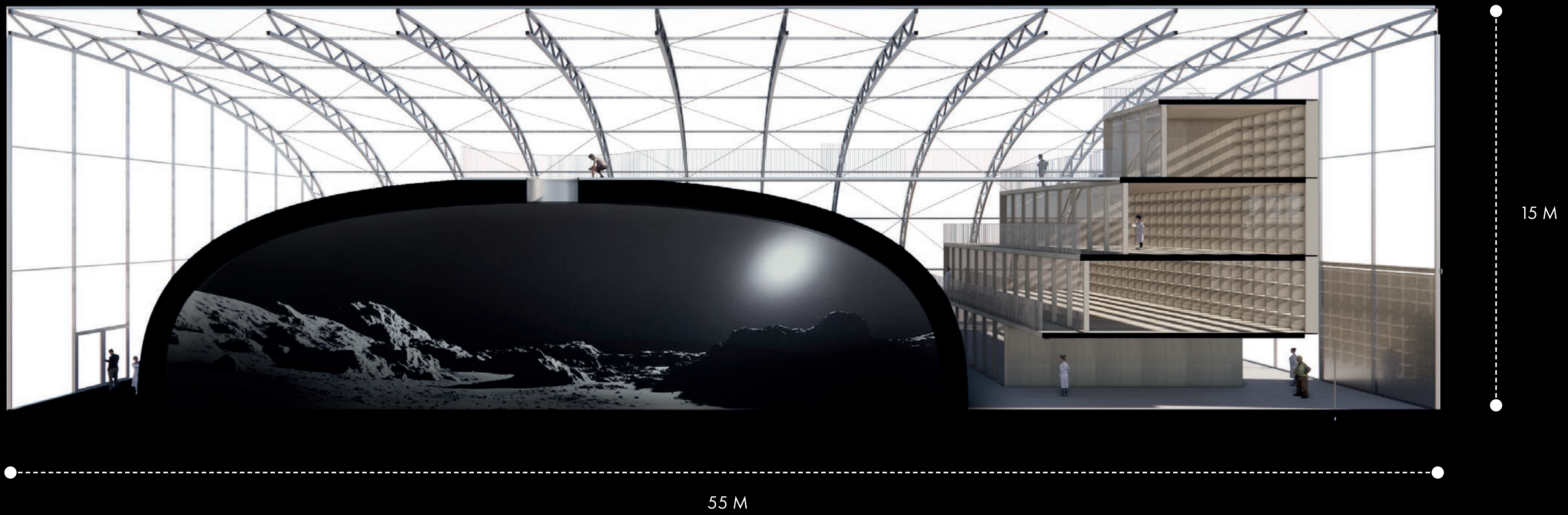
OFFICE/BOH

BRIDGE CONNECTION TO THE VACUUM CHAMBER TOP

STEEL STRUCTURE

SKYLIGHT VIEW DOWN INTO THE VACUUM CHAMBER

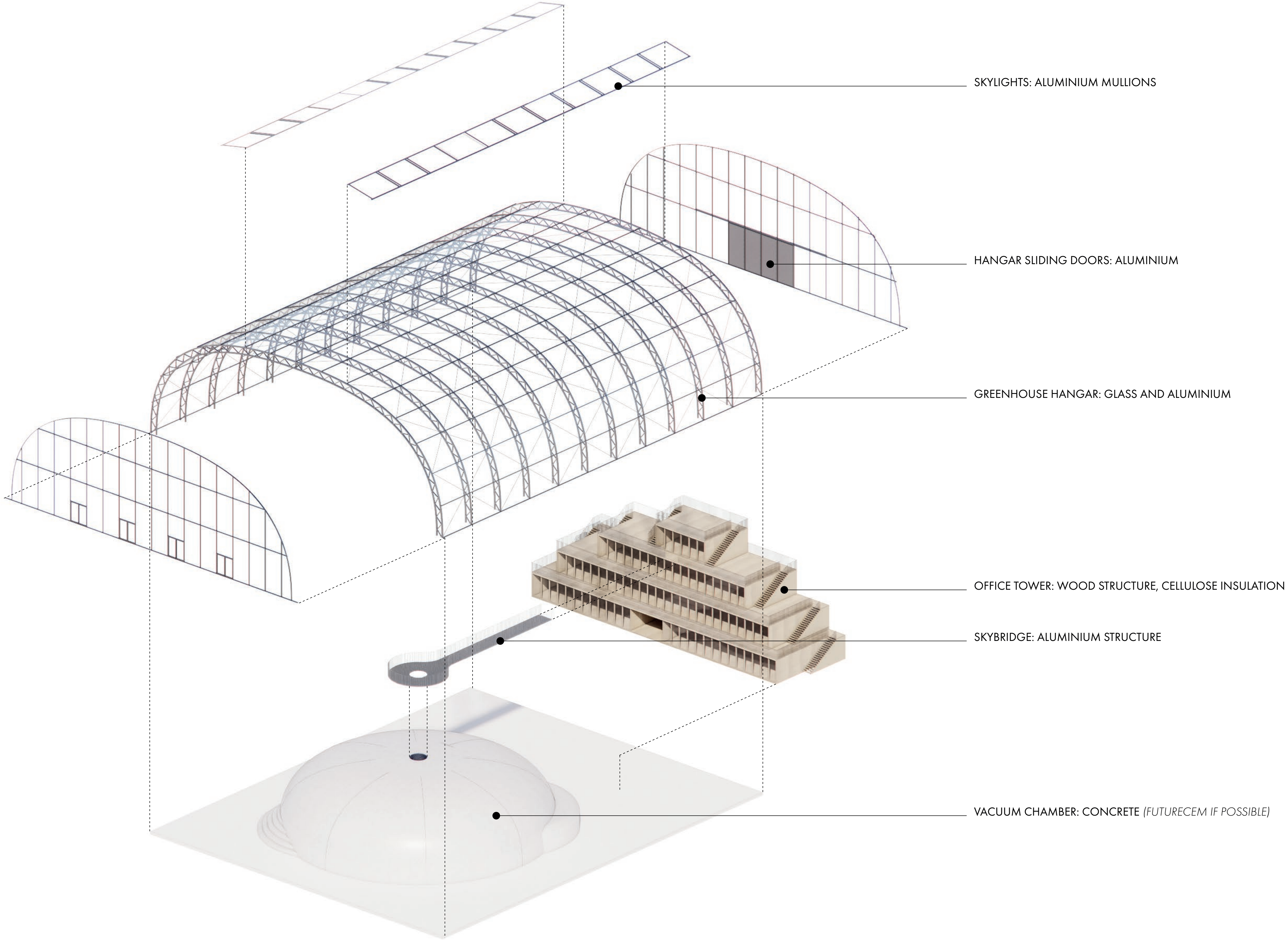
TO BE FURTHER STUDIED



SECTION

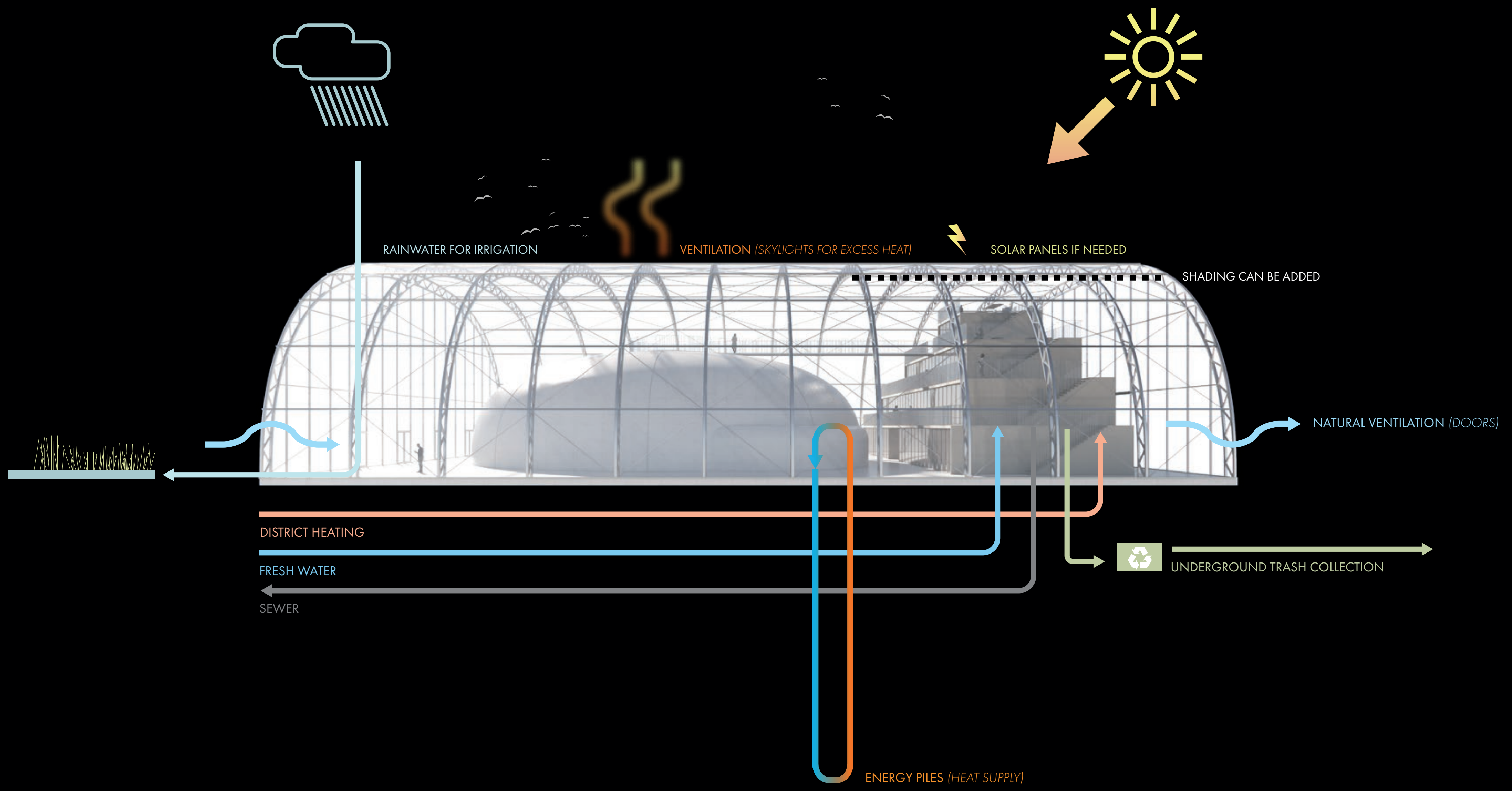
NORTH / SOUTH

SECTION
EAST / WEST



MATERIALS

BUILDING COMPONENTS FOR FURTHER DISCUSSION



SUSTAINABILITY

SYSTEMS FOR FURTHER DISCUSSION

MARS MOON TEST AND RESEARCH FACILITY
NIGHT VIEW FROM SØFTENVEJEN

Estimated Construction Costs for the Facility

Mars & Moon Test and Research Center

Item	Included	Estimate €
Land preparation	Geo, access and parking, utility conduits etc.	€ 1.893.000
Construction	Vacuum chamber, offices & glass house	€ 13.619.000
Additional cost items	Site setup and operation facilities	€ 681.000
Consulting services	Architects, management. & inspection	€ 3.404.000
Technical infrastructures	Pumps, cryogenic/heating systems	€ 4.161.000
Civil eng.	Technical advices and inspection	€ 624.000
Small size chambers	Vacuum and climated chambers for prototypes	€ 300.000
Other	Unforeseen cost (~20%)	€ 2.875.000
	In total €	27.557.000

Estimating the cost for a comprehensive and technically advanced facility like SpaceSite Lab requires a detailed understanding of many factors. While some of these are well known, others, particularly those related to the thermal vacuum chamber, involve some uncertainty.

