

DOCTORAL DISSERTATION

*Architecture in Extreme Conditions:
The Problem of Self-Sufficiency in Space Architecture and Its Impact
on Sustainable Development*

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**“We are called to be architects of the future,
not its victims.”**

- Buckminster Fuller

Para mi esposo, por acompañarme en este camino y creer en mí.

Streszczenie

Rozprawa doktorska dotyczy problemu samowystarczalności architektury w środowiskach ekstremalnych, ze szczególnym uwzględnieniem architektury kosmicznej. Przyjęto założenie, że architektura funkcjonująca w warunkach izolacji, zamknięcia i deficytu zasobów stanowi kontekst, w którym samowystarczalność ma charakter kluczowy i jest determinowana przez uwarunkowania środowiskowe oraz konieczność zapewnienia ciągłości funkcjonowania człowieka. Praca bada możliwości transferu wypracowanych w nim rozwiązań do zrównoważonej architektury ziemskiej.

Opracowanie porządkuje wiedzę dotyczącą rozwiązań zapewniających samowystarczalność i odporność architektury. W podejściu badawczym połączono analizę literatury z zakresu architektury kosmicznej, projektowania w środowiskach ekstremalnych oraz badań kosmicznych z doświadczeniami empirycznymi autorki i analizą porównawczą studiów przypadków obejmujących architekturę kosmiczną, habitaty analogowe oraz obiekty funkcjonujące w różnych warunkach skrajnych - polarnych i podwodnych.

W efekcie, zidentyfikowano siedem czynników samowystarczalności architektury charakterystycznych w środowiskach ekstremalnych (*Architectural Resilience Factors - ARF*), obejmujących autonomię zasobową, stabilność środowiska wewnętrznego, odporność systemową, adaptacyjność, organizację przestrzeni, dobrostan psychospołeczny oraz autonomię operacyjną. Na ich podstawie opracowano autorski, jakościowy model oceny autonomii środowiska zbudowanego: skalę samowystarczalności (*Self-Sufficiency Readiness Level - SSRL*), umożliwiającą identyfikację poziomów odporności architektury oraz dopasowanie poziomu autonomii do kontekstu i potrzeb. Skala stanowi kompleksowe ujęcie samowystarczalności architektury integrujące aspekty technologiczne i psychospołeczne.

Wyniki przeprowadzonych badań wskazują, że architektura kosmiczna i architektura środowisk ekstremalnych mogą dostarczać strategii i rozwiązań zwiększających odporność rozwiązań na Ziemi. Pokazują także, że rozwiązania samowystarczalności mogą być stosowane dla obiektów w warunkach ograniczonych zasobów i sytuacji kryzysowych, np. architektury krytycznej, schronów, lub w dobie zmian klimatu, przyczyniając się jednocześnie do zwiększenia ich samowystarczalności.

Abstract

This doctoral dissertation examines the problem of architectural self-sufficiency in extreme environments, with particular emphasis on space architecture. It is assumed that architecture operating under conditions of isolation, confinement, and resource scarcity represents a context in which self-sufficiency becomes a fundamental requirement, shaped both by environmental constraints and by the need to ensure the continuity of human functioning. In this perspective, the potential transfer of solutions developed in such conditions to terrestrial sustainable architecture is explored.

The dissertation organises knowledge about solutions that ensure the self-sufficiency and resilience of architecture. The research approach combines an analysis of literature in the fields of space architecture, design in extreme environments, and space research with the author's empirical experience and a comparative analysis of case studies, including space architecture, analog habitats, and terrestrial buildings operating under extreme conditions, like polar or underwater stations.

Seven key factors of architectural self-sufficiency derived from extreme environments were identified (*Architectural Resilience Factors - ARF*), including resource autonomy, stability of the internal environment, system resilience, adaptability, spatial organisation, psychosocial well-being, and operational autonomy. Based on these factors, an original qualitative model for the assessment of the autonomy of the built environment was developed: the self-sufficiency scale (*Self-Sufficiency Readiness Level - SSRL*), which enables the identification of thresholds of architectural resilience and the adjustment of the level of autonomy to context and needs. It also constitutes an original, comprehensive approach to architectural self-sufficiency integrating technological, environmental, and psychosocial aspects.

Research results indicate that space architecture and architecture of extreme environments provide strategies that increase the resilience and adaptability of terrestrial architecture. They also show that architectural self-sufficiency enables buildings to function under conditions of limited resources and crises, and find the application in object like critical architecture, shelters or impacted by climate change, contributing to increasing their self-sufficiency.

List of Abbreviations and Acronyms

Abbreviation	Explanation
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AR	Augmented Reality	ARF	Architectural Resilience Factors
BLSS	Bioregenerative Life Support System	BREEAM	Building Research Establishment Environmental Assessment Method
CDF	Concurrent Design Facility	CSA	Canadian Space Agency
DARPA	Defence Advanced Research Projects Agency	DLR	German Space Agency
ECLSS	Environmental Control and Life Support System	ESA	European Space Agency
EVA	Extravehicular Activity	F-MARS	Flashline Mars Habitat
GCR	Galactic Cosmic Radiation	GRP	Glass Reinforced Plastic
HERA	Human Exploration Research Analog	HRL	Habitability Readiness Level
HVAC	Heating, Ventilation and Air Conditioning	ICE	Isolated, Confined and Extreme (Environments)
IRL	Innovation Readiness Level	ISRU	In-Situ Resource Utilization
ISS	International Space Station	ITAR	International Traffic in Arms Regulations
JAXA	Japan Aerospace Exploration Agency	JPL	Jet Propulsion Laboratory
LEED	Leadership in Energy and Environmental Design	LEO	Low Earth Orbit

Abbreviation	Explanation		
MDRS	Mars Desert Research Station	MELiSSA	Micro-Ecological Life Support System Alternative
MIT	Massachusetts Institute of Technology	MLI	Multi-Layer Insulation
NASA	National Aeronautics and Space Administration	NASA-STD	NASA Standard Technical Document
NBL	Neutral Buoyancy Laboratory	NEEMO	NASA Extreme Environment Mission Operations
NHV	Net Habitable Volume	OWS	Orbital Workshop
PNRA	National Antarctic Research Programme (Italy)	POE	Post-Occupancy Evaluation
SICSA	Sasakawa International Centre for Space Architecture	SOM	Skidmore, Owings & Merrill
SPE	Solar Particle Event	SRL	Systems Readiness Level
SSRL	Self-Sufficiency Readiness Level	TRL	Technology Readiness Level
VR	Virtual Reality	YAC	Young Architects Competitions

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BACKGROUND

While exploring issues related to space architecture, a fundamental question was repeatedly raised, both by the surrounding environment and by the author herself: why do we explore Space? This question is broader than the subject of the dissertation, which is space architecture. Over several years of work on this topic, during more than fifty scientific and outreach presentations, attempts were made to reformulate an answer that would be practical, not only existential. In one of author's presentations, three main reasons were summarised as to why humanity constantly looks toward the stars: to understand what we already have; to discover what is unknown; and to fulfil a deeply rooted need to cross boundaries.

First, space exploration allows us to understand the Earth and the laws that govern it. Microgravity conditions on the International Space Station (ISS) make it possible to conduct scientific research in an environment separated from the influence of gravity, which significantly expands our knowledge of biology, physics, physiology, and human functioning.

Second, space exploration serves to discover what has so far remained unknown. Exploration programs such as Voyager 1 and 2, New Horizons, Perseverance, and the planned Europa Clipper mission allow for the gradual exploration of the nature of the Solar System, as well as the identification of potential locations for the existence of life beyond Earth. They expand the boundaries of human knowledge and support the development of fundamental natural sciences.

Third, exploration is part of human nature. Carl Sagan, the American astronomer, astrophysicist, and science communicator, wrote: "*We are wanderers. We have always been wanderers*"¹. His words emphasise this motive, as the drive to explore and expand the boundaries of knowledge arises from a deeply rooted need to understand who we are and where we are heading. Frank Borman, an astronaut of the Apollo 8 mission, expressed this in the following words: "*Exploration is really the essence of the human*

¹ Sagan, C. (1980). *Cosmos*. Random House.

spirit"². Just as the ancestors crossed the oceans in search of new lands, modern humanity is turning toward orbit, the Moon, and, in the longer term, toward Mars and beyond the boundaries of the Solar System.

But, there is the fourth aspect of space exploration, which is becoming increasingly important nowadays. It is the possibility of “healing,” expressed by the impact of space technologies on improving the quality of life on Earth. For the author, as a researcher and architect, it is particularly important that the research developed within this dissertation has a practical application in reality. Although space architecture remains a new and niche field of research, it can be observed that technologies and concepts developed in the context of extreme environments are increasingly returning to Earth as tools supporting sustainable development, social resilience, and adaptation to changing climatic conditions. It is allowing to understand more and to push the boundaries of functioning in extreme conditions, as shown in the figure below [Fig. 1].

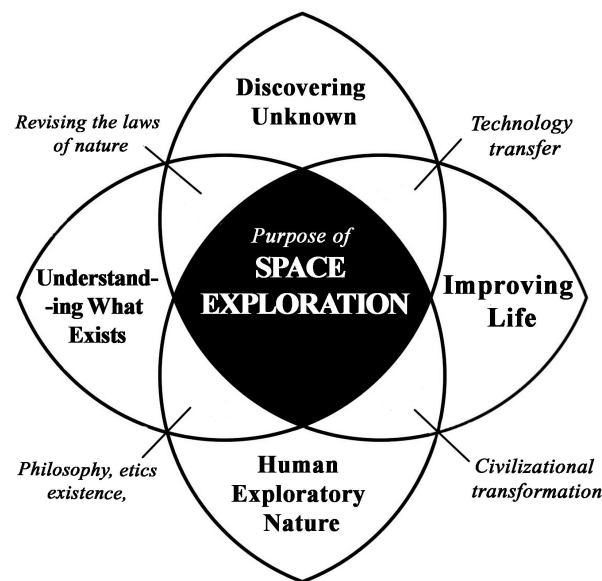


Fig. 1. Conceptual map of the four elements driving humanity into space (author's own elaboration, 2025).

It is precisely this fourth aspect - “healing” through space innovation - that forms the core of this doctoral dissertation. At the center of interest is the question of what we can

² NASA Administrator Honors Life of Apollo Astronaut Frank Borman. (2023). NASA. <https://www.nasa.gov/news-release/nasa-administrator-honors-life-of-apollo-astronaut-frank-borman/> (accessed: 04 February 2026).

learn (in the field of architecture and related areas) from past, present, and future space endeavours, even those that currently seem distant from implementation, and how these experiences can impact the design of Earth here and now. The dissertation examines space architecture both as a tool of exploration and as a design framework with significant implementation potential, inspiring the creation of self-sufficient, resilient, and sustainable living environments on Earth. At the same time, it draws attention to the question of whether self-sufficiency is needed, and to what extent.

The main inspiration was the concept of *Spaceship Earth*, explored by the author during her research in 2019 as part of the ART+DESIGN+SCIENCE art-and-science residency. Already in the mid-twentieth century, Richard Buckminster Fuller [fig. 2], an American architect, visionary, and innovator, emphasised the need to think about Earth as a shared, closed system. He introduced the concept of “*Spaceship Earth*” in order to make clear that our planet has limited resources and requires collective and responsible management, similar to a space habitat³. This concept, which redefined the way the natural environment was perceived, also became a starting point for reflection on architecture in a global and systemic context. Fuller was also the creator of one of the most recognisable structures of the twentieth century - the geodesic dome - whose lightness, modularity, and mechanical resilience continue to inspire designers of space habitats. His approach to design was based on the principle of ephemeralization, understood as “*doing more and more with less and less*”⁴. This principle appears to be extremely relevant today in the context of architecture in extreme environments and efforts toward self-sufficiency, both on Earth and beyond it.

³ Fuller, R. B. (2008). *Operating Manual for Spaceship Earth* (J. Snyder, Ed.; Original published 1969 ed.). Lars Müller Publishers.

⁴ Fuller, R. B. (1973). *Nine Chains to the Moon*. Cape.



Fig. 2. R. Buckminster Fuller, creator of the geodesic dome (source: Eastham, 2007).

In his book *Critical Path*, Fuller wrote:

„For the first time in history, it is now possible to take care of everybody at a higher standard of living than any have ever known... All humanity now has the option to become enduringly successful.”⁵

These words emphasise his belief in the transformative potential of technology as a means to serve humanity, rather than as a tool of domination commonly used today. In this spirit, this doctoral dissertation was developed, seeking to show that technologies, solutions, and design and construction strategies developed for space environments can and should be used to improve the quality of life on Earth, supporting sustainable development, community resilience, and human psychophysical well-being.

Although the scope of this dissertation goes beyond the traditional, building-centered understanding of architecture, this choice is fully conscious and justified by the nature of contemporary challenges. Humanity lives in a global, dynamic, and rapidly changing world, in which the key competence of the future is the ability to solve complex problems. These problems can be addressed only from an interdisciplinary perspective, such as the one adopted in this dissertation. Today, architecture more and more often is understood through its integrative function and becomes a field in which technical knowledge, environmental sciences, the humanities, engineering, biology, and future

⁵ Fuller, R. B. (1981). *Critical path*. St. Martin's Press.

studies come together. To responsibly design living environments, both on Earth and beyond it, it is necessary to be aware of the challenges and processes shaping the surrounding world and to be able to view design from multiple complementary perspectives. The perspectives as complex as the living environment itself.

1. Introduction

1.1. Motivation for Undertaking the Dissertation - Knowledge Transfer

The starting point of this research is the observation that technologies developed for the needs of space missions have, for decades, served as an impulse for technological and scientific development on Earth. This phenomenon is referred to as *spin-off*, meaning the adaptation of space solutions for terrestrial applications. The opposite process is *spin-in*, understood as the implementation of terrestrial technologies in space missions⁶. The phenomenon of technology transfer is consistently developed within the strategies of the space agencies, which perceive technology transfer as a process of knowledge circulation between different environments. The NASA Technology Transfer program has, for more than fifty years, documented the implementation of space technologies in the terrestrial sector, ranging from high-resilience materials developed for space missions to advanced filtration systems and biomedical sensors^{7,8}. In Europe, institutions such as the ESA Technology Broker support both the transfer of innovations from the space sector to industry and the reverse process, enabling the adaptation of terrestrial solutions in space projects on a broad scale⁹. The research conducted by NASA in space also has direct applications in the fields of design and ergonomics, with many implemented solutions. The Neutral Body Posture (NBP) [Fig. 3] was defined based on studies conducted on twelve individuals staying under microgravity conditions aboard the Skylab space station¹⁰. In the 1980s, NASA developed a set of detailed guidelines, including the Neutral Body Posture (NBP), aimed at designing onboard systems in a way that supports human health and safety. To date, this research has been applied, among others, in the design of seats for space shuttles and orbital stations, as well as in ergo-

⁶ Schlacht, I., Foing, B., Bannova, O., Blok, F., Mangeot, A., Nebergall, K., Ono, A., & Schubert, D. (2016a). *Existing and new proposals of Space analog, off-grid and sustainable habitats with Space applications*. 46th International Conference on Environmental Systems.

⁷ NASA - Spin-Off. (n.d.). *NASA Spinoff*. <https://spinoff.nasa.gov/> (accessed: 04 February 2026).

⁸ *Technology Transfer and Spinoffs*. (n.d.). NASA. <https://www.nasa.gov/space-technology-mission-directorate/technology-transfer-spinoffs/> (accessed: 04 February 2026).

⁹ European Space Agency. (2025). *ESA Technology Broker*. *ESA Technology Broker*. <https://commercialisation.esa.int/technology-broker/> (accessed: 04 February 2026).

¹⁰ NASA. (1995). *Man-Systems Integration Standards (NASA-STD-3000, Volume I)*. NASA Johnson Space Center, Houston, TX.

onomic car and aircraft seating, child safety seats, hospital and rehabilitation beds, and in the development of ergonomic office chairs and human-machine interface systems, including VR/AR and control cockpits.. Space is therefore a testing ground for technologies and a source of innovative solutions that improve the quality and safety of life, also on Earth.

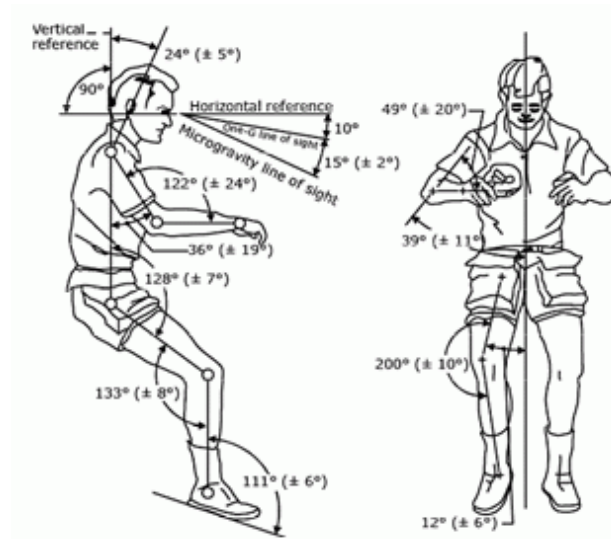


Fig. 3. Neutral Body Posture developed by NASA (source: NASA, 1995).

The process of spin-off and spin-in technology transfer operates on the basis of the exchange of experience and feedback. As noted by the Interaction Design Foundation, a *feedback loop* can be understood as a process in which information about the results of an action is fed back and used to modify its future application or behaviour¹¹. In design, this means a cyclical process of learning, drawing conclusions, and later adapting these solutions, which allows designers to improve systems based on experience and observation of the effects of earlier decisions. Donald A. Norman points out that *iteration* is a key mechanism in the design process, enabling the continuous improvement of products and user interaction¹². In contrast, Donald A. Schön describes design as “*a dialogue between the designer and the situation*”¹³, based on reflection, in which feedback

¹¹ Interaction Design Foundation. (n.d.). *What are Feedback Loops?* - updated 2025 | IxDF. <https://www.interaction-design.org/literature/topics/feedback-loops> (accessed: 04 February 2026).

¹² Norman, Donald. A. (2013). *The Design of Everyday Things: Revised and Expanded Edition*. Basic Books.

¹³ Schon, D. A. (1984). *The Reflective Practitioner: How Professionals Think In Action*. Basic Books.

shapes subsequent stages of the creative process. Therefore, also from the perspective of design, these processes of knowledge exchange can be successfully used and interpreted as a form of *feedback loop*¹⁴. In architecture, particularly in qualitative architectural research, this phenomenon finds practical application, among others, in the Post-Occupancy Evaluation (POE) method, which, as noted by Elżbieta Niezabitowska, allows for the creation of a feedback loop between the designer, the user, and the building through the evaluation of the performance of completed buildings¹⁵. Such an approach fits within the concept of design learning, in which theory, practice, and use form a shared circulation of knowledge.

In the case of architecture and the built environment, the circulation of information and feedback can play a significant role, as they directly concern the spaces of human activity within a specific environment. Solutions developed in response to limitations characteristic of extreme environments (e.g., space environments) can be observed, modified, reinterpreted, and adapted for the purposes of terrestrial architectural design. Therefore, extreme environments, characterised by a high level of constraints, constitute a context for the development of solutions addressing key challenges of contemporary terrestrial architecture, such as increasing needs for the resilience of the built environment to variable and extreme external factors. In the context of this dissertation, this phenomenon is illustrated by a looped learning model in which space architecture and terrestrial architecture function as interdependent laboratories for the development of technologies and self-sufficiency strategies based on spin-off and spin-in processes [Fig. 4]. This model is therefore based on the observation that solutions tested under extreme conditions or designed to operate in extreme environments can serve as reference points for terrestrial architecture, while at the same time, design experience from Earth provides valuable data for future space missions, with particular emphasis on research focused on spin-in solutions.

¹⁴ Feedback Loop. (n.d.). *Feedback Loop*. *Tempo.io*. <https://www.tempo.io/glossary/feedback-loop> (accessed: 04 February 2026).

¹⁵ Niezabitowska, E. (2014). *Metody i techniki badawcze w architekturze*. Wydawnictwo Politechniki Śląskiej.

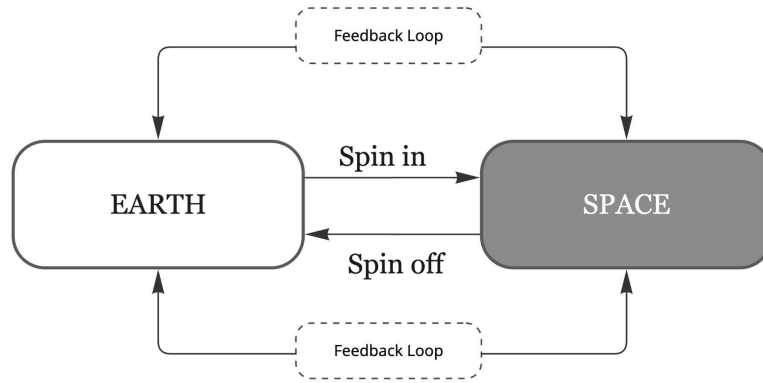


Fig. 4. Modified model of knowledge transfer between outer space and Earth (author's own elaboration based on: Schlacht, 2016a).

The motivation for undertaking this research is therefore the recognition of the potential of transferring space technologies to terrestrial infrastructure, which takes place in many areas, such as medicine, safety, technologies, and materials, improving quality of life and introducing innovation. Although the starting point of the considerations is space architecture, the issue of self-sufficiency also relates to other extreme environments, which are characterised by similar resource limitations, systemic isolation, and the need to integrate autonomous operational systems. Due to these shared characteristics of such environments, the space context and other extreme environments can be analysed within a single, coherent research perspective, which is consistent with research practices adopted in the scientific community.

1.2. State of the Art

The scientific literature on space architecture and extreme environments in the Polish language remains limited; however, in recent years, publications have appeared that have outlined the direction of development of this field in Poland. Authors addressing these issues include Klaudiusz Fross, Wiktoria Dziadula, Leszek Orzechowski, and researchers collaborating with them, associated, among others, with the LunAres habitat and projects in the field of extreme architecture. Of particular importance is the article by Fross, K., and Dziadula, W. (2021) *Kosmos na Ziemi - analogowe habitaty kosmicz-*

ne. *Badania jakościowe podczas symulowanej misji kosmicznej*¹⁶ (en. *Space on Earth: Analog Space Habitats. Qualitative Research during a Simulated Space Mission*), published in *Builder Science*, which is one of the first Polish-language scientific studies describing space architecture and the functioning of analog habitats from an architectural and human-centered design perspective. In subsequent years, several works further developing this topic were published, including analyses of research conducted in the LunAres habitat, such as: Fross, K., Dziaduła, W. (2022) *Analogowe habitaty kosmiczne - badania i koncepcja własna*¹⁷ (en. *Analog Space Habitats - Research and Author's Own Concept*); Fross, K., Dziaduła, W. (2022) *Qualitative research in the LunAres space habitat*¹⁸; Fross, K., Orzechowski, L., Dziaduła, W., Mintus, A. (2022) *The Panda Space Program in the LunAres habitat - research on needs and behaviour during isolation*¹⁹. These publications describe both the functional aspects of isolation habitats and the specificity of qualitative research conducted under conditions of a simulated space mission. The topic was also expanded to include theoretical reflection on design in extreme conditions, as exemplified by the article by Dziaduła, W., and Fross, K. (2022) *About architecture in extreme conditions. How can space and extreme environments help architects design better?*²⁰ as well as in a summary of activities carried out within the *Space Architecture Research Program* at the Silesian University of Technology, Faculty of Architecture^{21, 22}.

¹⁶ Fross, K., & Dziaduła, W. (2021). *Kosmos na Ziemi - analogowe habitaty kosmiczne. Badania jakościowe podczas symulowanej misji kosmicznej*. *Builder Science*, Tom: 288, Nr: 7. doi:10.5604/01.3001.0014.9334.

¹⁷ Fross, K., & Dziaduła, W. (2022). *Analogowe habitaty kosmiczne - badania i koncepcja własna*. *Builder Science*, Tom: 296, Nr: 3. doi:10.5604/01.3001.0015.7363.

¹⁸ Fross, K., & Dziaduła, W. (2022). *Qualitative research in the LunAres space habitat*. B. Komar, K. Fross, & B. Urbanowicz (Redaktorzy), *Multifaceted research in architecture*. Vol. 2, Architecture against the challenges of the future – smart architecture. Wydawnictwo Politechniki Śląskiej., 10-21.

¹⁹ Fross, K., Orzechowski, L., Dziaduła, W., & Mintus, A. (2022). *The Panda Space Program in the LunAres habitat - research on needs and behavior during isolation*. w B. Komar, K. Fross, & B. Urbanowicz (Redaktorzy), *Multifaceted research in architecture*. Vol. 2, Architecture against the challenges of the future – smart architecture (s. 22-33). Wydawnictwo Politechniki Śląskiej, 22-33.

²⁰ Dziaduła, W., & Fross, K. (2022). *About architecture in extreme conditions. How can space and extreme environment help architects design better?* 73rd International Astronautical Congress (IAC) Proceedings, International Astronautical Federation (IAF), Paris, France.

²¹ Fross, K. (2022). *Space architecture research programme*. T. Kozłowski (Redaktor), *Defining the Architectural Space - Avant-Garde Architecture*, 2022, vol. 2. Oficyna Wydawnicza Atut, Wrocławskie Wydawnictwo Oświatowe. doi:10.23817/2022.defarch.2-4

²² Fross, K. (2023). *Projekt badawczy architektury kosmicznej - misja Weninger*. *Builder*, Article 11., 8-9.

The literature on space architecture, extraterrestrial habitats, self-sufficiency systems, and human functioning in extreme environments is developed primarily in international research. Current and comprehensive compendia of knowledge in the field of space architecture include textbooks published by Springer. A key position among these is held by the publication by Sandra Häuplik-Meusburger and Sheryl Bishop, *Space Habitats and Habitability: Designing for Isolated and Confined Environments on Earth and in Space*²³, a study focused on the design of isolated environments. The book analyses architectural, ergonomic, psychosocial, and engineering conditions, constituting a fundamental source of knowledge on habitat design in the context of human perception, function, and enclosed environments. Another comprehensive textbook published by Springer is *Space Architecture Education for Engineers and Architects: Designing and Planning Beyond Earth*²⁴ (Häuplik-Meusburger & Bannova), presenting contemporary educational and design approaches applied in space architecture. An important publication describing the foundations and examples of architecture in extreme environments, with an in-depth focus on space architecture, is the work by Bannova, O. *Space Architecture: Human Habitats Beyond Planet Earth*²⁵. It is worth emphasising that Dr Olga Bannova is currently (2025) the Director of SICSA (Sasakawa International Center for Space Architecture, University of Houston)²⁶, the most renowned academic unit in the world dedicated to research on space architecture, which gives her scholarly work particular significance. A complement to the technical literature is the work of Sandra Häuplik-Meusburger: *Architecture for Astronauts: An Activity-Based Approach*²⁷, presenting an analysis of ergonomics and activities in space environments, constitutes a basis for design in an activity-based context.

Alongside architectural literature, publications addressing the human factor and psychology in extreme environments play an important role. A particularly significant con-

²³ Häuplik-Meusburger, S., & Bishop, S. (2021). *Space Habitats and Habitability: Designing for Isolated and Confined Environments on Earth and in Space*. Springer International Publishing.

²⁴ Häuplik-Meusburger, S., & Bannova, O. (2016). *Space Architecture Education for Engineers and Architects: Designing and Planning Beyond Earth*. Springer International Publishing.

²⁵ Bannova, O. (2021). *Space Architecture: Human Habitats Beyond Planet Earth*. DOM Publishers.

²⁶ University of Houston. (n.d.). *Sasakawa International Center for Space Architecture (SICSA)* <https://sicsa.egr.uh.edu/> (accessed: 04 February 2026).

²⁷ Häuplik-Meusburger, S. (2011). *Architecture for Astronauts: An Activity-based Approach*. Springer

tribution is made by the work of Peter Suedfeld, which focuses on human adaptation to isolation, environmental stress, and conditions of limited social contact^{28,29,30,31}- phenomena that are critical for long-duration space missions. It is worth noting that a large part of the global literature on isolated environments is produced within institutions conducting analog missions or simulated research programs, such as HI-SEAS (University of Hawaii), HERA (NASA), MDRS (The Mars Society), Concordia Station (ESA/PNRA), and DLR (German Space Agency), as well as at universities providing education in the field of extreme architecture, including the previously mentioned University of Houston/SICSA, Vienna University of Technology, Politecnico di Milano, and the Massachusetts Institute of Technology (MIT Media Lab).

In this dissertation, in the methodological context, an important role is played by publications examining research methods and techniques used in architecture, especially in the design and analysis of complex usable environments. Among the most important works are: Niezabitowska, E., *Metody i techniki badawcze w architekturze*³² (*en. Research Methods and Techniques in Architecture*) and Fross, K., *Badania jakościowe w projektowaniu architektonicznym na wybranych przykładach*³³ (*en. Qualitative Research in Architectural Design: Selected Case Studies*), which constitute a foundation for the structuring of qualitative research methods also used in the analysis of space habitats and isolated environments. A broad range of issues related to research in architecture, including qualitative research, is presented in publications such as *Case Study Research: Design and Methods* (Yin, 2014)³⁴ and *Architectural Research Methods* (Groat & Wang, 2013)³⁵.

²⁸ Suedfeld, P., & Palinkas, L. A. (2008). *Psychological effects of polar expedition*. *Lancet*, 12;371(9607). doi:10.1016/S0140-6736(07)61056-3.

²⁹ Suedfeld, P., & Palinkas, L. A. (2021). *Psychosocial issues in isolated and confined extreme environments*. *Neuroscience and Biobehavioural Reviews*, 126, 413-429. 10.1016/j.neubiorev.2021.03.032

³⁰ Suedfeld, P., & P. Mocellin, J. S. (1987). *The "Sensed Presence" in Unusual Environments*. *Environment and Behavior*, 19(1), 33-52.

³¹ Suedfeld, P., & Steel, D. G. (2000). *The environmental psychology of capsule habitats*. *Annual Review of Psychology*, 51, 227-253. 10.1146/annurev.psych.51.1.227

³² Niezabitowska, E. (2014). *Metody i techniki badawcze w architekturze*. Wydawnictwo Politechniki Śląskiej.

³³ Fross, K. (2012). *Badania jakościowe w projektowaniu architektonicznym na wybranych przykładach*. *Monografia*, [Politechnika Śląska] (T. 380). Politechnika Śląska.

³⁴ Yin, R. K. (2014). *Case Study Research: Design and Methods*. SAGE Publications.

³⁵ Groat, L. N., & Wang, D. (2013). *Architectural Research Methods*. Wiley.

1.3. Research Gap

Publications addressing the future of architecture indicate that threats to humanity (such as climate change, wars, pandemics, asteroids, and resource depletion) force humanity to seek alternative forms of habitation and point to the responsibility of architects for the direction and initiation of this change³⁶. Also, the idea of drawing inspiration for next-generation ecological building from space is reflected in the literature. In the publication *From Bauhaus to Ecohouse*³⁷, the authors draw attention to the way in which design has changed its character from architecture understood as an object to architecture understood as an environmental system, emphasising that architectural thinking developed, among others, in relation to closed habitats and space research, which constitutes an important foundation of contemporary concepts of sustainable development. The discourse related to the search for future directions of architecture highlights the importance of self-sufficiency and the use of dual-use space technologies. Long before the actual development of space architecture, a pioneer in presenting the significance of the logic of space systems as a model for terrestrial civilisation was R. Buckminster Fuller. His philosophy presents Earth as a closed life-support system that functions like a spaceship³⁸. It has finite resources, and survival depends on the effective management of energy and matter. Fuller postulates a shift from an exploitative model to a model in which architecture, technology, and infrastructural systems become tools for the stabilisation of the global ecosystem. In the *Critical Path*³⁹, he develops this concept toward systemic thinking about the development of civilization, in which the foundation of transformation toward sustainable, self-sufficient living environments is formed by technological innovation, system integration, and the optimization of structures derived from space solutions.

What, then, is the current state of knowledge in the field of space technologies, with particular emphasis on architecture and design? To answer this question, it is necessary

³⁶ Richards, M. A. (2010). *The End of the World and Architecture*. *Sage Journals*, Volume 2, Issue 5. <https://doi.org/10.1177/1946756710002005>

³⁷ Anker, P. (2010). *From Bauhaus to Ecohouse: A History of Ecological Design*. LSU Press.

³⁸ Fuller, R. B. (2008). *Operating Manual for Spaceship Earth* (J. Snyder, Ed.; Original published 1969 ed.). Lars Müller Publishers.

³⁹ Fuller, R. B. (1981). *Critical path*. St. Martin's Press

to shift the perspective from theoretical possibilities of transfer to experiences and research related to space and extreme environments - their scope, themes, and limitations. Existing scientific studies focus mainly on the analysis of space and extreme architecture in the context of ensuring survival in a given environment, emphasising the need to achieve increasingly higher levels of self-sufficiency with increasing distance, isolation, and mission duration⁴⁰. As mission duration and levels of risk increase, there is also a growing need to consider aspects such as environmental psychology, ergonomics, spatial perception, biocomfort, and possibilities for psychophysical regeneration. In long-duration missions, spaces in enclosed environments must ensure survival while also enabling users to maintain mental and physical health, effective cooperation, and efficient adaptation⁴¹. In the literature devoted to analog habitats (simulated space research facilities on Earth), their role in testing technologies under space-like conditions is increasingly emphasised, particularly in the areas of closed-loop resource circulation and internal environment management⁴² in other words, increasing levels of self-sufficiency and resilience.

The approach proposed in this dissertation constitutes a combination and extension of two key research directions: technology transfer and concepts of self-sufficiency developed in extreme environments. These topics are currently significant in the context of growing climatic, crisis-related, and urban challenges, as well as the transformation of the inhabited environment toward increasingly extreme conditions. In the existing literature, a comprehensive research stream dedicated to the possibilities of transferring design solutions developed for extreme environments, particularly space environments, to terrestrial architecture has not yet been established. Potential solutions suitable for implementation under terrestrial conditions, in the context of sustainable development, have also not been sufficiently identified, both in challenging environments (e.g., remote or climate-threatened areas) and in everyday architecture.

⁴⁰ Bannova, O. (2016). *Designing for Extremes: A Methodological Approach to Planning in Arctic Regions*. Department of Architecture, Chalmers University of Technology.

⁴¹ Häuplik-Meusburger, S. (2011). *Architecture for Astronauts: An Activity-based Approach*. Springer.

⁴² Häuplik-Meusburger, S., & Bishop, S. (2021). *Space Habitats and Habitability: Designing for Isolated and Confined Environments on Earth and in Space*. Springer International Publishing.

In order to work on the concept related to self-sufficiency, it is first necessary to examine systematics, classification, and reference frameworks. The author, particularly in the context of self-sufficiency in architecture, identified a lack of possibilities for comparing buildings in terms of their level of autonomous functioning and, consequently, a lack of tools for assessing this level. Despite the widespread use of technology maturity scales such as TRL (Technology Readiness Level) and inhabited environment scales such as HRL (Habitat Readiness Level), used especially in the context of extreme environments, the existing literature lacks a scale that would enable a comprehensive assessment of the level of architectural self-sufficiency. It is worth emphasising that current building certification systems (e.g., LEED, BREEAM, WELL)⁴³ focus mainly on selected aspects of sustainability and efficiency, but do not address issues that are crucial for the self-sufficiency of the built environment, such as the integration of life-support systems, functional resilience, user adaptation, the actual level of resource autonomy, or aspects of spatial psychology, whose importance and relevance have been particularly recognized through space projects. Therefore, in order to address the topic of self-sufficiency in a systematic manner, there is a lack of a tool that would make it possible to determine the level of self-sufficiency readiness of architecture and to compare design solutions in the context of space research and future scenarios on Earth.

1.4. Objectives and Scope

This dissertation aims to address the identified gaps in the current state of knowledge, primarily the lack of comprehensive and synthetic studies covering the issue of architectural self-sufficiency. In particular, this concerns the insufficient organisation of solutions developed in space environments and their relationship with terrestrial architecture, as well as the lack of tools enabling their comparison and assessment in the context of diverse operating conditions. This aim is pursued through the identification of technologies and strategies developed in space environments that influence the level of building self-sufficiency and contribute to redefining the way off-grid architecture is understood. The proposed approach extends the existing discourse by introducing a

⁴³ Xander van Baarsen, rhino.energy. (2024). *WELL vs. LEED vs. BREEAM: Key Differences and Focus Areas* <https://rhino.energy/blog/well-vs.-leed-vs.-breeam-compare-these-certifications-to-understand-their-focus-on-health-sustainability-and-environmental-impact> (accessed: 04 February 2026).

new research perspective on the comprehensive understanding of the problem of self-sufficiency in architecture and its transfer to terrestrial architecture. The dissertation also constitutes an attempt to structure and partially standardise the conceptual framework related to architectural self-sufficiency, including its levels, and components.

The dissertation addresses the issue of self-sufficiency in the architecture of extreme environments, with particular focus on space environments and analog habitats. The study attempts to systematically identify solutions which, although developed in response to the most extreme and isolated environments, may serve as inspiration or a direct response to challenges faced by terrestrial architecture. For this purpose, an original self-sufficiency assessment scale was developed - a tool that enables evaluation of facilities in both space and terrestrial contexts, providing universal criteria for assessing future architecture based on self-sufficiency. The dissertation assumes that self-sufficient architecture should be understood as an adaptive system, and that space technologies, as carriers of innovation with high transfer potential, can support the development of future construction characterised by increased durability, ecological performance, sustainability, and regenerative capacity.

In order to indicate the potential of design solutions, it was first necessary to organise them conceptually and semantically. For this reason, this dissertation undertakes an attempt to develop a multidimensional model for assessing the level of architectural self-sufficiency, understood as an integrated operational system encompassing a broad range of issues such as resources, technical systems, spatial organisation, and conditions of long-term human functioning, derived from experience gained in extreme environments. The research problem of the dissertation focuses on the identification of key factors of architectural self-sufficiency and on the development of an assessment model that enables their systematic organisation and comparison, and consequently methodologically supports the identification of directions and needs for transferring solutions from space architecture to the context of sustainable development on Earth.

For this dissertation, the following research questions were formulated:

1. What environmental, technological, and social factors determine the level of self-sufficiency in extreme environments?
2. How can experiences from space architecture and analog space missions support the development of architecture resilient to extreme conditions on Earth?
3. Is it possible to develop a multidimensional scale that enables the comparison and classification of architectural objects according to the degree of integration of autonomous systems?
4. What conclusions for the development of the scientific discipline of Architecture and Urban Planning, as well as for sustainable development strategies, can be drawn from the analysis of space architecture as a model of extreme self-sufficiency?

The main aim of the dissertation is to identify and categorise solutions that ensure self-sufficiency in extreme environments and, on this basis, to develop an integrated model for the assessment and development of autonomous, resilient, and independent architecture.

Specific Objectives were stated:

1. To examine the relationship between the characteristics of extreme environments and the degree of integration of self-sufficiency systems in space architecture and in buildings operating under extreme terrestrial conditions.
2. To identify and analyse technological and design solutions developed in the context of extreme architecture.
3. To indicate directions for the transfer of knowledge and technologies between space/extreme architecture and terrestrial architecture, in terms of spin-off and spin-in processes.

4. To identify and distinguish factors of architectural resilience and self-sufficiency (*ARF - Architectural Resilience Factors*), forming a basis for the analysis of solutions applied in extreme environments.
5. To develop an original scale for the assessment of architectural self-sufficiency - the *Self-Sufficiency Readiness Level (SSRL)*, based on ARF and adapted to a multidimensional evaluation of architectural self-sufficiency.
6. To formulate guidelines and recommendations for the development of future self-sufficient architecture, based on experience from space architecture and the results of the ARF and SSRL analyses.

Therefore, theses of the Dissertation as are followed:

Thesis 1: Space architecture, analog space missions, and buildings in extreme environments constitute a key source of design, technological, and operational knowledge that can be directly applied to the development of self-sufficient architecture on Earth.

Thesis 2: Architectural Resilience Factors (ARF) constitute a tool for the systematic assessment of the degree of integration of autonomous systems both in architecture operating under extreme environmental conditions and in buildings designed for everyday use under standard terrestrial conditions.

Thesis 3: The Self-Sufficiency Readiness Level (SSRL) scale is an effective tool for the multidimensional assessment of the level of self-sufficiency of buildings, enabling comparison, classification, and the identification of potential directions for the development of technologies and design strategies.

Thesis 4 : Technologies and design strategies developed for the needs of space architecture play an important role in shaping future models of sustainable development and in increasing the resilience of terrestrial architecture to future challenges.

1.5. Research Context and Limitations in Space Architecture

Research in the field of space architecture develops within a highly specific scientific context. Although space exploration began in 1961 with the first human spaceflight by Yuri Gagarin, it was not until 2002, during the International Astronautical Congress in Houston, that the definition and objectives of the field of “space architecture” were officially recognised⁴⁴. From that moment, the development of space architecture began to take on an interdisciplinary character. Despite the growing importance of this field, access to reliable scientific sources and data remains limited. One of the main research challenges is the insufficient amount of specialised literature, especially in the Polish language. Most available studies are published in English and are technical in nature, focusing on engineering or material aspects rather than on broadly understood architectural or social conditions. In addition, limited access to empirical data results from the fact that space exploration projects are conducted mainly by governmental institutions (such as NASA or ESA) or by private companies operating under conditions of strong technological competition. Moreover, space architecture, originating from space engineering, is by nature strongly interdisciplinary; a significant part of research and publications is developed within related fields such as environmental psychology, environmental engineering, materials science, and robotics. Despite this disciplinary dispersion, these works have a significant impact on the current state of knowledge and on the directions of development of extreme architecture.

⁴⁴ Team 11. (2002). *THE MILLENNIUM CHARTER*. spacearchitect.org. <https://spacearchitect.org/wp-content/uploads/2020/06/The-Millennium-Charter.pdf> (accessed: 04 February 2026).

Despite the global nature of space exploration, the United States currently constitutes the most dynamically developing accessible research environment in this field. This results from an extensive space program carried out by institutions such as NASA, DARPA, and the Jet Propulsion Laboratory (JPL), as well as a dynamic private sector, including SpaceX, Blue Origin, Axiom Space, and others. Their cooperation within the so-called *New Space Economy*⁴⁵ has enabled the generation of knowledge (although often limited), part of which constitutes a valuable source for this dissertation. A significant obstacle to conducting research is also the application of ITAR regulations (International Traffic in Arms Regulations) in the United States. These regulations aim to control the export of technologies that may have military applications. They also cover a range of space technologies, such as life-support systems and structural or material solutions. As the result, the access to many types of information, technical documentation, or projects is restricted exclusively to U.S. citizens or individuals holding special export licenses. Even scientific cooperation with American research centers requires particular caution and compliance with restrictions related to the publication of materials. For this reason, research in space architecture often relies on the analysis of fragmented data, mission reports, conference materials, conceptual designs, and available visualisations. In many cases, even obtained information cannot be directly published due to obligations resulting from non-disclosure agreements or technological security regulations. Despite the restrictions imposed by ITAR, the American environment remains the most developed and open research platform, and therefore constitutes a key reference point for research on space architecture. For this reason, the author decided to undertake a research internship in the United States⁴⁶, to become closer to institutions and teams directly involved in the development of this field. This stay allowed for a deeper understanding of the real technological and organisational conditions of space projects, but it was also associated with the need to comply with confidentiality rules. In many of the visited facilities, publishing photographs and detailed information is

⁴⁵ MIT Education (n.d.). *What is New Space Economy*. <https://professionalprograms.mit.edu/blog/technology/what-is-new-space-economy/> (accessed: 04 February 2026).

⁴⁶ Wyjazd badawczy do University of Houston, SICSA, możliwy dzięki Fundacji Kościuszkowskiej, US Exchange 2023/2024 (11.2023-01.2024).

prohibited, which constitutes a limitation for research in this discipline, including research conducted for this dissertation.

It is also worth noting that the dynamic development of the space sector is observed outside the United States as well, particularly in China, which in the last decade has developed a comprehensive space exploration program covering both uncrewed and crewed missions (the Tiangong space station and plans for the construction of lunar bases). However, due to information policy and the lack of open access to research results, the Chinese sector remains largely closed to independent researchers. As a result, the American knowledge base and research infrastructure currently constitute the primary and most transparent source of information, enabling the development of theoretical and design-oriented reflection in the field of space architecture.

2. Research Methodology and Tools

The scope of the dissertation includes the analysis of architecture operating under extreme conditions, classified as ICE environments (Isolated, Confined, Extreme), both in the context of the space environment and with reference to extreme environments on Earth. This approach corresponds to a methodological practice commonly adopted in research on space architecture, which involves extending analyses to terrestrial extreme environments as a shared interpretative framework with similar characteristics. The dissertation analyses both realised and conceptual projects related to orbital, lunar, and Martian stations, with particular emphasis on the impact of environmental requirements on design strategies that translate into self-sufficiency. In addition to space habitats, selected facilities operating under ICE conditions on Earth are also analysed, such as polar stations (e.g., Halley VI), underwater laboratories (e.g., Aquarius), and desert habitats (e.g., the Mars Desert Research Station). The methodology of the dissertation is based on the classification proposed by Elżbieta Niezabitowska⁴⁷, adopting a mixed research approach (including desk research, qualitative research, and case studies) to diversify the research process as much as possible and to reduce the risk of errors resulting from the subjective interpretation of complex phenomena.

⁴⁷ Niezabitowska, E. (2014). *Metody i techniki badawcze w architekturze*. Wydawnictwo Politechniki Śląskiej.

2.1. Research Framework and Structure of the Dissertation

Based on the conducted literature review, case studies, and the author's own empirical experience, a research model referred to as the Research Framework was developed. It serves as an analytical tool for the identification, classification, and assessment of design factors influencing the self-sufficiency of architecture operating in extreme environments. The model combines the results of the literature analysis, in which basic concepts related to self-sufficiency, system autonomy, and extreme architecture were defined, with the results of case studies covering both realised and conceptual projects of space habitats as well as terrestrial facilities operating under extreme conditions (such as polar stations, underwater laboratories, desert habitats, etc.).

The Research Framework [Fig. 5] was developed based on a mixed research approach, and it aims to indicate which design, technological, and environmental strategies enable the achievement of self-sufficiency in extreme architecture (ARF), and consequently to build an analytical tool that allows for the classification, comparison, and hierarchization of design solutions (SSRL), that lead to the identification of directions for the transfer of technologies and design strategies to terrestrial architecture.

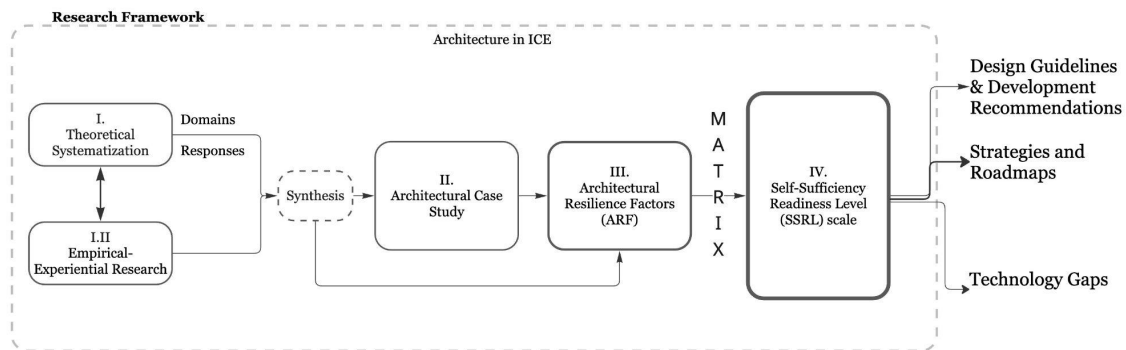


Fig. 5. Logic structure of the Research Framework (author's own elaboration, 2025).

The diagram on Figure 5 presents the logic of information flow and the relationships between subsequent stages of the research. The process begins with a literature review and an analysis of key concepts related to extreme architecture and self-sufficiency, which form the theoretical basis of the model. At this stage, domains were identified and understood as the main elements and issues related to design in extreme conditions. Next, a case study analysis was conducted in ICE environments, from which a set of design factors - Architectural Resilience Factors (ARF) - was identified. These factors were then compiled in the form of an analytical matrix, the purpose of which was to determine their relative importance and to assign them to individual levels of the author's architectural self-sufficiency scale, SSRL. The main outcome of the research process is the development of an analytical and design tool in the form of the SSRL scale, which enables the assessment and comparison of architectural solutions in terms of their level of self-sufficiency; design conclusions and recommendations result from the application of this scale.

The following table [Table 1] presents four stages of the research process adapted in this work.

Table 1. Research Process - aims and tools.

Phase	Process	Tools and Methods	Aim
I.I	Theoretical Systematization	Comparative analysis, literature review, analysis of definitions and classification of concepts.	Building the theoretical foundations for further research, identifying key definitions, classifications, and concepts. Identifying design principles and theories.
I.II	Empirical Experiential Research	Participant observation, research diary, study visits in ICE environments, professional and scientific collaborations with the space sector (LunAres, Space Architecture Research Program, SICSA, Extremo Technologies, NASA, ESA).	Acquisition of practical knowledge and empirical observations from real ICE environments and space projects; verification of theory through experience.
II	Architectural Case Study	Case study, comparative analysis.	Integration of theoretical and empirical knowledge; identification of common design patterns in extreme architecture.
III	Architectural Resilience Factors (ARF).	Categorisation and synthesis of qualitative data as a result of previous analyses and concepts.	Creation of an original set of indicators forming the basis for further analysis.
IV	Self-Sufficiency Readiness Level.	Conceptual analysis of system readiness levels in extreme environments. Synthesis of definitions and classifications used in the assessment of complex objects and infrastructures.	Development of an original analytical-design tool enabling the evaluation and comparison of architecture in terms of the level of self-sufficiency under ICE conditions, through assigning Architectural Resilience Factors (ARF) to specific levels of the scale.

2.2. Development of an Original Self-Sufficiency Scale and Its Assumptions

Within this dissertation, a research tool was developed with the aim of enabling a multidimensional assessment of the level of self-sufficiency of architectural objects. The tool was designed as a response to a research gap identified in the literature concerning the lack of a scale integrating technological, environmental, operational, psychosocial, and system-related factors within the assessment of architectural autonomy. The design of the scale was based on ARF factors identified through literature analysis, case studies, and the author's empirical experience. ARF constitute the foundation of the scale construction, which was developed in accordance with the following methodological assumptions:

1. Hierarchical structure - the scale defines successive levels of self-sufficient architectural readiness, from a fully dependent level to an off-grid level (fully autonomous).
2. Systemic completeness - each level includes technological, environmental, psychosocial, and operational aspects.
3. Interdisciplinarity - just as architecture and all aspects interacting with humans are interdisciplinary, the tool reflects the need to integrate knowledge from multiple fields, including architecture, systems engineering, biology, ergonomics, and psychology.
4. Comparative capability - the scale is intended to enable the assessment and comparison of different types of objects: space habitats, research stations under ICE conditions, and terrestrial buildings.

The scale construction process includes the following steps:

- Identification of original design domains and fields characteristic of extreme architecture based on a literature review;
- extraction of ARF as factors and responses determining resilience and self-sufficiency;

- analysis of the relationships between ARF and the stages of architectural concept development, modelled on the logic of a maturity scale;
- development of the structure of SSRL levels;
- development of evaluation criteria for each level, including technological, environmental, operational, and psychosocial components;
- preliminary validation of the tool through its application in the analysis of case studies.

2.3. Structure of the Dissertation

The dissertation consists of 13 chapters. The first two chapters (1. Introduction and 2. Research Methodology and Tools) describe the key theoretical issues related to the scope, objectives, and methodology of the study, explaining the author's original terms developed for this work (ARF and SSRF). Chapter three (3. Definitions and Literature Review) introduces and explains the basic definitions related to the subject of the dissertation, including, among others, extreme environments, space architecture, and ICE environments. Chapters four (4. Theory of Design in Space) and five (5. Architecture in Extreme Environments - Domains) are based on literature research and desk research that allow a theoretical reflection on the main elements, domains, and principles governing design in extreme and space architecture. These chapters aim to provide an understanding of the theoretical foundations of architectural functioning under conditions of isolation, environmental constraints, and limited resources. These considerations create the conceptual and methodological framework for the subsequent stages of the study. Chapter six (6. Empirical Experiences) summarises the key conclusions related to the author's experiences in activities connected with space architecture. These chapters constitute essential preparation for the next step, which is the case study analysis. Chapter seven (7. Case Study) contains an analysis of ten case studies of objects located in diverse extreme environments, including polar, desert, underwater, analog, and space environments. Chapter eight (8. Self-sufficiency - Analysis of Factors) presents the synthesised conclusions derived from the case studies and supported by architectural research. These conclusions include ARF factors, which were grouped and organi-

sed into a matrix in order to prepare the individual levels of the SSRF scale. The scale itself is presented in subsection 8.4, and its operation is pilot-tested in subsection 8.5. The concluding chapters include chapter nine (9. The Impact of the Self-Sufficiency Scale on Sustainable Development), which describes the relationship between these two issues, and chapter ten (10. Discussion), which provides a discussion of the undertaken topic and the obtained results. Chapter eleven (11. Conclusions) presents the overall conclusions of the doctoral dissertation, emphasising the significance of the research for the development of architectural theory and practice. Chapter twelve (12) summarises the achieved objectives of the dissertation with reference to the research questions and stated theses. Chapter thirteen (13) is the bibliography. At the end, there is attached the Annex with detailed heatmap analysis results from Chapter 8.

3. Definitions and Literature Review

In order to effectively address the issue of self-sufficiency, it is necessary to explain and characterise several key concepts related to architecture in extreme environments. Humanity has always inhabited environments that are more or less extreme; however, with the development of technology, increasing adaptation and mitigation of the negative effects of living in “hostile” conditions has become possible. Space environments are the most dangerous and extreme environments for human life and work. However, they are not the only ones humanity has encountered so far - today, polar stations, underwater stations, and highly isolated environments are also inhabited. In order to better understand design principles and strategies adopted in extreme environments, it is also important to examine the main assumptions underlying the development of the systematisation and classification of these issues.

3.1. Extreme Environments

In the literature, there are many definitions of *Extreme Environments (EE)* - and of the requirements that must be met for them to be classified as such. These definitions differ depending on the scientific discipline and the contexts in which they operate. For example, from the perspective of biological sciences, the broadest definition of extreme environments is presented by the authors in the *Encyclopedia of Astrobiology*⁴⁸, emphasising that an extreme environment is a living environment in which exceptionally difficult physicochemical conditions prevail for a given organism [Fig. 6]. These include, among others, very low or very high temperatures, extreme pH values, high pressure, high levels of radioactivity, or extreme salinity. These are conditions that are naturally considered highly unfavourable for most forms of life. Organisms capable of surviving and developing under such conditions are referred to as extremophiles⁴⁹ (extremus (Latin) - extreme, outermost; philos (Greek) - loving).

⁴⁸ Gómez, F. (2011). *Extreme Environment*. In *Encyclopedia of Astrobiology* (pp. 570-572). Springer. doi:10.1007/978-3-642-11274-4_566.

⁴⁹ Rothschild, L. J., & Mancinelli, R. L. (2001). *Life in extreme environments*. *Nature* 409.6823, 1092-1101. doi:10.1038/35059215,

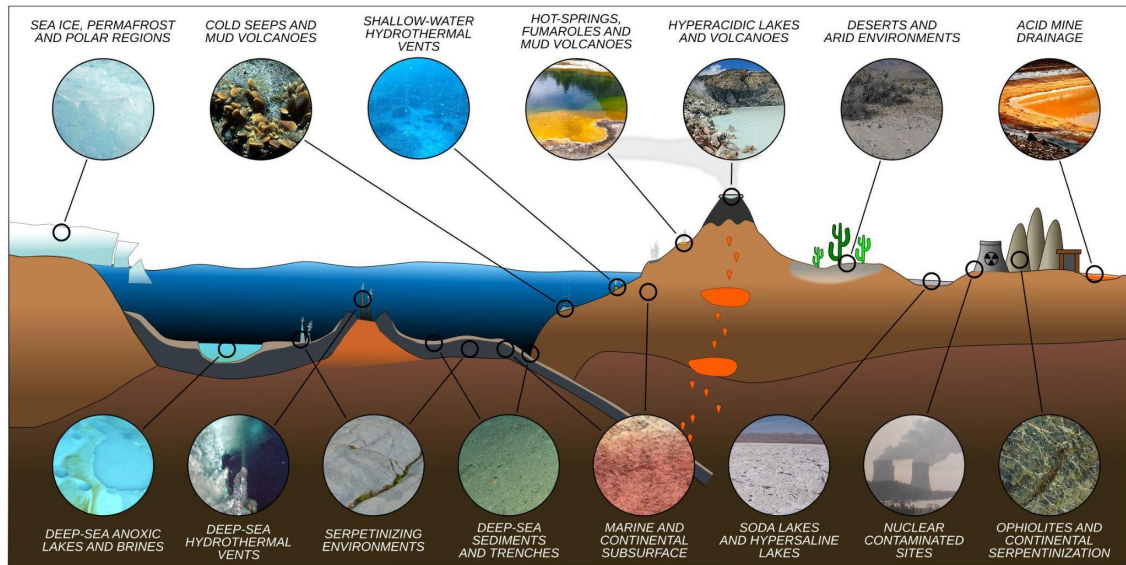


Fig. 6. Terrestrial extreme environments serving as natural niches for extremophile life (source: Merino et al., 2019).

Definitions that adopt an anthropocentric approach are also present taking into account psychosocial factors. Psychologists define extreme environments as spaces characterised by exceptional technological, social, and physical demands, which require humans to undergo significant adaptation in order to ensure effective functioning and interaction with the surrounding environment^{50,51,52}. Psychologist and researcher Peter Suedfeld points out that the term “extreme” refers to physical conditions that go significantly beyond the optimal range for human survival (although some groups may function in them), whereas “unusual” refers to environments that differ markedly from the familiar and accustomed living conditions of most, though not all, human communities. Some environments may be considered extreme and unusual only during periods of disturbance, such as natural disasters, industrial accidents, or wars. Many of them are also characterised by physical inaccessibility, great distance from known areas of human

⁵⁰ Barnett, J. S. & Kring, J. P. (2003). *Human Performance in Extreme Environments: A Preliminary Taxonomy of Shared Factors*. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, 47(8), 961-964. doi:10.1177/154193120304700802.

⁵¹ Manzey, D., & Lorenz, B. (1999, 4). *Human performance during prolonged space flight*. *Journal of Human Performance in Extreme Environments*, 123-127.

⁵² Morpew, M. E. (1999). *The Challenges of Long-Duration Spaceflight to Astronaut Safety, Performance, and Mission Success*. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, Volume 43, Issue 1. doi:10.1177/154193129904300112.

settlement, and a limited spatial extent⁵³. Although these definitions differ in scope and specification, they are connected by the possibility of characterising an environment or place as deviating from conditions that are optimal for functioning.

3.2. ICE (Isolated, Confined, and Extreme)

By further exploring the context of *Extreme Environments (EE)*, at the beginning of the 21st century, the term ICE was introduced into the literature as a result of increasing research on human functioning in extreme environments. ICE environments (Isolated, Confined, and Extreme) are understood as conditions in which people operate in isolation from the external world, within limited physical and psychosocial space, often under extreme environmental conditions that require a high level of adaptability and self-sufficiency. Examples of such environments include space habitats, polar stations, and submarines^{54,55}. Functioning in ICE environments (Isolated, Confined, and Extreme) is associated with a range of specific psychosocial challenges. Authors indicate that one of the main problems is isolation from society, close relationships, and familiar support structures, as well as the dependence of safety on technology⁵⁶. Long-term stay in isolation may lead to a deterioration of mental well-being, a sense of loneliness, and longing for everyday life routines⁵⁷.

⁵³ Suedfeld, P., & P. Mocellin, J. S. (1987). *The "Sensed Presence" in Unusual Environments. Environment and Behavior*, 19(1), 33-52.

⁵⁴ Suedfeld, P., & Steel, D. G. (2000). *The environmental psychology of capsule habitats. Annual Review of Psychology*, 51, 227-253. 10.1146/annurev.psych.51.1.227

⁵⁵ Golden, S. J., Chang, C., & Kozlowski, S. W.J. (2018). *Teams in isolated, confined, and extreme (ICE) environments. Journal of organisational Behavior*, 39(6). doi:10.1002/job.2288

⁵⁶ Suedfeld, P., & Palinkas, L. A. (2021). *Psychosocial issues in isolated and confined extreme environments. Neuroscience and Biobehavioural Reviews*, 126, 413-429. 10.1016/j.neubiorev.2021.03.032

⁵⁷ Suedfeld, P., & Palinkas, L. A. (2021). *Psychosocial issues in isolated and confined extreme environments. Neuroscience and Biobehavioural Reviews*, 126, 413-429. 10.1016/j.neubiorev.2021.03.032

3.3. Space Architecture

According to the definition used in the discipline:

“Space architecture is an interdisciplinary field concerned with the theory and practice of designing and constructing inhabited environments in outer space.”
(Team 11)⁵⁸.

Its formal foundations were defined in the Millennium Charter, created in 2002 by the group of Space Architects “Team 11”, signed by 43 representatives from 17 countries during the World Space Congress in Houston. The document defines the spatial specificity of extraterrestrial environments and emphasises that the key aspects of space architecture are motivation, interdisciplinary contribution, knowledge, and close cooperation with other disciplines⁵⁹. The manifesto addresses issues defined as categories of actions undertaken in the context of space architecture. They were formulated as a set of principles that take into account both human needs and design challenges in the extreme conditions of outer space. Namely:

- Sustainability, including the concepts of ecology, technology, economics, and social aspects;
- Human Interaction, divided into the categories: Human-Human, Human-Machine (product), Human-Universe (environment);
- The User;
- Human Factors;
- Social Aspects, emphasising that social life and interpersonal interactions are crucial, especially under conditions of isolation;
- Environmental Conditions - physical and environmental conditions that impose design constraints;

⁵⁸Team 11. (2002). *THE MILLENNIUM CHARTER*. spacearchitect.org. <https://spacearchitect.org/wp-content/uploads/2020/06/The-Millennium-Charter.pdf> (accessed: 04 February 2026).

⁵⁹ Bannova, O. (2021). *Space Architecture: Human Habitats Beyond Planet Earth*. DOM Publishers.

- Education, with an emphasis on multidisciplinary;
- Life Cycle;
- Humility; towards the hostile environment and scarce resources
- Benefits - of developing space architecture, postulating the inclusion of architects in the design of space facilities to achieve measurable improvements in the quality of designed spaces.

One of the co-creators of this theory is Marc Cohen, who in the article *The Continuum of Space Architecture: From Earth to Orbit* argues that space architecture should not be treated as a completely new field detached from terrestrial tradition, but rather as a natural extension of human responses to changing gravitational conditions ⁶⁰.

3.4. Analog habitats

In research on space architecture and preparation for crewed missions, so-called “analog” environments play an important role. These are natural locations on Earth that, in geological, climatic, biological, or operational terms, reflect selected characteristics of the environments of Mars, the Moon, or other celestial bodies. They constitute a platform that enables simulated missions, technology testing, geological research, and crew training under conditions that are difficult to reproduce in controlled settings. Such sites (e.g., Rio Tinto in Spain, the Atacama Desert in Chile, Svalbard and the McMurdo Dry Valleys in the Arctic, the Haughton Crater on Devon Island in Canada, or the volcanic fields of Iceland and Santorini) allow, among others, the study of exploration strategies, safety procedures, the use of tools and robots, sample verification technologies, and human behavior under challenging conditions⁶¹.

Analog terrains constitute natural environments that reproduce planetary characteristics, whereas analog habitats are purpose-designed research facilities created on Earth

⁶⁰ Cohen, M. (2012). *The Continuum of Space Architecture: From Earth to Orbit*. 42nd International Conference on Environmental Systems.

⁶¹ The Planetary and Space Sciences Research Institute, The Open University, UK. (n.d.). *Concepts for Activities in the Field for Exploration*. *Concepts for Activities in the Field for Exploration*. https://nebula.esa.int/sites/default/files/neb_study/1115/C4000104716ExS.pdf (accessed: 04 February 2026).

to simulate selected aspects of space missions, such as isolation, limited resources, extreme conditions, or life in a confined space. Their role is to provide a platform for testing life-support systems, validating technologies, training crews, and studying the psychological and social aspects of small-group functioning under stress. As researchers note, “analog” include a wide range of facilities, from polar stations and underwater laboratories to desert habitats, which enable research to be conducted on Earth⁶², instead of directly in the hard-to-access, expensive, and dangerous conditions of outer space. Analog habitats include a variety of forms and types of facilities that reflect selected aspects of space missions, depending on which environment or process they are intended to simulate⁶³. One group consists of isolation habitats, such as HI-SEAS in Hawaii, the Lunares Research Station in Poland, or HERA at the NASA Johnson Space Center [Fig. 7], designed to reproduce long-term isolation, limited space, and operational conditions characteristic of lunar and Martian missions. The second type includes underwater habitats, in which, as in the case of the Aquarius Reef Base used in NE-EMO missions, it is possible to test EVA (Extravehicular Activity) procedures, robotics, communication, and teamwork under conditions that partially simulate microgravity through neutral buoyancy in water. Another category consists of desert and volcanic habitats, such as the Mars Desert Research Station (MDRS) in Utah, used for geological, exploratory, and operational research, as well as for training in sample acquisition, rover testing, and the assessment of habitability in Mars-like environments.

A significant role is also played by polar habitats, including Concordia Station and F-MARS, which offer extreme isolation, low temperatures, harsh climate, and sensory monotony - factors that are crucial for research on human resilience and the durability of technical systems. Another group includes “laboratory” habitats, such as the BIOS-3 system in Russia or Biosphere 2 in Arizona, which enable research under fully controlled environmental conditions, including the analysis of closed resource cycles, atmospheric regeneration, food production, and crew functioning within hermetic systems.

⁶² Cromwell, R. L., Huff, J. L., Simonsen, L. C., & Patel, Z. S. (2021). *Earth-Based Research Analogs to Investigate Space-Based Health Risks*. *New Space*, 9(4). DOI: 10.1089/space.2020.0048

⁶³ Schlacht, I. L., Foing, B., Bannova, O., Blok, F., Mangeot, A., Nebergall, K., Ono, A., Schubert, D., & Kolodziejczyk, A. M. (2016). *Space Analog Survey: Review of Existing and New Proposal of Space Habitats with Earth Applications*. ICES-2016-367, 46th International Conference on Environmental Systems.



Fig. 7. NASA Human Exploration Research Analog (HERA) (source: NASA, n/d).

Analog habitats enable the investigation of habitability and human functioning. Researchers, in an analysis of 22 analog habitats and 8 research stations, demonstrated that such facilities provide key insights into the design and operation of future lunar and Martian bases, particularly in terms of resource management, reliability, and adaptability⁶⁴. Analog habitats can therefore be defined as terrestrial research testbeds that serve as a bridge between laboratory experiments and space missions.

3.5. Self-sufficiency

When attempting to find a definition of self-sufficiency in the literature, difficulties arise in formulating such a definition, as most publications in the architectural context focus almost exclusively on technological aspects related to the building. These definitions limit self-sufficiency primarily to:

- energy - its production and consumption (net-zero energy buildings)⁶⁵;

⁶⁴ Heinicke, C., & Arnhof, M. (2021). *A review of existing analog habitats and lessons for future lunar and Martian habitat*. REACH, Volumes 21-22. doi.org/10.1016/j.reach.2021.100038

⁶⁵ Hu, S., Zhou, X., Yan, D., Guo, F., Hong, T., & Jiang, Y. (2023). *A systematic review of building energy sufficiency towards energy and climate targets*. Building Technologies & Urban Systems Division Energy Technologies Area, Lawrence Berkeley National Laboratory. doi.org/10.1016/j.rser.2023.113316

- energy efficiency and emissions - CO₂ balancing and reduction of fossil fuel consumption⁶⁶;
- engineering system technologies - energy storage, HVAC optimisation, and passive systems⁶⁷;
- to a minor extent, water and material resources, usually treated as a supplement to the “net-zero” concepts”⁶⁸.

In this dissertation, a broader understanding of self-sufficiency is adopted, resulting from the analysis of the available literature and from design experience related to extra-terrestrial systems and habitats in extreme environments. This means that building self-sufficiency should not be perceived solely as the ability of the built environment system to function autonomously, but also as a concept that includes habitability, understood as the ability to ensure the quality of life of users under conditions of isolation and long-term stay (discussed in more detail in Chapter 5.4.1. Habitability).

Accordingly, self-sufficiency includes independence from external networks and the ability to operate under conditions of limited resources, crises, and changing needs, as well as factors related to human well-being. In the proposed understanding, self-sufficiency is therefore considered from a multidimensional perspective. It includes the pillars of sustainable development (environmental, economic, and social), the human factor related to psychophysical comfort and user health, closed-loop resource cycles (energy, water, air, waste, materials), as well as a life-cycle approach, which assumes the evaluation of solutions from the design phase, through construction and use, to the stage of dismantling and reuse of materials [Fig. 8]. Such an approach is closer to the concepts developed in space architecture, where self-sufficiency constitutes a sustaina-

⁶⁶ Gaspard, A., & et al. (2023). *Introducing sufficiency in the building sector in net-zero. Energy and Buildings*. doi.org/10.1016/j.enbuild.2022.112590

⁶⁷ Gagliano, A., Tina, G. M., & Aneli, S. (2025). *Improvement in Energy Self-Sufficiency in Residential Buildings Using Photovoltaic Thermal Plants, Heat Pumps, and Electrical and Thermal Storage. Energies, Research on Energy Efficiency and Energy Conservation: Current State and toward a Sustainable Future*, 18(5). doi.org/10.3390/en18051159

⁶⁸ Lopez, F. (2018). *Self-sufficiency in architectural and urban projects. Infrastructures in Practice*. doi:10.4324/9781351106177-7

ble development strategy, a condition for survival, and an integral part of designing human environments.

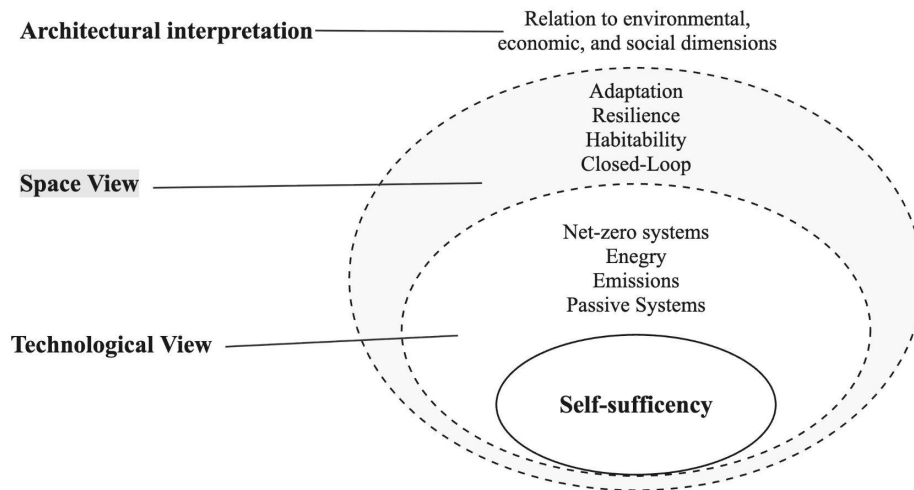


Fig. 8. Layered model of self-sufficiency adopted in the dissertation. The diagram presents self-sufficiency as a concept with a technological core, extended by elements derived from space architecture and extreme environment experience, and subsequently interpreted in the architectural context with reference to environmental, economic, and social dimensions (author's own elaboration 2026).

The concept of self-sufficiency adopted in this dissertation, therefore, refers to two principal groups of factors [Fig. 9]:

- Technological solutions, constituting a response to the challenges of the external environment, comprise specific solutions and strategies related to the following aspects:
 - Water, food, oxygen, and energy supply.
 - Shelter and safety provision.
 - Construction and logistics technologies, spatial solutions.

- Behavioral solutions responding to challenges of the internal environment, meaning the built and inhabited environment, including:
 - Interpersonal relations.
 - Organisation of life and space.
 - Psychological adaptation.
 - Environmental psychology.

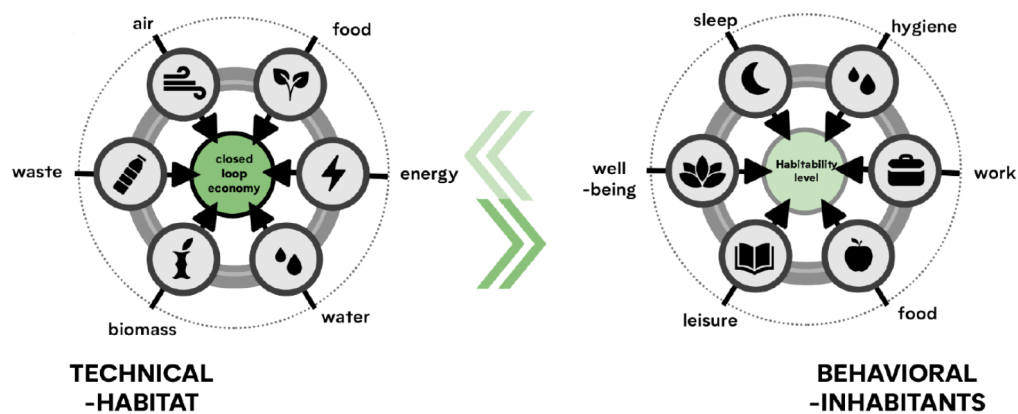


Fig. 9. Diagram illustrating the relationships between the technical self-sufficiency of a habitat and the level of habitability and user well-being within an integrated design process (author's own elaboration for research conducted at SICSA, Houston, 2025).

3.6. Readiness Levels Scales

To determine the level of technological maturity, *Technology Readiness Level* (TRL) indicators are used, along with their counterpart related to inhabited spaces - *Habitatation Readiness Level* (HRL). TRL is a nine-level scale developed by NASA in the 1970s, used to assess the maturity of a technology before its implementation in space missions [Fig. 10]. It defines whether a technology has been demonstrated in a laboratory, tested under conditions close to real use, or is fully ready for operation in outer

space⁶⁹. In contrast, HRL (Habitation Readiness Level) was developed as a counterpart to TRL, adapted to the assessment of habitability and the maturity of living environments [Fig. 11]. The HRL scale examines, among others, ergonomics, comfort, system integration, and psychological aspects of crew functioning, determining whether a habitat is ready for safe and long-term use⁷⁰.

Basic Technology Research	Level 1 : Basic principles observed and reported.
Research to Prove Feasibility	Level 2 : Technology concept and/or application formulated.
	Level 3 : Analytical and experimental critical function and/or characteristic proof of concept.
Technology Development	Level 4 : Component and/or breadboard validation in laboratory environment.
Technology Demonstration	Level 5 : Component and/or breadboard validation in relevant environment (ground or space).
	Level 6 : System/subsystem model or prototype demonstration in a relevant environment (ground or space).
System/Subsystem Development	Level 7 : System prototype demonstration in a space environment.
System Test, Launch and Operations	Level 8 : Actual system completed and “flight qualified” through test and demonstrations.
	Level 9 : Actual system “flight proven” through successful mission operations.

Fig. 10. Technology Readiness Levels (source: Connolly et al., 2006).

Habitation Systems Research	Level 1 : Human factors, crew systems, and life support research related to habitation systems
Conceptual and Functional Feasibility of the Technology	Level 2 : Habitation design and concepts, functional and task analysis
	Level 3 : Internal configuration functional definition and allocation, use of reduced scale models
	Level 4 : Full-scale, low-fidelity mockup evaluations
Demonstration of the Technology	Level 5 : Full-scale, high-fidelity mockups, human testing and occupancy evaluations
	Level 6 : Habitat and deployment field testing
Testing of the Technology and Technology Operations	Level 7 : Pressurized habitat prototype testing
	Level 8 : Actual systems completed and “flight qualified” through test and demonstration
	Level 9 : Actual system “flight proven” through successful mission operations

Fig.11. Habitation Readiness Levels (source: Connolly et al., 2006).

⁶⁹ NASA -TRL. (n.d.). *Technology Readiness Levels (TRLs)*. <https://esto.nasa.gov/trl/> (accessed: 04 February 2026).

⁷⁰ Connolly, J., Daues, K., Howard, Jr., R. L., & Touns, L. (2006). *Definition and Development of Habitation Readiness Level (HRLs) for Planetary Surface Habitats*. *Earth & Space 2006: Engineering, Construction, and Operations in Challenging Environment*. doi:10.1061/40830(188)81

Another scale derived from the concepts presented above is the *System Readiness Level* (SRL), proposed by Sauser and co-authors as an extension of TRL⁷¹, intended to assess the readiness of an entire system, the degree of its integration, and mutual compatibility. It examines whether system components are able to function together in a stable, predictable manner and in accordance with operational requirements. A nine-level Innovation Readiness Level (IRL) scale proposed by Smith is also used⁷², which likewise constitutes a parallel to TRL, but relates to the readiness of an innovation to enter the market, rather than referring exclusively to technology or space. This model classifies successive stages of development, from an unformed concept (IRL 1), through the development of a coherent business plan (IRL 5) and the preparation of an investor-oriented narrative enabling the acquisition of funding (IRL 7), to full commercial readiness (IRL 9). IRL extends the assessment process to include elements related to business model development and planning the operational implementation of technology. Another scale, the *Societal Readiness Level* (SRL), was developed by Innovation Fund Denmark to assess the degree to which society is prepared to adopt and use a new technology or innovation⁷³. Its successive levels cover a process ranging from the initial identification of social problems and needs, through the identification of key stakeholders, consultation and verification, to the development of a solution concept that incorporates user feedback. Higher levels of the scale concern testing and validation of the innovation under real-world conditions, assessment of its acceptability, preparation of an implementation strategy, and communication activities supporting adoption. The highest SRL level refers to full social acceptance, meaning that the solution has been adopted, understood, and recognised as valuable by the community for which it was created. The literature also includes examples of multi-dimensional “readiness” scales that go beyond classical technological scales. Holden proposes a model developed in the context of a sustainable circular bioeconomy, combining indicators of technological

⁷¹ Sauser, B., Verma, D., Ramirez-Marquez, J., & Gove, R. (2006). *From TRL to SRL: The Concept of Systems Readiness Levels*. *Conference on Systems Engineering Research*.

⁷² Smith, S. W. (2017). *Innovation Readiness Level*. <https://blog.theentrepreneursadvisor.com/2017/10/innovation-readiness-level/> (accessed: 04 February 2026).

⁷³ Innovation Fund Denmark. (2018). *Societal Readiness Levels (SRL) defined according to Innovation Fund Denmark*. <https://innovationsfonden.dk/en/about-innovation-fund-denmark> (accessed: 04 February 2026).

readiness (TRL), innovation readiness (IRL), and societal readiness (SRL)⁷⁴ [Fig. 12]. The author assumes that the development of new biological and bioeconomic solutions requires the parallel consideration of technical, operational, and social premises, and that their levels of maturity should be analysed in relation to one another.

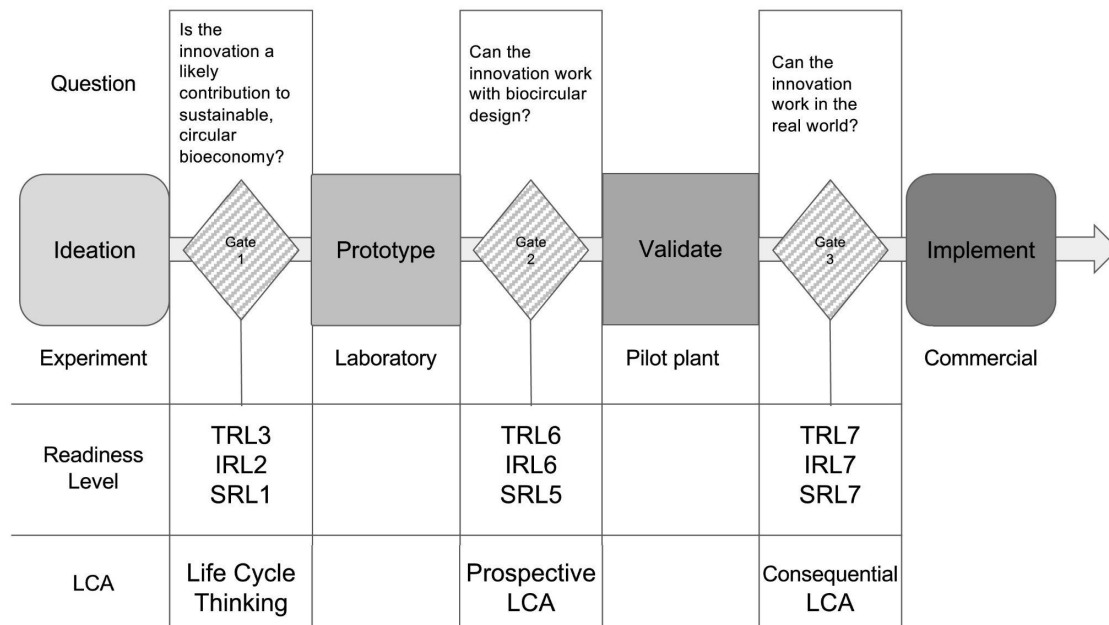


Fig. 12. Stage-gate approach in the circular economy model, in which individual stages correspond to achieving specific levels of the TRL, IRL, and SRL scales (source: Holden, 2022).

The Holden model uses a stage-gate approach and emphasises the importance of the technology life cycle and its operation within a circular economy framework.

4. Theory of Design in Space

Extreme architecture encompasses diverse environments in which human functioning requires the creation of a controlled, artificially sustained life-support system. It aims to ensure safety, stable environmental conditions, and the possibility of long-term habitation and research activities in situations where natural conditions prevent survival without advanced support. Beyond outer space, such hazardous conditions also occur on

⁷⁴ Holden, N. M. (2022). *A readiness level framework for sustainable circular bioeconomy*. *EFB Bioeconomy Journal*, Volume 2.

Earth, for example, in zones characterised by extreme temperatures, pressure, isolation, or limited resources, where the absence of atmosphere and gravity requires fully hermetic and autonomous architectural solutions. For this dissertation, an original classification of types of extreme architecture was developed and is presented in the diagram below [Fig. 13].

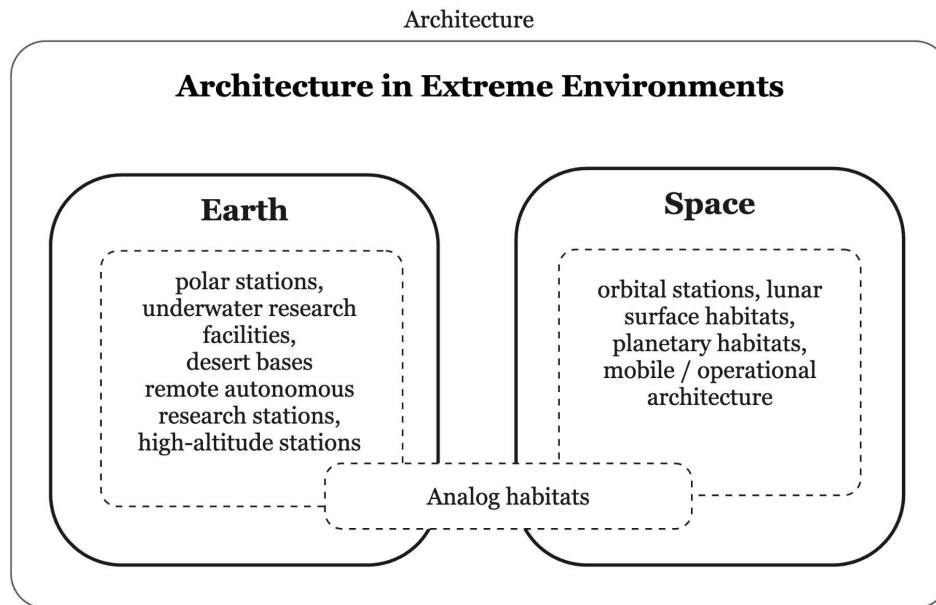


Fig. 13. Classification of environments and types of extreme architecture, including facilities operating on Earth, in outer space, and analog habitats as an element linking both research domains (adapted from: Dziadula & Fross, 2022).

The diagram illustrates the division of terrestrial and extraterrestrial extreme environments with examples, highlighting the particular role of analog habitats as an intermediate link “between” research conducted on Earth and experiments carried out in outer space. Within the broader field of architecture, extreme environment architecture constitutes a distinct domain, comprising both terrestrial and space architecture as its parts.

4.1. Domains - Principles of Design in Extreme Environments

The literature presents a consistent view that designing in extreme environments requires an integrated interdisciplinary approach, in which architecture serves as a bridge

between engineering, biology, and human psychology^{75,76,77,78}. As indicated by Peder Anker, space architecture develops a new paradigm and a new way of thinking about ecological design⁷⁹. As the author notes, the development of space architecture ideas during the Cold War period had a significant influence on the shaping of ecological design and the concept of self-sufficient life-support systems. Theories developed for long-duration space missions-particularly those related to ecology, energy, and waste-became an inspiration for environmental designers and architects in the 1970s. As Anker points out, the model of astronauts' life within an artificial ecosystem was interpreted as a metaphor for a sustainable relationship between humans and nature. These concepts, later transferred to terrestrial architecture, found reflection both in experimental projects such as Biosphere 2 in Arizona (discussed in more detail in Chapter 5.2) and in visions of future environments, such as Spaceship Earth at Epcot Center. Anker emphasises that the idea of life within a self-sufficient microsystem represented a key turning point in thinking about the relationship between humans, technology, and the environment.

In the literature on space habitat design, it is emphasised that in the early stages of space architecture development, the role of the architect was marginalised, and design decisions were made almost exclusively by engineers focused on efficiency and reliability. As noted by Sheryl Bishop, this resulted from a different perception of priorities. Humans (the so-called human factor) were considered an *unpredictable factor disrupting design optimality*⁸⁰. From a technical perspective, elements ensuring well-being and psychological comfort, as well as supporting familiar spatial orientation, were considered “unnecessary,” because space in microgravity can be used fully three-dimensionally, without maintaining a reference system known from Earth. This approach was

⁷⁵ Bannova, O. (2021). *Space Architecture: Human Habitats Beyond Planet Earth*. DOM Publishers.

⁷⁶ De Monchaux, N. (2011). *Spacesuit: Fashioning Apollo*. MIT Press.

⁷⁷ Zubrin, R., & Wagner, R. (2011). *The Case for Mars: The Plan to Settle the Red Planet and Why We Must*. Free Press.

⁷⁸ Häuplik-Meusburger, S., & Bishop, S. (2021). *Space Habitats and Habitability: Designing for Isolated and Confined Environments on Earth and in Space*. Springer International Publishing.

⁷⁹ Anker, P. (2010). *From Bauhaus to Ecohouse: A History of Ecological Design*. LSU Press.

⁸⁰ Häuplik-Meusburger, S., & Bishop, S. (2021). *Space Habitats and Habitability: Designing for Isolated and Confined Environments on Earth and in Space*. Springer International Publishing.

particularly evident when projects with a short temporal scope were considered, that is, missions in which humans were expected to adapt to the prevailing “dehumanised” conditions. For many years, this constituted a reason why architects and designers were not invited to teams designing habitats and crewed spacecraft. Their postulates concerning colour, aesthetics, vegetation, or environmental quality were perceived as potentially complicating the system, costly, and non-optimal-therefore unnecessary. Only over time, with the development of research on habitability and the psychology of confined spaces (Chapter 5.4), as well as with the increasing duration of missions, did it become understood that these “non-optimal” aspects are in fact critical for crew safety, well-being, and productivity. Gradually, studies on long-term isolation, the human factor, and psychology became one of the main arguments supporting the necessity of including designers, architects, and design professionals in interdisciplinary teams responsible for the design of space environments.

What, then, does the design process in space look like? Design principles in extreme conditions differ from conventional architectural processes due to distinct environmental conditions, technological constraints, and the psychophysical needs of users. The main difference is that extreme architecture involves issues related to survival and the need to account for elements such as life-support systems, limited resources, and conditions of isolation and microgravity (depending on the characteristics of the environment-each described in detail in Chapters 7 and 5.3). These conditions, among others, necessitate the use of advanced autonomous and technological solutions. From the perspective of the traditional design process, as noted by E. Niezabitowska (2018), design constitutes a dynamic structure encompassing stages of analysis, concept development, verification, and use, in which feedback between the designer, the user, and the environment plays a key role⁸¹. Similarly, the design process of space architecture is inherently iterative, non-linear, and interdisciplinarily integrated. As described by the authors of *Space Architecture Education for Engineers and Architects. Designing and Planning Beyond Earth*, design cycles “evolve through time and levels of development”⁸² and at

⁸¹ Niezabitowska, E. (2018). *Research Methods and Techniques in Architecture*. Routledge

⁸² Häuplik-Meusburger, S., & Bannova, O. (2016). *Space Architecture Education for Engineers and Architects: Designing and Planning Beyond Earth*. Springer International Publishing, p. 15

each stage with “increasing levels of detail at each sweep”⁸³. In this model, referred to as a cyclical or spiral design process, “in which the designer or the design organization iterates a sequence of conception, representation, and evaluation until arriving at a satisfactory solution”⁸⁴ [Fig. 14].

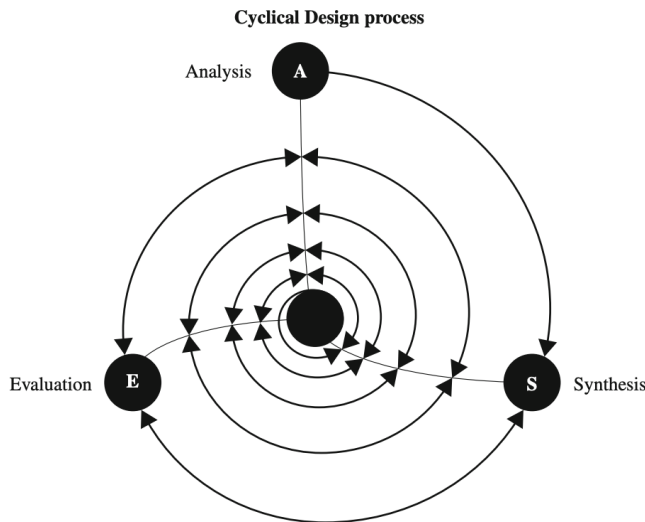


Fig. 14. Cyclical design process (source: Häuplik-Meusburger & Bannova, 2016).

If the design process itself is based on similar principles (iteration, feedback, and interdisciplinarity) then to fully understand the principles of designing in extreme environments, it is necessary to explain how the individual elements of the process are understood. The following overview is based on the previously cited model by E. Niezabitowska (2018)⁸⁵, where the “traditional” design process is presented in the diagram [Fig. 15], and references to the individual elements are summarised below in the table [Table 2].

⁸³ Häuplik-Meusburger, S., & Bannova, O. (2016). *Space Architecture Education for Engineers and Architects: Designing and Planning Beyond Earth*. Springer International Publishing. p.15

⁸⁴ Cohen, Marc M. (1996). *Mars mission design evaluation criteria*. In: *Proceedings of the 26th International Conference on Environmental Systems*, Monterey, California, SAE 961467. p. 2.

⁸⁵ Niezabitowska, E. (2018). *Research Methods and Techniques in Architecture*. Routledge

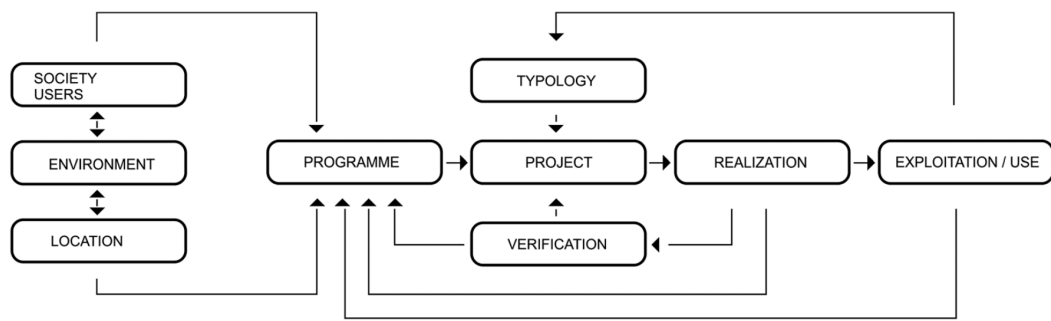


Fig. 15. Traditional design process according to E. Niezabitowska (2018).

Table 2. Characteristics of design process factors in space and extreme architecture and their impact on design solutions, with reference to elements of the “traditional” design process according to E. Niezabitowska (2018).

Process Element	In space: Characteristics	In space: Impact on design decisions
1. Society and users	Small, interdisciplinary groups in isolation; strong influence of psychological factors (stress, monotony, lack of privacy).	Design with consideration of environmental psychology in conditions of isolation.
2. Environment	Extreme conditions (e.g., lack of atmosphere, radiation, extreme temperatures, lack of resources).	Design with consideration of extreme external conditions.
3. Location	Extreme environments, analog habitats; limited access to energy, communication, and resources.	Design with consideration of environmental remoteness and its impact on transport and construction technologies.
4. Programme	Functions residential, research, medical, and recreational functions; integration with life-support systems.	Design with consideration of strict adaptation of functions to the program.

Process Element	In space: Characteristics	In space: Impact on design decisions
5. Typology	Depending on the external environment and the program.	Selection of a typology adapted to environmental conditions and available technologies.
6. Verification	Limited, costly, and hazardous.	Testing in analog habitats and mock-ups, enhanced safety procedures, and computer simulations.
7. Realisation	Limited by the scale of environmental conditions.	Design with consideration of the selection of appropriate construction technologies.
8. Project	Interdisciplinary approach: architecture + engineering + biology + psychology.	Necessity of integrating technical and human-centered systems.
9. Use	Continuous use; limited maintenance and repair possibilities, impact on safety.	Consideration of system autonomy and reliability, as well as the life cycle of the facility.

As shown in the table, the differences in the design, implementation, and use of facilities between terrestrial environments and space, as well as other extreme environments, result primarily from differing environmental and operational conditions, rather than from the distinctiveness of the design process itself.

4.2. Design Theory - Domains

In the course of work on this dissertation, the analysis of theoretical issues in space and extreme architecture made it possible to identify an original set of key design domains (fields, areas) that define the main areas of challenges in the context of creating extreme architecture, forming a framework for the theory of design in extreme environ-

ments. These include: Interdisciplinarity and Participation, Testing and Iteration, Resource Limitation, and Adaptation and Survival [Fig. 16].

- **Interdisciplinarity and Participation** are understood as the fact that designing in extreme environments requires cooperation among specialists from multiple fields and the active involvement of future users in the creative process.
- **Testing and Iteration** are components of the design process, as the design process is cyclical and based on repeated verification of concepts through simulations, experiments, and user studies. Each iteration leads to project refinement and increases its resilience to errors and changing environmental conditions.
- **Resource Limitation** as an architecture under conditions of isolation and limited access to resources requires the development of self-sufficient and energy-efficient systems. Design, therefore, involves minimising material consumption, implementing closed-loop resource cycles, and maximising the use of local potentials.
- **Adaptation and Survival**, as space must support human physical and psychological resilience, enabling functioning in extreme conditions. Design focuses on ensuring comfort, safety, and quality of life within a confined environment.

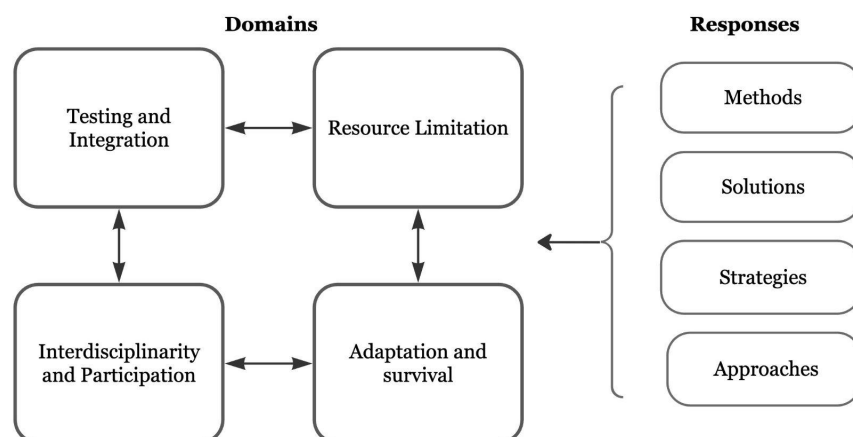


Fig. 16. Domains of design in extreme environments (author's own elaboration, 2026).

These domains form a system of mutual interdependencies, as each of them influences the others, generating a dynamic design process repeatedly emphasised in the literature. Their presence and characteristics affect design decisions, as well as the selection of appropriate methods, strategies, and approaches.

5. Architecture in Extreme Environments - Domains

The identification of individual domains made it possible to conduct a targeted literature review through systematic searches for references corresponding to the specific research problems of each domain. This allowed the source material to be organised and precisely assigned to the analysed areas. In the following subsections, these domains serve as a reference framework for analysis in the context of the role of architecture as a tool within the respective problem areas.