Thermal Vacuum Chamber

The primary cost element is the Dusty-Windy Thermal Vacuum Chamber (DWTVC) and its associated technical infrastructure, which includes an airtight entrance and specialized equipment such as pumps, cooling systems, and other operational components.

To detail this cost item, we consulted specialists in large concrete constructions and vacuum technology experts from the existing Planetary Environment Facility at Aarhus University. Based on their feedback, we have based our calculations on this information. Overall, we estimate that **35%** of the total cost of the facility is attributed to the vacuum chamber.

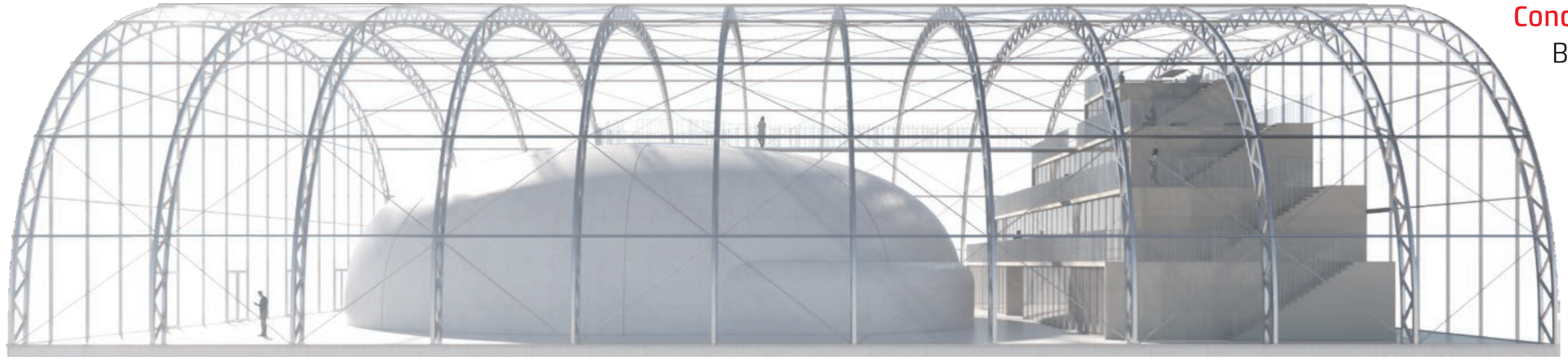
Office Tower

The Office Tower is designed as a light wood structure that sits within the greenhouse, like a house within a house. This design potentially reduces the required amount of insulation, avoids the need for water membranes in the roofing, and eliminates drainage issues.

The light structure spans four levels, organizing all office-related activities such as meeting rooms, toilets, and laboratory areas. Given the high complexity and expensive interiors, we estimate the cost to be around **20%** of the total facility cost. However, this estimate carries much less uncertainty compared to the thermal vacuum chamber.