5.1. The Role of Architecture as a Tool for Interdisciplinarity and Participation

Based on the previously cited publication *Space Architecture Education for Engineers and Architects: Designing and Planning Beyond Earth*⁸⁶, prepared by experts and practitioners involved in the design of space environments it is possible to identify key responses to the challenges of interdisciplinarity in the design of space architecture. Models such as the spiral design process, the multi-linear design process, or the expanded waterfall enable parallel work of multiple disciplines from the earliest phases of a project. This reduces disciplinary isolation, lowers the risk of errors resulting from a lack of information, and creates natural feedback points between teams. Brand N. Griffin, a long-time NASA architect associated with Lockheed Martin Space Operations and later Jacobs Engineering, participated for decades in the design and integration of habitats within programs such as the International Space Station. In his guest statement published in the above-mentioned book, Griffin describes the design of space architecture as a process of high complexity, in which multiple disciplines, objectives, and levels of organisation interact. He argues that “*iteration or revisiting the same question multiple times is vital to integration for reasons of process efficiency and flexibility*”⁸⁷ adding that “*space architects include these revisits in the process to avoid getting stalled, lo-*

⁸⁶ Häuplik-Meusburger, S., & Bannova, O. (2016). *Space Architecture Education for Engineers and Architects: Designing and Planning Beyond Earth*. Springer International Publishing.

⁸⁷ Häuplik-Meusburger, S., & Bannova, O. (2016). *Space Architecture Education for Engineers and Architects: Designing and Planning Beyond Earth*. Springer International Publishing, p. 152

ing balance, and getting locked into poor solutions”⁸⁸. He points out that, unlike traditional linear models, design integration is an iterative and unpredictable process. Griffin emphasises that, in the space context, the architect assumes the role of a mediator who must combine engineering logic with design intuition and coordinate collaboration among different technical teams.

Thus, another important aspect is the inclusion of the architect in the role of a systems integrator, which represents a new, expanded definition of professional competence. The space architect is described as a person who is able to simultaneously understand user needs, possess a foundational knowledge of systems engineering, conduct negotiations between teams, and integrate different perspectives into a coherent whole. Such a role enables the mitigation of conflicts between disciplines and skilful balancing between technological and psychological requirements. Marc Cohen points to the importance of participatory design research as an alternative to classical, hierarchical engineering methods⁸⁹. In this approach, “*design as a research process to develop requirements and criteria*” and it leads to “*explicit decision-making that considers all the relevant information, not just conveniently compartmentalized information*”⁹⁰. Designing in outer space, therefore, consists of adapting technology to humans, as well as actively co-creating solutions with users, taking their experience into account. This thesis on the need to include users in the design process is also confirmed by research conducted by Ilaria Schlacht in her doctoral dissertation *SPACE HABITABILITY. Integrating Human Factors into the Design Process to Enhance Habitability in Long Duration Missions*⁹¹. The author, analysing differences in perception between astronauts and employees of the space sector “on Earth”, demonstrated that the priorities of users of isolated environments significantly differ from the assumptions of designers and engineers. In the survey study, 5 out of 6 astronauts indicated privacy as a key need, while the majority of “ground-based” employees (8 out of 13) preferred the concept of open space. These

⁸⁸ Häuplik-Meusburger, S., & Bannova, O. (2016). *Space Architecture Education for Engineers and Architects: Designing and Planning Beyond Earth*. Springer International Publishing, p. 152

⁸⁹ Cohen, M. (1990). *A Participatory Planning Alternative for Mars Mission Design*. REV. 3/12/93, p. 9

⁹⁰ Cohen, M. (1990). *A Participatory Planning Alternative for Mars Mission Design*. REV. 3/12/93, p. 9

⁹¹ Schlacht, I. L. (2012). *SPACE HABITABILITY Integrating Human Factors into the Design Process to Enhance Habitability in Long Duration Missions*. PhD Dissertation - Technische Universität Berlin.

results revealed a clear gap between the pragmatic approach and the user approach, resulting from personal experience. In summary, as indicated in official NASA documents^{92,93}, the process of designing space architecture is a combination of human sciences, systems engineering, and architecture in an iterative cycle of research, design, testing, and implementation.

The third solution, indicated as a condition for effective interdisciplinary cooperation, is multidisciplinary education. Häuplik-Meusburger and Bannova emphasise the necessity of developing educational programs that prepare designers to work in environments requiring knowledge at the intersection of architecture, engineering, ergonomics, space medicine, and psychology⁹⁴. They also indicate the importance of cooperation with industry and learning based on projects carried out in direct contact with practitioners and space institutions.

The fourth element is the use of visual tools as a common language between disciplines. 3D models, technical drawings, visualisations, virtual reality, and mock-ups become translation tools enabling communication between teams with different nomenclature and working methods - this scope also directly relates to the next domain, Testing and Integration. From the perspective of interdisciplinarity, inclusion of modern visual technologies in the design process reduces communication barriers, allows faster identification of inconsistencies between assumptions, and at the same time facilitates joint design decision-making.

5.2. The Role of Architecture as a Tool for Testing and Integration

Designing space architecture develops in conditions in which humans can survive only thanks to technology, inside a specially designed structure, vehicle, life support system, or spacesuit. In this field, a common saying appears that life in space is life inside a machine. Extreme environments require the creation of solutions that are reliable, ergo-

⁹² NASA. (1995). *Man-Systems Integration Standards (NASA-STD-3000, Volume I)*. NASA Johnson Space Center, Houston, TX.

⁹³ NASA. (2014). *HUMAN INTEGRATION DESIGN HANDBOOK (HIDH) (NASA/SP-2010-3407/REV1 ed.)*. NASA - National Aeronautics and Space Administration.

⁹⁴ Häuplik-Meusburger, S., & Bannova, O. (2016). *Space Architecture Education for Engineers and Architects: Designing and Planning Beyond Earth*. Springer International Publishing.

nomie, and repeatedly tested, because the smallest design error can lead to serious risk to health or life. NASA defines this risk as “*risk of incompatible vehicle or habitat design*”, emphasising that incorrect solutions may become one of the most serious factors of mission failure⁹⁵. In response to this challenge, an extensive system of tests and simulations has been developed, including both technological research and psychological studies on human functioning in isolation (conducted since the 1970s, among others in pressure chambers and research habitats in Houston)⁹⁶, as well as physical testing of infrastructure elements in conditions similar to those present in outer space. As Marc Cohen notes, “*access to space is so difficult, dangerous, and expensive, the disciplines of engineering, operations, and space architecture attempt to simulate every aspect of space habitats that they can before finalizing the design*”⁹⁷. Testing on Earth, where consequences are significantly smaller, has become the foundation of the design process - for example, through analog environments and analog habitats.

5.2.1. Analog Environments

The first concepts of analog research environments appeared parallel to the development of space exploration in the 1960s. Before specialised habitats simulating space missions were created, scientists used existing extreme environments on Earth as natural laboratories to test technologies and procedures. Already in this period, significant similarities between human functioning in deep underwater conditions and life in outer space began to be recognised. Both environments are characterised by isolation, limited mobility, high technological requirements, and the necessity of constant control of life support systems. Therefore, underwater mission projects became an important reference point in the search for methods of simulating stays in outer space for NASA.

⁹⁵ NASA. (2016). *Risk of Performance Errors Due to Training Deficiencies* [Evidence Report, Human Research Program Space Human Factors and Habitability Element]. NASA <https://humanresearchroadmap.nasa.gov/Evidence/reports/TRAIN.pdf> (accessed: 04 February 2026).

⁹⁶ Häuplik-Meusburger, S., & Bishop, S. (2021). *Space Habitats and Habitability: Designing for Isolated and Confined Environments on Earth and in Space*. Springer International Publishing.

⁹⁷ Cohen, M. (2012). *Code and Standard Research for Space Habitat Analogues AIAA SPACE 2012 Conference & Exposition*. p.1.

One of the first examples of this approach was the Ben Franklin mission in 1969, led by Jacques Piccard⁹⁸. Although it was formally an oceanographic expedition, its scientific value for future space missions proved significant. The environment of extreme underwater isolation and the weeks-long cooperation of a six-person crew created conditions enabling analysis of group functioning in a situation comparable to early crewed space-flight projects. In this context, an engineer representing NASA participated in Piccard's expedition, whose task was to conduct observations related to the psychological effects of long-term isolation. As a result, the first underwater expeditions became precursors of contemporary scientific analog habitats, proving that extreme terrestrial environments can effectively support research preparing for crewed missions in outer space. That experiences have formed foundations of the later "analog missions" approach.

Currently, one of the key environments used in astronaut training is the *Neutral Buoyancy Laboratory (NBL)* operated by NASA⁹⁹. It is the largest training pool in the world, where conditions similar to work in microgravity are recreated through neutral buoyancy. In the NBL, astronauts train EVA (Extravehicular Activities) procedures, learn movement in spacesuits, and test basic operational sequences in a safe, controlled environment¹⁰⁰.

Other advanced simulation tools are analog habitats and full-scale mock-ups. These are research facilities that replicate the operational conditions of a space mission¹⁰¹. The term analog habitat in English means "equivalent habitat" or "analogous" and refers to a facility replicating the functions of a planned station, not to "analog habitats" in the common, technical understanding of the word "analog" meaning manual. In these envi-

⁹⁸ NASA, Ferguson, M. J., & May, C. B. (1970). *USE OF THE BEN FRANKLIN SUBMERSIBLE AS A SPACE STATION ANALOG*. National Aeronautics and Space Administration https://seawifs.gsfc.nasa.gov/FRANKLIN/DOCS/BEN_FRANKLIN_SPACE_STATION_ANALOG.VOLUME.1.reduced.pdf (accessed: 04 February 2026).

⁹⁹ NASA (n.d.) *Neutral Buoyancy Laboratory*. <https://www.nasa.gov/johnson/neutral-buoyancy-laboratory/> (accessed: 04 February 2026)

¹⁰⁰ Jairala, J., Durkin, R., Marak, R., Prince, A., Sipila, S., Ney, Z., Parazynski, S., & Thomason, A. (2012). *Extravehicular Activity Development and Verification Testing at NASA's Neutral Buoyancy Laboratory*. *42nd International Conference on Environmental Systems*. doi.org/10.2514/6.2012-3592

¹⁰¹ Heinicke, C., & Arnhof, M. (2021). *A review of existing analog habitats and lessons for future lunar and Martian habitat*. *REACH*, Volumes 21-22. doi.org/10.1016/j.reach.2021.100038

ronments, tests of technologies of the life support systems, psychological studies, operational scenarios, and simulated crew missions are conducted^{102, 103}.

Analog research environments allow testing of technology and solutions in a broad perspective, like:

- relations between space, technology, and the user are examined;
- human behaviour during long-term isolation is evaluated;
- ergonomics, operational procedures, and system integration are tested;
- emergency scenarios are validated.

One of the largest experiments related to the creation of closed, self-sufficient ecosystems was the *Biosphere 2* project implemented in Arizona (USA). The complex was established in the early 1990s as a continuation of earlier research on closed-loop systems. Biosphere 2 was designed as a multi-scale model of a complex ecosystem, including seven biomes: rainforest, ocean with a coral reef, wetlands, savanna, desert, and two anthropogenic biomes: an agricultural zone and a residential-laboratory section¹⁰⁴ [see: Fig. 17 and 18]. The total area of the facility and its biological diversity made it one of the most ambitious undertakings in the history of research on self-sufficiency^{105, 106}.

¹⁰² Schlacht, I., Foing, B., Bannova, O., Blok, F., Mangeot, A., Nebergall, K., Ono, A., & Schubert, D. (2016). *Existing and new proposals of Space analog, off-grid and sustainable habitats with Space applications*. 46th International Conference on Environmental Systems.

¹⁰³ De la Torre, G. G., Groemer, G., Diaz-Artiles, A., & ., e. a. (2024). *Space Analogs and behavioural Health Performance Research review and recommendations checklist from ESA Topical Team*. npj | microgravity, 10 (98). doi.org/10.1038/s41526-024-00437-w

¹⁰⁴ Biosphere 2. (n.d.). *Biosphere 2*. <https://biosphere2.org/> (accessed: 04 February 2026).

¹⁰⁵ Marino, B. D.V., & Odum, H.T. (1999). *Biosphere 2: Introduction and research progress*. *Ecological Engineering* 13.

¹⁰⁶ Walter, A., & Lambrecht, S. C. (2004). *Biosphere 2 Center as a unique tool for environmental studies*. *Journal of Environmental Monitoring*, Issue 4. doi.org/10.1039/B315788A.

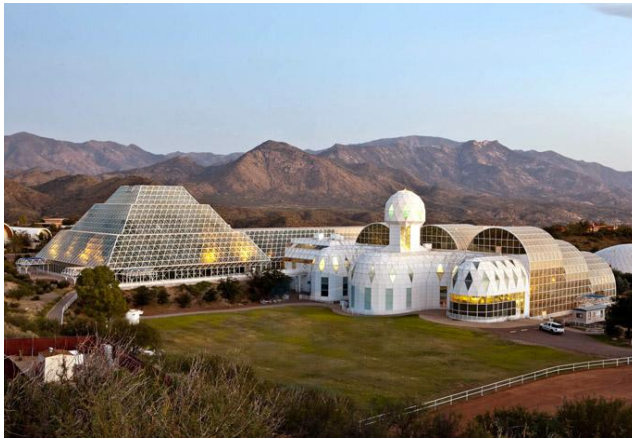


Fig. 17. Biosphere 2 research facility (source: Biosphere 2, n.d.).

Fig. 18. Biosphere 2, interior showing the savanna and ocean ecosystems (source: Rogers, 2025).

During the first Biosphere 2 mission, an eight-person crew remained in complete isolation for two years. Despite its level of advancement and scale, the experiment revealed numerous problems, including decreases in oxygen levels, difficulties in maintaining food production, and destabilisation of plant and animal populations. Significant psychosocial challenges also occurred, resulting from long-term isolation and intensive interdependence of crew members. The second mission, shorter in duration, allowed full resource self-sufficiency to be achieved and provided valuable data on the functioning of closed ecosystems, biome dynamics, and the design of multi-component diets under conditions of limited resources¹⁰⁷. Biosphere 2 remains one of the key projects in research on autonomous systems and models of future space habitats and extreme environments on Earth.

5.2.2. New technologies

Building and functioning of analog environments as testing facilities requires high organisational and financial resources; therefore, an important element of this process is also digital simulations and virtual environments (VR/AR), which enable testing of

¹⁰⁷ Marino, B. D.V., & Odum, H.T. (1999). *Biosphere 2: Introduction and research progress. Ecological Engineering* 13.

spaces requiring high costs or infrastructure that is impossible or expensive to physically construct^{108,109}. Virtual environments allow, among others:

- testing of ergonomics, scale, and functional layouts,
- verification of interfaces and operational processes,
- analysis of spatial orientation and perception,
- rapid iteration of design solutions before construction of mock-ups.

For example, at SISCA, at the University of Houston, a virtual and mixed reality laboratory operates where it is possible to test space-based projects, with an additional immersion element provided by a microgravity simulation system using a special suspended structure¹¹⁰. Importantly, solutions tested in this “terrestrial phase of space” - in habitats or mock-ups - have the potential for transfer both toward space (spin-out) and to Earth (spin-off), already finding applications in self-sufficient buildings, emergency response systems, infrastructure for extreme environments, and low environmental impact projects¹¹¹.

5.3. The Role of Architecture as a Tool for Resource Limitations

In environments with limited resources, architecture extends beyond functioning as a passive shelter. The structure becomes an active element of a larger life support system, responding both to pressure from the external environment and to processes occurring inside the habitat. Unlike terrestrial architecture, functioning in a stable climate and usually with constant access to infrastructure, architecture in conditions of isolation and limited resources must operate continuously and, to a large extent, be resource self-suf-

¹⁰⁸ Basu, T., Bannova, O., & Camba, J. D. (2021). *Mixed reality architecture in space habitats*. *Acta Astronautica*, Volume 178,, 548-555.

¹⁰⁹ Imhof, B., Nelson, J., Kumar Madakashira, H., Aabloo, A., Weiss, P., & Ševčík, D. (2016). *SHEE - a Self-deployable Habitat for Extreme Environments Exploitation and lessons learnt from testing*. *46th International Conference on Environmental Systems*.

¹¹⁰ University of Houston. (2023). *Mixed Reality Raising the Bar for Space Architecture on the Moon and Mars*. *VR Laboratory at SICSA*. <https://stories.uh.edu/2023-space-mixed-reality/index.html> (accessed: 04 February 2026).

¹¹¹ Schlacht, I., Foing, B., Bannova, O., Blok, F., Mangeot, A., Nebergall, K., Ono, A., & Schubert, D. (2016). *Existing and new proposals of Space analog, off-grid and sustainable habitats with Space applications*. *46th International Conference on Environmental Systems*.

ficient. Therefore, form, organisation, technologies, and materials do not result only from user needs, but also from the character of the location in which a given structure is intended to operate. Extreme environments, such as regions of lunar polar craters containing ice in permanently shadowed areas¹¹², Mars with ISRU potential¹¹³ or extreme terrestrial analogues, create their own sets of limitations but also possibilities. Environmental context is, therefore, one of the design factors in extremes. Also, in extreme conditions, the interior of habitats is primarily a controlled environmental system in which air, water, energy, and food circulate in closed or semi-closed loops. The structure is intended to enable and support this circulation, based on recirculation technologies, in-situ systems, energy recovery, or bioregenerative processes, such as oxygen and biomass production by microalgae. Importantly, humans are an integral element of the metabolic chain, which is confirmed by the conclusions of the MELiSSA program of the European Space Agency¹¹⁴.

Finally, architecture performs the function of an interface between humans and technological systems. In isolated environments, the user's ability to understand and operate processes related to resources becomes a condition of safety¹¹⁵. Spatial layout influences the clarity of interfaces, distribution of sensors, workflows, the possibility of human error, and environmental intuitiveness. These aspects are key elements in human functioning under conditions of fatigue, disorientation, or simply poor physical condition caused by microgravity conditions. In this perspective, architecture is a tool supporting human orientation, operability, and decision-making.

¹¹² Li, S., Lucey, P. G., Milliken, R. E., Hayne, P. O., Fisher, E., Williams, J.-P., Hurley, D. M., & Elphic, R. C. (2018). *Direct evidence of surface exposed water ice in the lunar polar regions*. *Proceedings of the National Academy of Sciences*. doi.org/10.1073/pnas.1802345115

¹¹³ Hoffman, J. A., Hecht, M. H., Rapp, D., Hartvigsen, J. J., SooHoo, J. G., Aboobaker, A. M., McClean, J. B., Liu, A. M., Hinterma, E. D., Nasr, M., Hariharan, S., Horn, K. J., Meyen, F. E., Okkels, H., Steen, P., Elangovan, S., Graves, C. R., Khopka, P., Madsen, M. B., Eisenman, D. J. (2022). *Mars Oxygen ISRU Experiment (MOXIE)-Preparing for human Mars exploration*. *Sci Adv.*, 8(35)

¹¹⁴ Lasseur, C., Brunet, J., de Weever, H., Dixon, M., Dussap, G., Godia, F., Leys, N., Mergea, M., & Van Der Straeten, D. (2010). *MELiSSA: THE EUROPEAN PROJECT OF CLOSED LIFE SUPPORT SYSTEM*. *Gravitational and Space Biology*, 23(2).

¹¹⁵ NASA (2022). *NASA Space Flight Human-System Standard, Volume 2: Human Factors, Habitability, and Environmental Health*. *NASA-STD-3001, Volume 2, Revision C*. NASA Technical Standard.

5.3.1. External Environment Requirements

Architecture operating in environments with limited resources is primarily shaped by external conditions, which determine both possibilities and limits - its *design guidelines*. As emphasised in contemporary studies in the field of space architecture, habitat design requires recognition of the relationship between structure and the environment in which it is intended to operate¹¹⁶. Therefore, below [Tab. 3], the main differences depending on the type of extreme space environment are presented - where humans stay and work (or may potentially stay and work in the future). As a reference point, they are compared with terrestrial conditions. The conditions are presented from the most distant: Mars, the Moon, and LEO (Low Earth Orbit - a low Earth orbit on which the International Space Station orbits). LEO is not a celestial body but an orbital environment; therefore, temperature and pressure values refer to exposure conditions rather than ambient atmospheric parameters.

¹¹⁶ Bannova, O. (2021). *Space Architecture: Human Habitats Beyond Planet Earth*. DOM Publishers.

Table 3. Summary of the main differences in the characteristics of extreme space environments (adapted from W. Dziadula, 2021).

	Earth (ref.)	Mars	Moon	LEO
				
1. Temperature	- 88°C to 58°C	-125°C do +20°C (locally), medium ~ -60°C	-173°C (night) do +127°C (day)	-150°C to +120°C (shadow/sun surface)
2. Distance from the Earth	0 (reference point)	55,7 mln - 401 mln km (travel window every 3 years)	356 - 384 thousand km	400 km (ISS)*
3. Atmospheric composition	Nitrogen (77%), oxygen (21%), argon (0.9%), carbon dioxide (0.04%)	Carbon dioxide (95%), ~ nitrogen (2%), ~ argon (2%), other (0.4%)	Helium (25%), neon (25%), hydrogen (23%), argon (20%) (exosphere - unstable, rarefied)	Thermosphere: atomic oxygen, nitrogen, helium (extremely rarefied)
4. Atmospheric pressure	1x AZ** (1013,25 hPa)	0,01 x AZ** (600 Pa)	10 -13 x AZ** (ultra-high vacuum)	0,0001 hPa (thermosphere)
5. Gravitational acceleration	9,81 m/s ²	3,711 m/s ²	1,62 m/s ²	Microgravity (~10 ⁻⁶ g)
6. Length of the day	24 h	24 h 39 min	655 h 15 min (27,3 dni)	90 min (ISS)
7. Human presence / Accessibility	~8,1 mld (2024/2025)	0 (visited 0)	0 (visited 12)	~700+ astronauts (in 2025)
8. Radiation ***	Very low (protected by the magnetosphere and atmosphere)	High cosmic radiation (lack of magnetosphere)	Very high radiation (lack of atmosphere and magnetosphere)	Moderate, high UV

	Earth (ref.)	Mars	Moon	LEO
9. Environmental hazards	In the future: Climate change, irreversible environmental changes, overpopulation, limited resources, and air and water pollution.	Temperature fluctuations, dust storms (up to 300 km/h), micrometeorites	Micrometeorites, extreme thermal cycles, electrostatic regolith, vacuum	Space debris accelerated to several thousand km/h, in a vacuum.
10. Resource availability	High	Low	Low	Very Low

* Vicinity of Earth orbit (ISS location).

** AZ - Earth's atmosphere (adopted reference unit).

*** (GCR - Galactic Cosmic Rays, SPE - Solar Particle Events, UV and ionising radiation).

The parameters presented in the table determine the design approach to architecture in these environments. Each of them generates separate technical, material, and organisational requirements - design decisions.

Then, how do individual elements influence architecture?

- *Temperature* is one of the factors influencing form and construction. Extreme temperature ranges require the use of advanced insulation, minimisation of energy losses, and construction of structures with limited heat exchange surfaces. In many locations, maintaining thermal stability becomes a key design challenge.
- *Distance from Earth* influences logistics, construction methods, and the required level of system autonomy. In orbit, staged assembly of large installations from multiple modules delivered in separate launches of carrier rockets is possible, including frequent replacement of components and technical support. The modules themselves must be adapted to specific and current rocket parameters, for example, for Mars, the only currently available (2026) launch technology is the Starship rocket proposed by SpaceX, with a diameter of approximately 10 m.

The Moon remains logistically accessible, but costs and mass limitations determine prefabrication and the necessity of maximum reliability. In the case of Mars, distance and rare launch windows mean that structures must be integrated, failure-resistant, and largely dependent on local resource production, because their servicing and expansion are practically limited. Thus, distance enforces both a change in construction strategy and the level of self-sufficiency in the context of operational duration.

- *Atmospheric composition* determines the tightness and the organisation of habitats. The absence of an atmosphere on the Moon and in orbit requires full hermetic sealing of the internal environment, the use of airlocks, and active life support systems. Mars, despite its thin atmosphere, offers unique ISRU (In-Situ Resource Utilisation) potential due to the presence of carbon dioxide, which can be processed into oxygen and fuel. Earth's atmosphere remains the only natural buffering system; therefore, outside it, architecture must assume full responsibility for environmental stability. Closely related to the atmosphere is the pressure factor, which in low-pressure environments requires the use of pressure structures with shapes that minimise stress, for example, cylinders, domes, or inflatable modules. Mars, whose pressure is only 0.6% of Earth's value, requires full hermetic sealing, and lunar and orbital vacuum impose the necessity of maintaining artificial pressure in every room.
- *Gravity* influences both ergonomics and spatial organisation. On the ISS, microgravity determines the arrangement of equipment, the behaviour of fluids, waste management, and work methods. On Mars and the Moon, reduced gravity affects structural stability, movement safety, and still unknown long-term health consequences. This requires the creation of spaces enabling, for example, compensatory exercise. From an ergonomic perspective, lack of gravity or altered gravity influences the ergonomic design of every space inside the habitat, including stairs, handrails, ceilings, and passages, caused by different movement dynamics in space.

- *The length of the day* directly affects the human circadian rhythm and the functioning of energy systems. Mars, due to its cycle similar to Earth's, is an exception. At the same time, the ISS experiences sunrise every 90 minutes, and the Moon offers extremely long days and nights lasting approximately 14 Earth days. Lighting, circadian rhythm control, and energy planning during periods without sunlight therefore become key design elements.
- *Cosmic radiation* is a design factor related to the safety of health and life. The Moon and Mars, which lack a strong magnetic field, are exposed to intense galactic radiation, solar storms, and the full spectrum of UV radiation. This requires the use of thick radiation shielding, usually made of regolith, ice, or hydrogen-rich materials. Radiation also influences interior organisation; “safe rooms”, zones minimising exposure, and spatial layouts reducing radiation doses become necessary.
- *Environmental hazards* such as dust storms on Mars, lunar dust, micrometeoroids, or orbital vacuum determine structural durability and material resistance. Architecture must be capable of operating in an environment requiring multiple redundancies and the possibility of rapid isolation of damaged modules, which directly affects design.
- The final factor is the *availability of local resources*. On the Moon, the primary raw material is regolith and ice in permanently shadowed regions. On Mars, atmospheric and geological resources are available, enabling the production of oxygen, fuel, and water. In orbit, the only local resource is solar energy, which limits the possibilities of on-site construction and production.

After presenting environmental hazards (radiation, extreme temperatures, distance from Earth, and logistical limitations), contemporary strategies of shaping planetary habitats are essentially a catalog of architectural responses to these factors. Kriss J. Kennedy in *The Vernacular of Space Architecture*¹¹⁷ proposed an evolutionary classification of spa-

¹¹⁷ Kennedy, K. J. (2002). *The Vernacular of Space Architecture*. AIAA Space Architecture Symposium, AIAA 2002-6102.

ce habitats, including: (I) modules fully transported from Earth, (II) prefabricated systems with partial on-site assembly, and (III) structures largely based on the use of local resources. In practice, most projects are hybrids because they combine elements of rigid modules, expandable structures, and structures made from in-situ materials. In another terms, ISRU is the design of infrastructure in order to *live from local resources*. Heavy, massive structural elements can be created from regolith, ice, or other local raw materials, while from Earth, mainly special components such as life support systems, interfaces, and equipment can be delivered. Thanks to ISRU, the mass launched from Earth is reduced, lowering costs and mitigating risks. This approach, however, requires preparation of infrastructure: robots for digging and transporting regolith, systems for its processing, and energy to power the entire process¹¹⁸. In architectural design, this means that the form and location of habitats must be predetermined by the possibilities of obtaining and processing materials on-site, for example, proximity to ice deposits at the lunar poles or in sulfur-rich regions on Mars, where it is possible to produce, for example, sulfur concrete. One of the most intensively developed ISRU technologies is 3D printing from regolith (from a loose layer). In lunar and Martian concepts, a robot “with a scoop” collects loose regolith and then applies it in layers, sintering it with a laser or using solar concentrators, creating shielding or infrastructure¹¹⁹. Such shells provide radiation protection against micrometeoroids and allow stabilisation of temperature inside modules¹²⁰. On Mars, mixtures such as Marscrete, that is, sulfur concretes based on regolith and sulfur, are being developed, designed specifically for additive printing¹²¹. Projects prepared within the NASA 3D-Printed Habitat Challenge show that

¹¹⁸ Cesaretti, G., Dini, E., De Kestelier, X., Colla, V., & Pambaguian, L. (2014). *Building components for an outpost on the Lunar soil by means of a novel 3D printing technology*. *Acta Astronautica*, Volume 93, 430-450. doi.org/10.1016/j.actaastro.2013.07.034

¹¹⁹ Leach, N. (2014). *3D Printing in Space*. *Architectural Design*, 84(6). doi:10.1002/ad.1840

¹²⁰ Sun, W., Dang, F., Zhou, Y., Wen, S., Zhou, C., Shi, Y., & Ding, L. (2025). *Additive Manufacturing of Lunar Regolith: A Review*. *Additive Manufacturing Frontiers*, Volume 4, Issue 3. https://doi.org/10.1016/j.amf.2025.200225

¹²¹ Troemner, M., Ramyar, E., Marrero, R., Mendu, K., & Cusatis, G. (2021). *Marscrete: A Martian Concrete for Additive Construction Applications Utilizing In Situ Resources*. *Earth and Space 2021 Proceedings*. doi/abs/10.1061/9780784483374.074

“printed” architecture becomes a factor organising the interior and functional layout of habitats^{122, 123}.

The second important architectural and technological response developed particularly within space architecture is expandable (inflatable/deployable) structures. Their advantage is a favourable ratio of usable volume to transported mass, which directly addresses payload limitations. A classic example is the TransHab module, whose multilayer composite shell, after expansion, creates a large, lightweight interior with relatively low launch mass¹²⁴. As emphasised by Häuplik-Meusburger and Bannova, expandable technologies are perceived as disruptive, because they can fundamentally change the design of both spacecraft and surface habitats¹²⁵. However, they usually require supplementation with a rigid “core” with ECLSS systems and additional shielding layers (for example, a regolith berm), which again forces thinking about architecture as a hybrid of several technologies.

Another group of solutions responding to external conditions are strategies of using natural terrain formations, including lava caves and other subsurface forms. Researchers indicate that lunar structures may be located on the open surface, but primarily it is reasonable to place them in craters, near cliff walls, or inside lava tubes, where geology itself provides partial radiation and thermal protection¹²⁶. Such locations enable the reduction of the thickness of artificial shells and transfer of part of the protective functions. This has direct consequences for the selection of construction technologies, assembly sequences, and distribution of logistic modules. An example of such an integrated approach is the *Lunae Abyssi* project - a concept of a base in a lunar lava cave, which received GOLD Mention in the YAC and ESA Tropical Team competition in

¹²² Roman, M. C., Kim, T., Prate, T. J., & Mueller, R. P. (2017). *NASA Centennial Challenge: 3D-Printed Habitat*. *American Institute of Aeronautics and Astronautics 2017 Proceedings*, AIAA 2017-5279 Session: In-Space Manufacturing and Assembly. doi.org/10.2514/6.2017-5279

¹²³ NASA Centennial Challenges. (2025). *3D-Printed Habitat Challenge*. NASA. <https://www.nasa.gov/prizes-challenges-and-crowdsourcing/centennial-challenges/3d-printed-habitat-challenge/> (accessed: 04 February 2026).

¹²⁴ Howe, A. S., & Sherwood, B. (Eds.). (2009). *Out of this World: The New Field of Space Architecture*. American Institute of Aeronautics and Astronautics.

¹²⁵ Häuplik-Meusburger, S., & Bannova, O. (2016). *Space Architecture Education for Engineers and Architects: Designing and Planning Beyond Earth*. Springer International Publishing.

¹²⁶ Benaroya, H. (2018). *Building Habitats on the Moon: Engineering Approaches to Lunar Settlements*. Springer International Publishing. doi.org/10.1007/978-3-319-68244-0

2023¹²⁷. The station project assumes delivery from Earth to the Moon of core modules with life support systems, surrounded by double-layer expandable shells, and the entire structure is located in a natural lava “corridor”. Surface infrastructure, such as landing platforms and roads, is designed to be printed from regolith, which combines the expandable approach with ISRU. In this way, architecture simultaneously uses three levels of protection: natural cave shielding, artificial shells from local materials, and pressure shells of habitats.

The most speculative, yet promising response to resource limitations is biological construction materials, including *mycoarchitecture* (structures made of mycelium composites)¹²⁸. Mycelium, when combined with plant fibres and the mineral fraction of regolith, can create lightweight, insulating biocomposites with extraterrestrial potential¹²⁹. Such “growing” materials can be transported in the form of minimal cargo mass (for example, dried mycelium and growth medium), and then activated on-site, which radically reduces the demand for traditional materials.

5.3.2. Internal Environment Requirements

In conditions of isolation and limited resources, the internal environment of a habitat becomes a factor determining its quality in terms of habitability. From this level, NASA defines the minimum requirements that every closed environment must meet: appropriate oxygen concentration, CO₂ control, stable temperature and humidity, access to

¹²⁷ Drozdowska, P., Dziaduła, W., Fikus, W., Mintus, A., Orzechowski, L., Pietrzych, J., & Rębisz, M. (2024). NEW DESIGN APPROACH FOR LUNAR HABITATION IN LAVA TUBES - LUNAE ABYSSI PROJECT DESCRIPTION AND DETAILS. 75 th International Astronautical Congress (IAC) Proceedings

¹²⁸ Rothschild, L. J., Maurer, C., Paulino-Lima, I. G., Senesky, D., Wipat, A., & Head III, J. (2018). Myco-architecture off planet: growing surface structures at destination NIAC 2018 Phase I Final Report.

¹²⁹ Brandić Lipińska, M., Maurer, C., Cadogan, D., Head, J., Dade-Robertson, M., Paulino-Lima, I. G. P.-L., Liu, C., Morrow, R., Senesky, D. G., Theodoridou, M., Rheinstädte, M. C., Zhang, M., & Rothschild, L. J. (2022). Biological growth as an alternative approach to on and off-Earth construction. *Frontiers in Built Environment, Sec. Sustainable Design and Construction*(Volume 8). doi.org/10.3389/fbuil.2022.965145

water, food, hygiene, and psychophysiological conditions necessary to maintain health^{130, 131}.

Humans consuming food with a caloric value appropriate for health also generate organic and metabolic waste, which must be processed. These assumptions are also important from the design perspective, because they define what infrastructure must be provided, what processes must be closed in a loop, and how architecture influences their operation. The internal environment must therefore include a set of rooms and functional zones whose existence results directly from human physiology and the requirements of life support systems. These include:

- ECLSS modules (Environmental Control and Life Support System),
- hygiene and sanitary rooms,
- food and meal preparation zones,
- storage areas for water, food, and system components,
- medical zones,
- cultivation and bioreactor rooms,
- technical modules responsible for filtration, recovery, and circulation of resources.

Moreover, all these rooms must be logically and functionally connected within one circulation, in order to minimise energy losses, shorten work trajectories, reduce human errors, and facilitate service access.

Historical experiments of closed-loop systems demonstrated the necessity of strict integration of architecture with environmental systems. One of the most important examples was the Soviet BIOS-3 experiment, conducted in the 1960s and 1970s, in which long-term tests of human functioning in a nearly completely closed ecological life sup-

¹³⁰ NASA. (2022). *NASA SPACE FLIGHT HUMAN-SYSTEM STANDARD [VOLUME 2: HUMAN FACTORS, HABITABILITY, AND ENVIRONMENTAL HEALTH]*. In NASA-STD-3001, VOLUME 2, REVISION C (Rev. C ed.). NASA TECHNICAL STANDARD.

¹³¹ NASA. (2014). *HUMAN INTEGRATION DESIGN HANDBOOK (HIDH)* (NASA/SP-2010-3407/REV1 ed.). NASA - National Aeronautics and Space Administration.

port system were carried out¹³². The results of this program led to the development of full-scale simulators in which even 95% of water was recovered through condensation of water transpired by plants and its further purification into potable and sanitary water. All organic waste was processed in photobioreactors and bioreactors, which served the roles of stabilising the resource cycle and producing part of the biomass¹³³. Contemporary life support systems, such as the ECLSS system on the International Space Station, achieve water recovery efficiency reaching approximately 93%, using a combination of vacuum distillation, condensation and filtration processes, and the Sabatier reaction; carbon dioxide reacts with hydrogen, leading to water production¹³⁴. Despite many years of development, it remains largely a technological system that requires frequent servicing and high reliability.

Microorganisms, including microalgae, currently constitute a developing direction of bioregenerative closed-loop *BLSS (Biological Life Support Systems)*¹³⁵. In one process, they can (the process of photosynthesis): produce oxygen, bind CO₂, purify water, process organic waste, and produce nutritional biomass. In a closed loop, microalgae function as “green bioreactors”, whose products, such as oxygen, water, and biomass, return in the loop back to humans. Humans, in turn, provide CO₂, metabolic heat, and waste, which become elements of the cycle¹³⁶. The most advanced space program investigating the role of microorganisms in life support systems is the European *MELiSSA (Micro-Ecological Life Support System Alternative)*, conducted since 1989 by ESA. MELiSSA is based on a multi-compartment, bioregenerative system in which each module is responsible for a specific metabolic process [Fig. 19]. This system is designed as a full

¹³² Salisbury, F. B., Gitelson, J. I., & Lisovsky, G. M. (1997). *Bios-3: Siberian Experiments in Bioregenerative Life Support*. *BioScience*, Vol. 47, No. 9. doi.org/10.2307/1313164.

¹³³ Salisbury, F. B., Gitelson, J. I., & Lisovsky, G. M. (1997). *Bios-3: Siberian Experiments in Bioregenerative Life Support*. *BioScience*, Vol. 47, No. 9. doi.org/10.2307/1313164.

¹³⁴ Seedhouse, E. (2020). *International Space Station Life Support System*. In *Life Support Systems for Humans in Space*. Springer International Publishing. doi.org/10.1007/978-3-030-52859-1_5.

¹³⁵ Santomartino, R., Averagesch, N. J. H., Bhuiyan, M., Cockell, C. S., Colangelo, J., Gumulya, Y., Lehner, B., Lopez-Ayala, I., McMahon, S., Mohanty, A., Santa Maria, S. R., Urbaniak, C., Volger, R., Yang, J., & Zea, L. (2023). Toward sustainable space exploration: a roadmap for harnessing the power of microorganisms. *Nature Communications*, 14/1391. doi.org/10.1038/s41467-023-37070-2.

¹³⁶ Yang, L., Li, H., Liu, T., Zhong, Y., Ji, C., Lu, Q., Fan, L., Li, J., Leng, L., Li, K., & Zhou, W. (2019). *Microalgae biotechnology as an attempt for bioregenerative life support systems: problems and prospects*. *J Chem Technol Biotechnol* 2019, 94, 3039-3048. doi:10.1002/jctb.6159.

alternative to purely technological ECLSS, capable of sustaining human life in conditions of long-term isolation with maximum resource recovery¹³⁷.

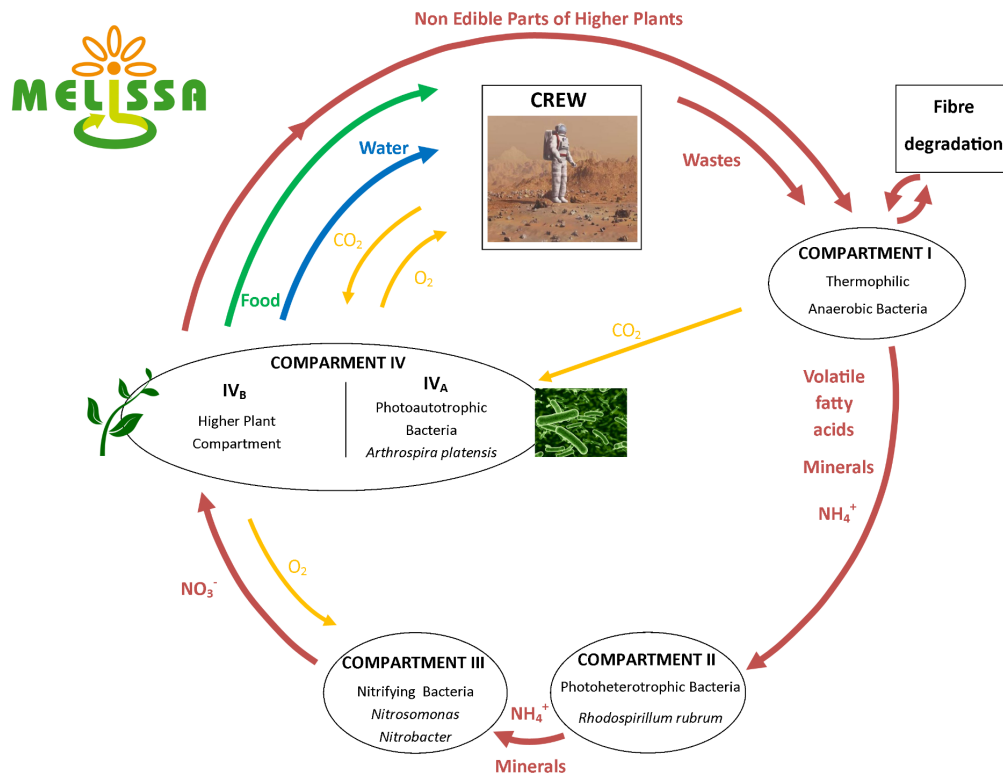


Fig. 19. Diagram of the bio-regenerative loop of the MELiSSA (Micro-Ecological Life Support System Alternative) system. The system consists of five metabolic compartments responsible for waste recycling, oxygen production, biomass and water generation, and a closed circulation of resources between the crew, microorganisms, and plants (source: European Space Agency, n.d.).

Microorganisms constitute a component of future self-sufficient habitats because they can carry out most of the processes required to maintain closed resource loops, from air and water purification, through waste processing, to the production of food, energy, and materials. As emphasised by Santomartino and collaborators, microorganisms can replace or complement energy-intensive physicochemical systems by enabling the recyc-

¹³⁷ European Space Agency. (n.d.). MELiSSA - Closed Loop Compartments. https://www.esa.int/Enabling_Support/Space_Engineering_Technology/Melissa/Closed_Loop_Compartments (accessed: 04 February 2026).

ling of CO₂ into oxygen, the mineralisation of waste, the production of biomass, and the stabilisation of nutrient cycles in isolated environments¹³⁸. Microalgae, as well as photosynthetic bacteria, can take over part of the functions of existing ECLSS systems while at the same time serving as a source of micronutrients in the astronauts' diet. Microorganisms also play a role in waste bioprocessing. They can convert human metabolic waste into nutritive biomass and compounds necessary for plant growth. At the same time, they support cultivation through nitrogen compounds and the plant microbiome, which makes food systems more independent. The authors of the article also point to their potential in in-situ pharmaceutical production, which is necessary in long-duration missions where pharmaceuticals lose their stability¹³⁹. One of the developing functions of microorganisms is biomining, confirmed in experiments conducted on the ISS, enabling the extraction of oxygen, iron, nickel, or rare earth elements from Martian and lunar regolith¹⁴⁰. In this way, microorganisms can support local production of materials, fertilisers, or intermediate products. Researchers also indicate the possibility of biological production of construction materials, such as biocement or composites, as well as energy through microbial fuel cells and hydrogen production. In architectural terms, microorganisms transform the built object into a metabolic environment in which resources circulate in closed or semi-closed loops¹⁴¹.

5.4. The Role of Architecture as a Tool for Survival and Adaptation

In ICE environments, a range of stressors can be identified and divided into physical and psychosocial factors¹⁴². The main physical stressors include changes in pressure,

¹³⁸ Santomartino, R., Aversch, N. J. H., Bhuiyan, M., Cockell, C. S., Colangelo, J., Gumulya, Y., Lehner, B., Lopez-Ayala, I., McMahon, S., Mohanty, A., Santa Maria, S. R., Urbaniak, C., Volger, R., Yang, J., & Zea, L. (2023). *Toward sustainable space exploration: a roadmap for harnessing the power of microorganisms*. *Nature Communications*, 14/1391. doi.org/10.1038/s41467-023-37070-2

¹³⁹ Santomartino, R., Aversch, N. J. H., Bhuiyan, M., Cockell, C. S., Colangelo, J., Gumulya, Y., Lehner, B., Lopez-Ayala, I., McMahon, S., Mohanty, A., Santa Maria, S. R., Urbaniak, C., Volger, R., Yang, J., & Zea, L. (2023). *Toward sustainable space exploration: a roadmap for harnessing the power of microorganisms*. *Nature Communications*, 14/1391. doi.org/10.1038/s41467-023-37070-2

¹⁴⁰ Santomartino, R., Zea, L., & Cockell, C. S. (2022). *The smallest space miners: principles of space biomining*. *Extremophiles*, Volume 26, article number 7. doi.org/10.1007/s00792-021-01253-w

¹⁴¹ Santomartino, R., Blanco, G. R., Gudgeon, A., Hafner, V. O. P., Stirpe, A., Waterfall, M., Cayzer, N., Pichevin, L., Calder, G., Birkenfeld, K. R., Waajen, A. C., McLaughli, S., Mariani, A., Balsamo, M., Neri, G., Eades, L. J., & Cockell, C. S. (2024). *Testing microbial biomining from asteroidal material onboard the International Space Station*. [Preprint]. bioRxiv. doi.org/10.1101/2024.01.13.575412

¹⁴² Connors, M. M., Harrison, A. A., & Akins, F. R. (1985). *Living Aloft: Human requirements for extended spaceflight*. NASA Scientific and Technical Information Branch, (Washington, DC).

extreme temperatures, and atypical environmental hazards such as radiation. These threats are often combined with physical distance from familiar surroundings and limited possibilities for interaction with the external environment¹⁴³. An additional physical burden in ICE environments is the limited quality of the built environment, including poor ventilation, monotonous surroundings, restricted living space, and a lack of diverse visual stimuli. All of these factors contribute to both physical and mental exhaustion. Many tasks performed in such conditions are repetitive and often perceived as “meaningless,” which can further negatively affect the psychological condition of mission participants.

Social and psychological stressors are also significant. People living in such environments often experience a lack of privacy and are forced into constant interaction with others, which can generate tension and conflict¹⁴⁴. Research conducted at the Lunares Research Station in 2021 confirmed the strong impact of a lack of privacy on reduced well-being¹⁴⁵. Another important aspect is the loss of a clear sense of time, disturbances of the circadian rhythm caused by the absence of natural light or irregular lighting cycles, as well as the so-called *Zeitgeber effect*, meaning the disruption of the internal biological clock¹⁴⁶. In addition, crew members often struggle with the inability to separate work life from private life, limited contact with family and the outside world, restricted

¹⁴³ Evans, G. W., Stokols, D., & Carrère, S. (1988). *Human adaptation to isolated and confined environments: Preliminary findings of a seven-month Antarctic winter-over human factors study*. NASA Scientific and Technical Information Branch (NASA-CR-177499).

¹⁴⁴ Häuplik-Meusburger, S., Binsted, K., & Bassingthwaighe, T. (2017). *Habitability Studies and Full Scale Simulation Research: Preliminary themes following HISEAS mission IV*. 47th International Conference on Environmental Systems.

¹⁴⁵ Fross, K., & Dziadula, W. (2021). *Kosmos na Ziemi - analogowe habitaty kosmiczne. Badania jakościowe podczas symulowanej misji kosmicznej*. *Builder Science*, Tom: 288, Nr: 7, doi:10.5604/01.3001.0014.9334

¹⁴⁶Quante, M., Mariani, S., Weng, J., Marinac, C. R., Kaplan, E. R., Rueschman, M., Mitchell, J. A., James, P., Hipp JA, J. A., Cespedes Feliciano, E. M., Wang, R., & Redline, S. (2019). *Zeitgebers and their association with rest-activity patterns*. *Chronobiol Int.*, 36(2):203-213. doi: 10.1080/07420528.2018.1527347.

diets¹⁴⁷ and sleep disturbances¹⁴⁸. All of these factors lead to reduced well-being, decreased performance, and potential long-term psychological consequences.

Users experience stress and a sense of danger, which influences how they perceive space. Peter Suedfeld notes that despite these challenges, people may also experience positive psychological effects¹⁴⁹. He proposes focusing on positive psychology and emphasises experiences such as a sense of meaning and fulfilment derived from participating in important missions, personal growth and the development of psychological resilience, as well as pride in taking part in a unique undertaking that serves the common good.

5.4.1. Habitability

How does this well-being issue relate to design problems? The *NASA-STD-3001* document clearly states that a confined environment must support not only physical safety, but also behavioural health, cognitive performance, and stress regulation during long-term isolation¹⁵⁰. Architecture must therefore fulfil a psychosocial life-support role, meaning that it should organise interactions, allow for withdrawal, prevent conflicts, and support human regenerative rhythms. In the approach of Bishop and Häuplik-Meusburger, human adaptation does not result solely from the amount of available physical space, but from the relationship between space, resources, physiology, and social dynamics in a constrained environment¹⁵¹.

The most comprehensive analysis of habitability (understood as the ability of a living environment to sustain long-term, healthy, and functional human life) was proposed by

¹⁴⁷ Cohen, M. M., & Häuplik-Meusburger, S. (2015). *What do we give up and leave behind? 45th International Conference on Environmental Systems 45th International Conference on Environmental Systems ICES*.