Greenhouse Hanger

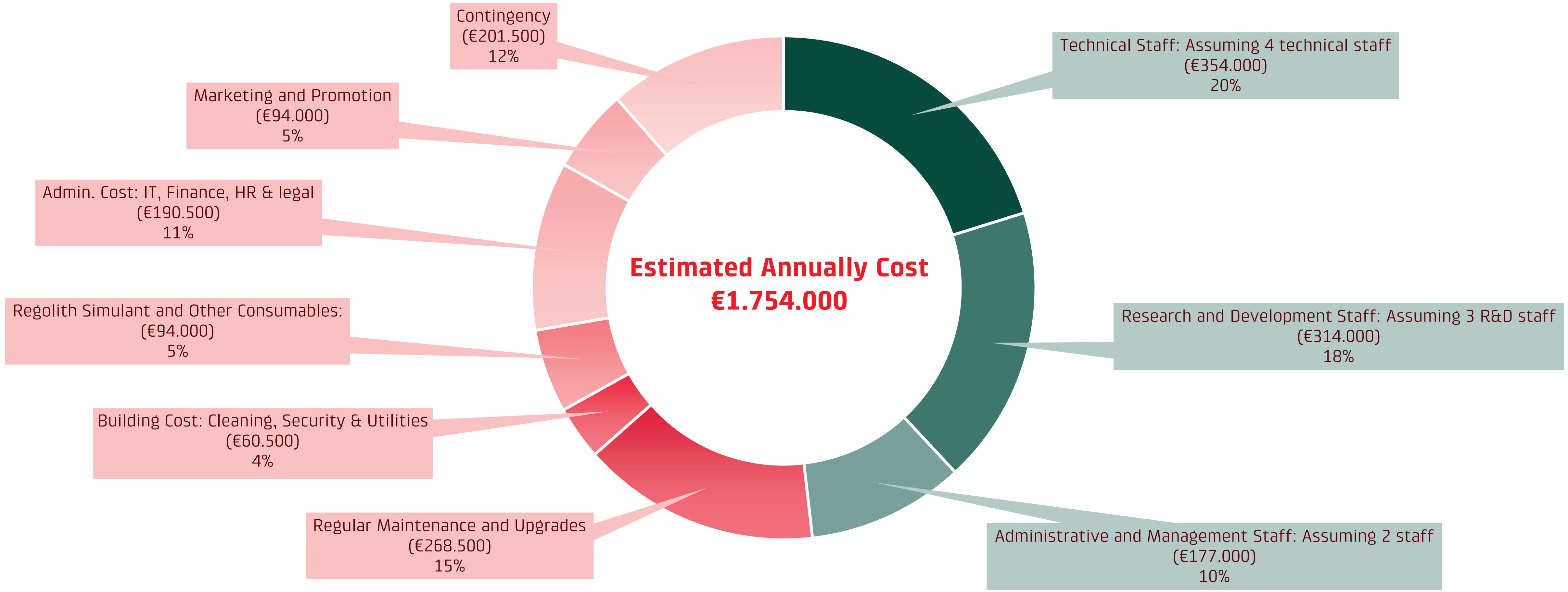
The greenhouse hangar is primarily constructed from glass and steel, featuring large skylight openings for natural ventilation. While unheated, it protects the working areas around the thermal vacuum chamber and the office tower from wind, rain, and snow. The details regarding ventilation and material selection are still under development. The "house within a house" method is established, but certain cost elements require further analysis. Overall, we estimate that **45%** of the total cost is attributed to the greenhouse hangar.



Conclusion

Based on our calculations, the total estimated cost for the SpaceSite Lab facility is approximately **27.5 million euros**, with the thermal vacuum chamber contributing 35% and having the highest uncertainty.

Basic Operational Costs for a Full-Scale Moon and Mars Test and Research Facility



The figure is based on data related to salary, maintenance costs, and utility expenses. It reflects typical costs for technical, R&D, and administrative personnel, using standard industry rates in Denmark. Utility costs, such as electricity, water and heating are estimated based on expected average usage and current prices.

The breakdown also includes projected expenses for upgrades, marketing and consumables, all derived from historical data and expert estimates. Additionally, some unforeseen costs are accounted for.