¹⁴⁸ Nasrini, J., Hermosillo, E., Dinges, D. F., Moore, T. M., Gur, R. C., & Basner, M. (2020). Cognitive Performance During Confinement and Sleep Restriction in NASA's Human Exploration Research Analog (HERA). *Frontiers in Physiology*, Sec. Environmental, Aviation and Space Physiology (Volume 11). doi:10.3389/fphys.2020.00394

¹⁴⁹ Suedfeld, P. (2001). *Applying Positive Psychology in the Study of Extreme Environments*. *Journal of Human Performance in Extreme Environments*, 6(1), Article 6. doi:10.7771/2327-2937.1020

¹⁵⁰ NASA (2022). *NASA Space Flight Human-System Standard, Volume 2: Human Factors, Habitability, and Environmental Health*. NASA-STD-3001, Volume 2, Revision C. NASA Technical Standard. <https://standards.nasa.gov/standard/nasa/nasa-std-3001> (accessed: 04 February 2026).

¹⁵¹ Häuplik-Meusburger, S., & Bishop, S. (2021). *Space Habitats and Habitability: Designing for Isolated and Confined Environments on Earth and in Space*. Springer International Publishing.

Connors, Harrison, and Akins (1985)¹⁵². Based on many years of isolation research, they presented a model set of environmental requirements covering four main areas: the physical environment, health and recreation, privacy, and the combined effects of stressors. This framework [Fig. 20], frequently referenced in later NASA studies, became the foundation for the contemporary understanding of what constitutes a *good living environment in isolation* that meets habitability standards. Habitability, therefore, defines conditions that support adaptation, including space and its quality, sensory regulation of the environment, privacy, ergonomics, and the possibility of rest and recreation.

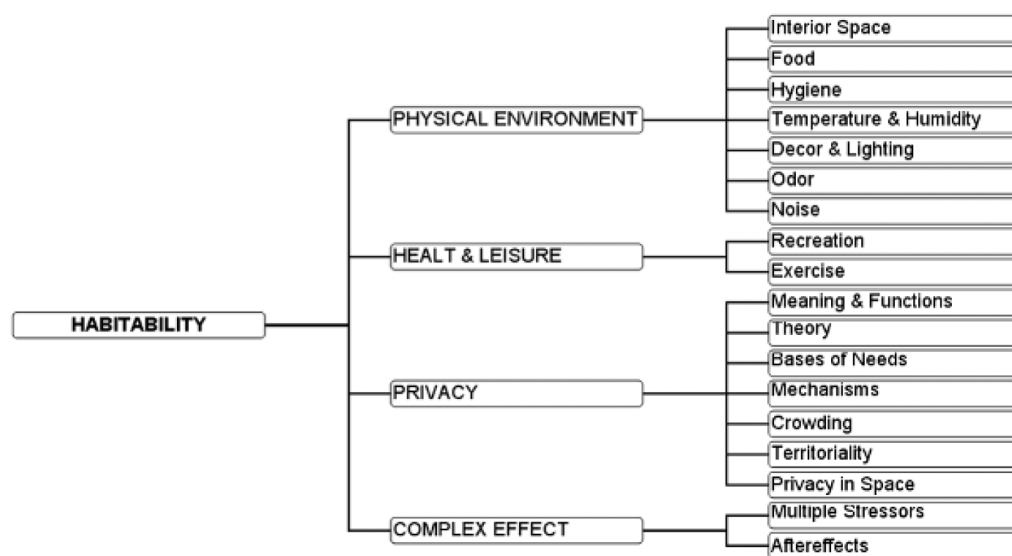


Fig. 20. Structure of habitability elements in NASA space project designs (source: Connors et al., 1985; Schlacht, 2012).

As Schlacht notes in her research, habitability is the result of a complex interaction of physiological, psychological, and social factors, which in extreme environments reinforce each other and can lead either to adaptation or to overload¹⁵³. Schlacht emphasises that adaptation depends on identifying and controlling so-called stressors, that is, stimuli that overload perception and the nervous system. In her model, four main categories are distinguished: physical factors (noise, temperature, odors), social factors (crowding,

¹⁵² Connors, M. M., Harrison, A. A., & Akins, F. R. (1985). *Living Aloft: Human requirements for extended spaceflight*. NASA Scientific and Technical Information Branch, (Washington, DC).

¹⁵³ Schlacht, I. L. (2012). *SPACE HABITABILITY Integrating Human Factors into the Design Process to Enhance Habitability in Long Duration Missions*. PhD Dissertation - Technische Universität Berlin.

loss of privacy), operational factors (lack of control over work and time), and sensory factors (monotony, sensory overload or sensory deprivation). Referring to it, document *Living Aloft: Human requirements for extended spaceflight* classifies noise, odours, and sensory overload as key habitability factors that are often overlooked or underestimated¹⁵⁴. Noise generated by ventilation, ECLSS equipment, pumps, and devices affects sleep, concentration, and mental health. Since the 1970s, NASA has conducted research on minimum noise levels compatible with behavioural health; excessive background noise increases stress and leads to fatigue. Among all these factors, odors are described as one of the strongest and most frequently neglected stimuli. Connors notes that in isolation, odours can trigger conflicts, discomfort, and even nausea. Sensory comfort also includes temperature, humidity, and lighting quality. Strong technical lighting without a circadian cycle disrupts sleep rhythms and reduces performance.¹⁵⁵ Therefore, “good” habitats must provide sensory diversity and allow the crew to regulate their environment.

To carry out a space mission, a full crew is required, usually 4-6 people, depending on mission assumptions. A repeatedly emphasised aspect is the need for privacy, which increases with the duration of isolation, especially in long-duration missions exceeding 30 days. The NASA Standards document NASA-STD-3001 defines privacy as a system requirement in the area of hygiene and as a key element of behavioural health, particularly in relation to sleep¹⁵⁶. Privacy includes visual, acoustic, and organisational control; it enables temporary withdrawal, psychological and medical consultations, stress reduction, and regulation of the intensity of social interactions.

5.4.2. Ergonomics and Use

One of the key components of habitability is the ability to control the environment. Schlacht shows that a sense of agency (such as the ability to regulate light, sound, per-

¹⁵⁴ Connors, M. M., Harrison, A. A., & Akins, F. R. (1985). *Living Aloft: Human requirements for extended spaceflight*. NASA Scientific and Technical Information Branch, (Washington, DC).

¹⁵⁵ Connors, M. M., Harrison, A. A., & Akins, F. R. (1985). *Living Aloft: Human requirements for extended spaceflight*. NASA Scientific and Technical Information Branch, (Washington, DC).

¹⁵⁶ NASA (2022). *NASA Space Flight Human-System Standard, Volume 2: Human Factors, Habitability, and Environmental Health*. NASA-STD-3001, Volume 2, Revision C. NASA Technical Standard. <https://standards.nasa.gov/standard/nasa/nasa-std-3001> (accessed: 04 February 2026).

sonal space, or activity schedules) has a stronger impact on adaptation than the sheer size of the usable volume¹⁵⁷. For this reason, design must incorporate mechanisms that enable individualisation and spatial flexibility, such as adjustable lighting, movable acoustic panels, visual partitions, and the possibility of transitioning between zones with different levels of stimulation. Consequently, interior design should account for sensory gradients, varied lighting types, changing surface textures, and the presence of elements that evoke the natural environment.

The design of living environments must also consider anthropometric changes resulting from microgravity or reduced gravity. As described in *Space Habitats and Habitability: Designing for Isolated and Confined Environments on Earth and in Space*, the human body adopts a neutral body posture in weightlessness, which differs from standing or seated postures on Earth¹⁵⁸. This shift affects how space is used, particularly in terms of ranges of motion, body orientation, required clearances between surfaces, and modes of movement. The absence of a defined “up” and “down” in microgravity means that surfaces are inherently multifunctional and that usable space effectively expands into three dimensions, even though the nominal volume remains limited. This increases demands related to storage, spatial planning, and orientation.

Additional precision is provided by the *NASA Human Research Program report*¹⁵⁹, which attempted to quantitatively define the minimum acceptable living volume (*Net Habitable Volume - NHV*) for long-duration missions, such as a 30-month Mars mission profile. A team of scientists and experts in ergonomics, psychology, architecture, and space medicine concluded that the absolute minimum required to maintain crew health, functionality, and performance is 25 m³ NHV per person. This value results from the analysis of behavioural factors, not only physiological ones, including the need for regeneration, control of stimuli, opportunities for isolation, effective work, maintenance

¹⁵⁷ Schlacht, I. L. (2012). *SPACE HABITABILITY Integrating Human Factors into the Design Process to Enhance Habitability in Long Duration Missions*. PhD Dissertation - Technische Universität Berlin.

¹⁵⁸ Häuplik-Meusburger, S., & Bishop, S. (2021). *Space Habitats and Habitability: Designing for Isolated and Confined Environments on Earth and in Space*. Springer International Publishing.

¹⁵⁹ Whitmire, A., Leveton, L., Broughton, H., Mathias, B., & Kearney, A. (2014). *Minimum Acceptable Net Habitable Volume for Long-Duration Exploration Missions Subject Matter Expert Consensus Session Report*. NASA Human Research Program (HRP).

of group cohesion, and the performance of operational tasks under conditions of limited resources and delayed communication. The authors also emphasise that mission duration radically changes the perception of space. Even a relatively large volume may become insufficient if the design does not provide functional diversity, privacy, and an appropriate sensory environment. Within the NHV framework, seven essential functional zones were defined that must be present in a habitat for it to be considered psychologically and operationally adequate. These include: (1) private sleeping and recovery quarters (crew quarters), (2) a shared space for eating, communication, and recreation, (3) a scientific and operational work area, (4) a space for exercise and EVA preparation, (5) hygiene facilities, (6) circulation paths enabling conflict-free crew movement, and (7) access to storage areas (stowage). Each of these spaces has specific functional requirements. For example, private cabins should provide a minimum of 5.4 m³ and function as zones of sensory isolation; shared spaces must accommodate the entire crew and offer varied visual stimulation, preferably with access to a window; work areas require acoustic separation and the ability for several people to work simultaneously; and exercise areas should contain at least two training devices and allow for basic medical procedures. NASA also strongly emphasises the importance of proper storage planning, noting that incorrect estimation of supplies in long missions can lead to uncontrolled reduction of usable living space¹⁶⁰.

A related concept is the *Adequate Volume*, understood as sufficient functional volume. As described by Häuplik-Meusburger and Bishop, this is not an absolute value, but a complex relationship between physiological requirements, mission tasks, social dynamics, and individual preferences¹⁶¹. The authors point out that although there is no single universal “cubic meter value” per person, adaptation and well-being depend on whether space allows for daily activities, privacy, sleep, social interaction, and resource storage - meaning how comfortably and satisfactorily these needs can be fulfilled.

¹⁶⁰ Whitmire, A., Leveton, L., Broughton, H., Mathias, B., & Kearney, A. (2014). *Minimum Acceptable Net Habitable Volume for Long-Duration Exploration Missions Subject Matter Expert Consensus Session Report*. NASA Human Research Program (HRP).

¹⁶¹ Häuplik-Meusburger, S., & Bishop, S. (2021). *Space Habitats and Habitability: Designing for Isolated and Confined Environments on Earth and in Space*. Springer International Publishing.

The main psychological and behavioural conclusions from the NASA report¹⁶² and the research by Häuplik-Meusburger i Bishop¹⁶³ and the research by Häuplik-Meusburger and Bishop highlight that space is a qualitative concept, not only a geometric one. Even a large volume can be perceived as “insufficient” if it does not allow control over stimuli, provide privacy or isolation, or support a diversity of activities. Conversely, a well-designed habitat with limited space can better support adaptation if it ensures a balance between social integration and withdrawal, environmental variety, conditions supporting regeneration and concentration, and basic functional elements. The authors stress that visual monotony, constant noise, insufficient privacy, lack of personalisation, and excessive density significantly increase the risk of reduced operational performance, interpersonal conflicts, and mood disorders. In addition, studies of analog stations show that over time there is a growing need for “psychological distance,” such as quiet spaces, transitional zones, or individual sleep cabins that allow breaks from interaction¹⁶⁴. The absence of such options increases the risk of conflict, irritability, and decreased efficiency¹⁶⁵.

5.4.3. Spatial Perception, Sensory Experience, Biophilia

Increasing attention in the scientific community is being given to the previously mentioned issue of spatial perception, the study of which is playing an increasingly important role in space design, including in major research institutions such as NASA. An example, although not initially related to space, but later frequently referenced, is research on the influence of greenery on the perception of space, including the reduction of stress symptoms. In the article *View Through a Window May Influence Recovery from Surgery*¹⁶⁶, the author presents the results of a groundbreaking study comparing the re-

¹⁶² Whitmire, A., Leveton, L., Broughton, H., Mathias, B., & Kearney, A. (2014). *Minimum Acceptable Net Habitable Volume for Long-Duration Exploration Missions Subject Matter Expert Consensus Session Report*. NASA Human Research Program (HRP).

¹⁶³ Häuplik-Meusburger, S., & Bishop, S. (2021). *Space Habitats and Habitability: Designing for Isolated and Confined Environments on Earth and in Space*. Springer International Publishing.

¹⁶⁴ Fross, K., & Dziadula, W. (2021). *Kosmos na Ziemi - analogowe habitaty kosmiczne. Badania jakościowe podczas symulowanej misji kosmicznej*. *Builder Science*, Tom: 288, Nr: 7, doi:10.5604/01.3001.0014.9334

¹⁶⁵ Connors, M. M., Harrison, A. A., & Akins, F. R. (1985). *Living Aloft: Human requirements for extended spaceflight*. NASA Scientific and Technical Information Branch, (Washington, DC).

¹⁶⁶ Ulrich, R. S. (1984). *View Through a Window May Influence Recovery from Surgery*. *Science*. doi: 10.1126/science.6143402

covery of patients after gallbladder surgery depending on the view from their hospital room window. It was shown that patients with a view of nature (in this case, trees) recovered faster, required fewer strong painkillers, and experienced fewer complications than patients whose windows faced a brick wall. This study became a foundation for further research on so-called *supportive design* (supportive environments). It laid the groundwork for the development of design approaches focused on user well-being, demonstrating the significant impact of greenery and contact with nature on both physical and mental health. Subsequent studies by Ulrich from 1991, conducted together with a research team, had a review character and significantly expanded earlier conclusions regarding the influence of the physical environment on the healing process¹⁶⁷. The authors emphasised that factors such as access to nature, appropriate lighting, noise control, and spatial layout can reduce stress levels and improve patient well-being, thereby supporting faster recovery.

In parallel, in the 1980s, as a result of research on the relationship between humans and nature, the concept of biophilia emerged¹⁶⁸, which later began to be integrated into design for extreme and space environments. Many authors emphasise in their work the importance of patterns present in nature for the design of living spaces. Their research indicates that reproducing natural structures and rhythms in architecture and interiors can genuinely improve well-being, adaptive capacity, and human performance^{169, 170}. In subsequent years of research, it was postulated that spaces should be shaped not only to ensure physical safety, but also to functionally support users and promote their psychological well-being¹⁷¹. These concepts contributed to the development of biophilic design, a design approach that connects architecture with elements of nature and became a foundation for designing environments oriented toward human well-being, including in

¹⁶⁷ Ulrich, R. S., Simons R. F., Losito B. D., Fiorito E., Miles M. M., Zelson M. (1991). *Stress recovery during exposure to natural and urban environments*. *Journal of Environmental Psychology*, 11. doi.org/10.1016/S0272-4944(05)80184-7.

¹⁶⁸ Wilson, E. O. (1984). *Biophilia*. Harvard University Press.

¹⁶⁹ Wise, J. A., & Taylor, R. P. (2002). *Fractal Design Strategies for Enhancement of Knowledge Work Environments*. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, Volume 46, Issue 9. doi.org/10.1177/154193120204600905

¹⁷⁰ Kellert, S. R., Heerwagen, J., & Mador, M. (Eds.). (2008). *Biophilic Design: The Theory, Science and Practice of Bringing Buildings to Life*. Wiley.

¹⁷¹ Taylor, R. P., & Sprott, J. C. (2008). *Biophilic fractals and the visual journey of organic screen-savers*. *Nonlinear Dynamics, Psychology, and Life Sciences*, 12(1), 117-129

the context of extreme living environments. Thanks to research focused on perception, human behaviour, psychology, and the experience of space, scientists were able to identify an optimal level of visual complexity perceived by the human brain, at which an image has a relaxing rather than stressful effect. By analysing brain responses to different levels of scene complexity of the built environment, nature, and even artworks by Pollock, researchers gained insight into these mechanisms^{172, 173}. In the article *Reduction of Physiological Stress Using Fractal Art and Architecture*¹⁷⁴, Richard P. Taylor describes a series of experiments suggesting that images containing fractal patterns of medium complexity (that is, with a fractal dimension D in the range of 1.3-1.5) can effectively reduce physiological stress. A NASA experiment involving Taylor and James Wise showed that viewing artworks containing such patterns reduced skin conductance by up to 60%, indicating a decrease in stress levels among participants while performing cognitive tasks.^{175, 176} Examples of fractal complexity levels are shown in the figure below [Fig. 21].

¹⁷² Taylor, R. P., Spehar, B., Van Donkelaar, P., & Hagerhall, C. M. (2011). *Perceptual and physiological responses to Jackson Pollock's fractals*. *Front. Hum. Neurosci.*, Sec. Sensory Neuroscience. doi.org/10.3389/fnhum.2011.00060

¹⁷³ Taylor, R. P., Micolich, A., & Jonas, D. (1999). *Fractal Analysis Of Pollock's Drip Paintings*. *Nature*, 3rd June edition. doi.org/10.1038/20833

¹⁷⁴ Taylor, R. P. (2006). *Reduction of Physiological Stress Using Fractal Art and Architecture*. *Leonardo*, Vol. 39, No. 3, 245-251. JSTOR MIT-Press

¹⁷⁵ Taylor, R. P. (2006). *Reduction of Physiological Stress Using Fractal Art and Architecture*. *Leonardo*, Vol. 39, No. 3, 245-251. JSTOR MIT-Press

¹⁷⁶ Wise, J. A., & Taylor, R. P. (2002). *Fractal Design Strategies for Enhancement of Knowledge Work Environments*. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, Volume 46, Issue 9. doi.org/10.1177/154193120204600905

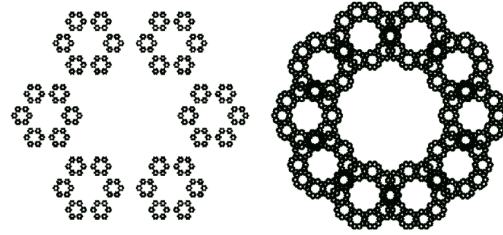


Fig. 4. A visual demonstration of the effect of increasing D for a fractal pattern: two fractal polygons with low (left) and high (right) D values.

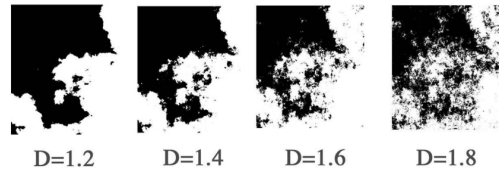


Fig. 5. Fractal images generated using the mid-point displacement method. The fractal dimension increases from left to right: $D = 1.2, 1.4, 1.6$ and 1.8 (Note: all images have an identical density ratio of 50:50 for the black and white regions).

Fig. 21. Fractals with different levels of complexity (D). From left to right, increasing levels of complexity (source: Taylor & Sprott, 2008).

The results of these studies indicate that integrating specific natural patterns into the built environment can be an effective tool for reducing stress and supporting human psychophysical adaptation, which gives them particular importance in the design of long-duration space habitats and other isolated environments.

6. Empirical Experiences

Empirical experiences constitute an important component of this research, enabling the verification of theoretical assumptions within a practical design and experimental context. The conducted activities include both conceptual projects and research implementations in the field of space and extreme architecture, carried out within academic and industrial cooperation. Among them, the author's participation in the simulated space mission PANDA (2021), conducted in the LunAres Research Station in Piła, is of particular importance. This mission enabled direct observation and analysis of human functioning in an isolated environment, taking into account spatial, ergonomic, and psychosocial aspects. The acquired experience made it possible to understand the practical challenges related to designing habitats for long-duration crewed missions and became

a reference point for further research on architectural self-sufficiency in both space and terrestrial contexts.

Another practical experience is the *Lunae Abyssi* project, which received a Gold Mention in the international YAC Moon Station competition in cooperation with the European Space Agency. Its concept constituted a study of lunar architecture based on principles of self-sufficiency, environmental adaptation, and integrated engineering structure in the isolated environment of subsurface lunar lava tubes.

A further research contribution was work on bio-regenerative life support systems carried out during a three-month research internship at the Sasakawa International Center for Space Architecture (SICSA), University of Houston, where models of living spaces integrating biological environmental components within closed life-support loops were developed. In parallel, the Space Volcanic Algae project was conducted, involving a biotechnological experiment carried out aboard the International Space Station in cooperation with NASA, ESA, and the Polish Ministry of Development and Technology. It aimed to investigate the potential of extremophilic microalgae in life-support processes and oxygen production under microgravity conditions.

These project-based experiences constitute a practical verification of the concept of feedback between terrestrial and space environments and provide an empirical foundation for formulating guidelines for the development of self-sufficient architecture of the future.

6.1. Analog Space Mission PANDA

One of the author's key empirical experiences was the simulated space mission PANDA (Pandemic Analog Mission, Q1.M01.2021)¹⁷⁷, conducted at the LunAres Research Station in Piła, one of the few facilities in Europe enabling environmental isolation¹⁷⁸ [Fig. 22]. The mission was carried out in cooperation with the Polish Ministry of Health du-

¹⁷⁷ Lunares Research Station. (n.d.). *Misja PANDA - Lunares*. https://lunares.space/realizacje/panda-mission-m01_q121/ (accessed: 04 February 2026).

¹⁷⁸ Lunares Research Station. (n.d.). *Lunares Space - LunAres Research Station*. <https://lunares.space/> (accessed: 04 February 2026).

ring the COVID-19 pandemic, and its aim was to study the impact of long-term isolation on team behaviour and well-being in a confined environment. The project had an interdisciplinary character, combining psychological, ergonomic, and architectural research, and demonstrated how technologies and strategies developed for space missions can be applied in crises on Earth, such as isolation during a pandemic.



Fig. 22. PANDA mission crew in front of the LunAres Research Station (source: LunAres Research Station, n.d.).

The LunAres habitat is a ground-based analog facility designed to simulate long-term human functioning under conditions of isolation and limited resources. Its spatial layout is based on a clear functional division [Fig. 23], including research, residential, operational, and technical support zones, with a central shared space serving communication and integration functions. An important element of the facility is the airlock connected to the EVA zone, which enables the simulation of extravehicular procedures and the testing of operational sequences characteristic of space missions¹⁷⁹ [Fig. 24]. The architecture of Lunares is modular in character and subordinated to operational and research

¹⁷⁹ Lunares Research Station. (n.d.). Lunares Space - LunAres Research Station. <https://lunares.space/>. (accessed: 04 February 2026).

requirements, functioning as a controlled test environment for analysing relationships between space, technology, and the user under extreme conditions.

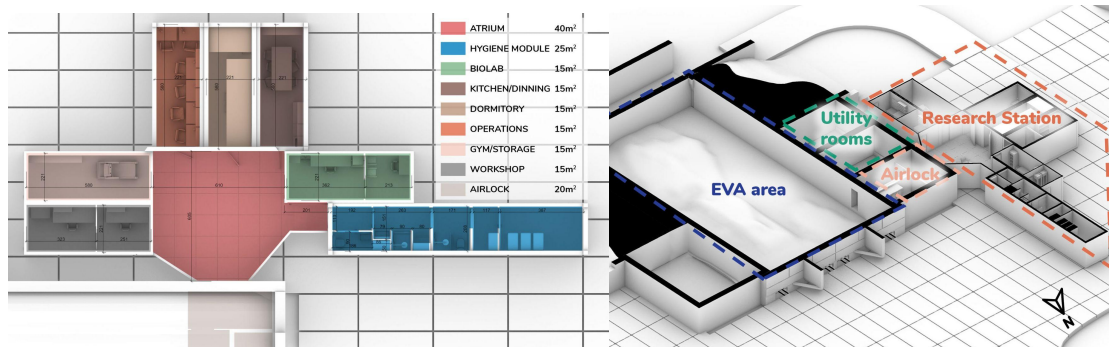


Fig. 23 (left). Functional-spatial layout of the Lunares habitat (source: Lunares Research Station).

Fig. 24 (right). Elements of the Lunares habitat: research zone and EVA zone with airlock (source: Lunares Research Station).

During a two-week stay in isolation in the role of an analog astronaut, the author conducted qualitative and expert research on the functionality, organisation, and ergonomics of the habitat space. Physical and psychosocial factors were analysed, including the impact of the lack of natural stimuli, limited space, and circadian rhythm on work efficiency and crew mood¹⁸⁰. The mission results confirmed that adaptation mechanisms in space isolation are largely similar to those observed during the period of pandemic quarantine. In both cases, the following factors are of key importance:

- maintaining a balance between privacy and collaboration,
- access to elements of nature (biophilic design), even in a simulated form,
- differentiation of spatial functions, enabling switching between work, rest, and physical activity modes,
- control of light and circadian rhythm to support psychophysical health,

¹⁸⁰ Fross, K., & Dziadula, W. (2021). Kosmos na Ziemi - analogowe habitaty kosmiczne. Badania jakościowe podczas symulowanej misji kosmicznej. *Builder Science*, Tom: 288, Nr: 7, doi:10.5604/01.3001.0014.9334

- and providing sensory stimuli that counteract monotony and stress.

The collected data, based on observations, crew diaries, and questionnaires, were used to develop a set of design recommendations (guidelines) for isolated environments, covering aspects of spatial organisation, materials, light, and perception. These conclusions constitute an example of knowledge transfer from space research to civilian applications, highlighting that studies of isolation in space provide valuable guidance for the design of environments with limited social contact¹⁸¹.

The conclusions from the PANDA mission became the starting point for the author's master's thesis project, *S.A.V.E. - Space Analog Village on Earth*, which proposed a self-sufficient underwater analog habitat¹⁸². The project, developed under the supervision of Prof. Klaudiusz Fross, combined experience from analog missions with research on extreme architecture, using the analogy between the underwater environment and microgravity conditions. The S.A.V.E. station was designed as a modular, rotational research complex inspired by orbital structures, enabling the testing of solutions related to closed-loop water, energy, and air systems (ECLSS) as well as biotechnology, including the application of biotechnology to life support systems. The underwater habitat was intended to function as an analog laboratory of self-sufficiency, allowing the study of relationships between architecture, humans, and the environment under extreme conditions. On the next page, the author's note is presented as a part of astronaut's diary, taken during the analog mission in Lunares¹⁸³.

¹⁸¹ Fross, K., Orzechowski, L., Dziaduła, W., & Mintus, A. (2022). *The Panda Space Program in the LunAres habitat - research on needs and behavior during isolation*. w B. Komar, K. Fross, & B. Urbanowicz (Redaktorzy), *Multifaceted research in architecture*. Vol. 2, Architecture against the challenges of the future – smart architecture (s. 22-33). Wydawnictwo Politechniki Śląskiej, 22-33

¹⁸² Fross, K., & Dziaduła, W. (2022). *Analogowe habitaty kosmiczne - badania i koncepcja własna*. *Builder Science*, Tom: 296, Nr: 3. doi:10.5604/01.3001.0015.7363

¹⁸³ Fross, K., Orzechowski, L., Dziaduła, W., & Mintus, A. (2022). *The Panda Space Program in the LunAres habitat - research on needs and behavior during isolation*. w B. Komar, K. Fross, & B. Urbanowicz (Redaktorzy), *Multifaceted research in architecture*. Vol. 2, Architecture against the challenges of the future – smart architecture (s. 22-33). Wydawnictwo Politechniki Śląskiej, 22-33

Hard to sleep.... someone in the capsule next to me snores like a malfunctioning ventilation unit, and to make things worse, I think we're starting to have an issue with CO₂ buildup due to poor air circulation. I woke up with a dull headache again; the kind you get when the atmosphere reminds you it's not really your friend.

I gave up on sleep and started the day early.

Most of today was spent in our hydroponic corner. We irrigated one batch of plants with greywater from hand washing, comparing their growth to the control set. It still feels strange to reuse every drop, but in here recycling. It's a survival. Surprisingly, the plants look healthy. Another small reminder that life adapts even faster than we do.

Food is still freeze-dried and textureless, but I'm beginning to accept this beige mush as my new normal.

The rover gave us trouble again, and tomorrow is our EVA. We spent hours 3D-printing missing parts and fixing whatever we could. By evening, it moved a little. Not enough to make us confident, but enough to give us hope we won't be walking the entire route on foot.

- W.

- _____

Diary entry from the PANDA2021 analog mission in the Lunares habitat (author's elaboration 2021).

6.2. Student Research Missions: SIRIUS, HESTIA I and PEGASUS

Between 2022 and 2024, three research missions were carried out at the Lunares Research Station in Piła as part of the activities of the SpaceDesign Student Research Group at the Faculty of Architecture of the Silesian University of Technology: *SIRIUS* (2022), *HESTIA I* (2023), and *PEGASUS* (2024). These projects were developed as part of the research and educational programme *Scientific Program of Space Architecture (SPSA)*, which has been developed at the Faculty of Architecture of the Silesian University of Technology since 2017¹⁸⁴. Their aim was an empirical investigation of the impact of architecture and spatial organisation on human behaviour in conditions of isolation, in both ergonomic and psychosocial dimensions.

Each experiment carried out by the students during the missions addressed a distinct research topic within the space architecture studies [Fig. 25 and 26]. The *SIRIUS* mission (2022, student Igor Gdula) focused on the study of adaptation processes and methods of creating a supportive environment for psychological well-being in a confined space, using qualitative post-occupancy evaluation (POE) methods and the concept of supportive design. The *HESTIA I* mission (2023, student Julia Brędkowska) concentrated on the analysis of private and shared spaces within the habitat, taking into account individual user needs under conditions of long-term isolation. The research included behavioural observations and an analysis of functional layouts and their influence on stress levels and social relations. The *PEGASUS* mission (2024, student Natalia Ściora) had an analytical and observational character. It focused on tracking user paths, activity dynamics, and spatial accessibility for different participant profiles, including people with limited mobility (persons with disabilities). All three projects were carried out in a research-design format using onboard diaries, participant observation, and individual interviews. As part of the *SIRIUS* mission, a model of a supportive environment in a space habitat was developed, based on R. S. Ulrich's model of a supportive environment in Supportive Design Theory [Fig. 27].

¹⁸⁴ *Scientific Programme of Space Architecture* utworzony pod kierunkiem Prof. PŚ, dr hab. inż. arch. Klaudiusza Fross, ówczesnego Dziakana.



Fig. 25 (left). Photograph from the HESTIA I mission (on the right: student Julia Brędkowska).

Fig. 26 (right). Photograph from the PEGASUS mission (second from the right: student Natalia Ściora).

The collected data made it possible to formulate shared conclusions and design recommendations that can be applied in the design of space habitats as well as in the development of self-sufficient architecture on Earth:

- Spatial flexibility - the habitat should allow changes in function, layout, and modes of use depending on mission phases and crew needs.
- Balance between privacy and community - it is necessary to design spaces that enable both social interaction and individual withdrawal.
- Importance of shared space (atrium) - a central, multifunctional space that integrates the crew plays a key role in maintaining psychological well-being and effective communication.
- Balanced activity rhythm - architecture should support the circadian rhythm, allow variation in activity levels, and simulate the daylight cycle.
- Integration of natural elements (biophilic design) - vegetation, natural textures, and simulation of the external environment significantly reduce stress and support regeneration.
- Possibility of space personalisation - introducing individual elements and symbols of user identity strengthens the sense of control and belonging.

- Inclusive design - diversity of users (age, nationality, mobility) supports the creation of flexible and universal spaces.

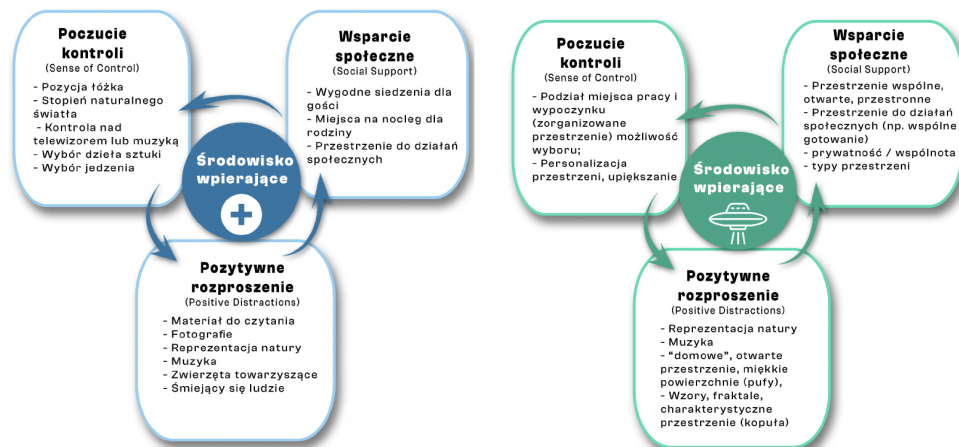


Fig. 27. Two diagrams showing elements of a supportive environment design aimed at stress reduction. The diagram on the right illustrates the understanding of supportive environmental factors in the context of space and extreme architectural design. The diagram on the left refers to Roger Ulrich's Supportive Design Theory for medical environments (author's own elaboration based on Ulrich et al., 1991, and conclusions from the SIRIUS missions).

The students' experiences confirmed that a space habitat should be understood as an environmental system in which human adaptation and interaction with space are key factors under conditions of isolation.

6.3. *Lunae Abyssi* Project

An important element of the author's own design experience, which directly influenced her understanding of architecture in extreme conditions, is her participation in the development of the *Lunae Abyssi* concept - an awarded lunar habitat project located inside a lava tube cave in the Lacus Mortis region [see: Fig. 28]. The project was developed by an interdisciplinary team and received a GOLD Mention in the Moon Station Competition organised by YAC in cooperation with the ESA Topical Teams on Planetary Caves. The detailed concept was described in a publication presented at the 75th International Astronautical Congress in Milan in 2024¹⁸⁵. The project is significant because it integrates issues of habitability, modularity, ISRU, and space psychology in a way that responds to both the technical and psychosocial requirements of future crews.



Fig. 28. Lunae Abyssi habitat located within a lunar lava tube. Visualisation showing double inflatable structures and the rigid core of the modules (courtesy of the Lunae Abyssi team).

Lunae Abyssi was designed as a base located inside a lava tube cave in the Lacus Mortis region, reflecting the growing interest in using subsurface structures as natural

¹⁸⁵ Drozdowska, P., Dziadula, W., Fikus, W., Mintus, A., Orzechowski, L., Pietryszyn, J., & Rębisz, M. (2024). *New Design Approach for Lunar Habitation in Lava Tubes: Lunae Abyssi Project Description and Details*. 75th International Astronautical Congress (IAC) Proceedings, Milano, Italy.

shields against radiation, thermal extremes, and micrometeoroids. Moreover, the project clearly emphasises that architecture should respect the existing geology by integrating it with infrastructure. Lava tubes create exceptional scientific opportunities, as they can become sites for geological, geotechnical, astrobiological, and environmental research related to extremophiles, microclimates, and thermal stability¹⁸⁶.

The use of a cave as a natural “first layer of protection” responds to key environmental factors identified in the literature on extraterrestrial architecture, including the need to reduce the mass of artificial shielding and to stabilise internal conditions. The concept assumes the use of four functional modules: observational, control, research, and recreational. Each module consists of a rigid technological core with deployable envelopes forming the main usable spaces [Fig. 29]. The double-layer envelopes operate at different pressure levels (0.5 bar and 1 bar), creating zones with differentiated functions as well as an additional technical space. This solution reflects a contemporary hybrid approach, in which deployable elements complement prefabricated modules delivered from Earth, and the entire system is placed within a natural structure. According to the approach described in the literature, this type of combination increases transport efficiency, interior adaptability, and environmental protection^{187,188}.

The project also includes a wide range of ISRU strategies, including:

- regolith-printed landing pads and access infrastructure,
- dust protection shields and terrain barriers,
- structural elements reinforcing the cave entrance.

¹⁸⁶ Drozdowska, P., Dziadula, W., Fikus, W., Mintus, A., Orzechowski, L., Pietryszyn, J., & Rębisz, M. (2024). *New Design Approach for Lunar Habitation in Lava Tubes: Lunae Abyssi Project Description and Details. 75th International Astronautical Congress (IAC) Proceedings*. Milano, Italy.

¹⁸⁷ Howe, A. S., & Sherwood, B. (Eds.). (2009). *Out of this World: The New Field of Space Architecture*. American Institute of Aeronautics and Astronautics.

¹⁸⁸ Häuplik-Meusburger, S., & Bannova, O. (2016). *Space Architecture Education for Engineers and Architects: Designing and Planning Beyond Earth*. Springer International Publishing.

The integration of ISRU with architecture responds to the logistical constraints of crewed missions. It aligns with the approach discussed in the literature on third-class habitats, in which a significant portion of the structural mass is sourced locally¹⁸⁹.

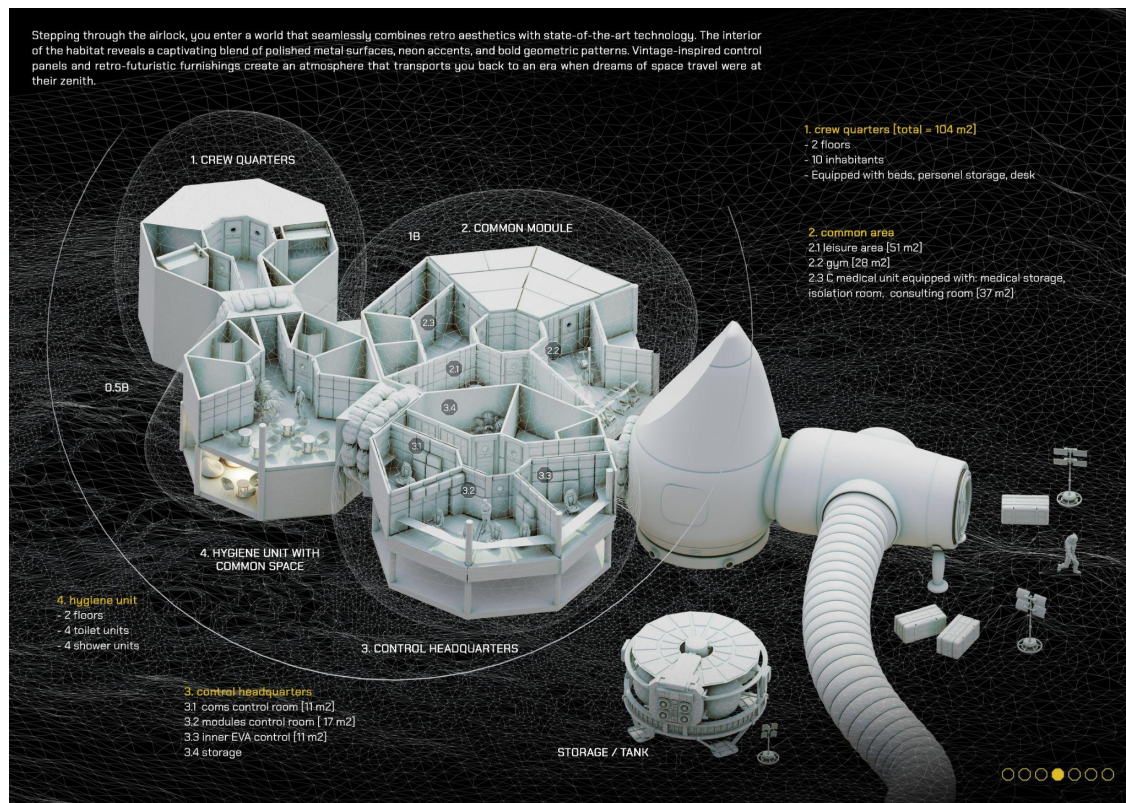


Fig. 29. Interior of a single structure with different types of modules (courtesy of the *Lunae Abyssis* team).

In the arrangement of the individual modules, the direction of access, the geometry of the corridor, and the availability of load-bearing surfaces were taken into account. The cave simultaneously serves as a protective shield, a thermal buffer, a technical space, and a natural “circulation corridor” around which the base is organised.

¹⁸⁹ Kennedy, K. J. (2002). *The Vernacular of Space Architecture*. AIAA Space Architecture Symposium, AIAA 2002-6102.

6.4. APA Mission Mars

As part of the research and design activity, a study concept of a modular space base was developed [Fig. 30], prepared by a team of students from the *SPSA's* Student Research Group under the supervision of Prof. Klaudiusz Fross and with the participation of the author of this dissertation. The project focused on the development of a space habitat intended for research in extreme conditions, with the assumption of simulating lunar and Martian environments. The designed complex has the character of a modular, deployable, and transportable base, capable of functioning as a self-sufficient environment in terms of energy, water, oxygen, and food production. The concept assumed the integration of advanced monitoring and management systems, including building automation (NAZCA MBS), an industrial Internet of Things platform (NAZCA 4.0), environmental and infrastructure protection systems (APA SHILD), and an intelligent energy optimisation platform (IPOE)¹⁹⁰. The applied solutions enabled continuous monitoring of environmental and technical parameters as well as user activity.

The functional program of the base included capsules with diversified functions: residential, laboratory, hydroponic cultivation (soilless), technical, and storage. Two main types of capsules were designed: rectangular, expandable modules with variable usable area, and spherical “origami-type” capsules, deployed from a cylindrical form optimised for rocket transport. The formal and structural inspiration for the deployable forms was the logic of origami as a system of transformable spatial structures. The basic base configuration consisted of six capsules (three rectangular and three spherical), communication connectors, a flight simulator functioning as an antechamber, and an external protective dome simulating Martian or lunar environmental conditions in the context of ground testing. The base was designed for the stay of 4-6 users for a period of up to two weeks, as a test environment for integrated systems of self-sufficiency, operational autonomy, and human-technology-space relations.¹⁹¹.

¹⁹⁰ Based on technologies of APA Group / APA Group. (n.d.). *APA - Integracja automatyki | Robotyka i cyfryzacja przemysłu*. <https://apagroup.pl/> (accessed: 04 February 2026).

¹⁹¹ Fross, K. (2024). Habitat Kosmiczny "APA Misja MARS". *EMNK 2024 „50 wybitnych osiągnięć śląskiej nauki”*, 72-73. <https://us.edu.pl/dzien-nauki-polskiej-w-europejskim-miescie-nauki-katowice/> (accessed: 04 February 2026).

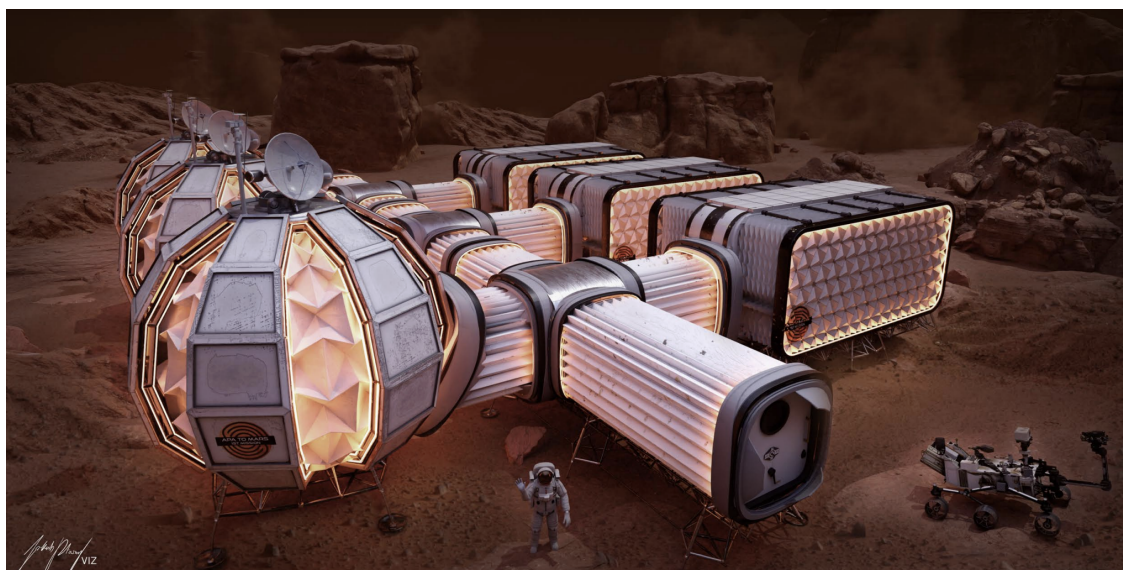


Fig. 30. Visualisation of the modular space base concept (APA Mission MARS) (source: materials of the Space Design Student Research Group; visualisation: Jakub Ptaszny, 2022).

The APA Mission MARS project, carried out in cooperation with an external partner, was included in the list of the “50 Outstanding Achievements of Silesian Science”¹⁹².

6.4. Bio-Regenerative Life Support Systems - own research

In the design of space habitats and advanced built environments on Earth, bio-regenerative systems (discussed in more detail in Section 5.3.2) are playing an increasingly important role, as they enable participation in closed resource loops and reduce dependence on continuous external supplies by using natural processes such as photosynthesis¹⁹³. Bio-Regenerative Life Support Systems (BLSS) represent one of the key technologies supporting self-sufficiency, as they allow air, water, and waste to be transformed into resources that can be reused by the crew^{194, 195}. The importance of BLSS results prima-

¹⁹² Fross, K. (2024). Habitat Kosmiczny "APA Misja MARS". *EMNK 2024 „50 wybitnych osiągnięć śląskiej nauki”*, 72-73. <https://us.edu.pl/dzien-nauki-polskiej-w-europejskim-miescie-nauki-katowice/> (accessed: 04 February 2026).

¹⁹³ Kane, M., & Shasteen, K.C. (2024). *Importance and challenges of integrating BLSS into ECLSS*. *Acta Astronautica*, Volume 220, 185-196. doi.org/10.1016/j.actaastro.2024.04.016

¹⁹⁴ Skoog, I. Å. (1984). BLSS: *A contribution to future life support*. *Advances in Space Research*, Volume 4, Issue 12, 251-262. doi.org/10.1016/0273-1177(84)90569-6

¹⁹⁵ Bartsev, S. I., Gitelson, J. I., Lisovsky, G.M., Mezhevikin, V.V., & Okhonin, V.A. (1996). *Perspectives of different type biological life support systems (BLSS) usage in space missions*. *Acta Astronautica*, Volume 39, Issue 8, 617-622. doi.org/10.1016/S0094-5765(97)00012-X

rily from the relationship between the mass transported on a mission and the amount of resources that can be produced locally. In traditional physicochemical systems, every kilogram of oxygen, water, and food must be launched from Earth, which, with launch costs of several thousand dollars per kilogram, creates a significant logistical and economic barrier for long-duration missions.

In response to these challenges, Extremo Technologies, a Polish biotechnology startup, developed the AirO₂ project, an architectural prototype of a bio-regenerative module based on microalgae¹⁹⁶. The AirO₂ bio-panel [Fig. 31] integrates processes of CO₂ sequestration, oxygen production, and real-time visualisation of biological activity, creating an architectural element that filters air and produces nutritious biomass. The panel was designed as a scalable module suitable for terrestrial environments, such as offices, schools, residential areas, and recreational interiors, and as a prototype technology that could, in the future, be integrated into orbital and lunar habitats.

The development of AirO₂ led to the *Space Volcanic Algae* project¹⁹⁷, which represents a scientific extension and experimental validation of BLSS-oriented assumptions. Within this experiment, extremophilic microalgae originating from volcanic ecosystems on Earth were tested in an orbital environment for the first time. These species are characterised by exceptional tolerance to low pH, high temperatures, high CO₂ concentrations, and radiation-induced damage, making them a promising biological resource for future bio-regenerative systems in space conditions¹⁹⁸. The Space Volcanic Algae experiment was conducted as part of the IGNIS mission, the first Polish technological-scientific mission involving a Polish astronaut, Dr. Sławosz Uznański-Wiśniewski [Fig. 32], organised in cooperation with the Ministry of Development and Technology, the Polish Space Agency, and the European Space Agency. The experiment was carried out during the Axiom 4 mission on 25 June 2025 and had a demonstrator character, enabling veri-

¹⁹⁶ Extremo Technologies. (n.d.). *Extremo Technologies*. <https://extremo.tech> (accessed: 04 February 2026).

¹⁹⁷ Extremo Technologies. (n.d.). *Space Volcanic Algae - ISS*. <https://extremo.tech/2024/07/26/volcanic-space-algae-iss-2/> (accessed: 04 February 2026).

¹⁹⁸ Dziaduła, W., Borowska, E., Urbańska, W., & Nowak, B. (2023). *Innovations in bio-space architecture for climate change relief. International Astronautical Congress (IAC) Proceedings 2023*, International Astronautical Federation (IAF), Baku, Azerbaijan.

fication of the technology in the environment of the International Space Station¹⁹⁹. The ISS experiment, as part of the AirO₂ implementation, made it possible to test and confirm whether the species used in the bio-panel can maintain metabolic stability, photosynthesis rate, and structural integrity, also beyond Earth.



Fig. 31 (left). Conceptual graphic of the bio-panel developed by Extremo Technologies, based on volcanic microalgae (source: courtesy of Extremo Technologies).

Fig. 32 (right). Dr Sławosz Uznański-Wisniewski on the International Space Station holding a microlaboratory equipped with “cube” sensors containing extremophilic algae (source: courtesy of ESA/NASA/Axiom)

The conclusions from both projects indicate that the integration of biotechnology with architecture has the potential to transform buildings and habitats into metabolic systems capable of producing resources. The projects also confirm that microorganisms characterised by high environmental resistance (including in space) can function as stable functional units within closed-loop systems, and that biological processes can be successfully combined with architectural functions. At the same time, the implementation of AirO₂ and Space Volcanic Algae revealed a significant technological gap in the integration of biotechnology with architecture and sustainability systems. At present, there is a lack of mature solutions that combine microbiological systems with building materials, HVAC (Heating, Ventilation, and Air Conditioning) installations, and indoor envi-

¹⁹⁹Axiom Space. (n.d.). *Axiom Mission 4*. Axiom Space. <https://www.axiomspace.com/missions/ax4> (accessed: 04 February 2026).

ronmental control tools. Meaning that bioreactors still operate as components separated from the building structure.

7. Case study

Based on the adopted research assumptions, a case study analysis was conducted, the aim of which was a detailed examination of solutions related to self-sufficiency in extreme environments. In this dissertation, the architectural case study method functions both as an analytical tool and as a way of building design-oriented knowledge. As emphasised by E. Niezabitowska, referring to Richard Foqué²⁰⁰, case studies occupy an important position in architecture because they allow researchers to “*examine existing buildings, their design processes, logic, context, and operating conditions*”²⁰¹. Foqué points out that, unlike experimental sciences, architecture cannot rely solely on controlled experiments; therefore, the analysis of complex, multidimensional cases constitutes the most effective method of understanding architecture as a knowledge-based practice. Case studies are not limited to describing a building or object but also include its relationships with the environment, users, and systems. Foqué distinguishes multiple case studies, which enable the comparison of several objects and the identification of patterns, typologies, and design paradigms. This form of research is particularly important in extreme environments, where architectural solutions are often developed at the limits of technological and psychosocial possibilities. Their analysis allows for the formulation of knowledge of a universal nature, that is, transferable to other projects and contexts.

The selection of case studies in this dissertation was purposive (purposive sampling) and was guided by the possibility of analysing architecture operating under extreme environmental, logistical, and resource constraints. The selected objects and research environments differ in terms of the degree of isolation, duration of use, level of dependence on external infrastructure, and the scope of integration of autonomous systems. This approach made it possible to extract a wide range of adaptive solutions for specific

²⁰⁰ Foqué, R. (2010). *Building Knowledge in Architecture*. UPA.

²⁰¹ Niezabitowska, E. (2014). *Metody i techniki badawcze w architekturze*. Wydawnictwo Politechniki Śląskiej.

case examples. The analysis allows for the identification of both recurring and unique design strategies, adaptive mechanisms, and technologies supporting self-sufficiency, which constitute a basis for future design-oriented and theoretical research. Moreover, the case study method enables the evaluation of architecture as a complex system composed of technical and psychosocial components, which is of key importance for the study of habitats in which humans operate within an assumed environment encompassing contexts broader than the building alone. In accordance with this approach, this chapter applies multiple case studies, covering both facilities operating in real ICE (Isolated, Confined, Extreme) conditions and conceptual projects of proposed future extra-terrestrial bases, with a focus on technological and psychosocial solutions. The analysis includes polar, desert, underwater, and orbital environments, which, despite programmatic differences, are united by the necessity to function in isolation from external resources, limited space, and extreme environmental loads. Analog habitats were also included in the study as an inseparable element of extreme architecture with a well-documented scope and research background.

Overview of selected facilities included in the case study analysis:

7.1. Polar Environments

7.1.1. Halley VI Research Station (Antarctica), because it is a modular polar research station designed to operate in extreme environmental conditions.

7.1.2. FMARS (Flashline Mars Arctic Research Station), because it is an isolated analog habitat on Devon Island in the Arctic, simulating conditions of Martian missions.

7.2. Desert Environments

7.2.1. Analog environments: MDRS (Mars Desert Research Station), because it is an analog habitat repeatedly used by NASA and The Mars Society for Martian mission simulations.

7.2.2. Desert Mars Analog Ramon Station (D-MARS), because it is an isolated analog habitat located in desert conditions.

7.3. Underwater Environments

7.3.1. Tektite, because it is one of the most important projects in the history of underwater research, is groundbreaking for the development of long-duration saturation missions and space research.

7.3.2. Aquarius Reef Base, because it is an underwater research station used, among others, in the NASA NEEMO program.

7.4. Space Environments (LEO - Low Earth Orbit)

7.4.1. Skylab, because it was the first American orbital station and a pioneering example of research on long-term human presence in orbit.

7.4.2. International Space Station (ISS), because it is the largest orbital laboratory, continuously inhabited since 2000.

7.5. Lunar Environments (conceptual projects)

7.5.1. Foster + Partners' Lunar Base Concept, because it is a partially 3D-printed lunar base concept developed in cooperation with ESA.

7.6. Martian Environments (conceptual projects)

7.6.1. Hassell + Eckersley O'Callaghan Martian Habitat, because it is a Martian habitat concept combining inflatable structures with regolith shielding, a project awarded in a NASA competition.

Each case study analysis is introduced by a subsection describing the environment in which the facility is located, because, as established in the previous parts of the thesis, the external environment determines the selection of applied design and technological solutions. At the end of each description, a summary table is included, synthesising the discussed issues and distinguishing technological and psychological solution domains

as two complementary components derived from the preceding literature analyses. The comparison is presented in the form of a table with a *Design Challenge* column, representing the design challenge/constraint, and the corresponding specific solution implemented in a given project or facility, the *Design Factor*.

7.1. Polar Environments

Polar environments are characterised by extremely low temperatures, which during the winter period in Antarctica can drop even below -80°C , typically to around -55°C ²⁰². An additional factor is the seasonality of sunlight, manifested in the phenomena of polar day and polar night, which have a significant impact on human biological rhythms as well as on the energy systems of facilities²⁰³. Strong katabatic winds, reaching considerable speeds, pose a threat to infrastructure, while geographic isolation means that access to facilities is seasonal and requires complex logistics. The lack of local natural resources (food, drinking water, construction materials) necessitates the use of recycling systems and careful supply planning. From a psychosocial perspective, staying in polar environments involves long-term isolation, disrupted circadian rhythm, limited living space, and the necessity of close coexistence in small groups²⁰⁴.

7.1.1. Halley VI

Halley VI, located on the Brunt Ice Shelf in Antarctica, is the world's first mobile research station of this type [Fig. 33]. The architects of the station were Hugh Broughton Architects, working together with industry consultants and contractors, including AECOM, Galliford Try International, Billings Design Associates, and Colour Effects. The station operates under the management of the British Antarctic Survey and was designed for conducting atmospheric, geological, and glaciological research, including

²⁰² British Antarctic Survey. (2014). *Halley VI Research Station*. <https://www.bas.ac.uk/polar-operations/sites-and-facilities/facility/halley/> (accessed: 04 February 2026).

²⁰³ Suedfeld, P., & Palinkas, L. A. (2008). *Psychological effects of polar expedition*. *Lancet*, 12;371(9607). doi:10.1016/S0140-6736(07)61056-3.

²⁰⁴ Stuster, J. (2010). *behavioural Issues Associated With Long Duration Space Expeditions: Review and Analysis of Astronaut Journals*. Experiment 01-E104 (Journals) Final Report for NASA.

long-term monitoring of the ozone layer²⁰⁵. The station can accommodate up to 16 people during the winter and up to 62 during the summer season, with mission durations ranging from three to nine months²⁰⁶.

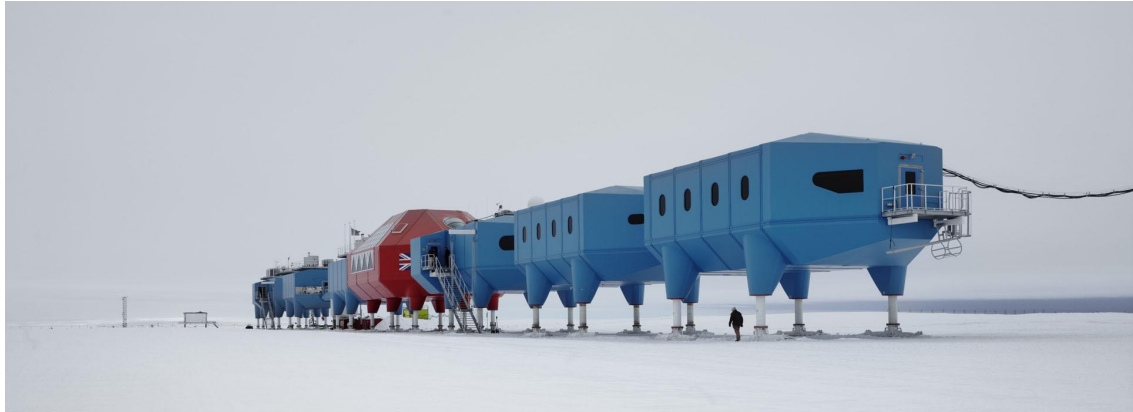


Fig. 33. Halley VI from the north (źródło: *SpaceArchitect.org*, n.d.)

As emphasised by the authors of the facility, previous structures in this region failed because they either collapsed under the weight of snow or were not resistant to extreme climatic conditions²⁰⁷. These experiences led to the development of Halley VI as a modular structure that “climbs” above the snow surface. Each of the eight modules is supported on hydraulic legs ending with “skis,” which makes it possible to relocate the entire station as the glacier gradually moves toward the ocean. The modules were fully prefabricated and assembled only on site in order to minimise problems resulting from harsh conditions. Their structure consists of a steel frame clad with highly insulated GRP composite panels²⁰⁸.

The design also addressed issues of living and working comfort in isolation. The interiors [Figs. 34 and 35] were designed with the involvement of psychologists, with a carefully selected colour palette to mitigate the effects of the long polar night, and the use

²⁰⁵ Hugh Broughton Architects. (n.d.). *Halley VI British Antarctic Research Station*. Hugh Broughton Architects - Halley VI. <https://hbarchitects.co.uk/halley-vi-british-antarctic-research-station/> (accessed: 04 February 2026).

²⁰⁶ British Antarctic Survey. (2014). *Halley VI Research Station*. <https://www.bas.ac.uk/polar-operations/sites-and-facilities/facility/halley/> (accessed: 04 February 2026).

²⁰⁷ Hugh Broughton Architects. (n.d.). *Halley VI British Antarctic Research Station*. Hugh Broughton Architects - Halley VI. <https://hbarchitects.co.uk/halley-vi-british-antarctic-research-station/> (accessed: 04 February 2026).

²⁰⁸ Slavid, R. (2015). *Ice Station: The Creation of Halley VI: Britain's Pioneering Antarctic Research Station*. Park Books.

of daylight-simulating lamps to regulate circadian rhythms. Natural materials, such as wood, were used to provide sensory contact with nature, while the spatial organisation and lighting support social interaction and reduce the sense of isolation²⁰⁹.



Fig. 34 (left). Halley VI bedroom (source: SpaceArchitect.org, n.d.).

Fig. 35 (right). Social Module (source: SpaceArchitect.org, n.d.).

Life-support systems were designed to operate independently for each module, allowing for emergency operation. The modules are connected by technical bridges enabling the exchange of energy, water, and wastewater [Fig. 36]. The heat recovery system is complemented by additional heat recovery solutions and auxiliary renewable installations used seasonally, while fresh water production relies on snow-melting installations. Wastewater is treated using UV radiation and centrifuges, and the purified water is returned to the environment. Solid waste is collected and incinerated, and in the future it may be used as fertiliser²¹⁰.

²⁰⁹ Hugh Broughton. *Behind the architecture of the UK's Antarctic station*. (2013). British Council. <https://www.britishcouncil.org/voices-magazine/behind-the-architecture-of-the-uks-antarctic-station> (accessed: 04 February 2026).

²¹⁰ Slavid, R. (2015). *Ice Station: The Creation of Halley VI : Britain's Pioneering Antarctic Research Station*. Park Books.

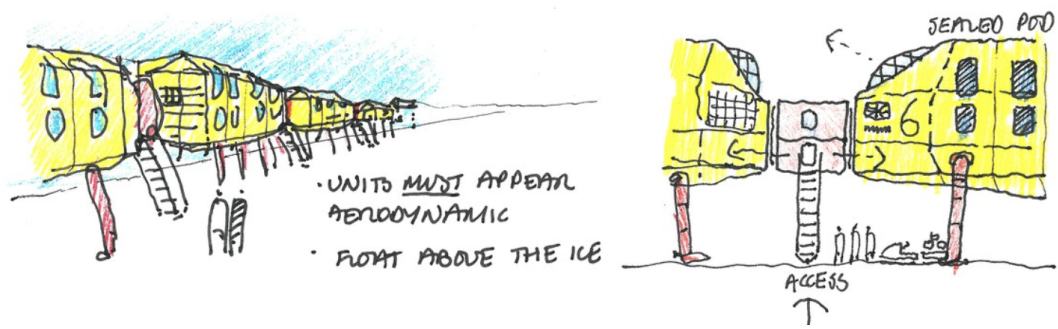


Fig. 36. Concept sketch (source: Hugh Broughton Architects, n.d.).

Halley VI consists of eight interconnected modules forming a linear arrangement [Fig. 37]. Each module was designed to perform a specific function, allowing for an efficient separation of work areas and everyday living spaces. The station structure includes residential modules providing private cabins and social spaces, research laboratories intended for atmospheric, glaciological, and geological analyses, as well as technical and energy modules responsible for the operation of the entire system. A central position is occupied by the shared module, which serves as a recreational and integrative space for the crew. The functional division was designed so that each module can operate independently in emergency situations, increasing safety and flexibility of use in the extreme Antarctic conditions²¹¹.

²¹¹ Slavid, R. (2015). *Ice Station: The Creation of Halley VI : Britain's Pioneering Antarctic Research Station*. Park Books.

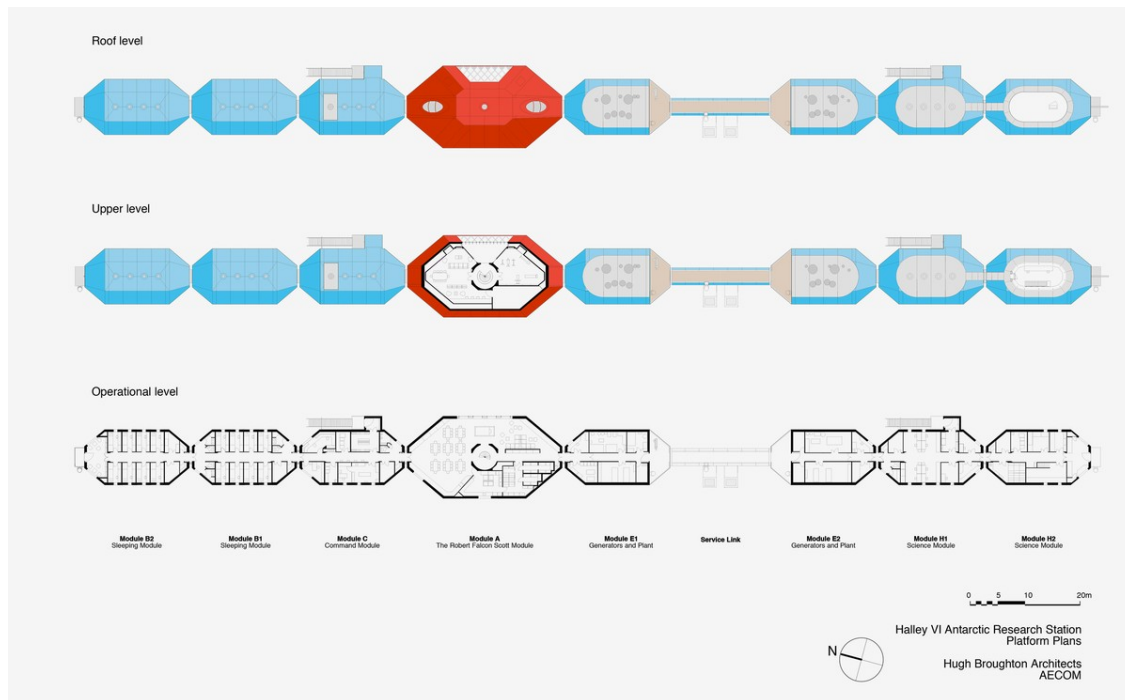


Fig. 37. Halley VI plans (source: Hugh Broughton Architects, n.d.).

The colour palette of the façades was also developed to counteract environmental monotony and the negative effects of the long polar night. The most characteristic solution is the central module in red, which functions as the heart of the station, housing the dining area, recreational space, and meeting areas. This colour was chosen for its stimulating and energising character, which supports activity and social integration under conditions of isolation²¹². At the same time, the red module serves as a clear landmark, facilitating orientation within and around the complex. In the residential zones, cooler and more subdued colours were used, promoting rest and psychological calm.

The following table [Table 4] provides a synthetic summary of the Halley VI case study analysis, organising the main design challenges and the applied response strategies.

²¹² Slavid, R. (2015). *Ice Station: The Creation of Halley VI : Britain's Pioneering Antarctic Research Station*. Park Books.

Table 4. Summary - Synthesis of Case Study Analysis - Halley VI

Design Challenge (constraint)	Design Factor (solution)
Technological Solutions	
Function: research base, scientific studies for personnel in winter and in summer.	Modular base; habitation modules, research laboratories, technical and energy support facilities, communal spaces, and a communication module.
Burial and structural sinking in snow.	Modules placed on hydraulic supports equipped with ski-like foundations.
Extreme cold and strong winds.	Steel structure combined with insulation using GRP composite panels.
Logistical challenges.	Prefabrication of modules and on-site assembly.
Glacier movement toward the ocean.	Station mobility – ability to relocate modules.
Sustainable resource management.	Heat recovery system, snow melting, water and waste recycling.
Operation during emergency conditions.	Independent modules with dedicated power supply and systems.
Psychosocial Solutions	
Long polar night and lack of natural light.	Daylight-simulating lamps; colour palette selected in collaboration with psychologists.
Living and working in isolated, extreme conditions – occupational hygiene.	Separation of living and working areas through an extended circulation corridor; provision of shared, integrative spaces and private quarters.
Isolation and environmental monotony.	Use of natural materials (e.g., wood, texture, scent); red module as a characteristic element and spatial dominant.
Need for comfort and social integration.	Carefully designed lighting and spatial planning support social interaction.

7.1.2. FMARS

Flashline Mars Arctic Research Station (FMARS) was established in 2000 as an initiative of The Mars Society, founded by Robert Zubrin in 1998²¹³. The station was built on Devon Island in Canada, in the Arctic region, which, in terms of climate and geology, constitutes one of the best terrestrial analogs of conditions found on Mars [Fig. 38].



Fig. 38. Flashline Mars Arctic Research Station (FMARS) (source: Shiro, 2019; Wikimedia Commons).

FMARS takes the form of a cylindrical, two-level habitat with a diameter of approximately 8 meters, designed to accommodate a small crew. A typical rotation includes 4-6 people, and mission duration ranges from several weeks to several months. The main objective of FMARS is to conduct simulations of Martian missions under conditions of isolation and limited resources; exploratory procedures, crew management systems, communication protocols, and life-support strategies in a closed environment are tested there²¹⁴.

The spatial layout of FMARS is based on a two-level cylindrical structure with a diameter of approximately eight meters. The habitat is divided into zones: the lower level serves technical functions, while the upper level is dedicated to residential and social spaces [Fig. 39]. The lower level includes technical and laboratory functions, housing

²¹³ Flashline Mars Arctic Research Station. (n.d.). <https://fmars.marssociety.org/about-the-fmars/> (accessed: 04 February 2026).

²¹⁴ Clancey, W. J. (2002). *A FRAMEWORK FOR ANALOG STUDIES OF MARS SURFACE OPERATIONS Using the Flashline Mars Arctic Research Station*. NASA/Ames Research Center. <https://billclancey.name/ClanceyMarsSoc2000.pdf> (accessed: 04 February 2026).

facilities for scientific research, storage areas, and energy and life-support systems. The upper level is intended for residential and social purposes and includes private crew quarters, a kitchen, a dining area, and a common space for integration and recreation²¹⁵. This functional division enables a clear separation of work from everyday life while allowing for efficient use of limited space. The solution increases crew operational ergonomics and supports research on the dynamics of small-group functioning under conditions of isolation, an essential element in the simulation of future Martian missions.

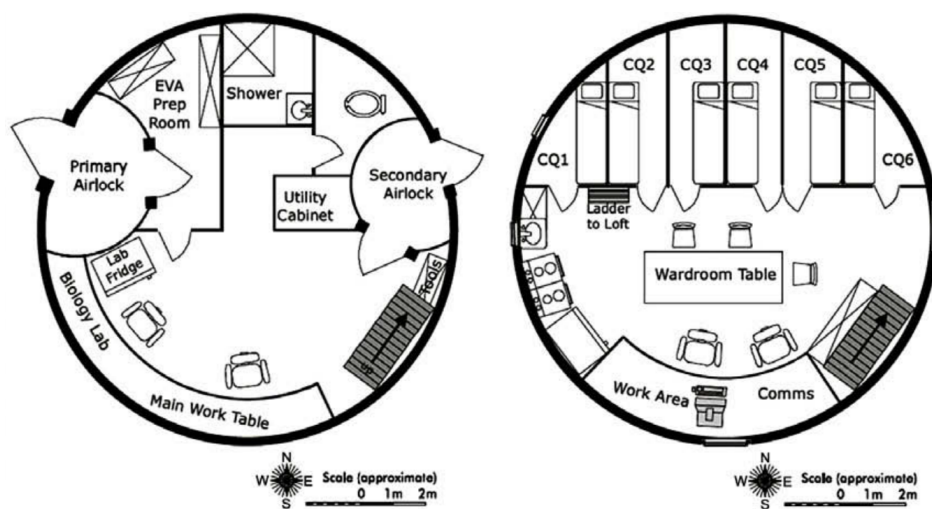


Fig. 39. FMARS plan. Layout of the lower (left) and upper floors (right) (source: Osburg, 2004).

The technological solutions include systems for energy production and conservation (combustion generators, experimental solar panels), water recovery and storage, as well as basic air purification systems²¹⁶. In terms of psychosocial solutions, FMARS allows the study of how a small group of people functions under conditions of isolation, a monotonous environment, and delayed communication with “mission control.” A day-night rhythm imitating space mission conditions is applied, along with protocols of limi-

²¹⁵ Ferrone, K., Cusack, S. L., Garvin, C., Kramer, W. V., Palaia, J. E., & Shiro, B. (2010). *Flashline Mars Arctic Research Station (FMARS) 2009 Crew Perspectives*. *SpaceOps 2010 Conference*, AIAA 2010-2258. doi:10.2514/6.2010-2258

²¹⁶ Bamsey, M., Berinstein, A., Auclair, S., Battler, M. M., Binsted, K., Bywaters, K. F., Harris, J., Ko-
brick, R. L., & McKay, C. P. (2009). *Four-month Moon and Mars crew water utilization study conducted at the Flashline Mars Arctic Research Station, Devon Island, Nunavut*. *Advances in Space Research*, 43, 1256-1274.

ted contact with the outside world and duty rotations, to test the psychological and social resilience of the crew²¹⁷. An important element is also simulated EVA activities in suits, which introduce additional stress and fatigue while simultaneously training safety procedures and cooperation in an extreme environment.

The following table [Table 5] provides a synthetic summary of the FMARS case study analysis, organising the main design challenges and the applied response strategies.

²¹⁷ Clancey, W. J. (2002). *A FRAMEWORK FOR ANALOG STUDIES OF MARS SURFACE OPERATIONS Using the Flashline Mars Arctic Research Station*. NASA/Ames Research Center. <https://billclancey.name/ClanceyMarsSoc2000.pdf> (accessed: 04 February 2026).

Table 5. Summary - Synthesis of Case Study Analysis - FMARS

Design Challenge (constraint)	Design Factor (solution)
Technological Solutions	
Operation in Arctic isolation.	Diesel generators and solar panels as energy sources.
Limited access to water.	Water storage and recovery system.
Limited air resources and the need for recirculation.	Basic filtration systems and internal atmosphere control.
Small, confined space and transport logistics in Mars-type cargo constraints.	Two-level cylindrical structure compatible with cargo dimensions (laboratory and habitation areas).
Simulation of field exploration.	EVA procedures using suits in challenging terrain.
Transport and logistical constraints.	Prefabricated structure, simple to assemble in field conditions.
Psychosocial Solutions	
Small, isolated crew (4–6 people).	Rotation of duties and clear role distribution.
Long-term isolation and environmental monotony.	Simulation of day/night rhythm and organisation of life through structured schedules.
Remote location - limited communication with “mission control.”	Delayed communication protocols and psychological resilience testing.
Stress associated with EVA operations.	Simulated EVA procedures and teamwork and safety training.
Need for social integration and privacy in a confined space.	Shared living and recreational areas on the upper level.

7.2. Desert Environments

Desert environments constitute research contexts for analog architecture, particularly related to the exploration of Mars. The literature on planetary analogs emphasises that hyper-arid deserts, such as the Atacama or Mojave, exhibit environmental characteristics especially similar to conditions on the surface of Mars, including extreme aridity, low water availability, high levels of UV radiation, and limited biological activity²¹⁸. These properties make desert areas frequently used as natural laboratories for testing technologies, operational procedures, and life-support systems.

The characteristics of desert environments include a set of extreme climatic factors. One of the key parameters is a large diurnal temperature amplitude. During the day, surface temperatures may exceed 45°C, while at night they can drop below 0°C due to low air humidity and the lack of atmospheric heat retention²¹⁹. As a result, rapid changes in thermal loads occur, which require the use of technologies with high thermal inertia, passive solutions, and appropriately designed solar protection. Desert environments are also characterised by extremely low relative humidity, low annual precipitation, and high levels of insolation, which lead to rapid material degradation and the need to apply strategies that minimise the impact of radiation. In the context of extreme architecture, the isolation of deserts and their limited access to resources are also of particular importance. In many desert regions, access to energy, water, or transport infrastructure is limited or nonexistent, which makes them valuable platforms for testing self-sufficient solutions, resource recovery technologies, and off-grid energy systems. Such environments allow for a realistic simulation of logistics and operational challenges associated with future crewed missions²²⁰.

²¹⁸Antunes, A., Lau Vetter, M. C. Y., Flannery, D., & Li6, Y. (2023). Editorial: Mars analogs: Environment, habitability and biodiversity. *Frontiers in Astronomy and Space Sciences*, Volume 10 - 2023. doi.org/10.3389/fspas.2023.1208367

²¹⁹ Middleton, N., Thomas, D. S. G., & United Nations Environment Programme. (1992). *World Atlas of Desertification*. Edward Arnold.

²²⁰ Bannova, O. (2016). *Designing for Extremes: A Methodological Approach to Planning in Arctic Regions*. Department of Architecture, Chalmers University of Technology.

7.2.1. MDRS - Mars Desert Research Station

Mars Desert Research Station (MDRS), located near Hanksville in the state of Utah, USA, is one of the longest-operating analog habitats used for research related to future crewed missions to Mars [Fig. 40]. The station was designed and is maintained by The Mars Society as a site for conducting field research under conditions of isolation, limited space, and landscape morphology similar to that of Mars²²¹. The terrain surrounding MDRS is described in the literature as a Mars analogue site, as its rock outcrops, diverse surface textures, geological layering, and rich colouration are well suited for testing geological perception, EVA exploration, and the simulation of astronaut activities²²². In particular, studies indicate the presence of numerous erosional landforms, surfaces with strong colour contrasts, and layered structures, which constitute a natural testbed for computer vision methods and field documentation²²³.



Fig. 40. MDRS facility complex (source: The Mars Society, n.d.).

²²¹ Mars Desert Research Station. (n.d.). *Mars Desert Research Station*. <http://mdrs2016.marssociety.org/about/index.html> (accessed: 04 February 2026).

²²² Martins, Z., Sephton, M.A., Foing, B.H., & Ehrenfreund, P. (2011). *Extraction of amino acids from soils close to the Mars Desert Research Station (MDRS), Utah*. *International Journal of Astrobiology*, 10 (3), 231-238.

²²³ Gross, C., Wendt, L., McGuire, P.C., Bonnici, A., Foing, B.H., Souza-Egipsy, V., Bose, R., Walter, S., Ormö, J., Díaz-Martínez, E., Oesker, M., Ontrup, J., Haschk, R., & Ritter, H. (2009). *Testing the Cyborg Astrobiologist at the Mars Desert Research Station (MDRS), Utah*. *European Planetary Science Congress Proceedings*, 4.

Mars Desert Research Station consists of a group of facilities arranged along a main circulation axis leading from the residential-operational building toward the research modules [Fig. 41]. The central element of the station is the Hab (the Habitat) which takes the form of a two-level cylindrical structure with a compact layout. This corresponds to typical design solutions considered for future Martian habitats, where modularity, efficient use of space, and reduction of structural mass are key factors²²⁴. Hab serves as the starting point for all EVA operations and as the center of crew life and work.

To the east of the Hab, scientific and technical facilities are located. In its immediate vicinity is the GreenHab, a greenhouse module in which plant cultivation, aquaponic experiments, and studies on temperature and microclimate control are conducted. Its function is to simulate biologically based life-support systems (ECLSS) relying on food and oxygen production. Another facility is the Science Dome, a domed building intended for geological, biological, and analytical research. It contains laboratory space equipped for the analysis of samples collected during EVA field activities. The domed form represents a design interpretation of lightweight pneumatic structures considered in extraterrestrial architecture.

The station also includes an Observatory, used for observations of stars and solar activity. Its research program covers both planetary science and crew training in the use of optical instruments²²⁵. All MDRS modules are connected by a network of circulation paths, and their layout reflects the functional logic of a planned Martian base: separation of residential and laboratory spaces, provision of safe access during EVA, and the ability to conduct parallel experiments without disrupting habitat operations. The entire complex serves as infrastructure for human factors research, testing operational procedures, and evaluating architectural and technological solutions under conditions of isolation and a Mars-like environment.

²²⁴ Häuplik-Meusburger, S. (2011). *Architecture for Astronauts: An Activity-based Approach*. Springer.

²²⁵ Vanderdonckt, J., Vatavu, R.-D., Manon, J., Saint-Guillain, M., Lefevre, P., & Marquez, J. J. (2024). *Might as Well Be on Mars: Insights on the Extraterrestrial Applicability of Interaction Design Frameworks from Earth*. Conference: CHI '24: CHI Conference on Human Factors in Computing Systems. doi:10.1145/3613905.3650807



Fig. 41. MDRS facility complex (source: Vanderdonckt et al., 2024).

The lower level of the main HAB serves as the operational zone, integrating technical, preparatory, and laboratory activities. It contains two airlocks (the main and the engineering airlock), an EVA preparation area with analog spacesuits, a workshop, and a biological-geological laboratory [Fig. 42]. This layout reflects the logic of extravehicular operations, in which the sequence-preparation → EVA exit → return → decontamination and sample transfer-must proceed smoothly without interfering with the living space²²⁶. MDRS allows this principle to be tested in practice: the lower level is an intensively used, high-stress operational space where research work is carried out, equipment is prepared, and field missions are supported [Fig. 43].

The upper level of the HAB serves residential and social functions and constitutes a “habitable environment” in which the crew spends most of its time outside EVA and technical tasks. It includes six small private cabins, a kitchen, a dining area, computer workstations, and a common space²²⁷. The central dining area, as the key point of the entire level, functions as a place for meals and as a space of social regulation that influences the synchronisation of daily rhythms and the stabilisation of interpersonal dynamics, which is particularly important in isolated environments.

²²⁶ Doule, O. (2014). *MDRS - Mars Analog Outpost Growth*. AIAA SPACE Forum, AIAA SPACE 2014 Conference and Exposition. doi:10.2514/6.2014-4407

²²⁷ The Mars Society. (n.d.). Mars Desert Research Station. The Mars Society, <https://www.marssociety.org/> (accessed: 04 February 2026).

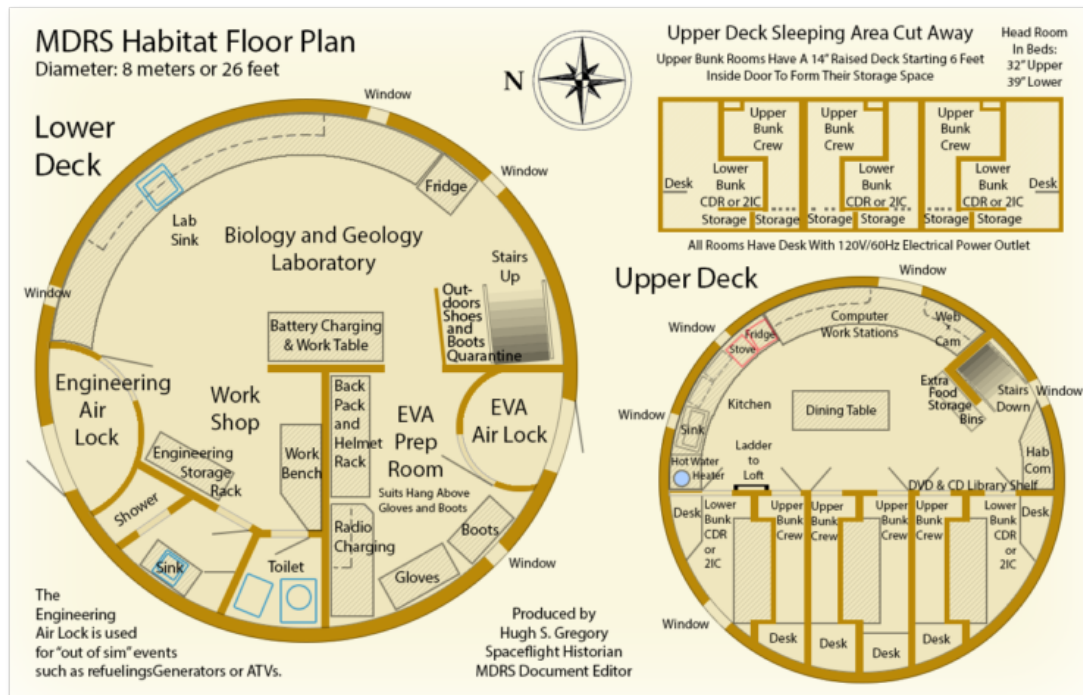


Fig. 42. Plan of the MDRS HAB (source: The Mars Society, n.d.).

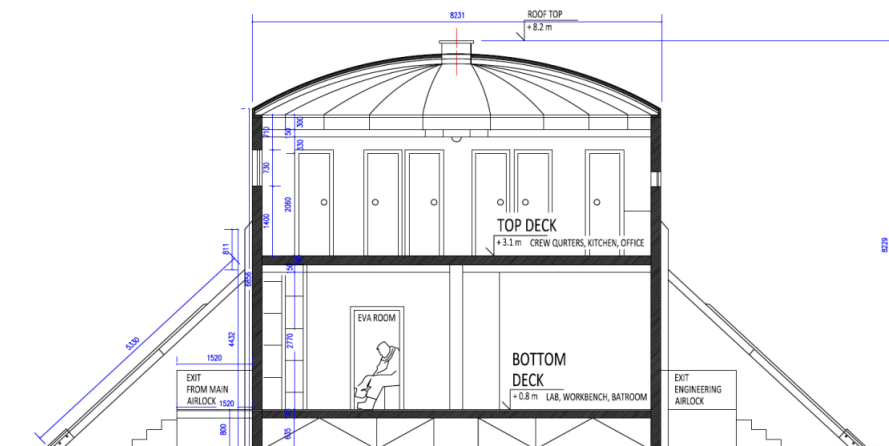


Fig. 43. Section through the MDRS Hab (source: Doule, 2014).

The following table [Table 6] provides a synthetic summary of the MDRS case study analysis, organising the main design challenges and the applied response strategies.

Table 6. Summary - Synthesis of Case Study Analysis - MDRS

Design Challenge (constraint)	Design Factor (solution)
Technological Solutions	
Limited access to water in a desert environment.	Water storage system and strict rationing protocols.
Energy supply in the absence of infrastructure.	Diesel generators as the primary energy source, solar panels
High temperature amplitudes and intense solar exposure.	Thermal insulation of the Hab.
Dust, erosion, and dry winds characteristic of Utah.	Reinforced entrances, platforms, and EVA airlocks
Maintaining stable conditions for biological research.	GreenHab: humidity, temperature, and LED lighting control systems
Simulation of Martian EVA conditions.	Analog suits limiting mobility and visibility;
Limited field communication.	Fixed reference points (Hab, Dome, Observatory) as navigation elements.
Station maintenance under conditions of isolation from technical support.	Simple, modular constructions
Demand for space for scientific analysis.	Science Dome with facilities for geological and biological analyses.
Psychosocial Solutions	
Isolation and limited social contact.	Central shared space in the Hab
Monotonous landscape.	Differentiated module forms
Lack of privacy within a small crew.	Individual sleeping cabins, personal micro-space.
Stress in a hostile environment.	Green, humid GreenHab space as an element of nature.
Difficulty separating work from rest.	Physical separation of functions.
Loss of spatial orientation in a monotonous terrain.	Clear module identification and axial layout improving wayfinding while wearing suits with limited visibility.

7.2.2. D-MARS

Desert Mars Analog Ramon Station (D-MARS) is an Israeli research infrastructure located in Makhtesh Ramon in the Negev Desert, designed as a Mars analog base enabling simulated crewed missions, technological testing, and psychosocial research in extreme environmental conditions [Fig. 44]. The station was established in 2018 and from the outset has been developed as a project combining scientific research, education, and the development of space technologies²²⁸. Its location within Makhtesh Ramon was selected due to its exceptional similarity to Martian environments and, consequently, its suitability for research focused on geology.

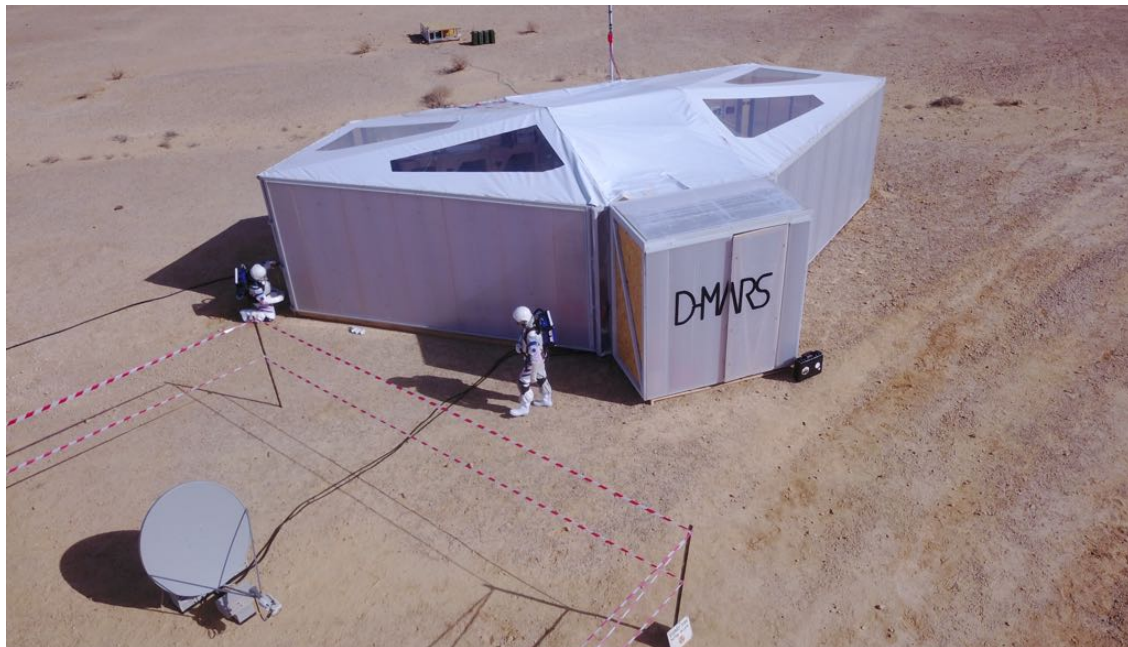


Fig. 44. D-MARS project, Oded Aharonson drone EVA footage (source: Kletetschka & Aharonson, 2018; Wikimedia Commons).

The architectural concept of the D-MARS habitat is based on three main design assumptions: mobility, scalability, and the diversification of interior spaces. The structure was designed as an expandable module based on a 6-meter transport container, which serves as a stable core containing water, electrical, and communication installations. On both sides of the container, there are two fold-out wings which, when deployed, incre-

²²⁸ Rubinstein, H., Abramovich, R. S., Barnett, D. L., Shikar, A., Helmann, Y. Y., Nevenzal, H., Vizel, N., Paz, Y., Dahan, D., Bainberg, S., Yoffe, G., Henn, N., Ryazanskiy, M., Mauda, S., Kushnir, N., Orlov, Y., Margulyan, K., Schenker, E., & Aharonson, O. (2019). The 2019 Analog Mars Mission Season at The Desert Mars Analog Ramon Station. Proceedings of 70th International Astronautical Congress (IAC-19).

ase the usable area from approximately 15 m² to over 60 m² [Fig. 45c]. This enables the simulation of the full operational cycle of future missions, from transport and landing, through habitat deployment, to its expansion into residential and research mode²²⁹.

The interior of the habitat was designed as a compact yet multifunctional space, accommodating elements necessary for conducting a scientific mission [Fig. 45a]. The station includes a laboratory equipped with a biosafety cabinet, a workstation for geological and microbiological research, a hydroponic tray for plant cultivation, a common area serving as a dining space and a place for teamwork, six wood-clad sleeping cabins, a kitchenette, and a small bathroom²³⁰. The design also allows for the expansion of the system with additional modules, which can be connected in various configurations to create more complex functional layouts [Fig. 45b].

²²⁹ Rubinstein, H., Abramovich, R. S., Barnett, D. L., Shikar, A., Helmann, Y. Y., Nevenzal, H., Vizel, N., Paz, Y., Dahan, D., Bainberg, S., Yoffe, G., Henn, N., Ryazanskiy, M., Mauda, S., Kushnir, N., Orlov, Y., Margulyan, K., Schenker, E., & Aharonson, O. (2019). *The 2019 Analog Mars Mission Season at The Desert Mars Analog Ramon Station*. Proceedings of 70th International Astronautical Congress (IAC-19).

²³⁰ Rubinstein, H., Abramovich, R. S., Barnett, D. L., Shikar, A., Helmann, Y. Y., Nevenzal, H., Vizel, N., Paz, Y., Dahan, D., Bainberg, S., Yoffe, G., Henn, N., Ryazanskiy, M., Mauda, S., Kushnir, N., Orlov, Y., Margulyan, K., Schenker, E., & Aharonson, O. (2019). *The 2019 Analog Mars Mission Season at The Desert Mars Analog Ramon Station*. Proceedings of 70th International Astronautical Congress (IAC-19).

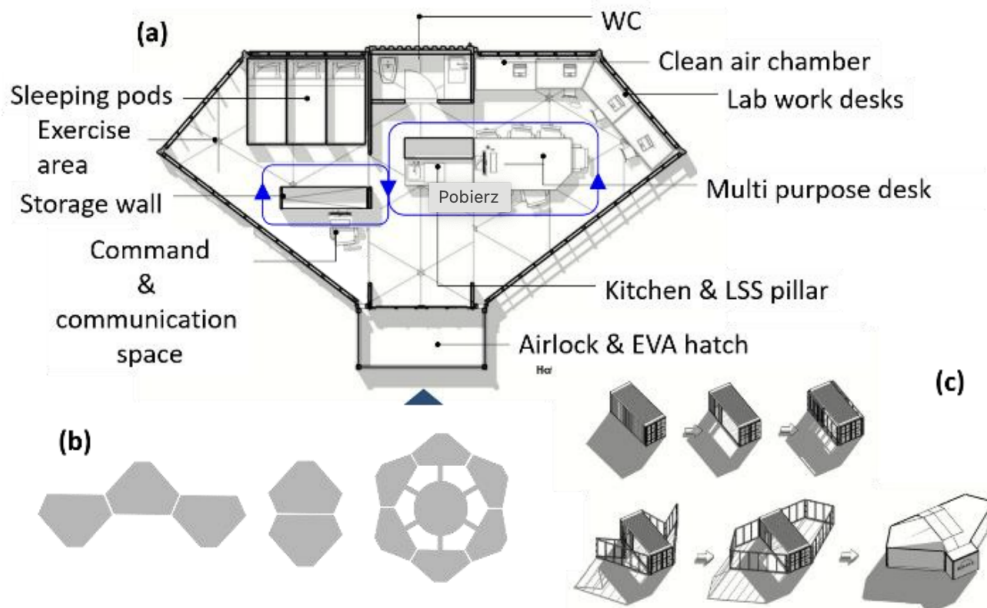


Fig. 45. a) Habitat floor plan, b) Possible module configurations, c) Deployment scheme (source: Rubinstein et al., 2019).

D-MARS operates as a platform for conducting simulated crewed missions, including testing EVA procedures, medical operations, studies on work efficiency in isolation, and psychological analyses related to stress, sleep, cognitive load, and communication dynamics. Missions conducted in 2019 included, among others, a landing mission, a series of medical missions, and an eleven-day scientific mission during which analog astronauts carried out scientific experiments and performed EVA activities.

The following table [Table 7] provides a synthetic summary of the D-MARS case study analysis, organising the main design challenges and the applied response strategies.

Table 7. Summary - Synthesis of Case Study Analysis - D-MARS

Design Challenge (constraint)	Design Factor (solution)
Technological Solutions	
Extreme conditions of the hyper-arid makh-tesh.	Mobile, insulated structure; container-based system with deployable wings (15 → 60 m ²).
Remote location.	Deployable structure odzwierciedlająca pełny cykl misji (transport - deployment-operacje).
Limited energy availability.	Solar panels + generator; energy telemetry; power rationing protocols.
Operations in a Mars-analog terrain.	Dedicated EVA suits, EVA procedures, rover robotics, short-range communication system.
Need for laboratory research.	Compact laboratory with biosafety cabinet; geo- and microbiological workstations.
Potential failures and maintenance requirements.	EVA-based maintenance procedures, equipment redundancy, repair simulations.
Psychosocial Solutions	
Isolation and limited spatial volume.	Spatial enhancement: differentiated micro-zones, colour schemes, materials; shared common space.
Limited privacy.	Separate sleeping cabins.
EVA workload and operational stress.	Structured EVA schedule, donning/doffing procedures, ground support.
Risk of interpersonal conflicts.	Psychological selection, clear role division, teamwork training.

7.3. Underwater Environments

Underwater environments constitute an important element in testing habitation technologies, life-support systems, and human behaviour in isolation. Interest in the underwater environment as a potential space for human activity is not a modern phenomenon; as early as the 16th century, technical concepts enabling temporary human presence underwater appeared, exemplified by Leonardo da Vinci's designs of diving apparatus²³¹. A breakthrough moment came in the 1960s, when the first inhabitable underwater habitats were developed²³². A key factor distinguishing underwater environments from other terrestrial analogs is the influence of hydrostatic pressure, which alters respiratory physiology, metabolism, and the body's response to physical effort. During longer missions, risks such as nitrogen narcosis, oxygen toxicity, decompression sickness, and thermoregulation disorders emerge²³³. This necessitates the use of advanced safety procedures and decompression plans, making these environments important simulations for research on crewed mission safety in space, where the margin for error is similarly narrow.

From the perspective of designing underwater structures, the fundamental characteristic of this environment is constant hydrostatic pressure, which requires maintaining the internal pressure of habitats at a level corresponding to their depth of immersion. Unlike terrestrial habitats, underwater structures operate under high-pressure conditions, which affects both human physiology and the design of life-support systems. Another key aspect of underwater environments is three-dimensional mobility and natural buoyancy, which make it possible to simulate certain aspects of work in microgravity. While most terrestrial habitats are unable to reproduce weightlessness conditions, underwater environments allow for the simulation of microgravity effects, that is, a state comparable to astronauts' work in outer space. For this reason, since the 1960s, underwater environments have remained the only realistic analog for training EVA activities, te-

²³¹ Leonardo da Vinci, *Codex Atlanticus*, szkice i projekty aparatury nurkowej, f. 1069 recto., *Biblioteca Ambrosiana*, <https://www.ambrosiana.it/en/discover/masterpieces/codex-atlanticus/> (accessed: 04 February 2026).