Revenue Estimates for the Facility

Space Projects

Program			Yearly Revenue
Argonaut (ESA)			€ 420.000
Lunar Descent Element (lander)	€	96.000	
Cargo Platform Elements	€	180.000	
Payloads	€	144.000	
Artemis (NASA)			€ 503.438
Artemis Lunar Terrain Vehicle	€	45.000	
Griffin Mission One - Astrobotic	€	84.375	
Intuitive Machines PRIME-1	€	126.563	
Commercial Lunar Payloads (CLPS)	€	202.500	
EVA Suits	€	45.000	
HAKUTO-R Mission 2			€ 117.000
RESILIENCE Lander	€	72.000	
Lunar Cruiser	€	45.000	
Mars Sample Return			€ 108.000
Sample Return Continuation	€	18.000	
Sample Fetch Rover	€	90.000	
SciSpacE CORA			€ 500.000
Physical Science	€	125.000	
Life Science	€	125.000	
Moon & Mars Science	€	250.000	
			€ 1.648.438

Terrestial Projects

Types			Yearly Revenue
Air and Sensor Technique			€ 167.200
Test & Certification	€	61.600	
R&D	€	105.600	
Extreme Climate Testing			€ 95.040
Environmental Testing	€	52.800	
Larger Machineries	€	42.240	
			€ 262.240