²³² Miller, J. W., & Koblick, I. G. (1984). *Living and working in the sea*. Van Nostrand Reinhold.

²³³ Bennett, P. B., & Elliott, D. H. (1993). *Physiology and Medicine of Diving*. Saunders Ltd.

sting tools, limited mobility, working with loads, and maneuvering in “microgravity-like” conditions (e.g., the NEEMO project)²³⁴. Underwater environments are also characterised by a high level of psychological isolation, comparable to polar or orbital habitats. Staying in a closed, hermetic space with limited access to light, the need to use protective suits, and constant stress resulting from environmental pressure increases sensitivity to stress, sensory overload, interpersonal conflicts, and disturbances of circadian rhythms. Research shows that long-duration underwater missions induce neurobehavioural responses similar to those observed in space missions, and factors such as noise, visual monotony, and the inability to evacuate quickly intensify the effects of isolation²³⁵. The first fully inhabitable underwater stations were the habitats of Jacques Cousteau’s Conshelf program, carried out between 1962 and 1965²³⁶. Conshelf I and II enabled long-term human presence under saturation conditions at relatively shallow depths, while Conshelf III, located at a depth of approximately 100 meters, became the first example of a deep-sea pressurised habitat in which integrated life-support systems and the organisation of collective life in an extreme environment were tested. Although the program did not lead to the creation of permanent underwater colonies, it represented a fundamental stage in the development of extreme architecture and one of the first experiments in which closed-system concepts, the ergonomics of minimal living spaces, and the psychosocial functioning of crews in isolation were examined²³⁷. Experience from the Conshelf program is still regarded today as a reference point in research on inhabiting high-pressure and underwater environments and as a model example of architectural design determined by extreme conditions²³⁸.

²³⁴ Chappell, S. P., Abercromby, A. F., Todd, W., Reagan, M., & Gernhardt, M. L. (2013). *NEEMO 16: Evaluation of Systems for Human Exploration of Near-Earth Asteroids. International Conference on Environmental Systems (ICES)*. doi:10.2514/6.2013-3508A high level of psychological isolation also characterises underwater environments

²³⁵ Suedfeld, P., & Steel, D. G. (2000). *The environmental psychology of capsule habitats. Annual Review of Psychology*, 51, 227-253. 10.1146/annurev.psych.51.1.227

²³⁶ Kallipoliti, L. (n.d.). *Closed Worlds. Closed Worlds - Conshelf II/III*. <https://www.closed-worlds.com/conshelf-ii-iii> (accessed: 04 February 2026).

²³⁷ Kallipoliti, L. (n.d.). *Closed Worlds. Closed Worlds - Conshelf II/III*. <https://www.closed-worlds.com/conshelf-ii-iii> (accessed: 04 February 2026).

²³⁸ Richards, M. A. (2010). The End of the World and Architecture. *Sage Journals*, Volume 2, Issue 5. doi.org/10.1177/1946756710002005

7.3.1. Tektite

The Tektite project [Fig. 46] was initiated in the late 1960s as a joint undertaking of the U.S. Navy, the Department of the Interior, NASA, General Electric, and academic institutions, making it one of the first fully cooperative scientific, technological, and space-related programs²³⁹. The impulse for the project was the need to create a research platform that would allow scientists to conduct long-term in situ observations in a reef environment, which could not be achieved through conventional surface-based diving limited by decompression requirements and short bottom times²⁴⁰. At the same time, the GE “Man-in-the-Sea” program and NASA recognised the potential of underwater habitats as analogs for space missions, particularly in terms of habitability, work in isolation, crew psychology, and life-support systems. The project was carried out in Lameshur Bay on the island of St. John, U.S. Virgin Islands.

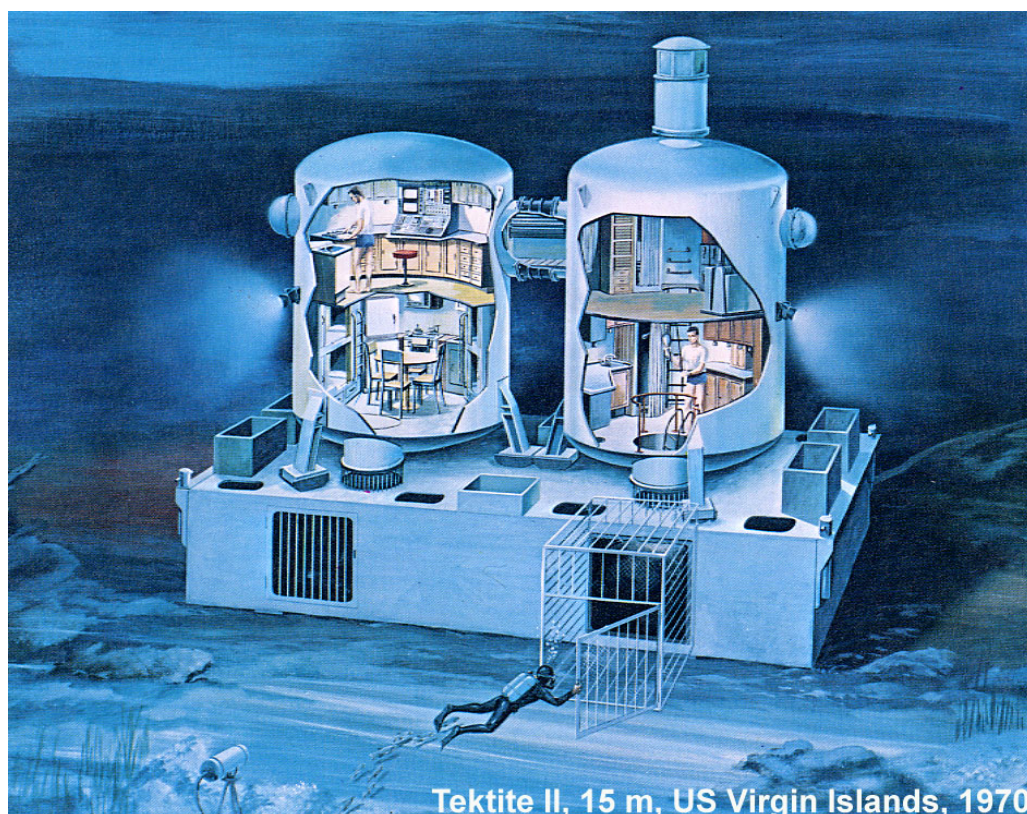


Fig. 46. A drawing of the American habitat Tektite II (source: *Ocean 71*, n.d.).

²³⁹ Ray, E., & Cohen, R. M. (1970). “Tektite”: A Blueprint for Cooperative Undersea Scientific Programs. *Bulletin of the Atomic Scientists*, 26:2, 35-40. doi: 10.1080/00963402.1970.11457770

²⁴⁰ Clifton, E. H., Mahnken, C. V. W., Van Derwalker, J. C., & Waller, R. A. (1970). Tektite 1, Man-in-the-Sea Project: Marine Science Program. *Science*, Volume 168, Number 3932, 659-663.

The first mission, Tektite I, began in February 1969 and lasted sixty days. A four-person crew of biologists and geologists conducted research under full saturation conditions at a depth of approximately 15 meters. The habitat was delivered, stabilised, and anchored with the participation of Underwater Construction Team One²⁴¹. The installation was a significant engineering achievement and contributed to the formation of permanent U.S. Navy construction teams specialised in underwater operations. During the mission, long-term observations of fish, lobsters, and other reef organisms were carried out, along with studies of bioturbation processes and environmental measurements; at the same time, the scientists themselves became subjects of medical and physiological research related to breathing an N₂/O₂ atmosphere under pressure, CO₂ control, and the effects of isolation and routine on psychomotor performance²⁴².

The Tektite habitat consisted of two steel pressurised cylinders with a height of approximately 5.6 m and a diameter of about 3.8 m, mounted on a shared supporting platform²⁴³. The cylinders were connected by a horizontal tunnel. They contained four functional levels: a communication and operational space, a living area with bunks and a kitchen, a technical section housing life-support systems, and a lower level with suit storage and the so-called wet porch, an entry lock used for daily diving exits [Fig. 47]. The habitat functioned as an ambient-pressure facility, meaning that the internal pressure corresponded to the pressure at the operating depth; the atmosphere consisted of a nitrogen-oxygen mixture, and CO₂ was continuously removed chemically by absorption systems²⁴⁴. The habitat structure was organised with a clear division into operational, residential, and technical spaces, making Tektite an early example of architecture fully subordinated to an extreme environment.

²⁴¹ *Project Tektite I and the Birth of the Underwater Construction Teams*. (n.d.). Seabee Magazine. <https://seabeemagazine.navylive.dodlive.mil/News/Article/2610129/project-tektite-i-and-the-birth-of-the-underwater-construction-teams/> (accessed: 04 February 2026).

²⁴² Clifton, E. H., Mahnken, C. V. W., Van Derwalker, J. C., & Waller, R. A. (1970). *Tektite I, Man-in-the-Sea Project: Marine Science Program*. *Science*, Volume 168, Number 3932, 659-663.

²⁴³ Clifton, E. H., Mahnken, C. V. W., Van Derwalker, J. C., & Waller, R. A. (1970). *Tektite I, Man-in-the-Sea Project: Marine Science Program*. *Science*, Volume 168, Number 3932, 659-663.

²⁴⁴ Clifton, E. H., Mahnken, C. V. W., Van Derwalker, J. C., & Waller, R. A. (1970). *Tektite I, Man-in-the-Sea Project: Marine Science Program*. *Science*, Volume 168, Number 3932, 659-663.

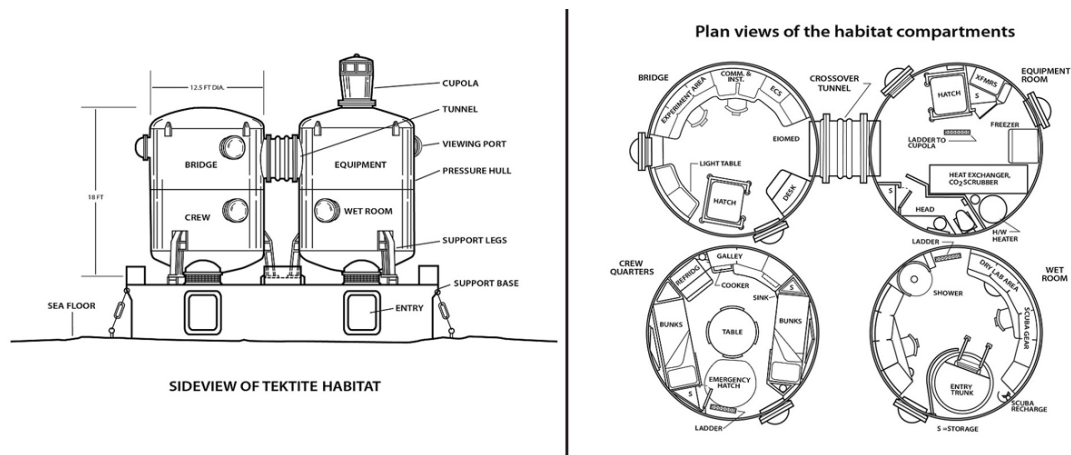


Fig. 47. Section through Tektite I (left). Floor plans (right). The Project Tektite I habitat consists of two vertical steel cylinders attached to a rectangular steel base. Each cylinder contained two large compartments for crew accommodation, control, research, and diving operations (source: Seabee Magazine).

One year after the completion of the first mission, Tektite II was initiated, consisting of ten missions lasting from two to four weeks. The crews consisted of five people, including one engineer; one of the missions was carried out by an entirely female crew. NASA used Tektite II as a platform for research on habitability and the psychology of isolation, developing a set of tools including personality tests, daily mood measurements, environmental assessments, and analyses of crew interactions and behaviour²⁴⁵. The results indicated that staying in a confined habitat led to emotional flattening and a gradual decline in energy levels; a key factor influencing the evaluation of the habitat proved to be so-called task support, meaning the availability of space and tools necessary to perform work. The organisation of leisure time also played an important role: the most valued activities were reading, music, and conversations unrelated to the mission, and crew members clearly felt the lack of contact with family. An additional stress factor was the inability to evacuate quickly; full decompression required approximately twenty-three hours²⁴⁶.

²⁴⁵ Airesearch Manufacturing Company. (1972). *TEKTITE II HABITABILITY RESEARCH PROGRAM*. NASA Report: 71-6192-1, 8-25100.

²⁴⁶ Airesearch Manufacturing Company. (1972). *TEKTITE II HABITABILITY RESEARCH PROGRAM*. NASA Report: 71-6192-1, 8-25100. Consists of: pressurised Module (laboratory), Exposed Facility (external platform), and Logistics Module. The largest laboratory on the ISS.

The following table [Table 8] provides a synthetic summary of the Tektite I case study analysis, organising the main design challenges and the applied response strategies.

Table 8. Summary - Synthesis of Case Study Analysis - Tektite I

Design Challenge (constraint)	Design Factor (solution)
Technological Solutions	
Unstable seabed terrain.	Special Construction; anchoring and installation using UCT-1.
High pressure and saturation environment underwater.	Steel ambient-pressure cylinders.
Limited usable space.	Dual-cylinder layout with four functional zones.
Provision of air and energy.	Umbilical connection to a service barge.
Control of N ₂ /O ₂ atmosphere.	CO ₂ scrubbers and continuous monitoring.
High hydrostatic pressure.	Wet porch (entry airlock).
Risk of contamination.	Separate equipment zone and hygiene procedures.
Need for effective communication.	Operations center with communication systems and control panels.
Psychosocial Solutions	
Isolation and lack of contact with outside.	Communication schedules and shared rituals.
Monotony and mood decline.	Books, music, and recreational - personal spaces.
Lack of privacy.	Individual bunks and separation of zones.
Stress related to lack of evacuation options.	Safety procedures and system redundancies of the systems.
Lack of task support.	Reorganisation of tools and workstations.

7.3.2. Aquarius Reef Base

Aquarius Reef Base [Fig. 48] is an underwater habitat used both for oceanographic research and as an extreme-environment analog for NASA space programs²⁴⁷. It represents a continuation of earlier experiments with seafloor habitats, such as Tektite, however, its unique distinguishing feature is its permanent, long-term research infrastructure and the ability to conduct repeated missions at a fixed location. The habitat is located off the coast of Key Largo, Florida, at a depth of approximately 19-20 meters on Conch Reef, one of the best-studied reef areas of the Atlantic, characterised by high water clarity, rich biodiversity, and environmental stability²⁴⁸.



Fig. 48. *Aquarius Reef Base* (source: NOAA, National Marine Sanctuaries, n.d.).

Since 2001, the NEEMO (NASA Extreme Environment Mission Operations) program has been conducted at the station, consisting of a series of training and research missions during which astronauts and scientists live under conditions of long-term isolation, limited space, lack of rapid evacuation capability, and the necessity to work in protective systems-factors that are critical for the design of space missions. NASA treats Aquarius as a high-fidelity analog environment in which it is possible to test EVA

²⁴⁷ Miller, S. L., & Cooper, C. (2001). *The Aquarius Underwater Laboratory: America's "Inner Space" Station*. *Marine Technology Society Journal*, Vol. 34, No.4, 69-74. <https://doi.org/10.4031/MTSJ.34.4.9>

²⁴⁸ Miller, S. L., & Cooper, C. (2001). *The Aquarius Underwater Laboratory: America's "Inner Space" Station*. *Marine Technology Society Journal*, Vol. 34, No.4, 69-74. <https://doi.org/10.4031/MTSJ.34.4.9>

architectures, tools, communication protocols under time delays, operational procedures, and habitability elements such as spatial division, ergonomics, and daily schedule structure²⁴⁹. Research conducted in Aquarius includes scientific fields such as coral reef observation, pollution monitoring, long-term ecosystem measurements, and the development of in situ research methodologies. The habitat allows saturation divers to work for up to 9 hours per day, which dramatically increases research efficiency compared to surface-based diving²⁵⁰. Another area is simulated space exploration. NEEMO missions (including NEEMO 7 and NEEMO 16) have enabled testing of surgical operations in isolation with telemedical support, robotic procedures, anchoring and manoeuvring techniques in quasi-microgravity, geological tools, and mission architecture concepts for near-Earth asteroids²⁵¹. The final area addresses the psychology of extreme environments, including monitoring mood, team dynamics, functioning in confined spaces, recovery processes, and work organization under conditions of isolation and saturation.

The architecture of the Aquarius habitat is the result of many years of evolution in underwater construction. The habitat consists of two main spaces [Fig. 49]: the wet porch, an entry chamber with a moon pool located in the lower part of the structure, allowing divers direct access to the marine environment; and the main living chamber, which contains workstations, monitoring systems, a kitchen, bunks, sanitary facilities, and a recreational area²⁵². The structure is made of steel cylindrical pressure vessels, supported on six legs that provide stability on the seabed. A key infrastructure element connecting the habitat to the surface is the Life Support Buoy, which contains compressors, gas tanks, generators, communication systems, and redundant safety mechanisms²⁵³.

²⁴⁹ Todd, B., & Reagan, M. (2004). *The NEEMO Project: A report how NASA utilizes the "Aquarius" undersea habitat as an analog for long-duration space flight*. *Earth and Space ASCE 2004 Proceedings*, (Engineering, Construction, and Operations in Challenging Environments), 751-758.

²⁵⁰ Miller, S. L., & Cooper, C. (2001). *The Aquarius Underwater Laboratory: America's "Inner Space" Station*. *Marine Technology Society Journal*, Vol. 34, No.4, 69-74. <https://doi.org/10.4031/MTSJ.34.4.9>

²⁵¹ Thirsk, R., Williams, D., & Anvari, M. (2006). *NEEMO 7 undersea mission*. *Acta Astronautica*, 60 (2007), 512 - 517. doi:10.1016/j.actaastro.2006.09.015

²⁵² Thirsk, R., Williams, D., & Anvari, M. (2006). *NEEMO 7 undersea mission*. *Acta Astronautica*, 60 (2007), 512 - 517. doi:10.1016/j.actaastro.2006.09.015

²⁵³ Smith, G. A., & Rounds, R. S. (1988). *Scientific, Technological, and Social Impact of NOM's Mobile Undersea Research Habitat*. *Oceans '88 - A Partnership of Marine Interests. Proceedings*. doi:10.1109/OCEANS.1988.794835

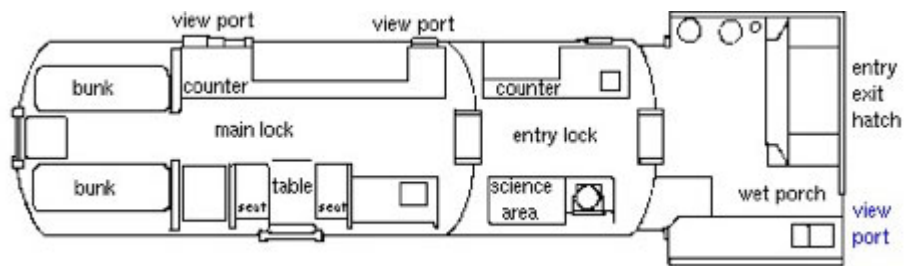


Fig. 49. *Aquarius floor plan (source: NOAA, National Marine Sanctuaries, n.d.).*

The interior of the habitat is designed with great attention to functional zoning. The operational zone contains consoles for communication with the control center, as well as panels monitoring atmospheric conditions and environmental systems. The living section includes a small kitchen, sanitary facilities, and a shared space [Fig. 50] where briefings, meals, and recreational activities take place. Depending on the mission, Aquarius can accommodate a crew of 4-6 people for up to approximately 10 days, with decompression carried out inside the habitat and typically lasting several hours²⁵⁴.

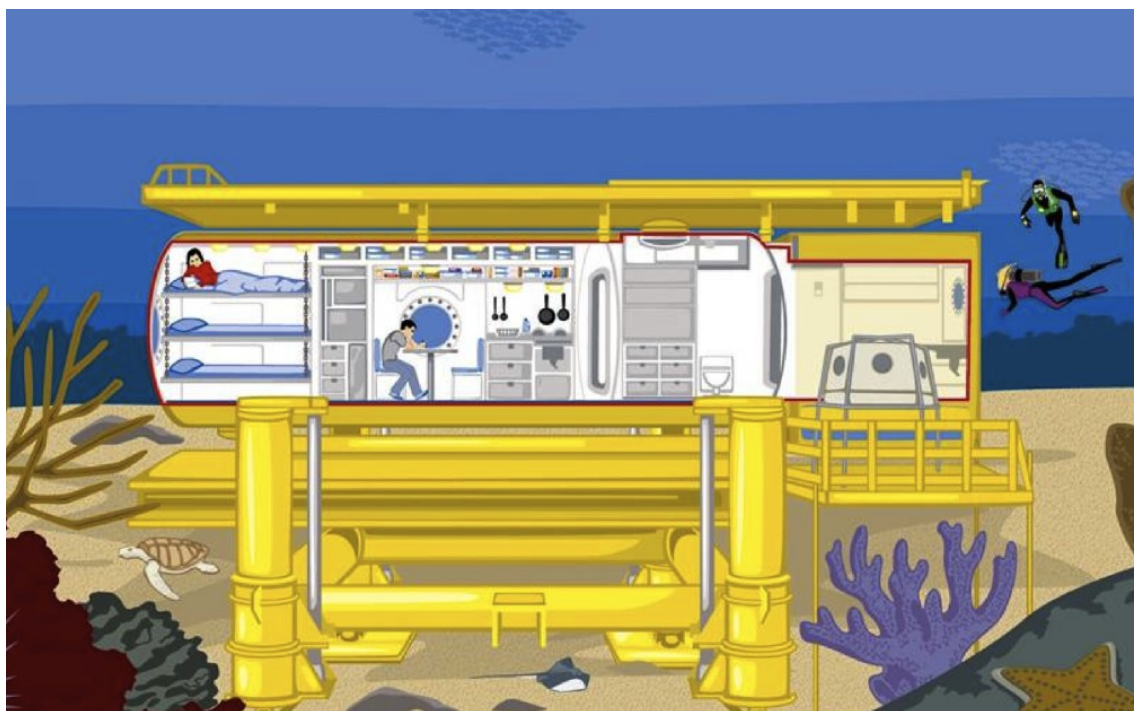


Fig. 50. *Section, Aquarius (source: Florida International University, n.d.).*

²⁵⁴Miller, S. L., & Cooper, C. (2001). *The Aquarius Underwater Laboratory: America's "Inner Space" Station. Marine Technology Society Journal*, Vol. 34, No.4, 69-74. <https://doi.org/10.4031/MTSJ.34.4.9>

The table below [Table 9] provides a synthetic summary of the Aquarius case study analysis, organising the main design challenges and the applied response strategies.

Table 9. Summary - Synthesis of Case Study Analysis - Aquarius

Design Challenge (constraint)	Design Factor (solution)
Technological Solutions	
Unstable terrain.	Steel frame and anchoring system.
High-pressure environment.	Wet porch / moon-pool.
Limited space.	Compact functional layout.
Limited resources.	Redundant sensors and telemetry.
Power supply and communication problems.	Umbilical connection and radio systems.
Limited interior volume.	Modular equipment (tools, EVA systems).
Psychosocial Solutions	
Crowding and lack of privacy.	Clear division of internal zones.
Monotony.	Shared activities, media, personal activities.
EVA fatigue.	Task rotation, breaks, structured scheduling.
Work in quasi-microgravity.	Stabilisation exercises and anchoring points.

7.4. Environment of Microgravity (LEO - Low Earth Orbit)

The first crewed spaceflight took place on 12 April 1961, when Yuri Gagarin orbited the Earth aboard the Vostok 1 spacecraft, opening the era of human presence beyond the atmosphere ²⁵⁵. Since then, astronaut activity has gradually evolved from short-duration orbital missions to long-term habitation of space stations, beginning with the Salyut series (1971), followed by Mir (1986-2001), and culminating in the International Space Station (ISS), which has been continuously inhabited by successive crews since 2000²⁵⁶.

The LEO environment is characterised by a set of unique physical factors: microgravity resulting from continuous free fall, vacuum with pressures on the order of 10^{-7} - 10^{-9} bar, high levels of ionising radiation, and exposure of structures to micrometeoroids and orbital debris ²⁵⁷. Temperatures experienced by external spacecraft components in low Earth orbit undergo extreme fluctuations due to solar illumination and the absence of atmospheric convection. According to design data for space systems, extreme temperatures on external vehicle surfaces can reach values of approximately $\pm 200^{\circ}\text{C}$, which constitutes a fundamental boundary parameter for the design of thermal systems²⁵⁸. Microgravity has a profound effect on human physiology, leading to bone mass loss, muscle atrophy, changes in the circulatory and balance systems, and disturbances of spatial orientation - phenomena widely documented in medical research conducted on the ISS²⁵⁹. Vacuum and radiation require orbital habitats to have airtight structures, multi-layer radiation shielding, and redundancy of critical systems, as even minor failures can pose a threat to crew life²⁶⁰.

²⁵⁵ Siddiqi, A. A., & NASA History Office. (2011). *Challenge to Apollo: The Soviet Union and the Space Race, 1945-1974* (NASA History Series SP-2000-4408). www.Militarybookshop.CompanyUK.

²⁵⁶ Baker, D. (2016). *International Space Station: An Insight Into the History, Development, Collaboration, Production and Role of the Permanently Manned Earth-orbiting Complex*. Haynes Publishing UK.

²⁵⁷ National Research Council. (2008). *Managing Space Radiation Risk in the New Era of Space Exploration*. National Academies Press. doi.org/10.17226/12045

²⁵⁸ Wertz, J. R., & Larson, W. J. (Eds.). (1999). *Space Mission Analysis and Design*. Springer Netherlands.

²⁵⁹ Williams, D., Kuipers, A., Mukai, C., & Thirsk, R. (2009). *Acclimation during space flight: effects on human physiology*. *Canadian Medical Association Journal*, 180(13), 1317-1323. doi: 10.1503/cmaj.090628

²⁶⁰ Baker, D. (2016). *International Space Station: An Insight Into the History, Development, Collaboration, Production and Role of the Permanently Manned Earth-orbiting Complex*. Haynes Publishing UK.

The operation of habitats in LEO also requires advanced life-support systems (ECLSS), which are responsible for maintaining the composition of the breathing atmosphere, controlling pressure, temperature, and humidity, recycling air and water, and removing CO₂ and atmospheric contaminants²⁶¹. These systems must operate continuously for months or years, and their design is based on redundancy, automation, and the ability to rapidly isolate damaged modules²⁶². At the same time, the orbital environment necessitates precise interior architecture: compact, modular, with a clear functional division and logistical control, in order to ensure both operational efficiency and minimum psychosocial comfort conditions²⁶³. Long-term isolation and the limited space of orbital stations also affect astronaut behaviour and psychological well-being. Multi-month missions are associated with monotony, restricted social contact, task pressure, lack of privacy, and the need to cooperate within the same group over extended periods. Research conducted by NASA shows that psychosocial factors-such as daily structure, interpersonal relations, support from Earth, and spatial organisation-are as important as technical systems in maintaining mission safety^{264, 265}.

7.4.1. Skylab

Skylab, launched into orbit in 1973, was the first American space station and the largest orbital habitat of its time²⁶⁶ [Fig. 51]. Its creation resulted from the decision to adapt hardware from the Apollo program, primarily the Saturn V rocket stage, whose liquid hydrogen tank was converted into a spacious living and research module. As described by Compton and Benson in the extensive monograph *Living and Working in Space*, this approach made it possible to create a station with an exceptionally large internal volu-

²⁶¹ Carrasquillo, R. L. (2005). ISS ECLSS Technology Evolution for Exploration. 43rd AIAA Aerospace Sciences Meeting and Exhibit, AIAA-2005-0337. doi.org/10.2514/6.2005-337

²⁶² Eckart, P. (2010). *Spaceflight Life Support and Biospherics*. Springer Netherlands.

²⁶³ Howe, A. S., & Sherwood, B. (Eds.). (2009). *Out of this World: The New Field of Space Architecture*. American Institute of Aeronautics and Astronautics.

²⁶⁴ Schlacht, I. L. (2012). *SPACE HABITABILITY Integrating Human Factors into the Design Process to Enhance Habitability in Long Duration Missions*. PhD Dissertation - Technische Universität Berlin.

²⁶⁵ Häuplik-Meusburger, S., & Bishop, S. (2021). *Space Habitats and Habitability: Designing for Isolated and Confined Environments on Earth and in Space*. Springer International Publishing.

²⁶⁶ NASA. (1977). Skylab, Our First Space Station. NASA SP-400.

me, offering a completely new level of usability compared to earlier crewed capsules²⁶⁷.

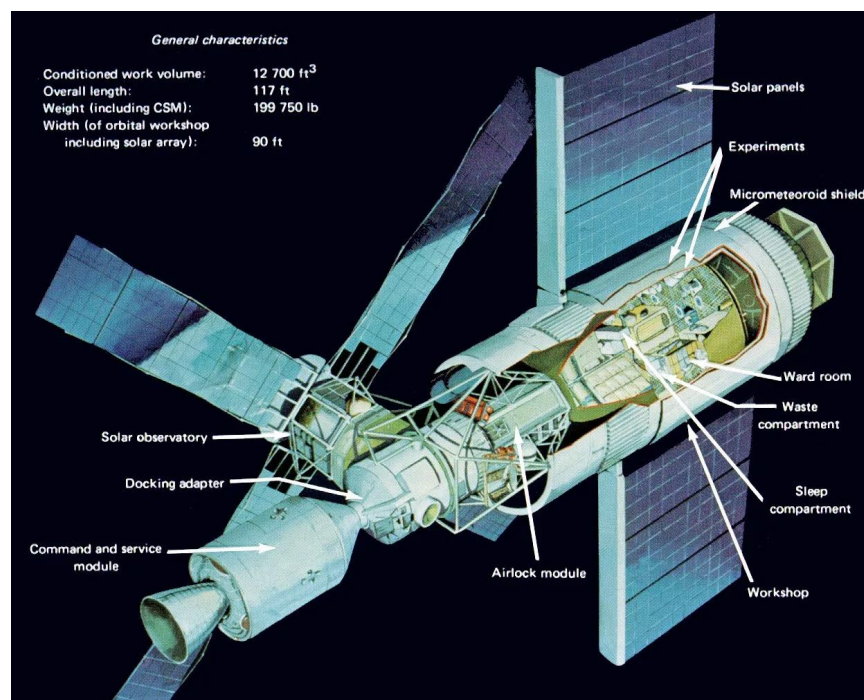


Fig. 51. Graphic depicting Skylab (source: NASA, 1977).

The central element of Skylab's architecture was the Orbital Workshop (OWS), a cylindrical structure with a volume of approximately 350 m³, divided into two functional levels. The lower section contained the living area with three individual sleeping cabins, a kitchen and dining area, hygiene facilities, and medical support spaces. The upper level functioned as a laboratory area, with workstations arranged for physiological, materials, and technological experiments. The interior layout, clearly visible in preserved NASA diagrams and photographs [Fig. 52], was based on an "open plan" principle, which enabled free work and movement in microgravity²⁶⁸. Astronauts emphasised that the large central space played an important psychological role, providing a sense of comfort and openness, as confirmed by detailed descriptions in NASA SP-4208²⁶⁹.

²⁶⁷ Compton, W. D., & Benson, C. D. (1983). *LIVING AND WORKING IN SPACE A History of Skylab* (Vol. TL789.8.UbS5546). NASA-SP-4208.

²⁶⁸ NASA. (1977). *Skylab, Our First Space Station*. NASA SP-400.

²⁶⁹ Compton, W. D., & Benson, C. D. (1983). *LIVING AND WORKING IN SPACE A History of Skylab* (Vol. TL789.8.UbS5546). NASA-SP-4208.

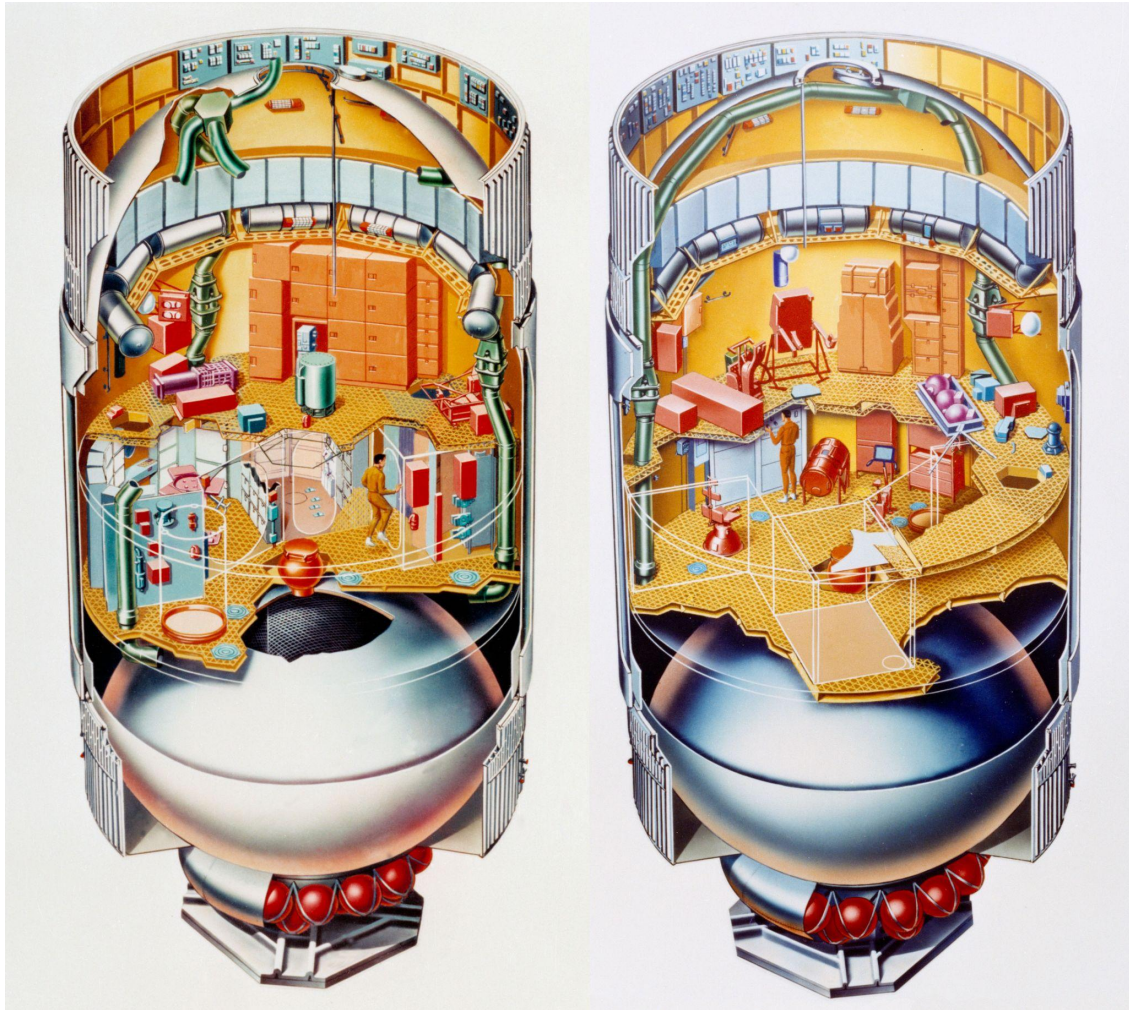


Fig. 52. Artist concept - Cutaway view Skylab 1 Orbital Workshop (OWS). Cutaway diagram of the Skylab living and working quarters (source: NASA Skylab, n.d.).

The interior design of Skylab was one of the first examples of the conscious application of habitability engineering principles in space architecture²⁷⁰. Raymond Loewy acted as an external consultant for human-centered design, while NASA design teams were responsible for the development of functional and operational solutions for the internal environment, with contributions from, among others, Elliott Dalton. As emphasised in *Space Architecture Education for Engineers and Architects: Designing and Planning Beyond Earth*²⁷¹, Loewy introduced the concept of colour and functional differentiation of space, arguing that visual monotony in microgravity could intensify stress, disorien-

²⁷⁰ Häuplik-Meusburger, S., & Bannova, O. (2016). *Space Architecture Education for Engineers and Architects: Designing and Planning Beyond Earth*. Springer International Publishing.

²⁷¹ Häuplik-Meusburger, S., & Bannova, O. (2016). *Space Architecture Education for Engineers and Architects: Designing and Planning Beyond Earth*. Springer International Publishing.

tation, and crew fatigue. As a result of his recommendations, Skylab interiors gained varied colours, clear visual accents, and a colour hierarchy that facilitated orientation and the distinction of functional zones, while also improving the psychological comfort of the astronauts. The Skylab design introduced three individual sleeping cabins (crew quarters), which constituted the first fully separated private living spaces in the history of long-duration orbital habitats. These cabins were designed with the possibility of enclosure, acoustic insulation, and personalisation, which was of fundamental importance for privacy and psychophysical regeneration of crew members. One of Loewy's most well-known contributions was the proposal of the wardroom window, a large window facing Earth, which NASA initially rejected as an "unnecessary luxury." Loewy argued, however, that visual contact with Earth was essential for psychological well-being and for counteracting isolation. Ultimately, the window was installed, and astronauts repeatedly emphasised its importance for regeneration, a sense of connection with home, and maintaining motivation during long missions. The importance of the shared wardroom space (a place for eating, conversation, and rest) was also emphasised as the center of social life on the station. The wardroom design, based on an analysis of interpersonal needs in an isolated environment, became one of the most important elements influencing morale and team integration, and later served as a model for common modules on the ISS²⁷². Two additional modules were connected to the OWS. The Multiple Docking Adapter served as a node connecting to the Apollo spacecraft and housed control interfaces as well as an access point to the Apollo Telescope Mount, a set of telescopes for solar observation. This telescope enabled the most advanced solar observations in the history of U.S. crewed missions²⁷³. The second module, the Airlock Module, contained the EVA airlock along with key life-support systems and atmospheric control.

Skylab also served as a platform for an extensive scientific program. The most important research included physiological experiments (monitoring changes in skeletal, muscular, circulatory, and sensory-motor systems), which provided the first long-term data

²⁷² Häuplik-Meusburger, S., & Bannova, O. (2016). *Space Architecture Education for Engineers and Architects: Designing and Planning Beyond Earth*. Springer International Publishing.

²⁷³ NASA. (1969). *SCIENTIFIC EXPERIMENTS FOR THE APOLLO TELESCOPE MOUNT. NASA TECHNICAL NOTE - NASA - TN - 5020*.

on human adaptation to microgravity ²⁷⁴. In parallel, solar observations were conducted, yielding unique data on the structure of the solar corona and solar activity. Integrated Earth observations were also carried out, including geology, agriculture, and hydrology, as documented in dedicated NASA reports²⁷⁵. In addition, Skylab was used to test material processing technologies in microgravity, including fluid dynamics and experimental physicochemical processes.

The following table [Table 10] provides a synthetic summary of the Skylab case study analysis, organising the main design challenges and the applied response strategies.

²⁷⁴ Compton, W. D., & Benson, C. D. (1983). *LIVING AND WORKING IN SPACE A History of Skylab* (Vol. TL789.8.UbS5546). NASA-SP-4208.

²⁷⁵ NASA. (1976). *Skylab earth resources experiment package /EREP/ - Sea surface topography experiment*. NTRS - NASA Technical Reports Server, <https://ntrs.nasa.gov/citations/19760050022> (accessed: 04 February 2026).

Table 10. Summary - Synthesis of Case Study Analysis - Skylab

Design Challenge (constraint)	Design Factor (solution)
Technological Solutions	
Limited possibilities for infrastructure construction.	Adaptation of the S-IVB rocket LH ₂ tank → OWS with two levels.
Limited space.	Open-plan layout with clear zoning (work/living).
Life environment in microgravity.	Complete ECLSS: CO ₂ control, humidity regulation, air circulation.
Energy limitations.	Large solar arrays, load management.
Requirement for large working volume.	Cylindrical volume, 6.6 m diameter (~350 m ³).
Docking integration in an external environment	Dedicated module - Multiple Docking Adapter.
Psychosocial Solutions	
Risk of claustrophobia.	Large, open OWS volume; high internal volume.
Sensory monotony.	Interior color schemes and layout based on Loewy's design principles.
Lack of privacy.	Individual sleeping cabins.
Need for social integration.	Wardroom and shared dining table.
Orientation difficulties in 0G.	Clear visual coding and spatial zoning.
Stress related to isolation.	Division into work, living, and rest zones.
Need for movement and physical activity.	Dedicated exercise area.
Sense of social isolation.	Wardroom window (view of Earth).

7.4.2. International Space Station (ISS)

The International Space Station (ISS) [Fig. 53] has been continuously inhabited since 2 November 2000²⁷⁶. In research on long-term human exposure to microgravity, particular importance was attached to missions during which crew members spent more than 340 days on the ISS in a single stay. Current plans assume the decommissioning of the station in the second half of the 2020s, with the program expected to end around 2030, when the ISS is to be replaced by commercial orbital stations and new research platforms²⁷⁷. However, at present, it remains a reference model for the design of habitats in microgravity, and its development represents a crucial stage in the evolution of orbital architecture. Its creation was the result of multilateral cooperation between NASA, Roscosmos, ESA, JAXA, and CSA, and the integration of the station (conducted since 1998) proceeded through dozens of assembly stages in orbit²⁷⁸.



Fig. 53. International Space Station (ISS) in its full orbital configuration, including the U.S. and Russian segments, truss structure with photovoltaic arrays, laboratory modules, life support systems, and robotic elements. (source: NASA – ISS, n.d.).

²⁷⁶ NASA - ISS. (2020) *The International Space Station: 20 Years of Communications Excellence*. NASA. <https://www.nasa.gov/missions/station/the-international-space-station-20-years-of-communications-excellence/> (accessed: 04 February 2026).

²⁷⁷ NASA. (2024). FAQs : *The International Space Station Transition Plan*. NASA. <https://www.nasa.gov/faqs-the-international-space-station-transition-plan/#q2> (accessed: 04 February 2026).

²⁷⁸ *Encyclopedia Britannica 10-Minute Guide: Space*. (2017). Publications International, Limited.

The station was designed as a scientific laboratory in microgravity, a technology testing platform, and an environment for conducting medical, biological, materials, and engineering research, as well as Earth observation²⁷⁹. At the same time, the station serves as research infrastructure, a technology demonstration system for long-duration missions, and a testbed for preparations for the exploration of the Moon and Mars. The station enables long-term experiments, particularly studies related to human adaptation, degradation of the musculoskeletal system, fluid dynamics, and material behaviour²⁸⁰. At the same time, the ISS is a site of intensive testing of life-support technologies, where ECLSS systems have been gradually upgraded to increase the closure of air and water loops, reduce logistical demands, and raise the level of autonomy²⁸¹.

The architecture of the station results from its modular construction, with each segment contributing a specific function: scientific, technical, or residential [Fig. 54]. The personalisation of crew quarters, rest areas, and the shared dining area constitutes an important element of adaptation and the sense of “inhabitation”²⁸².

²⁷⁹ Baker, D. (2016). *International Space Station: An Insight Into the History, Development, Collaboration, Production and Role of the Permanently Manned Earth-orbiting Complex*. Haynes Publishing UK.

²⁸⁰ NASA. (2010). *Reference Guide to the International Space Station* (NP-2010-09-682-HQ ed.). National Aeronautics and Space Administration.

²⁸¹ Stockman, B., Boyle, J., & Bacon, J. (2010). *International Space Station Systems Engineering Case Study*. Air Force Institute of Technology, OMB No. 0704-0188, Report.

²⁸² Cromwell, R. L., Huff, J. L., Simonsen, L. C., & Patel, Z. S. (2021). *Earth-Based Research Analogs to Investigate Space-Based Health Risks*. *New Space*, 9(4). doi: 10.1089/space.2020.0048



Fig. 54. Interior of the International Space Station (ISS) showing the combined working and living space of the station under conditions of continuous crew presence during the AX-3 mission (January 2024). Photo: Marcus Wandt (2025).

The total volume of the ISS is approximately 915 m³, of which residential and laboratory space accounts for about 400 m³ of effectively usable area²⁸³. The American, European, Japanese, and Russian modules [Table 11] are arranged in a complex manner, forming a sequence of spaces in which microgravity requires the full use of all walls as functional surfaces, and the traditional “up-down” orientation is replaced by ergonomics based on the placement of equipment and air-flow paths ²⁸⁴.

²⁸³ NASA. (2010). *Reference Guide to the International Space Station* (NP-2010-09-682-HQ ed.). National Aeronautics and Space Administration.

²⁸⁴ Cromwell, R. L., Huff, J. L., Simonsen, L. C., & Patel, Z. S. (2021). *Earth-Based Research Analogs to Investigate Space-Based Health Risks*. *New Space*, 9(4). doi: 10.1089/space.2020.0048

Table 11. Overview of ISS modules and their functions (source: ISS National Laboratory, 2024; NASA, 2009a).

Module	Owner	Type	Description
Zarya	Roskosmos	Functional module	First ISS module; provides propulsion, attitude control, fuel systems, and cargo storage.
Zvezda (Service Module)	Roskosmos	Habitation and service module	Primary living space of the Russian segment: crew cabins, galley, toilet, attitude control systems, Russian ECLSS (Elektron, Vozdukh).
Poisk	Roskosmos	Airlock and docking module	Supports EVA operations using Russian Orlan suits; docking ports for Soyuz and Progress spacecraft.
Rassvet	Roskosmos	Logistics and docking	Storage module with an additional docking port.
Nauka	Roskosmos	Laboratory and habitation module	Additional living space, research equipment, and life support systems
Unity	NASA	Connecting node	Links the Russian and U.S. segments of the ISS; distributes power and data.
Destiny Laboratory	NASA	Scientific laboratory	U.S. laboratory; conducts biological, physical, materials, and medical experiments.
Harmony	NASA	Node and docking module	Connects Destiny, Kibo, and Columbus; includes docking ports for Crew Dragon, Cygnus, etc.
Tranquility	NASA	Life support systems and recreation	Houses the Water Recovery System, toilets, exercise equipment, and the Cupola module.

Module	Owner	Type	Description
Cupola	NASA	Observation module	Panoramic windows; used for robotic arm operations; an element important for psychological well-being.
Quest Airlock	NASA	EVA airlock	Primary airlock for spacewalks; supports EMU and Orlan suits.
Permanent Multipurpose Module	NASA/ASI	Logistics	Storage, workspace, and support element for resupply missions.
BEAM	NASA/Bigelow	Experimental module	Inflatable test module investigating structural concepts for future commercial space stations.
Columbus Laboratory	ESA	Laboratory	European laboratory for biological, physical, and technological research.
Kibo	JAXA	Laboratory complex	Consists of: pressurised Module (laboratory), Exposed Facility (external platform), and Logistics Module.

One of the architectural elements is the Columbus module [Fig. 55], ESA's European laboratory, with a pressurised volume of approximately 75 m³ and a length of 6.9 m, equipped with ten experimental workstations (*racks*) that support medical, biological, materials, and technological research²⁸⁵. Its interior is designed in a characteristic rhythm of segmented panels integrating power, data, and ECLSS systems, while maintaining full compatibility with the other laboratories of the station. Columbus functions as a space of “specialised work,” in which ergonomics, visual modularity, and controlled environmental conditions enable precise execution of experiments.

²⁸⁵ NASA. (2010). *Reference Guide to the International Space Station* (NP-2010-09-682-HQ ed.). National Aeronautics and Space Administration.

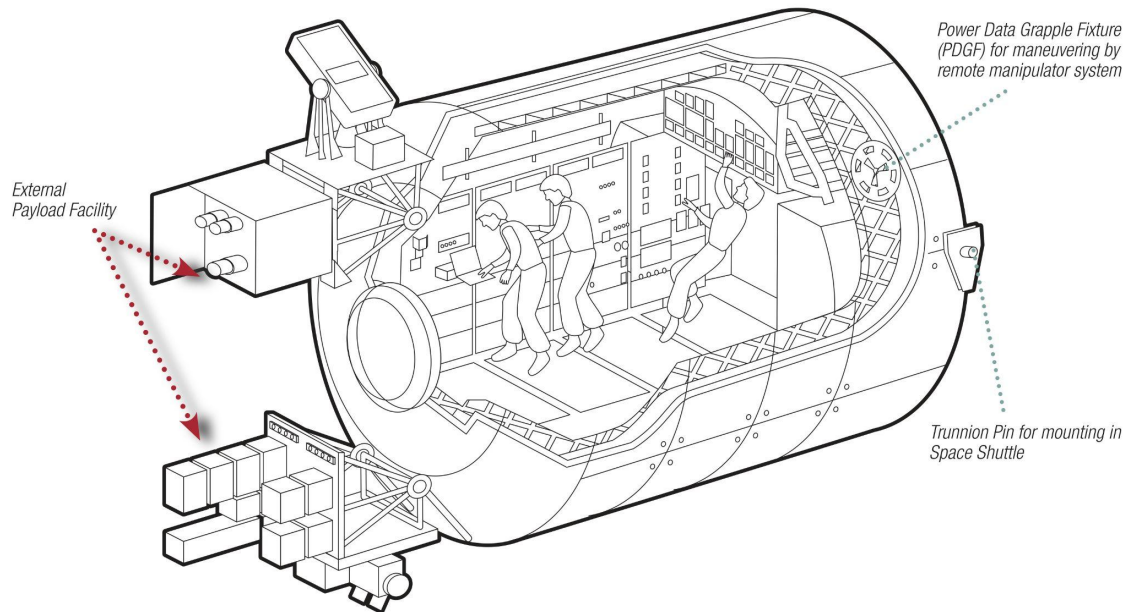


Fig. 55. Columbus laboratory module, schematic view showing the layout of the working space and the integration of research workstations within the orbital habitat (source: NASA - Destiny, n.d.).