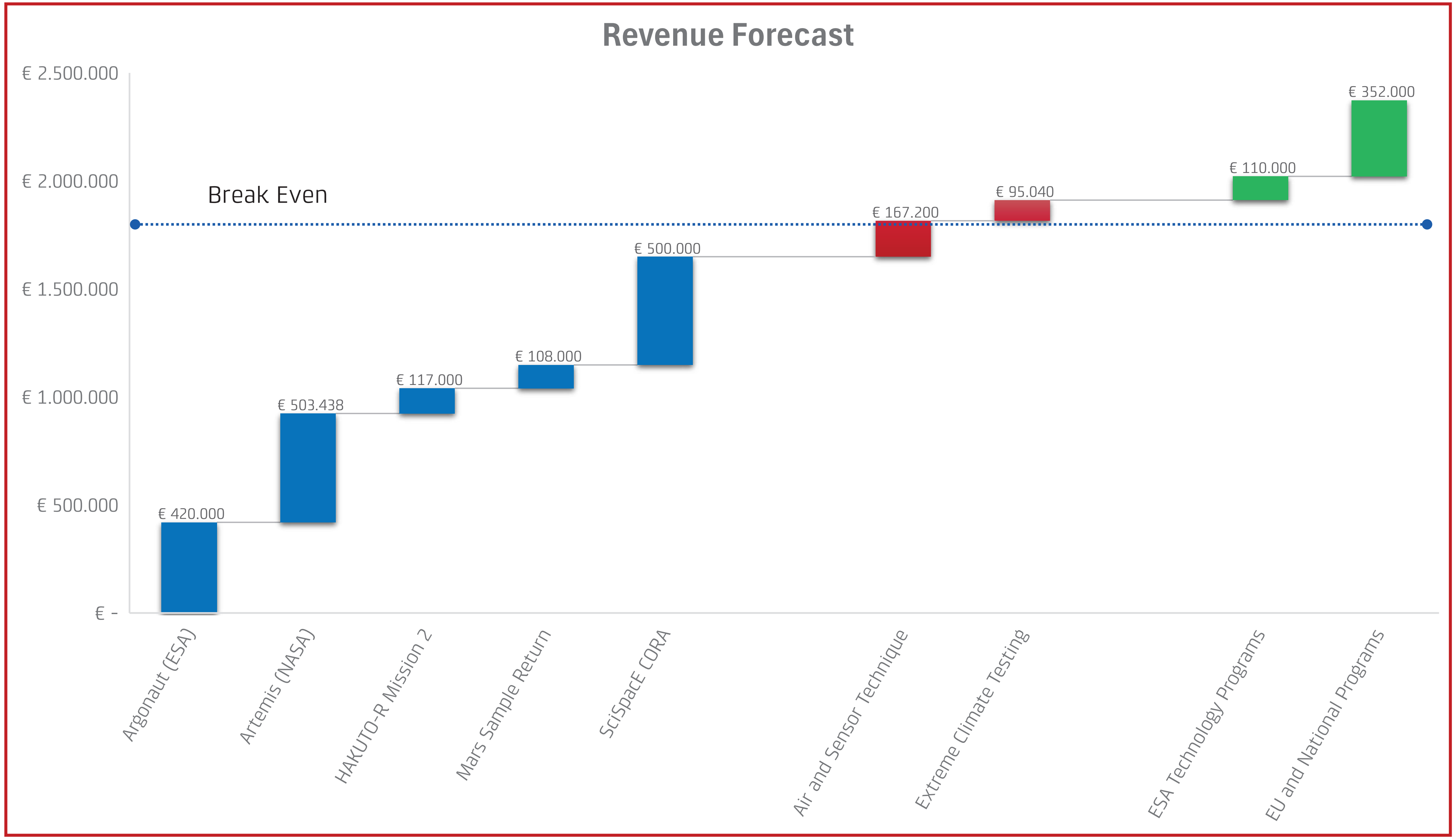
Funded Projects

Programs			Yearly Revenue
ESA Technology Programs			€ 110.000
TDE, GSTP, Prodex	€	110.000	
EU and National Programs			€ 352.000
Horison Europe	€	176.000	
National Funding	€	176.000	
Ph.D Program	€	-	
			€ 462.000

Methodology for calculating revenue

The methodology for calculating revenue estimates begins by identifying project categories and use cases within known programs. For each use case, the number of days per campaign, campaigns per year, load rate, and likelihood of occurrence are determined. These parameters are used to compute the estimated load days per year, which are then multiplied by the daily price to determine the yearly revenue for each use case.

Revenue Stair for the Facility



The graph presents the revenue forecast as a stepped representation in euros for each project category.

The "Break Even" point indicates the revenue threshold required to cover the facility's operational costs.

Conclusion is, that despite uncertainties surrounding some high-profile campaigns, such as Argonaut and Artemis, there remains potential to successfully operate the facility as a viable business.

Viable Financial Business Model

Funding and Investment

- **Government Grants and Space Agency Funding:** Significant funding will be sourced from national and international space agencies, supporting the primary construction costs.
- **Public-Private Partnerships:** Collaborations with private companies interested in space technology and terrestrial applications in extreme environments will provide additional funding and investment for having pre-reserved access.
- **Enterprise Foundations:** Danish foundations that support scientific initiatives and strengthen competitiveness within Danish businesses, particularly in the industrial sector, are also expected to provide funding.

Revenue Streams Resulting from Facility Operation

- **Service Fees:** Fees for using the facility will be a primary revenue source. This includes testing services for space assets, terrestrial equipment, and environmental studies across various sectors such as transportation, appliances, agricultural, and meteorological.
- **Collaborative Project**s: Joint funded projects with industry partners can bring in additional revenue, often involving co-development of technologies and services.
- **Consultancy and Expertise:** Offering consultancy services in outer space testing and certification, environmental testing, and other specialized areas can generate important revenue.
- **Incubation Services:** Offering access to experienced mentors, affordable office space, and test facilities for space developments. *This activity is self-sustaining and does not contribute to net profit or estimates in this brief.*

Costs

The total estimated construction costs for the facility, primarily funded via grants, are €27,557,000.

The annual operational cost is estimated at €1,754,000 which equates to approximately minimum rate of €8.800 per day.

Annual Revenue Contributing to Operations after 3 years.

- Space Assets Testing and Certification: €1.7 million (hereof large scale ~50%)
- Terrestial Application: €0,3 million (all large scale installations)
- Collaborative Funded Projects: €0,5 million
- Incubation Services: *self-sustaining*

Depreciation Allowance per Year (headroom for refund)

€1.7 + €0,3 + €0,5 - €1.75 millon = €0.75 millon per year

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