A distinctive element of ISS architecture is also the Cupola, a seven-window observatory installed on the Tranquility module [Fig. 56]. The Cupola has a diameter of 3 m, a height of 1.5 m, and offers a panoramic view of Earth and the external structures of the ISS²⁸⁶. Its design responds both to operational needs (it serves as the primary workstation for controlling the Canadarm2 robotic arm) and to psychosocial needs: the literature indicates that the Cupola functions as a “micro-regenerative space,” supporting crew psychological well-being through visual contact with the planet, the day-night cycle, and the broader mission context²⁸⁷. Its windows are made of multilayer *fused-silica* panes with micrometeoroid protection systems, making it the most structurally advanced window construction in the history of spaceflight.

²⁸⁶ NASA. (2010). *Reference Guide to the International Space Station* (NP-2010-09-682-HQ ed.). National Aeronautics and Space Administration.

²⁸⁷ Damjanov, K., & Crouch, D. (2018). *Orbital Life on the International Space Station. Space and Culture*, Volume 22, Issue 1



Fig. 56. NASA astronaut and Expedition 68 Flight Engineer Josh Cassada peers through one of the seven windows in the cupola, the International Space Station's "window to the world" (NASA, Cupola, 2023).

The architecture of the International Space Station is based on materials designed for the extreme conditions of low Earth orbit, including temperature fluctuations from -150°C to $+120^{\circ}\text{C}$, atomic oxygen erosion, UV radiation, and micrometeoroid impacts. The primary structure of pressurised modules is made of lightweight and high-strength aluminium alloys, providing resistance to launch loads and internal pressure²⁸⁸. The external surfaces are covered with multilayer thermal insulation MLI (Multi-Layer Insulation), composed of thin layers of Mylar or Kapton with aluminium reflective coatings, whose function is to control the thermal balance and protect against radiative heating²⁸⁹. Protection against micrometeoroids is provided by Whipple Shield-type shielding, consisting of an aluminium pressure wall and external composite layers made of Kevlar and Nextel; these materials absorb impact energy by dispersing fragments

²⁸⁸ NASA. (2010). *Reference Guide to the International Space Station* (NP-2010-09-682-HQ ed.). National Aeronautics and Space Administration.

²⁸⁹ Christiansen, E. L., Nagy, K., Lear, D. M., & Prior, T. G. (2009). *Space station MMOD shielding*. *Acta Astronautica*, Volume 65, Issues 7-8, 921-929. doi.org/10.1016/j.actaastro.2008.01.046

before they reach the main structural wall of the module.²⁹⁰ The use of Kevlar increases resistance to penetration, while ceramic Nextel provides thermal stability under high temperature gradients. Because ISS structures are exposed to atomic oxygen, which causes polymer degradation, MLI blankets are additionally coated with aluminium or SiO₂, and in selected areas Kapton is used due to its high chemical and thermal resistance²⁹¹. The complex combination of metal alloys, composites, mylar-based insulation, and multilayer micrometeoroid protection ensures the long-term durability of the ISS over decades²⁹².

A key technological component of the station is the ECLSS (*Environmental Control and Life Support System*). This system is responsible for atmospheric control, water exchange and recovery, oxygen recycling, CO₂ removal, waste management, and thermal stabilisation [Fig. 57]. The experience gained constitutes a foundation for future lunar and Martian habitats, as it has shown that the main challenge is not the operating principle of the systems themselves, but their reliability, serviceability, and the wear of auxiliary components (sorbent beds, filters, valves, sensors)²⁹³. The life-support system of the International Space Station is a complex set of technologies maintaining stable environmental conditions that enable long-term crew habitation in microgravity. In the U.S. segment of the station, the Water Recovery System (WRS) and the Oxygen Generation System (OGS) play a key role, enabling the recovery of 90-95% of usable water and the production of oxygen through electrolysis, which significantly reduces the need for logistical resupply. In the Tranquility module, a Sabatier reactor is also used, combining hydrogen from the OGS with carbon dioxide to produce water that can be reintroduced into the cycle, partially closing the air-water loop²⁹⁴. The Russian segment of the station uses its own regenerative systems (Elektron for oxygen generation and Vozdukh for CO₂ removal), providing redundancy and increasing the station's resilience to

²⁹⁰ Häuplik-Meusburger, S. (2011). *Architecture for Astronauts: An Activity-based Approach*. Springer.

²⁹¹ Häuplik-Meusburger, S. (2011). *Architecture for Astronauts: An Activity-based Approach*. Springer.

²⁹² NASA. (2010). *Reference Guide to the International Space Station* (NP-2010-09-682-HQ ed.). National Aeronautics and Space Administration

²⁹³ Carrasquillo, R. L. (2005). *ISS ECLSS Technology Evolution for Exploration*. 43rd AIAA Aerospace Sciences Meeting and Exhibit, AIAA-2005-0337. doi.org/10.2514/6.2005-337

²⁹⁴ Carrasquillo, R. L. (2005). *ISS ECLSS Technology Evolution for Exploration*. 43rd AIAA Aerospace Sciences Meeting and Exhibit, AIAA-2005-0337. doi.org/10.2514/6.2005-337

failures²⁹⁵. Although the ISS has highly advanced water recovery and partial atmospheric recycling, its life-support loop is not fully autonomous. The system achieves near-complete closure of the water cycle, while the atmospheric cycle remains closed only at about 40-60%, requiring periodic resupply of gases and consumables by cargo spacecraft²⁹⁶.

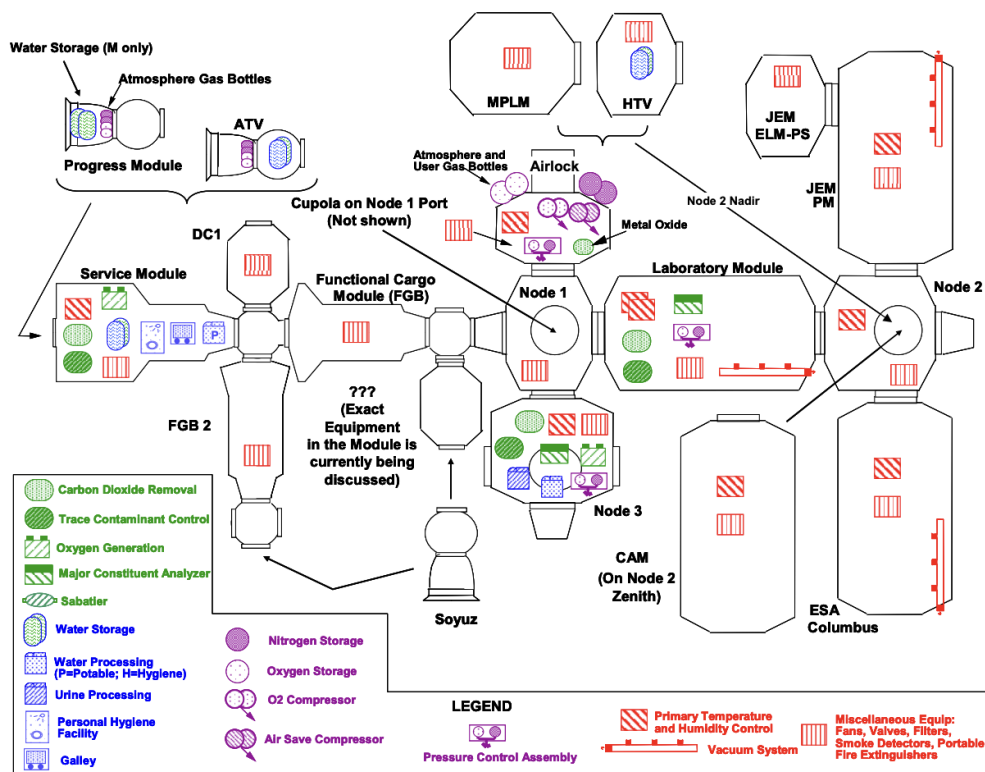


Fig. 57. Diagram of the distribution of Environmental Control and Life Support System (ECLSS) systems on the International Space Station (source: Carrasquillo, 2005).

The following table [Table 12] provides a synthetic summary of the ISS case study analysis, organising the main design challenges and the applied response strategies.

²⁹⁵ NASA. (2010). *Reference Guide to the International Space Station* (NP-2010-09-682-HQ ed.). National Aeronautics and Space Administration

²⁹⁶ Lobascio, C. (2011). *Environmental Control and Life Support Systems, from Low Earth Orbit to Planetary Exploration* (Vol. In S. Häuplik-Meusburger & B. Bannova (Eds.), *Space Architecture for Architects and Engineers*, Series Editor: Douglas A. Vakoch). Springer. doi:10.1007/978-3-319-19279-6

Table 12. Summary - Synthesis of Case Study Analysis - ISS

Design Challenge (constraint)	Design Factor (solution)
Technological Solutions	
Extreme temperature fluctuations.	Multilayer insulation (MLI) using Mylar/Kapton coated with aluminium.
Risk of perforation by micrometeoroids and orbital debris.	Whipple Shield protection using layers of aluminum, Kevlar, and Nextel
Material erosion caused by atomic oxygen in LEO.	Use of Kapton and SiO ₂ /Al coatings on MLI layers.
Limited availability of water resupply.	Regenerative Water Recovery System (WRS) recovering 90–95% of water from urine and condensation.
Requirement for continuous oxygen production.	Oxygen Generation System – water electrolysis, operating in coordination with the Russian Elektron system.
Excess CO ₂ and the need for atmospheric regeneration.	Air system combined with a Sabatier reactor converting $\text{CO}_2 + \text{H}_2 \rightarrow \text{H}_2\text{O} + \text{CH}_4$.
Limited volume in microgravity.	Use of four spatial planes for equipment placement (no defined ceiling or floor).
Launch and orbital assembly constraints.	Structures made of aluminium alloys, lightweight yet resistant to launch loads.
Psychosocial Solutions	
Long-term isolation and continuous crewed operation over many months.	Modular architecture with clearly defined zones for work, recovery, experiments, and recreation.
Limited usable volume with a large crew.	Full use of walls in microgravity, rack-based layouts, compact ECLSS and storage solutions.
Requirement for continuous scientific operations.	Dedicated laboratories (Columbus, Destiny, Kibo) with integrated interfaces and experimental racks.

Design Challenge (constraint)	Design Factor (solution)
Need for operational observation and visual contact with Earth.	Cupola - observation module with seven windows, also serving as a robotic arm control workstation.
Psychological effects of isolation and a monotonous environment.	Spaces allowing personalisation (crew quarters), LED lighting simulating circadian rhythms, access to Earth views.
Complexity of mobility in microgravity.	Design of “flow paths,” placement of handrails, panels, and equipment, minimising collisions.
Requirement for ease of repair and modularity.	Standardised interfaces, easily replaceable racks, cross-agency compatibility.
Need for clear spatial orientation in the absence of gravity.	Colour coding of panels, functional zoning, and directional and zone markings.

7.5. Environment of the Moon

The surface of the Moon, due to the complete absence of an atmosphere and a very long day-night cycle lasting 29.53 Earth days, experiences extreme temperature variations, ranging from over +100°C in full sunlight to below −150°C at night, while in permanently shadowed polar regions temperatures can drop to around −230°C^{297,298}. The lack of an atmosphere also results in an almost perfect vacuum; surface pressure is approximately 3 nPa (which affects construction processes), causes material outgassing, and means that all structures must be designed as fully pressurised living environments. The lunar surface is additionally exposed to high levels of cosmic radiation, including both high-energy galactic radiation and solar events, which requires the use of thick regolith layers (up to several meters) to reduce radiation doses to levels safe for long-term human presence²⁹⁹. Another significant factor is micrometeoroids, which bombard the surface at velocities of several tens of kilometers per second and can pene-

²⁹⁷ Benaroya, H. (Ed.). (2010). *Lunar Settlements*. Taylor & Francis.

²⁹⁸ Benaroya, H. (2018). *Building Habitats on the Moon: Engineering Approaches to Lunar Settlements*. Springer International Publishing. doi.org/10.1007/978-3-319-68244-0

²⁹⁹ Benaroya, H. (Ed.). (2010). *Lunar Settlements*. Taylor & Francis.

trate thin material layers, necessitating additional structural protection. Low gravity, at about one-sixth of Earth's gravity, reduces the self-weight loads of structures, but at the same time creates uncertainty regarding long-term effects on human health and the functioning of life-support systems, which on Earth are designed under full-gravity conditions³⁰⁰. An important environmental aspect is also regolith, which is a highly abrasive, electrostatically charged lunar dust posing a threat to mechanical devices, air filtration systems, and spacesuits.

Since the first landing in 1969, a total of 12 astronauts have been on the surface of the Moon, all during the Apollo 11-17 missions³⁰¹. Current NASA plans, developed within the Artemis program, assume a return of humans to the lunar surface in the coming years, the construction of permanent orbital infrastructure (Gateway), and the establishment of the first long-term habitat outpost on the surface near the south pole, where geological and environmental conditions (including the presence of water in the form of ice) are crucial for future mission self-sufficiency^{302, 303}. The characterisation of the lunar environment thus becomes a fundamental basis for the design of future base architecture, in which radiation protection, thermal stability, structural hermeticity, and dust resistance are as important as functional and logistical aspects.

7.5.1 Moon Village

The Moon Village concept was first presented by the Director General of ESA, Jan Woerner, as a long-term vision of an international human presence on the Moon and the creation of a hub for cooperation between space agencies, research institutions, and the private sector. In the European Space Agency's approach, Moon Village represents a further stage of human presence on the Moon, it is a settlement equipped with residential, research, and energy infrastructure enabling long-term human operation in an

³⁰⁰ Benaroya, H. (2018). *Building Habitats on the Moon: Engineering Approaches to Lunar Settlements*. Springer International Publishing. doi.org/10.1007/978-3-319-68244-0

³⁰¹ NASA. (2024a). *The Apollo Program*. NASA Apollo. <https://www.nasa.gov/the-apollo-program/> (accessed: 04 February 2026).

³⁰² NASA. (2020). *NASA's Lunar Exploration Program Overview*. https://www.nasa.gov/wp-content/uploads/2020/12/artemis_plan-20200921.pdf (accessed: 04 February 2026).

³⁰³ NASA. (2020). *NASA's Plan for Sustained Lunar Exploration and Development*. <https://www.nasa.gov/general/nasa-outlines-lunar-surface-sustainability-concept/> (accessed: 04 February 2026).

extraterrestrial environment. This vision was subjected to detailed analysis in 2019-2020 within the ESA Concurrent Design Facility (CDF) study, carried out in co-operation with Skidmore, Owings & Merrill (SOM) and the Massachusetts Institute of Technology (MIT), the aim of which was to develop a preliminary habitat design and define its role within the broader structure of a lunar settlement ³⁰⁴.

It is worth noting that the Moon Village concept is based on earlier ESA work on extraterrestrial architecture, in particular the Lunar Outpost project [Fig. 58], developed in 2015 by Foster + Partners, Alta SpA, Monolite Ltd., and Scuola Superiore Sant'Anna as part of an ESA program focused on lunar structure printing³⁰⁵. This project explored the application of 3D printing technologies using local regolith as a construction material, as well as strategies for creating a protective shell over a lightweight, deployable habitation module³⁰⁶. The project also assumed the use of inflatable pressurised modules which, after deployment on the lunar surface, were to be automatically covered with a thick regolith layer produced by in-situ 3D printing, carried out by a robotic arm capable of sintering regolith using concentrated energy. The integrated vision of a lightweight habitation module and autonomous construction robots constituted one of the first realistic ESA scenarios for the use of local lunar resources, which directly influenced the later design assumptions of Moon Village.

³⁰⁴ ESA. (2020). *CDF STUDY REPORT MOON VILLAGE* Conceptual Design of a Lunar Habitat. CDF Study Report: CDF-202(A)

³⁰⁵ De Kestelier, X., Dini, E., Cesaretti, G., Colla, V., & Pambaguian, L. (2014). *The Design of a Lunar Outpost: 3D Printing Regolith as a Construction Technique for Environmental Shielding on the Moon. Fabricate, Negotiating Design & Making*. UCL Press. doi.org/10.2307/j.ctt1tp3c5w

³⁰⁶ Foster + Partners. (2012). *Lunar Habitation | Projects*. Foster + Partners. <https://www.fosterandpartners.com/projects/lunar-habitation> (accessed: 04 February 2026).

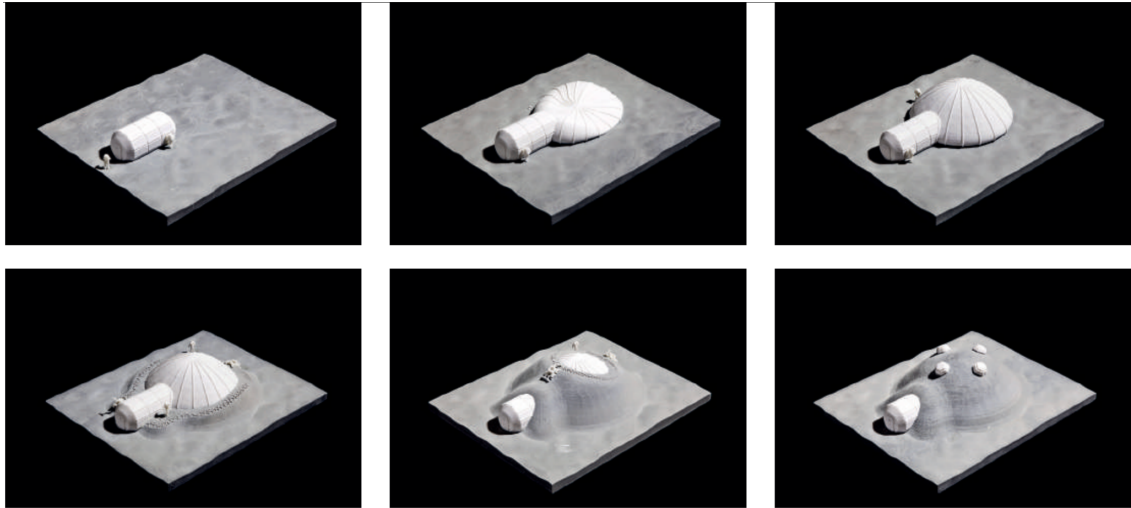


Fig. 58. Stages of the construction of the Lunar Outpost habitat, starting from a temporary highly pressurised inflatable dome that formed a support structure on which the regolith dome could be 3D printed (source: De Kestelier et al., 2014).

Based on the concept described above, a conceptual design of Moon Village was also developed. The mission is planned for a four-person crew, with a maximum stay initially assumed to be up to 500 days, but limited to approximately 300 days due to the accumulation of radiation dose. The preferred location for the settlement is areas of permanent or near-permanent solar illumination in the region of the lunar south pole, which enables more stable thermal conditions and ensures access to energy³⁰⁷. The lunar environment is characterised by extreme temperature fluctuations, the absence of an atmosphere, intense exposure to cosmic radiation, and the risk of micrometeoroid impacts³⁰⁸. Each of these factors defines key design parameters, such as the need for radiation shielding, maintaining a stable pressurised environment, minimising the mass of structures transported from Earth, and constructing infrastructure with a high level of operational autonomy.

In Moon Village [Fig. 59], individual modules perform diverse functions. The settlement is developed in a modular manner, and its spatial structure includes both residential and scientific habitats, as well as energy and logistical infrastructure and external

³⁰⁷ ESA. (2020). *CDF STUDY REPORT MOON VILLAGE Conceptual Design of a Lunar Habitat*. CDF Study Report: CDF-202(A)

³⁰⁸ Labeaga-Martínez, N., Sanjurjo-Rivo, M., Díaz-Álvarez, J., & Martínez-Frías, J. (2017). *Additive manufacturing for a Moon village*. *Procedia Manufacturing*, Volume 13

areas enabling robotic and crewed EVA activities³⁰⁹. Habitat modules are located in proximity to operational and energy infrastructure, and a significant part of the settlement landscape consists of regolith stockpiles, which are used as a construction resource and as radiation shielding. The urban layout of the settlement assumes the possibility of gradual expansion of its scale through the addition of further modules and new functions. Moon Village is designed as a site for geological and astrobiological research, testing of ISRU technologies, planetary robotics, and life-support systems, as well as a platform for EVA operations and logistics related to future crewed missions to Mars. The settlement also serves as a technology demonstrator, testing systems that may find applications on Earth, including closed-loop technologies, autonomous energy systems, and low-emission construction methods^{310,311}.



Fig. 59. Moon Village, view of the lunar settlement (source: Skidmore, Owings & Merrill (SOM), n.d.).

³⁰⁹ ESA. (2020). *CDF STUDY REPORT MOON VILLAGE Conceptual Design of a Lunar Habitat*. CDF Study Report: CDF-202(A)

³¹⁰ Inocente, D., Koop, C., Petrov, G. I., Hoffman, J. A., Sumini, V., Makaya, A., Arnhof, M., Lakk, H., Lamaze, B., Cowley, A., Binns, D., Landgraf, M., Messina, P., & Haigneré, C. (2019). *Master Planning and Space Architecture for a Moon Village*. 70th International Astronautical Congress (IAC) Proceedings.

³¹¹ Skidmore, Owings & Merrill. (n.d.). *Moon Village - SOM*. *Moon Village - SOM*. <https://www.som.-com/research/moon-village/> (accessed: 04 February 2026).

One of the technological foundations of Moon Village is the extensive use of locally available resources, in accordance with the ISRU principle [Fig. 60]. The analysis presented in the article *Additive Manufacturing for a Moon Village* by Labeaga-Martínez highlights the key role of additive technologies, particularly methods based on selective powder melting, which enable the use of regolith as a construction material³¹². This technology is especially well-suited to lunar conditions, as it can use solar energy as a heat source, operates in a vacuum, and allows for the fabrication of multilayer, solid structural shields. The authors further indicate that the thermal conditions of the lunar south pole are favourable for additive manufacturing technologies due to stable illumination and the reduction of extreme heating and cooling cycles.

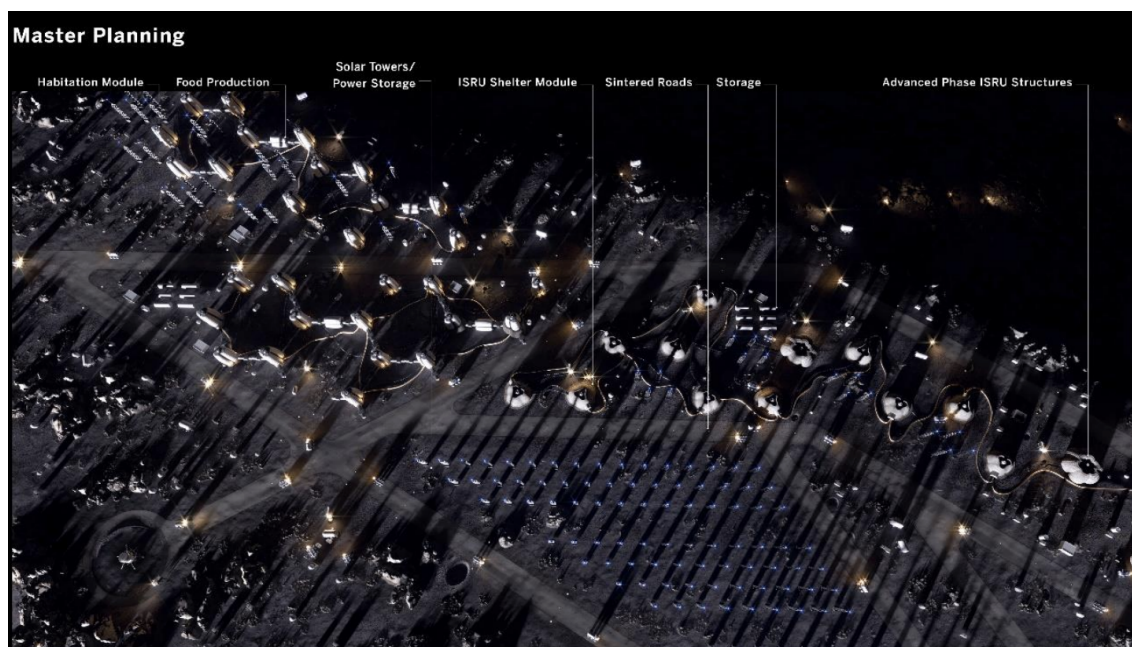


Fig. 60. Master plan scheme of Moon Village developed within the ESA Concurrent Design Facility, presenting the configurational layout of a future lunar settlement, including habitat modules, food production zones, energy installations, regolith processing areas (ISRU), and storage facilities. (source: ESA, 2020).

The construction technologies considered in the document concerning the feasibility study, *CDF STUDY REPORT MOON VILLAGE: Conceptual Design of a Lunar Habitat*, include diversified structures - ranging from rigid pressurised modules, through fle-

³¹² Labeaga-Martínez, N., Sanjurjo-Rivo, M., Díaz-Álvarez, J., & Martínez-Frías, J. (2017). *Additive manufacturing for a Moon village*. *Procedia Manufacturing*, Volume 13

xible inflatable elements, to hybrid architectures that, after deployment on the lunar surface, are autonomously covered with regolith by construction robots³¹³. Analyses presented in the CDF report indicate that systems using multilayer composites combined with a regolith layer serving as radiation and thermal shielding are particularly effective. The single module, ONE MOON, consists of a central rigid structural frame (Rigid Central Frame) surrounded by a deployable, multilayer inflatable envelope, which after full deployment provides a pressurised internal volume of 698.29 m³ [Fig. 61]. The structure takes the form of a vertical, multi-level module with a plan geometry close to a tripartite ellipse, which increases pressure resistance and facilitates the integration of floors. The interior is divided into five functional zones, the largest of which is the working space with a volume of 172.20 m³, complemented by a sleeping zone (59.10 m³), recreation and air circulation zone (61.98 m³), physical exercise zone (40.12 m³), and personal hygiene zone (30.43 m³). Additionally, approximately 24.70 m³ is allocated for the storage of equipment and consumables [Fig. 62].

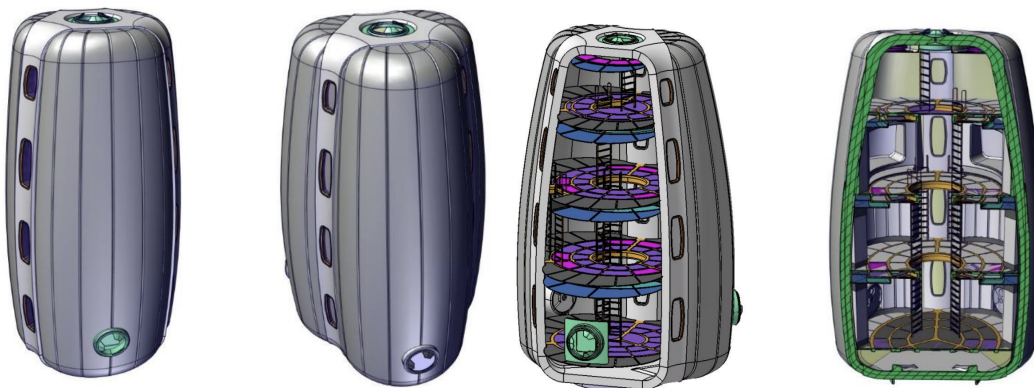


Fig. 61. Conceptual design of a single Moon Village habitat. A module with a rigid central core structure and an inflatable, multilayer envelope, with a visualisation of the floor layout and functional zones within the pressurised volume (source: ESA, 2020).

³¹³ ESA. (2020). *CDF STUDY REPORT MOON VILLAGE Conceptual Design of a Lunar Habitat*. CDF Study Report: CDF-202(A)

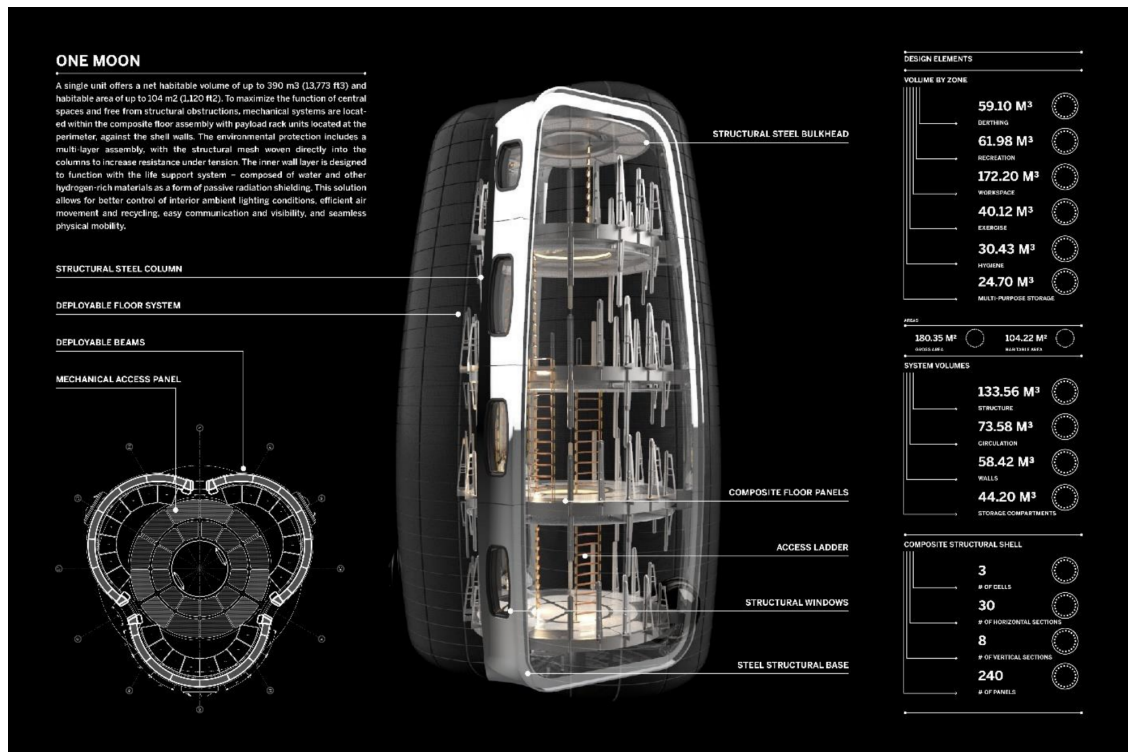


Fig. 62. Perspective section and horizontal plan illustrating the vertical multi-level arrangement, central rigid structural core, inflatable multilayer pressurized shell system, and the division of volume into functional zones, together with a summary of volumes and usable floor areas (source: ESA, 2020).

The habitation module assumes a functional division of space into zones for sleeping, work, research, food preparation, hygiene, and medical care [Fig. 63]. The CDF document emphasises that the interiors must be adaptive, acoustically separated, ergonomic under low-gravity conditions, and allow for the preservation of privacy, which is crucial during long-duration missions in isolation³¹⁴. The interiors are designed as modular structures with variable functions, integrated with life-support and internal communication systems.

A significant part of the interior layout consists of work and scientific zones [Fig. 64], where the crew conducts geological and biological research, ISRU tests, and operational tasks. The report also describes the necessity of locating environmental control and life-support systems (ECLSS) in a way that ensures both easy access to service compo-

³¹⁴ ESA. (2020). *CDF STUDY REPORT MOON VILLAGE Conceptual Design of a Lunar Habitat*. CDF Study Report: CDF-202(A)

nents and minimal acoustic disturbance. The ECLSS forms an integral part of the walls and underfloor service spaces. Another important interior element described in the CDF is the medical zone, designed as a small, separated module intended for medical interventions, isolation, and crew health monitoring. The presence of this space results from risks associated with radiation, mechanical injuries, exposure to lunar dust, and limited evacuation capabilities. The interior design also assumes the strategic placement of the airlock, which functions as a gateway between the pressurised module and the external environment. The airlock must allow for EVA suit storage, lunar dust decontamination, and rapid operational transitions. The CDF report also points to components related to energy and storage zones, which must be located in areas ensuring easy servicing and minimal thermal impact on the living space. Systems such as water storage, waste tanks, local heat generators, and thermal exchangers are arranged peripherally in order to separate them from crew quarters and improve the thermal efficiency of the module.



Figs. 63 and 64. Renderings of the proposed habitat interior. Crew quarters (left). Working and payload station (right) (source: ESA, 2020).

The structural systems of the habitat [Fig. 65] include a load-bearing section with a volume of 133.56 m³, life-support systems with a volume of 73.58 m³, an air circulation system (56.82 m³), and 44.20 m³ allocated for internal partitions and walls. The external shell consists of a composite structural envelope formed by 240 panels, divided into 30 horizontal and 8 vertical sections, supported by three main structural “cells” responsible for the uniform transfer of loads. The internal layer includes deployable floor panels, circulation elements such as ladders and technical shafts (instead of stairs in reduced

gravity), as well as observation openings in the form of reinforced structural windows³¹⁵.

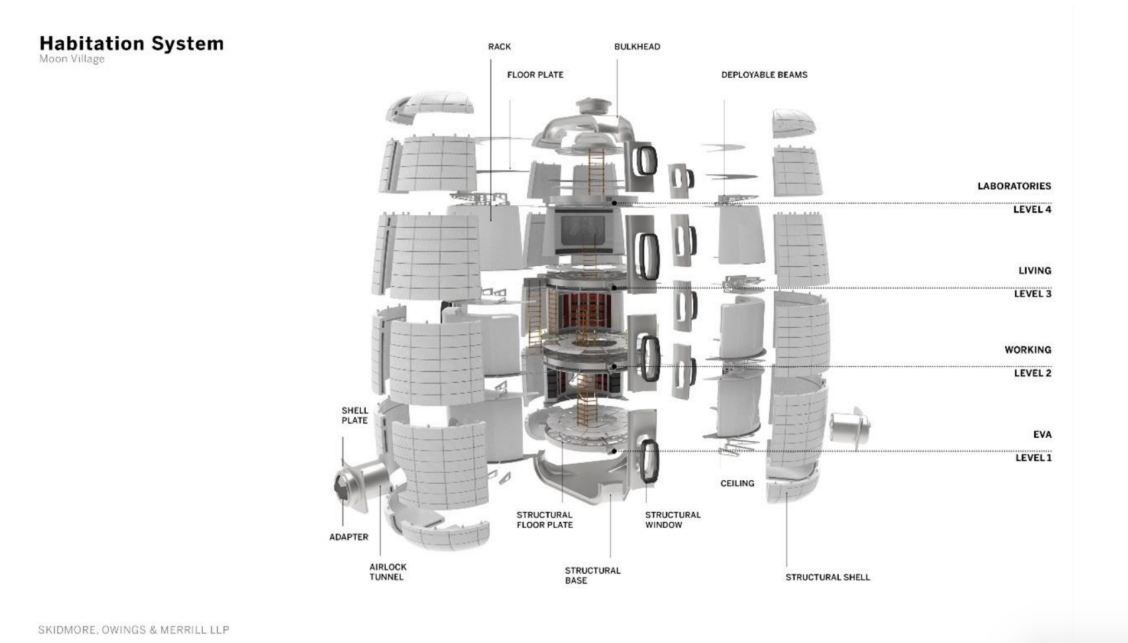


Fig. 65. Concept of the interior architecture of the Moon Village, exploded view(source: ESA, 2020).

Radiation protection is provided by a multilayer insulation structure designed to be covered with regolith deposited by robotic printing systems. The design also enable the possibility of integrating external micrometeoroid shields based on Whipple Shield-type solutions, adapted to low gravity and temperature variations reaching over 250°C in daily amplitude. By combining a rigid core with a flexible membrane, the habitat ensures high mechanical resistance as well as the ability to be compressed and transported within the cargo hold of lunar modules^{316,317}.

The table below [Table 13] provides a synthetic summary of the Moon Village case study analysis, organising the main design challenges and the applied response strategies.

³¹⁵ ESA. (2020). *CDF STUDY REPORT MOON VILLAGE Conceptual Design of a Lunar Habitat*. CDF Study Report: CDF-202(A)

³¹⁶ ESA. (2020). *CDF STUDY REPORT MOON VILLAGE Conceptual Design of a Lunar Habitat*. CDF Study Report: CDF-202(A)

³¹⁷ Skidmore, Owings & Merrill. (n.d.). *Moon Village - SOM*. Moon Village - SOM.<https://www.som.-com/research/moon-village/> (accessed: 04 February 2026).

Table 13. Summary - Synthesis of Case Study Analysis - Moon Village

Design Challenge (constraint)	Design Factor (solution)
Technological Solutions	
Transport constrained by mass and volume.	Inflatable, multilayer habitation module integrated with a lightweight central core.
Protection against radiation and micrometeoroids.	Multilayer composite shell combined with regolith covering as passive shielding.
Extreme temperature fluctuations.	Multilayer insulation and partial burial/covering of the habitat.
Requirement for long-term pressurisation integrity.	Rigid steel pressure core and segmented shell structure.
Limited availability of resources.	Design compliant with ISRU and prepared for integration of local materials, including development of automated 3D printing.
Assembly under lunar conditions.	Prefabrication combined with on-site deployment of structures (deployable systems).
Redundancy of critical systems.	Centralisation of technical systems within the core.
Limited astronaut mobility.	Vertical multi-level layout with internal ladder-based circulation.
Psychosocial Solutions	
Long-term isolation and monotony.	Clear functional division of space (sleep, work, recreation).
Lack of privacy.	Individual, separated sleeping areas.
Sensory overload.	Clear spatial hierarchy and organised interior layout.
Circadian rhythm disturbances.	Controlled internal lighting and vertical zoning of functional areas.
Potential interpersonal conflicts.	Designated shared and individual spaces.
Sense of confinement.	Vertical spatial organisation increasing perceived volume.
Limited contact with the external environment.	Structural windows as elements supporting orientation and psychological comfort.

7.6. The Environment of Mars

Mars is the fourth planet of the Solar System and one of the main targets of future crewed exploration due to its relative similarities to Earth, such as a comparable length of day and the presence of seasons resulting from the inclination of the planet's rotational axis³¹⁸. The distance between Mars and Earth changes depending on the orbital configuration of both planets. According to NASA data, the minimum distance is about 56 million kilometres, while in an unfavourable configuration it can exceed 400 million kilometres³¹⁹, which in planned missions translates into a journey lasting about 9 months, carried out within launch windows occurring approximately every 26 months. Mars has a very thin atmosphere, with an average surface pressure of about 0.6 kPa, which is less than 1% of Earth's atmospheric pressure³²⁰. The atmosphere consists mainly of carbon dioxide, with small amounts of nitrogen, argon, and trace quantities of oxygen and water vapour. Such low pressure prevents the stable existence of liquid water on the planet's surface under current climatic conditions³²¹. The climate of Mars is characterised by a low average surface temperature of about -60°C and very large daily and seasonal temperature amplitudes³²². During a single day, temperature differences can reach several tens of degrees Celsius, which is a direct result of the thin atmosphere and the planet's limited capacity to store heat. Although locally, especially in equatorial regions, surface temperatures may periodically exceed the melting point of ice, these phenomena are short-lived and do not lead to the persistent presence of liquid water³²³. One of the significant environmental factors on Mars is the widespread presence of

³¹⁸ Liu, J., Li, H., Sun, L., Guo, Z., Harvey, J., Tang, Q., Lu, H., & Jia, M. (2022). *In-situ Resources for Infrastructure Construction on Mars: A Review. International Journal of Transportation Science and Technology*, Volume 11, Issue 1, 1-16. doi.org/10.1016/j.ijtst.2021.02.001

³¹⁹ NASA - Mars. (n.d.). *Mars: Facts. NASA Science*. <https://science.nasa.gov/mars/facts/> (accessed: 04 February 2026).

³²⁰ Liu, J., Li, H., Sun, L., Guo, Z., Harvey, J., Tang, Q., Lu, H., & Jia, M. (2022). *In-situ Resources for Infrastructure Construction on Mars: A Review. International Journal of Transportation Science and Technology*, Volume 11, Issue 1, 1-16. doi.org/10.1016/j.ijtst.2021.02.001

³²¹ Rapp, D., Mungas, G. S., Easter, R. W., & Johnson, K. R. (2006). *Accessible Water on Mars and the Moon. Earth & Space 2006: Engineering, Construction, and Operations in Challenging Environment*. doi.org/10.1061/40830(188)74

³²² Liu, J., Li, H., Sun, L., Guo, Z., Harvey, J., Tang, Q., Lu, H., & Jia, M. (2022). *In-situ Resources for Infrastructure Construction on Mars: A Review. International Journal of Transportation Science and Technology*, Volume 11, Issue 1, 1-16. doi.org/10.1016/j.ijtst.2021.02.001

³²³ Rapp, D., Mungas, G. S., Easter, R. W., & Johnson, K. R. (2006). *Accessible Water on Mars and the Moon. Earth & Space 2006: Engineering, Construction, and Operations in Challenging Environment*. doi.org/10.1061/40830(188)74

dust, as well as global and regional dust storms. These phenomena can significantly limit access to solar energy and affect the operation of technical systems, which has been identified as a major challenge for future crewed missions and surface infrastructure^{324,325}. Numerous data indicate the presence of substantial water resources in the form of ice. Rapp's studies show that at mid and high latitudes, there is subsurface ground ice, often located beneath a thin, desiccated layer of regolith³²⁶. From the perspective of future crewed exploration, the Martian environment represents both a hazard and a potential source of resources. Extreme climatic conditions, low pressure, and planetary isolation require a high level of autonomy of life-support systems and infrastructure. At the same time, the availability of regolith, water ice, and mineral resources provides a basis for the development of ISRU strategies, which can significantly reduce the dependence of future missions on supplies from Earth³²⁷. The gravity on the surface of Mars is about 38% of Earth's gravity, which constitutes one of the key environmental differences compared to Earth.

7.6.1. Martian Habitat (NASA 3D Printed Habitat Challenge)

The Mars habitat design [Fig. 66], developed by the teams from Hassell Studio and Eckersley O'Callaghan, was created within the framework of NASA's Centennial Challenge: Three Dimensional (3D) Printed Habitat. The challenge aimed to test the feasibility of autonomous construction of residential infrastructure in extreme environments using 3D printing technology and local material resources³²⁸. This competition constituted a stage in the development of the In-Situ Resource Utilization (ISRU) concept, which seeks to minimise dependence on Earth-based supplies by utilising Martian rego-

³²⁴ Liu, J., Li, H., Sun, L., Guo, Z., Harvey, J., Tang, Q., Lu, H., & Jia, M. (2022). *In-situ Resources for Infrastructure Construction on Mars: A Review. International Journal of Transportation Science and Technology*, Volume 11, Issue 1, 1-16. doi.org/10.1016/j.ijtst.2021.02.001

³²⁵ NASA. (2009). *Human Exploration of Mars Design Reference Architecture 5.0*. NASA/SP-2009-566, Mars Architecture Steering Group.

³²⁶ Rapp, D., Mungas, G. S., Easter, R. W., & Johnson, K. R. (2006). *Accessible Water on Mars and the Moon*. Earth & Space 2006: Engineering, Construction, and Operations in Challenging Environment. doi.org/10.1061/40830(188)74

³²⁷ Liu, J., Li, H., Sun, L., Guo, Z., Harvey, J., Tang, Q., Lu, H., & Jia, M. (2022). *In-situ Resources for Infrastructure Construction on Mars: A Review. International Journal of Transportation Science and Technology*, Volume 11, Issue 1, 1-16. doi.org/10.1016/j.ijtst.2021.02.001

³²⁸ Hassell. (2018). *Mars Habitat. NASA 3D Printed Habitat Challenge*. <https://www.hassellstudio.com/project/nasa-3d-printed-habitat-challenge> (accessed: 04 February 2026).

lith as the primary construction material³²⁹. The project was developed in response to the requirements of the third phase of the competition, which emphasised architectural quality, the feasibility of the construction process, system autonomy, and scalability for actual Mars mission conditions. The habitat was designed as an environment capable of long-term operation under isolation, cosmic radiation, low gravity, and limited resource availability, while also considering the psychosocial aspects of crew life.³³⁰



Fig. 66. Mars habitat produced using additive manufacturing and local resources (ISRU), designed as part of the NASA 3D Printed Habitat Challenge (source: Hassell, 2018).

The habitat's form is monolithic and organic, with geometry optimised for additive manufacturing, uniform stress distribution, and structural resilience. The continuous structural shell [Fig. 67] simultaneously provides load-bearing capacity, protection, and insulation, eliminating the need for conventional prefabricated elements. This approach departs from traditional design paradigms and aligns with the logic of process-driven

³²⁹ Mueller, R. P., Prater, T. J., Roman, M., Edmunson, J. E., Fiske, M. R., & Carrato, P. (2019). *NASA CENTENNIAL CHALLENGE: THREE DIMENSIONAL (3D) PRINTED HABITAT, PHASE 3*. 70th International Astronautical Congress (IAC) Proceedings, IAC-19-E5.1.8.

³³⁰ Hassell. (2018). *Mars Habitat*. NASA 3D Printed Habitat Challenge. <https://www.hassellstudio.com/project/nasa-3d-printed-habitat-challenge> (accessed: 04 February 2026).

architecture, where form is a direct outcome of construction technology³³¹. A key aspect of the project is the implementation of advanced construction technologies based on autonomous 3D printing. The construction material is produced from local resources, which are sourced, processed, and utilised directly on-site. The construction process relies on a system of cooperating robots operating as a decentralised “swarm,” capable of executing successive stages of the build [Fig. 68]. This approach increases system resilience to individual unit failures and allows scaling of the construction process according to available resources and environmental conditions³³².

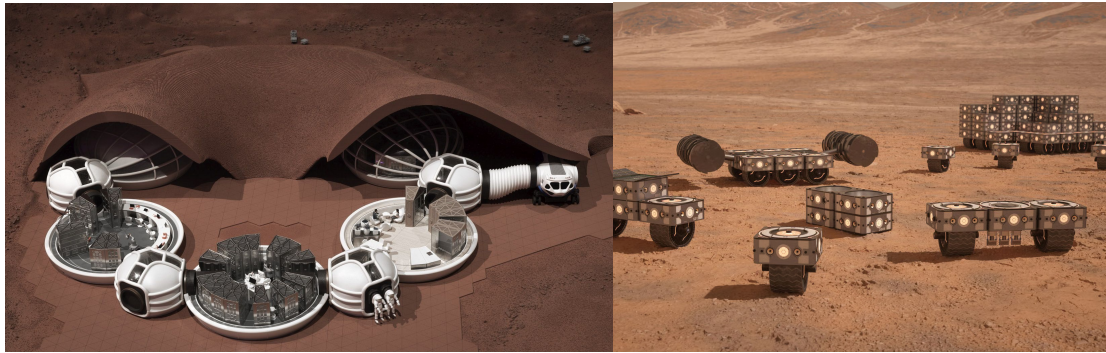


Fig. 67 (left) Integrated concept of the Mars habitat featuring a monolithic shell produced via additive manufacturing using local materials (source: Hassell, 2018)

Fig. 68 (right) Robotic swarm - autonomous construction process based on collaborative work of multiple construction robots (source: Eckersley O'Callaghan, n.d.).

The Mars habitat design is based on a three-layer system [Fig. 69], where the external structural shell plays a key role. It is a massive, continuous structure with variable thickness, designed to serve both as a load-bearing and protective element, providing radiation shielding, thermal stabilisation, and resistance to environmental loads typical of the Martian surface³³³. Inside the printed shell, a system of functional modules is located, designed as lightweight, prefabricated units to be installed after the external structure is completed. These modules organise the usable interior space and integrate

³³¹ Eckersley O'Callaghan. (n.d.). *Mars Habitat*. <https://www.eocengineers.com/projects/mars-habitat-390/> (accessed: 04 February 2026).

³³² Irawan, J., De Kestelier, X., Argyros, N., Lewis, B., & Gregson, S. (2019). *A Reconfigurable Modular Swarm Robotic System for ISRU(In-Situ Resource Utilisation) Autonomous 3D Printing in Extreme Environments. Impact: Design With All Senses, (DMSB 2019)Proceedings of the Design Modelling Symposium, Berlin 2019, 685-698.*

³³³ Hassell. (2018). *Mars Habitat. NASA 3D Printed Habitat Challenge*. <https://www.hassellstudio.com/project/nasa-3d-printed-habitat-challenge> (accessed: 04 February 2026).

life-support systems, technical installations, and equipment. Their modular nature allows for phased habitation, component replacement, and reconfiguration of interior layouts³³⁴. This solution separates protective and structural functions from residential functions, increasing system resilience to failures and facilitating adaptation over the course of the mission. Interior organisation relies on a modular system, where living, work, technical, and common functions are defined by a set of repetitive spatial units.

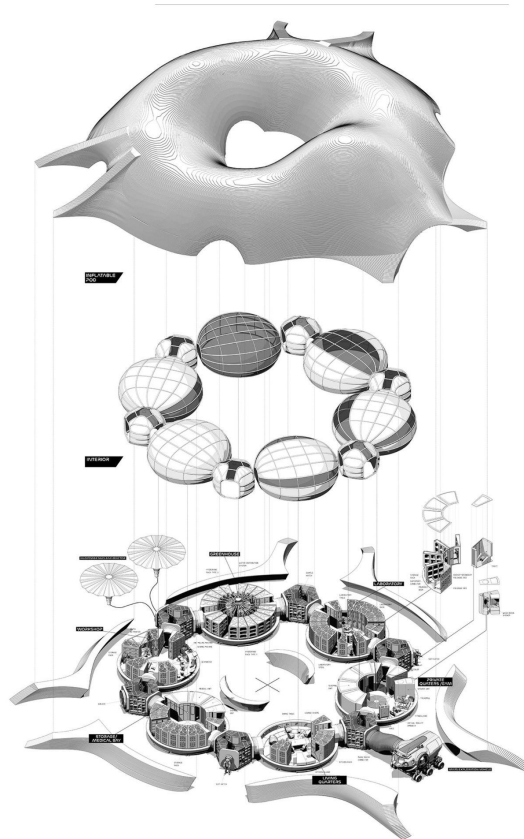


Fig. 69. Diagram of the three-layer architectural structure of the Mars habitat (source: Hassell, 2018).

The spatial program includes primary living, work, and technical zones. A clear distinction was made between private spaces, intended for rest and recovery, and common areas [Fig. 70], which concentrate work and research functions [Fig. 71], meal preparation, and social interaction. An important component of the interior layout is also the areas designated for plant cultivation and biological systems [Fig. 72], serving both a

³³⁴ Hassell. (2018). *Mars Habitat. NASA 3D Printed Habitat Challenge*. <https://www.hassellstudio.com/project/nasa-3d-printed-habitat-challenge> (accessed: 04 February 2026).

productive and environmental function, supporting atmospheric stabilisation and the crew's psychological well-being. The interior organisation follows a systems logic, where equipment, technical infrastructure, and the boundaries of usable space form a coherent framework, enabling efficient resource management and adaptation of the living environment for long-term Mars habitation.



Fig. 70. Interior of the common area of the Mars habitat, view (source: Hassell, 2018).



Fig. 71 (left). Interior of the laboratory module of the Mars habitat, integrated with research and control systems (source: Hassell, 2018).

Fig. 72 (right). Interior of the plant cultivation module, part of the bioregenerative system of the Mars habitat (source: Hassell, 2018).

The following table [Table 14] provides a synthetic summary of the case study analysis of the Martian Habitat, organising the main design challenges and the corresponding response strategies.

Table 14. Summary - Synthesis of Case Study Analysis - Martian Habitat

Design Challenge (constraint)	Design Factor (solution)
Technological Solutions	
Radiation and extreme Martian environmental conditions.	Thick, 3D-printed shell using ISRU.
Transport constraints.	Use of local ISRU resources.
Low gravity, pressure, and environmental constraints.	Optimised geometry for stress distribution and structural resilience.
Limited human presence.	Autonomous robotic construction systems.
Structural stability.	Continuous shell-based structural system.
Psychosocial Solutions	
Long-term isolation.	“Room with a view” toward Mars.
Lack of environmental stimuli.	Integration of plant cultivation.
Need for privacy.	Modular habitation units.
Psychological overload.	Clear spatial organisation.
Variability of crew needs.	Reconfigurable interior modules.
Circadian rhythm regulation.	Artificial and biologically tuned lighting.

7.7. Summary of Case Study

The analysed case studies, whether realised, experimental, or conceptual, demonstrate a wide spectrum of approaches to the issue of self-sufficiency in architecture for extreme environments. Each object responds to a different set of environmental, technological, and operational challenges, resulting from the nature of its surroundings (underwater, orbital, lunar, or analog) as well as the mission objectives and design scope. This compilation shows that there is no single universal architectural or technological solution. Adaptation is always contextual and graduated. Despite the sophistication of advanced systems, none of the studied objects achieve full, one-hundred per cent self-sufficiency simultaneously in environmental, technological, and logistical terms. Even in the most extreme space conditions, habitat functioning relies on partial closed-loop systems, which reduce dependence on external supplies but do not eliminate it completely (particularly in the context of closed-loop resources such as water, air, and energy). At the same time, the examined projects confirm that appropriately selected technologies and spatial strategies can significantly improve operational efficiency, enhance user safety, and reduce resource consumption. Therefore, the level of self-sufficiency is not an absolute goal but a variable dependent on a range of design, operational, and environmental factors.

The analyses indicate that the selection of technologies and architectural solutions in extreme environments is not determined solely by the environment itself. It is a complex configuration of design parameters, among which key factors include:

- number of users (size and composition of the crew),
- mission duration and mode of use (short-term vs. long-term),
- mission objectives (research, operational, demonstration, permanent habitation),
- risk level and allowable margin of error,
- extremity of the external environment (pressure, radiation, temperature, gravity),

- extremity of the internal environment (comfort, privacy, ergonomics, health),
- availability of local resources and the possibility of their utilisation (ISRU),
- autonomy of life-support systems,
- serviceability, repair, and reconfiguration capabilities,
- stage of technological development (test, demonstrator, operational deployment).

Additionally, the following general conclusions can be drawn regarding the examples analysed in the case studies:

- Extreme architecture as an integrated system: The case studies indicate that in extreme environments, architecture functions as a critical safety system, integrating spatial, technological, and operational solutions to ensure life protection and stable human functioning under elevated risk conditions.
- Integration of technical and environmental systems: In the examined objects, the level of self-sufficiency resulted from the integration of technical systems with spatial organisation rather than from the use of individual technological solutions. Particular emphasis is placed on closed-loop resource cycles and in-situ production.
- Spatial organisation and habitability: The analysis confirmed the significant impact of spatial organisation, functional zoning, and privacy levels on user functioning in isolation, identifying habitability as a key factor for long-term use.
- Modularity and flexibility: In both space and analog architecture, modularity and the ability to reconfigure space enhance the adaptability of objects to changing operational conditions and user needs.
- Common design mechanisms: Comparison of space, analog, and terrestrial objects revealed the existence of shared design mechanisms arising from similar

environmental constraints, while also showing variation in scale and intensity of their application.

8. Self-sufficiency - Analysis of Factors

This section presents an analysis of elements highlighted within case studies of extreme environments, including realised, experimental, and conceptual objects. Based on the compilation of design challenges (*Design Challenges*) and their corresponding architectural and technological strategies (*Design Factors*), a catalog of Architectural Resilience Factors (ARF) was developed. These factors identify recurring mechanisms of built environment adaptation to extreme conditions, regardless of specific geographic or planetary context, and serve as a starting point for further synthesis and the construction of an original model of architectural self-sufficiency.

8.1. Design Challenges and Design Factors - Summary

The analysis of the conducted case studies revealed a clear repetition of design challenges applied. Regardless of the scale of the building, the degree of its completion, or the specific environmental context, designers face similar problems related to life support, operational continuity, and maintaining user well-being under conditions of limited resource availability and high risk. The response to these challenges consists of diverse design strategies and technical or spatial solutions, referred to in this work as *Design Challenges* and *Design Factors*. During the analysis phase, a broad spectrum of such solutions was identified, including resource recycling systems, inflatable structures, modular spatial arrangements, redundancy of critical systems, functional zoning, and strategies supporting users' mental health.

In this study, it was assumed that for comparative analysis and the construction of a universal self-sufficiency scale, it is essential to move away from describing individual technologies (which respond specifically to the characteristics and requirements of a given environment) toward identifying overarching architectural strategies and capabilities derived from the main design challenges in extreme environments. For this re-

ason, the identified *Design Factors* were subjected to a process of synthesis and generalisation. The goal of this process was to isolate features of the built environment that do not refer to a specific technical solution (where possible) but describe its ability to respond to changing conditions, resource limitations, and user needs.

8.2. Catalog of Architectural Resilience Factors (ARF)

As a result of synthesising case study analyses, the concept of *Architectural Resilience Factors (ARF)* was introduced, understood as a set of overarching design factors describing the resilience of architecture in extreme conditions. In this work, ARF are defined as characteristics and strategies of the built environment that enable long-term functioning with limited dependence on external resources, under conditions of increased risk and uncertainty, while simultaneously considering technical, operational, and psychosocial aspects. These factors do not constitute a catalog of specific technologies or ready-made engineering solutions. They provide an analytical framework for comparing different types of buildings and evaluating their adaptive potential and level of self-sufficiency.

For clarity of organisation, the identified ARF factors have been grouped into seven overarching categories (ARF 1 to ARF 7), corresponding to key areas of architectural performance in extreme environments. These categories reflect fundamental human biological needs, system requirements, and spatial and psychological conditions relevant to long-term habitation. Within each category, detailed strategies (labelled ARF 1.1, ARF 1.2, etc.) were identified to specify the overarching resilience factors.

This two-level ARF structure (general categories and detailed strategies) allows for maintaining a high level of analytical abstraction while referencing real architectural and technological solutions. It also forms the basis for the next research stage: constructing the Self-Sufficiency Readiness Level (SSRL) scale.

Below [tab. 15] is a summary of all overarching ARF categories and their components. A descriptive section, explaining each element of the table, is presented in subsections 8.2.1-8.2.8.

Table 15. Summary of ARF categories and subcategories.

ARF Category	ARF Sub-component
ARF 1. Resource autonomy and metabolism	ARF 1.1 Water recirculation ARF 1.2 Water storage ARF 1.3 Local energy production ARF 1.4 Energy storage ARF 1.5 Local food production
ARF 2. Atmospheric and internal environment stability	ARF 2.1 Stabilisation of physiological living conditions ARF 2.2 Maintenance of indoor environmental quality ARF 2.3 Regulation of internal microclimate
ARF 3. System resilience and safety	ARF 3.1 Adaptable operational spaces ARF 3.2 Protection against environmental hazards ARF 3.3 Resistance to failure of single components
ARF 4. Structural, constructional, and material adaptability	ARF 4.1 Scalability and phasing of development ARF 4.2 In-situ repair and maintenance ARF 4.3 Rapid implementation of structures under limited transport resources
ARF 5. Organisation of space and functions	ARF 5.1 Basic functions ARF 5.2 Additional functions ARF 5.3 Universality and multifunctionality of architectural structures ARF 5.4 Clarity and operational order ARF 5.5 Regulation of social interactions
ARF 6. Psychosocial well-being	ARF 6.1 Stabilisation of biological rhythms ARF 6.2 Privacy control and regeneration ARF 6.3 Perceptual environmental quality ARF 6.4 Enhancement of sense of control and identity
ARF 7. Operational autonomy	ARF 7.1 Reduction of logistical dependence on external supply ARF 7.2 Automation of systems ARF 7.3 Capability for autonomous and continuous operation

8.2.1. ARF 1. Resource Autonomy and Metabolism

The objective of the *ARF Resource autonomy and metabolism* is to assess the ability of architecture to independently obtain, process, store, and recirculate essential resources required to sustain life and maintain the functioning of a facility under isolated conditions. ARF 1 addresses the question of the degree of dependence of the built environment on external material and energy supply. ARF 1 refers to the biological and technical “metabolism” of architecture, understood analogously to a living organism, as a system of matter and energy flows. In extreme environments, resource metabolism largely determines the possibility of long-term operation of a facility, regardless of its spatial form or level of comfort. Within this factor, the following aspects are considered:

- To what extent is the facility dependent on the external supply of water, energy, and food?
- Are resources consumed once, or are they recirculated?
- What are the limits of temporal autonomy of the system in the absence of supply?
- Does architecture enable a gradual increase in the autonomy level?

Analysis of case studies shows that none of the analysed facilities achieves full resource autonomy. Instead, strategies of partial loop closure are applied, which reduce but do not eliminate dependence on external logistics. ARF 1, therefore, has a gradational character and constitutes one of the key factors differentiating levels of self-sufficiency in the further part of the scale.

Table 16. Sub-ARF 1 with description.

ARF 1.1. Water recirculation	
Description	The ability of architecture to reuse greywater through recovery systems for greywater, blackwater, and condensate from air.
What problem solves?	Reduction of mass and frequency of water supply, which in extreme environments is one of the heaviest and most critical resources.
Example	Use of greywater, recovery of water from humidity.
ARF 1.2. Water storage	
Description	The ability to safely store water reserves to support the temporal autonomy of a facility.
What problem solves?	Providing a safety buffer in the event of recovery system failures or interruptions in supply.
Example	Integrated tanks in modules of analog habitats
ARF 1.3. Local energy production	
Description	The ability to generate energy at the location of the facility's operation.
What problem solves?	Reduction of dependence on external power sources and increased operational independence.
Example	Photovoltaic panels on the ISS
ARF 1.4. Energy storage	
Description	The ability to store energy to stabilise system operation during periods without production.
What problem solves?	Ensuring continuity of critical system operation.
Example	Batteries and energy storage systems in orbital stations.

ARF 1.5. Local food production

Description	The ability to produce food within the built environment.
What problem solves?	Reduction of logistical mass and improvement of users' psychological well-being.
Example	Bioregenerative food systems, hydroponics, aeroponics

8.2.2. ARF 2. Atmospheric and Internal Environment Stability

The objective of this factor is the ability of architecture to maintain physical conditions enabling safe and long-term human presence in a closed environment, independent of variable and often extreme external conditions. ARF 2 addresses the question of whether the built environment can create and maintain a stable internal microclimate, including atmospheric composition, temperature, humidity, and air quality, while limiting the risk of local environmental disturbances. Supporting questions include:

- Are environmental conditions controlled and stable over time?
- How does architecture respond to local microclimate disturbances?
- Is it possible to separate zones with different environmental requirements?

Stability of the internal environment constitutes one of the fundamental conditions for biological survival of users; however, its significance extends beyond physiological aspects. Even long-term minor deviations in environmental parameters may lead to reduced operational efficiency and increased psychological strain.

Table 17. Sub-ARF 2 with description.

ARF 2.1. Stabilisation of physiological living conditions

Description	The ability of architecture to maintain fundamental parameters of the internal environment.
What problem solves?	Enables breathing and functioning of the human body by maintaining life-support parameters independently of external atmospheric conditions.
Example	Control and maintenance of gas composition and critical life environment parameters (e.g. O ₂ /CO ₂)

ARF 2.2. Maintenance of indoor environmental quality

Description	The ability of architecture to maintain the cleanliness and stability of the environment.
What problem solves?	Limits the accumulation of chemical, biological, and particulate contaminants, which in closed environments may lead to deterioration of health and user performance.
Example	Air filtration systems and contamination control systems.

ARF 2.3. Regulation of internal microclimate

Description	The ability of the architectural system to control microclimatic parameters such as temperature, humidity, and airflow.
What problem solves?	Prevents physiological stress caused by uncontrolled temperature and humidity fluctuations and enables long-term presence in enclosed spaces without degradation of physical comfort.
Example	Temperature and humidity control systems integrated with air circulation and cooling systems.

8.2.3. ARF 3. System Resilience and Safety

The objective of ARF 3 is to assess the ability of architecture to maintain operational continuity under conditions of failure, disturbance, and unforeseen situations, without immediate loss of user safety or the need for evacuation. ARF 3 refers to architecture as a resilient system capable of absorbing errors and isolating hazards. Supporting questions include:

- Does the architecture enable localisation and isolation of failures without paralysis of the entire facility?
- To what extent do critical systems possess functional redundancy, not only technological redundancy?
- Is it possible to continue basic life-support and operational functions in the event of damage to single components?
- Does the facility enable repair, maintenance, and reconfiguration in situ, without dependence on external support?
- Do spatial and system solutions limit the propagation of hazards (fire, pressure loss, contamination, system failure)?
- To what extent does architecture support conscious risk management rather than only crisis response?

In extreme environments, failure is a planned design scenario that must be considered already at the conceptual stage. System resilience in this context consists of the ability of the architecture to limit and control such events. This factor emphasises the role of architecture as an active participant in the safety system.

Table 18. Sub-ARF 3 with description.

ARF 3.1. Adaptable operational spaces

Description	The ability of space to change function, configuration, or mode of use in response to changing operational conditions, system failures, or new requirements.
What problem solves?	Enables continuity of operations despite changes in usage scenarios, system limitations, or unforeseen events, without the need for expansion or evacuation.
Example	Multifunctional modules enabling adaptation of working space to research, maintenance, or residential functions.

ARF 3.2. Protection against environmental hazards

Description	Application of architectural and material solutions protecting users from extreme external factors.
What problem solves?	Ensures safe operation in environments with extreme physical parameters, where a lack of natural protection prevents long-term human presence.
Example	Multilayer protective shells, radiation shielding.

ARF 3.3. Resistance to the failure of single components

Description	Design of systems and structures in a way that enables continued operation despite damage to individual elements.
What problem solves?	Prevents situations in which failure of one component leads to loss of the entire system or a threat to user safety.
Example	Redundant life support and power supply systems.

8.2.4. ARF 4. Structural, Constructional, and Material Adaptability

ARF 4 refers to the ability of an architectural structure to adapt its form, construction, and applied materials to changing environmental, logistical, and operational conditions. It includes both geometric and assembly flexibility of the facility, as well as the possibility of using different construction technologies, including lightweight, deployable, pre-fabricated, and in-situ manufactured solutions. The objective of this factor is to enable rapid implementation of architecture under limited transport resources, minimise launch mass and volume, and increase structural resilience to changing environmental and operational conditions. ARF 4 supports the transition from static architecture to building systems that can be assembled in phases, reconfigured, and expanded without the need for complete structural replacement.

Within the context of ARF 4, the analysed facility can be assessed through the following questions:

- Can the structure be transported in a compressed or prefabricated form and then assembled on-site?
- Does the construction enable phased erection, reinforcement, or expansion over time?
- Are the applied materials resistant to long-term exposure to extreme or potentially extreme conditions (radiation, vacuum, extreme temperatures)?
- Can the facility be repaired or reinforced locally without the need to import full structural elements?
- Is it possible to use local resources (e.g. regolith) as part of the structure or protective layers?

In the analysed case studies, structural adaptability emerges as a necessary condition for the transition from short-term experimental habitats to permanent living environments.

Table 19. Sub-ARF 4 with description.

ARF 4.1. Scalability and phasing of development

Description	The ability of an architectural structure to gradually develop and expand over time, without the need for full implementation of the facility at the initial stage.
What problem solves?	Enables adjustment of development scale to changing user needs and available resources, reducing the risk of overinvestment at an early stage.
Example	Phased expansion of space stations, modularity.

ARF 4.2. In-situ repair and maintenance

Description	The ability to maintain, repair, and modify structural elements without the need for full replacement or external supply.
What problem solves?	Reduces vulnerability of the facility to technical degradation and failure and extends its life cycle in environments with limited access to maintenance infrastructure.
Example	In-situ manufacturing of components (3D printing).

ARF 4.3. Rapid implementation of structures under limited transport resources

Description	The ability of architecture to enable rapid assembly and activation of functional use with minimal transport mass and volume.
What problem solves?	Enables rapid achievement of minimum facility functionality under conditions of limited logistics and time pressure.
Example	Inflatable and deployable structures

8.2.5 ARF 5. Organisation of Space and Functions

ARF 5 refers to the organisation of internal space and the relationships between functions in closed and isolated environments. It includes functional layout, spatial hierarchy, level of clarity, and the possibility of separating and combining functions in response to user needs and operational scenarios. ARF 5 analyses architecture as a structure organising daily life, work, and regeneration under conditions of limited space and high psychophysical load.

The objective of ARF 5 is to ensure a clear, logical, and flexible spatial layout that supports effective operational functioning, reduces user conflicts, and enables a balance between work, rest, and social interactions. ARF 5 aims to organise space in a way that enables both basic and additional functions without overloading the internal environment.

Within ARF 5, the following questions are analysed:

- Is the functional layout clear and intuitive for users over long periods of use?
- Are spaces diversified in terms of function and intensity of use (work, rest, interaction)?
- Is it possible to separate conflicting functions (noise, odours, privacy)?
- Does architecture enable spatial hierarchy (private, semi-private, shared)?
- Does space allow flexible assignment of functions depending on changing mission requirements?

ARF 5 constitutes a link between technical and psychosocial dimensions of architecture.

Table 20. Sub-ARF 5 with description.

ARF 5.1. Basic functions

Description	Provision of spaces enabling essential life and operational activities.
What problem solves?	Ensures continuity of user functioning by providing a minimum functional program independent of environmental conditions.
Example	Sleeping, working, and hygiene zones.

ARF 5.2. Additional functions

Description	Provision of spaces not directly related to survival functions, but supporting well-being and quality of life.
What problem solves?	Increases the psychosocial resilience of users over long time periods.
Example	Recreation, observation, or individual activity zones.

ARF 5.3. Universality and multifunctionality of architectural structures

Description	Design facilitating multifunctional use of space.
What problem solves?	Allows flexible reconfiguration in case of operational changes or system failure.
Example	Modularity (residential and technical modules can change function depending on season, number of users, or operational conditions).

ARF 5.4. Clarity and operational order

Description	A logical and unambiguous spatial layout supporting orientation and efficient use of the facility.
What problem solves?	Reduces disorientation, operational errors, and cognitive overload resulting from unclear spatial organisation.
Example	Hierarchical spatial layout with clearly defined functions and circulation paths.

ARF 5.5. Regulation of social interactions

Description	The ability of architecture to support and moderate social interactions through the layout and accessibility of shared and private spaces.
What problem solves?	Reduces interpersonal conflicts and social overload.
Example	Separation of shared and individual spaces.

8.2.6. ARF 6. Psychosocial Well-being

ARF 6 includes factors influencing the psychological condition and social relations of users. It focuses on environmental perception, the possibility of personalisation, quality of stimuli, and the support of biological rhythms. ARF 6 analyses architecture as an active element capable of mitigating stress, monotony, and sensory overload. The objective of ARF 6 is to support long-term psychological and social stability of users through the design of an environment that enables regeneration, a sense of control, privacy, and identification with space. ARF 6 aims to limit the negative effects of isolation, which in extreme environments constitute one of the main risks to mission continuity.

Within ARF 6, the following questions are analysed:

- Does architecture enable a sense of privacy and control over personal space?
- Do users have the possibility to personalise space, including modification of visual and functional stimuli?
- Does the environment support circadian rhythms, regeneration, and sleep quality?
- Does the space offer diversity of sensory stimuli, limiting monotony and overload?
- Does architecture support healthy social interactions, for example, by enabling withdrawal?

Architecture, through scale, colour scheme, spatial organisation, and adaptability, can perform stabilising and therapeutic functions. ARF 6, therefore, constitutes a necessary complement to system and resource factors, shifting the focus of analysis toward long-term habitability quality rather than survival alone.

Table 21. Sub-ARF 6 with description.

ARF 6.1. Stabilisation of biological rhythms

Description	Design of environments supporting natural circadian rhythms of users through lighting, daily organisation, and temporal cues.
What problem solves?	Reduces sleep disorders, fatigue, and temporal disorientation resulting from the absence of natural day-night cycles.
Example	Lighting systems with variable colour temperature.

ARF 6.2. Privacy control and regeneration

Description	Provision of the possibility of temporary withdrawal from shared spaces and psychological and physical regeneration.
What problem solves?	Reduces social overload, interpersonal stress, and psychological fatigue.
Example	Individual private spaces.

ARF 6.3. Perceptual environmental quality

Description	Design of environments supporting positive perception through scale, proportions, colour schemes, and materials.
What problem solves?	Prevents sensory overload or sensory deprivation.
Example	Variation of interior colours and materials, external views, and biophilic elements.

ARF 6.4. Enhancement of the sense of control and identity

Description	Enabling users to influence and personalise their environment.
What problem solves?	Reduces feelings of helplessness and alienation and strengthens identification with the place of habitation.
Example	Possibility of individual arrangement of personal space in residential modules.

8.2.7. ARF 7. Operational Autonomy

ARF 7 refers to the ability of architecture to function operationally in conditions of limited or delayed external support. It includes the level of system automation, integration of external operations with internal space, and the ability to maintain continuity of operations without the need for immediate intervention or evacuation of users. ARF 7 analyses architecture as an environment capable of initiating and sustaining operational activities in a relatively independent manner. The objective of ARF 7 is to ensure continuity of facility operation under conditions of operational isolation by reducing dependence on external emergency procedures, supply chains, and control systems. ARF 7 supports the design of architecture that enables users to respond to events, perform maintenance activities, and execute mission tasks without the need for immediate logistical or decision-making support from outside the facility.

Within ARF 7, the following questions are analysed:

- Does architecture enable independent execution of operations without constant external support?
- To what extent are systems automated, and to what extent do they require continuous user intervention?

- Is it possible to safely conduct external operations in direct connection with the facility?
- Does architecture enable maintenance of basic operational functions in situations of delayed communication or lack of supply?
- Do spatial and system solutions support flexible management of logistics and resources?

Table 22. Sub-ARF 7 with description.

ARF 7.1. Reduction of logistical dependence on external supply

Description	The ability of architecture to minimise the need for regular supply of materials, spare parts, and operational resources from external sources.
What problem solves?	Reduces vulnerability of facility operation to supply chain disruptions and logistical delays. Example
Example	High resource recovery systems and the possibility of local repair and manufacturing of components, e.g. through 3D printing.

ARF 7.2. Automation of systems

Description	Application of automated and semi-autonomous systems supporting management of the environment, resources, and infrastructure.
What problem solves?	Reduces user workload related to routine operational activities and decreases the risk of human error.
Example	Automated environmental and resource control systems, sensors.

ARF 7.3. Capability for autonomous and continuous operation

Description	The ability to maintain stable operation of a facility over extended periods without direct external support or continuous external operational control.
What problem solves?	Enables long-term activities in environments with limited communication and restricted access to external assistance.
Example	Integrated life support systems.

8.3. Comparative Analysis of ARF Factors

After identifying the catalog of Architectural Resilience Factors (ARF) along with their corresponding strategies and solutions, the next methodological step is to move from qualitative description to comparative analysis in order to hierarchize their impact on self-sufficiency. This requires examining which strategies are critical at each stage of the environment's functioning, as well as identifying the points at which the dominant system paradigm shifts from dependence on external resources toward autonomy.

8.3.1. Analysis Criteria

The analysis of ARF factors was based on three criteria corresponding to successive levels of built environment performance over time. The selection of survival, operability, and well-being reflects a systemic understanding of the built environment as a complex socio-technical system. These criteria correspond to three levels of system stability: physical stability (survival), functional stability (operability), and psychosocial stability (well-being). Only the simultaneous fulfilment of all three levels enables the long-term existence of the system without degradation of its functions.

Analysis criteria: Phases of built environment system stability:

(A) Survival - Objective: short-term

Refers to the most basic level of built environment functioning, enabling temporary

human presence in a given environment. This is the minimal level, sufficient for existence but inadequate for long-term use. Its time horizon is short-term and serves as a starting point for further stages of system development.

(B) Operability - Objective: medium-term

Describes the level at which the built environment can function stably over time and support planned activities or missions without continuous external support. At this stage, the system is no longer purely reactive and begins to operate continuously and in a controlled manner. This medium-term level allows for maintaining activity without degrading essential functions.

(C) Well-being - Objective: long-term, sustained

Refers to the highest level of built environment performance, in which long-term use is possible without negative consequences for humans or the system as a whole. At this stage, the environment maintains life-supporting and operational functions and additionally enables adaptation, psychosocial stability, and durability of human-space relationships. Well-being is long-term and constitutes a condition for true system sustainability, especially in residential environments.

To capture the relationships between ARF factors and the adopted criteria, a criticality matrix was developed and presented in the form of a heatmap. The heatmap serves as an analytical and diagnostic tool, identifying where the critical emphasis of the solutions lies.

The use of the heatmap thus enables:

- Identification of strategies critical for survival, operational functionality, and well-being;
- Observation of the stage at which a given operational criterion begins to play a significant role over time;
- Indication of moments where the paradigm of environmental functioning changes, for example, the shift from logistics based on external supply to recovery and regeneration systems;

- Consequently, the hierarchy of self-sufficiency strategies from least to most critical forms the basis for assigning corresponding requirements to the SSRL self-sufficiency assessment scale.

8.3.2. Heatmap

Due to the scale and complexity of the compilation, the full ARF strategy criticality matrix is presented in Appendix A, while the aggregated point results for individual elements are shown below (1 – marginal significance and 5 – critical significance (necessary condition)).

Table 23. Aggregated point values of the criticality of strategies implementing Architectural Resilience Factors (ARF) based on the analytical matrix (criteria A+B+C).

No.	Name	A+B+C
1.	ARF 3.2 Protection against environmental hazards	15
2.	ARF 5.1 Basic functions	15
3.	ARF 2.1 Stabilisation of physiological living conditions	14
4.	ARF 2.3 Regulation of internal microclimate	14
5.	ARF 3.3 Resistance to failure of single components	14
6.	ARF 1.1 Water recirculation	14
7.	ARF 1.3 Local energy production	14
8.	ARF 2.2 Maintenance of indoor environmental quality	13
9.	ARF 1.5 Local food production	13
10.	ARF 7.2 Automation of systems	12
11.	ARF 3.1 Adaptable operational spaces	12
12.	ARF 5.4 Clarity and operational order	12
13.	ARF 5.3 Universality and multifunctionality of architectural structures	12
14.	ARF 6.2 Privacy control and regeneration	12
15.	ARF 7.3 Capability for autonomous and continuous operation	12
16.	ARF 1.2 Water storage	12
17.	ARF 1.4 Energy storage	12
18.	ARF 4.2 In-situ repair and maintenance	11
19.	ARF 4.1 Scalability and phasing of development	11

No.	Name	A+B+C
20.	ARF 4.3 Rapid implementation of structures under limited transport resources	11
21.	ARF 6.1 Stabilisation of biological rhythms	11
22.	ARF 5.5 Regulation of social interactions	10
23.	ARF 7.1 Reduction of logistical dependence on external supply	10
24.	ARF 5.2 Additional functions	9
25.	ARF 6.4 Enhancement of sense of control and identity	7
26.	ARF 6.3 Perceptual environmental quality	7

8.3.3. Conclusion of Factor Analysis

The application of the heatmap primarily revealed clear distinctions between elements critical for the mere survival of the system and those influencing its stability, resilience, and long-term operational quality. The analysis showed that factors related to environmental protection, the stabilisation of physiological conditions, and the provision of basic functions exhibit the highest level of criticality, while elements associated with spatial adaptability and psychosocial well-being gain significance at higher stages of system maturity. The heatmap also proved to be a useful tool for identifying qualitative thresholds, where the character of a facility's functioning changes. Transition points became evident between states: from a facility fully dependent on external infrastructure, through partially regenerative systems, to autonomous and self-regulating solutions. These transition points served as the basis for defining the successive levels of the scale.

Insights derived from the heatmap analysis led to the development of an original seven-level scale aimed at describing degrees of architectural maturity in terms of self-sufficiency. This scale is based on a qualitative description of how a facility functions as an environmental, technical, and social system. Each SSRL level corresponds to a specific set of functional characteristics, directly derived from the observed differences in the criticality of the analysed factors.

8.4. Developing the Self-Sufficiency Scale

8.4.1 Definition of Self-Sufficiency

For this dissertation, the following original definition of architectural self-sufficiency was adopted, developed based on a review of literature on space habitats, and extreme architecture:

Architectural self-sufficiency is the ability of the built environment to support long-term human functioning, based on the integration of technological, spatial, and psychosocial solutions that enable stable relationships between humans, the interior of the facility, and the external environment under conditions of limited external support.

8.4.2. Levels of the Scale

The development of the SSRL scale was based on the analysis of a heatmap, which revealed the discontinuous nature of transitions between successive operational states of a facility. The Self-Sufficiency Readiness Level (SSRL) scale is design to be descriptive and functional (qualitative). Each level is defined by the way the facility functions as an environmental, technical, and spatial system. This approach allows the scale to be applied to a variety of facilities, both in the context of space architecture and analog habitats, as well as to terrestrial buildings operating under diverse conditions, including crises or limited infrastructure. The successive levels of the SSRL scale reflect an increasing degree of integration of environmental, technical, and user-related processes. At the lower levels, architecture primarily acts as a resource receiver and stabiliser of basic usage conditions.

As the scale level increases, the facility assumes greater responsibility for local environmental regulation, resource production and recovery, and the organisation of space conducive to long-term user functioning. At the highest levels, architecture functions as an integrated system capable of adaptation, self-regulation, and maintenance of psycho-

social well-being under conditions of isolation and elevated risk, for example, by creating a supportive environment.

A key assumption of the scale is its non-normative character. SSRL serves as an analytical tool for comparing facilities, design scenarios, and the degree of transfer of solutions developed in space architecture to terrestrial applications, rather than prescribing a “target” level that must be achieved in every case.

In simplified terms, these assumptions can be presented as follows:

- **Lower SSRL levels:** architecture “takes from” the environment and relies on external dependence;
- **Intermediate SSRL levels:** architecture “regulates and stabilises” its relationship with the environment, reducing dependence.
- **Higher SSRL levels:** architecture supports and enhances the quality of the environment.

The seven-level structure of the scale allows for sufficiently precise differentiation between successive stages of maturity while maintaining clarity and enabling qualitative interpretation. Each SSRL level describes a characteristic model of facility functioning, which can then be used in case analyses, comparative studies, and scenario-based considerations. The description of individual elements is presented analogously to the TRL scale and its derivatives.

8.4.3. Levels of Self-Sufficiency Readiness Scale (SSRL)

SSRL-1 - Infrastructure-Dependent Building

The facility operates fully dependent on external infrastructure systems. Energy, water, and environmental stabilisation are provided via external networks, and the building does not produce or recover resources in any meaningful way. Architecture acts as a passive consumer of resources, providing basic functional and operational capabilities without actively regulating the internal environment or consciously supporting long-term user well-being.

SSRL-2 - Building Supporting Operational Efficiency

The facility still relies on external supply sources, but isolated solutions appear that reduce resource consumption or support internal environmental stability. These may include passive strategies or localised recovery systems, which improve operational efficiency but do not fundamentally change the building's dependence on external infrastructure. Technical systems operate independently without full integration.

SSRL-3 - Partially Regenerative Building

The building begins local production and recovery of selected resources, with some environmental processes managed on-site. Limited resource storage allows for short-term operation during external supply disruptions. Systems are monitored and partially automated, and the architecture supports basic spatial orientation, user rhythms, and conditions for user regeneration.

SSRL-4 - System-Integrated Building

The building functions as a coherent environmental-technical system in which production, recovery, and storage processes are interconnected. Architecture actively stabilises microclimatic conditions and enables continuity of operation during temporary external supply interruptions. Spaces are clear and adaptable, supporting both operational efficiency and long-term use.

SSRL-5 - Operationally Autonomous Building

The building can operate long-term with minimal dependence on external infrastructure. Most critical resources are produced, recovered, and stored locally, and technical systems are automated and resilient to failures. Architecture allows on-site repair and adaptation, and the spatial layout supports both effective work and user regeneration under increased isolation or load.

SSRL-6 - Self-Regulating Building

The facility functions as a self-regulating environment, capable of adapting to long-term changes in external and internal conditions. Technical, environmental, and spatial systems are interlinked and respond to changing user needs and resource availability.

Architecture stabilises biological rhythms, supports social interactions and user control, enabling high-quality functioning without constant external supply.

SSRL-7 - Fully Self-Sufficient Building

The building operates as a long-term, stable, closed architectural-environmental system. All key processes related to energy, water, environmental conditions, and operational functioning are carried out locally and continuously. Architecture supports both physical survival and psychosocial well-being, enabling long-term living and working in isolation without system or human degradation.

The SSRL scale, in a concise and graphic form [Fig. 73], is presented below, starting from the highest (most self-sufficient) level:

- **Fully Self-Sufficient Habitat (SSRL-7)**
Local production, Closed loops, Human well-being integrated
- **Self-Regulating Environment (SSRL-6)**
Adaptive systems, Psychosocial stability, Minimal logistics
- **Operationally Autonomous Building (SSRL-5)**
Local resources, In-situ maintenance, High system resilience
- **System-Integrated Building (SSRL-4)**
Linked systems, Resource buffering, Environmental control
- **Partially Regenerative Building (SSRL-3)**
Local recovery, Limited storage, Assisted stability
- **Efficiency-Oriented Building (SSRL-2)**
Passive strategies, Reduced consumption, External dependence
- **Infrastructure-Dependent Building (SSRL-1)**
External supply, No local production, Basic functionality

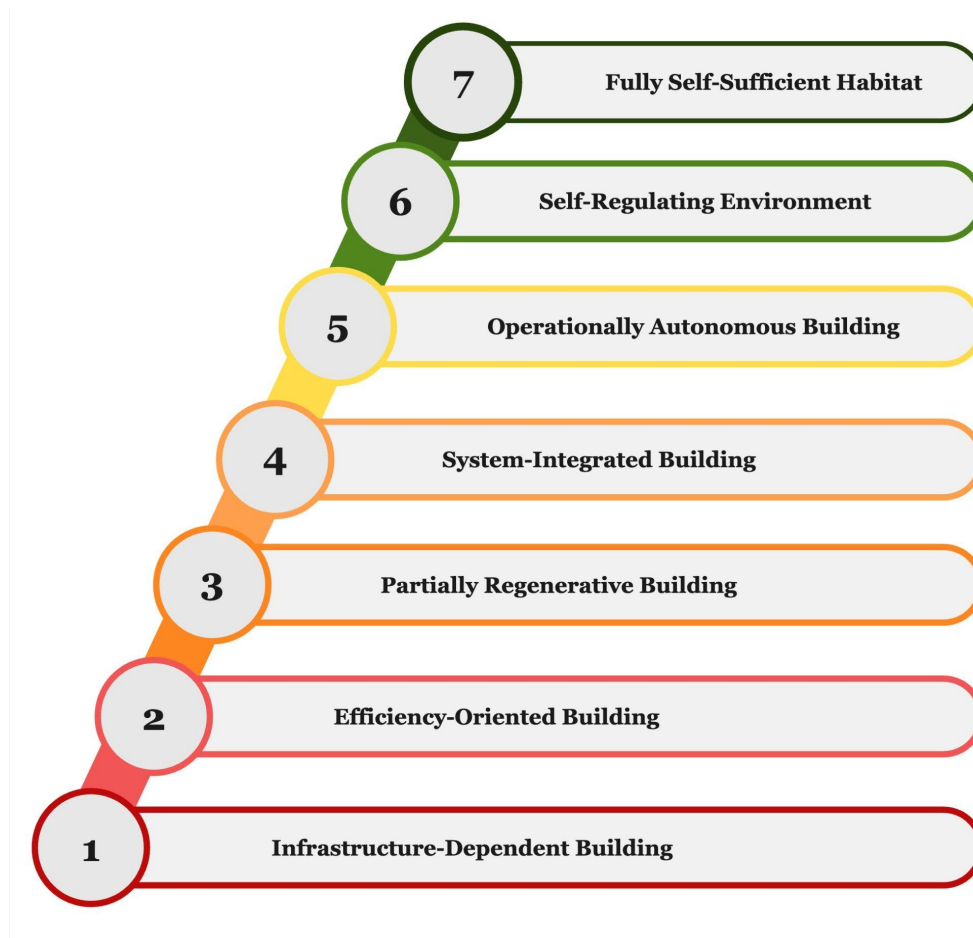


Fig. 73. The SSRL scale illustrates qualitative thresholds of architectural self-sufficiency, from infrastructure-dependent buildings to fully self-sufficient habitats (author's own elaboration, 2025).

The developed SSRL scale is a synthetic tool designed to organise the concept of architectural self-sufficiency in a clear, comparable manner that can be applied across different design and research contexts. The scale is not intended for precise measurement of technical parameters, but for a qualitative assessment of how a facility functions as an integrated system. Its primary value lies in identifying qualitative thresholds between successive stages of architectural maturity. Rather than depicting a continuous increase in efficiency, the scale highlights transition points where the nature of the facility's relationship with resources, the environment, and users changes. This allows for the determination of whether a facility operates as an infrastructure-dependent element, a partially regenerative system, or an autonomous, self-regulating environment.

The SSRL scale can be used as an analytical tool in comparative studies, enabling the assignment of analysed facilities to specific levels of self-sufficiency. In this framework, each level corresponds to the dominant operational model of the facility, rather than the maximal achievement of individual technical solutions. This makes it possible to compare facilities of different scales, functions, and locations, both in the context of space architecture and analog habitats, as well as terrestrial built environments. The scale is particularly useful as a design and scenario-planning tool. At the design stage, it allows for the deliberate determination of a target level of self-sufficiency based on project assumptions, user needs, and environmental conditions. In this way, SSRL enables analysis of the consequences of aiming for higher or lower levels of architectural autonomy.

8.5. Pilot Use of the Scale

To verify the consistency and usefulness of the developed SSRL scale, a pilot comparative analysis was conducted on selected existing architectural facilities with highly diverse functions, scales, and environmental contexts. The purpose of the analysis was to test whether the SSRL scale allows for the identification of the dominant operational model of a facility in terms of its level of self-sufficiency. The selected cases include both facilities fully dependent on external infrastructure and those aiming for operational or environmental autonomy. The analysis is qualitative and based on publicly available project descriptions, declared functional assumptions, and the actual functioning of the facilities. Assignment to a specific SSRL level is based on a comprehensive evaluation of the building's operation from a qualitative, expert perspective. The application of the scale in this dissertation is of a pilot nature and serves solely to assess its usefulness as an interpretive framework.

Table 24. Pilot testing of the SSRL scale - comparison of buildings with varying levels of functional self-sufficiency (terrestrial buildings only).

Level	Building	Justification for level assignment	Key solutions
SSRL-1	The Shard, UK	The facility operates fully dependent on external energy, water, and cooling systems. There is no local production or resource recovery at a scale affecting operational autonomy. Architecture acts as a passive consumer of infrastructure.	Central systems, HVAC, district cooling, urban infrastructure
SSRL-2	Wodny Park Tychy, Poland	The facility is highly optimised in terms of energy and environmental performance, but functions as part of the city system. Energy production and resource loops are coupled with external infrastructure, without autonomous operation capabilities.	Biogas cogeneration, integration with the urban system
SSRL-3	One Angel Square, Manchester, UK	The building implements local energy and water recovery and possesses partial resource loops, enabling disturbance buffering. It still functions within the urban structure and is not designed for full autonomy.	Cogeneration, heat recovery, rainwater harvesting, passive systems
SSRL-4	Bullitt Center, Seattle, USA	The facility is designed as an integrated environmental system, with local energy and water production and strong demand reduction. It operates as a coherent system, though still within the regulatory framework of the city.	PV, net-zero energy balance, local water recovery and retention

Level	Building	Justification for level assignment	Key solutions
SSRL-5	Earthship Bio- tecture , Taos, USA	Buildings designed for long-term off-grid operation with local production of energy, water, and partial food. Operational autonomy is a design goal, and the architecture allows on-site adaptation and maintenance.	PV + storage, rainwater, internal loops of water, food, energy
SSRL-6	Biosphere 2 , Arizona, USA,.	The facility functions as a complex, self-regulating environment, with closed ecological loops and environmental feedback. It exceeds the scale of a single building, becoming an experimental research habitat.	Biomes, closed loops of gases and water (the facility operates as a self-regulating environment of experimental character, without full long-term stability)
SSRL-7	* No existing facility has been assigned to SSRL-7. This level is treated as a reference and theoretical level, corresponding to a long-term stable, fully self-sufficient habitat, which has not yet been realised with current technology and system organisation.		

9. Impact of the Scale on Sustainable Development

The SSRL scale aligns with systemic approaches to sustainable development, enabling the assessment of architecture through the lens of how the built environment functions. In this context, sustainability can be understood not only as the reduction of negative environmental impact but, above all, as the ability of architecture to function over the long term under varying resource, environmental, and social constraints. The SSRL scale, therefore, allows the concept of sustainability to be linked with levels of autonomy, resilience, and system integration, providing an interpretive tool that goes beyond the traditional distinction between “sustainable” and “unsustainable” solutions.

The application of the SSRL scale allows for the analysis of architecture's impact on sustainable development by relating successive levels of self-sufficiency to the three classical pillars: environmental, economic, and social. Each of these pillars is strengthened in a different way as the scale level increases, highlighting that self-sufficiency is not a one-dimensional design goal.

Environmental impact

At the lower levels of the scale (SSRL-1 and SSRL-2), the impact of architecture on the environment is mainly focused on mitigating the negative effects of a facility's operation, such as energy consumption or emissions. These actions are reactive in nature and concentrate on improving the efficiency of existing systems. Intermediate levels (SSRL-3 and SSRL-4) introduce architecture into the realm of partial regeneration and environmental stabilisation through local resource recovery, system integration, and disturbance buffering. The facility begins to play an active role in local resource cycles. At the higher levels (SSRL-5 and SSRL-7), architecture functions as part of the local ecosystem, capable of long-term operation with minimal external intervention. In this context, environmental impact includes the ability to maintain stable environmental conditions over an extended time horizon.

Economic impact

From an economic perspective, the SSRL scale allows sustainable development to be considered not only in terms of investment costs but also operational costs, risk, and system resilience. Economic sustainability at lower levels is short-term and highly dependent on environmental stability. As the SSRL level increases, a facility's ability to amortise costs over time grows through local production, resource storage, and reduced logistical dependency. At higher levels, self-sufficiency translates into greater predictability of operation and a reduction of operational risk, which is particularly important for facilities operating in crisis or extreme conditions.

Social impact

At the lower SSRL levels, social aspects are secondary to the provision of basic usability and safety. As the SSRL level increases, architecture increasingly influences user quality of life, stabilisation of biological rhythms, legibility of space, social interactions, and the sense of control over the environment. At the highest levels, psychosocial well-being becomes an integral component of system functioning, determining its long-term durability and efficiency. In this sense, the social dimension is not an add-on to sustainability but one of the key factors determining the capacity of the environment for prolonged use.

The SSRL scale adopted in this dissertation demonstrates that increasing the level of self-sufficiency also impact the sustainable development in the complex way. Also, the SSRL scale allows for the systematisation of architecture's impact on environmental, economic, and social dimensions through the lens of autonomous system integration, resource management, and conditions for long-term human functioning in enclosed environments. In this sense, it extends the classical understanding of sustainability to include aspects critical in extreme conditions, such as system resilience, adaptive capacity, disturbance buffering, and habitability.

The application of the SSRL scale enables an organised and transparent transfer of knowledge from space architecture to terrestrial architecture. The highest levels of the scale, developed under extreme conditions, serve as reference points, while intermediate levels indicate solutions that can be adapted in cities, neighbourhoods, and critical infrastructure, depending on local needs and conditions. This makes the influence of space architecture on terrestrial architecture more explicit and measurable, and self-sufficient solutions developed for space environments strengthen the approach to sustainable building by enhancing resilience, resource efficiency, and adaptive capacity.

10. Discussion

10.1. Limitations of the Scale

The developed SSRL scale was defined as a tool primarily referring to and derived from the analysis mainly of a single architectural facility. This narrowing of scope allowed for precise analyses and descriptions of the relationships between architecture, resources, and users, but it also represents one of the main limitations of the scale. Architecture does not exist in isolation, but is part of complex spatial, infrastructural, and social systems. In this context, the SSRL scale does not describe self-sufficiency at a broader, urban level. Its application to levels beyond a single building would require significant modifications of its assumptions, extending them to meet specific objectives while taking into account, among other things, infrastructure networks, transportation systems, resource logistics, and collective-level management mechanisms.

10.2. Does Every Building Need to be Self-Sufficient?

One of the key conclusions from the analysis of the SSRL scale is that not every building needs (or should) aim for high levels of self-sufficiency-unless there is a specific need. This is particularly true in urban environments, where extensive and relatively stable infrastructure networks exist. In such contexts, high autonomy of an individual facility may be justified functionally and economically. In these cases, achieving intermediate SSRL levels can be optimal, enhancing efficiency, resilience, and stability while still benefiting from the advantages of operating within a networked system. The SSRL scale consciously allows for the adjustment of self-sufficiency levels to the context, function, and expected duration of use of the facility.

In this context, selected self-sufficiency factors (ARF) already adapted successfully in terrestrial practice are particularly significant, even though they originate from the design logic of space architecture and ICE environments. Additive technologies initially developed for the autonomous construction of space habitats under resource-limited conditions are now applied in social and affordable housing projects. For example, company ICON has implemented 3D-printed building structures using local mate-

rials³³⁵, which shortens supply chains, reduces costs, and limits resource consumption. These solutions do not lead to full autonomy of the facilities but support selected aspects of self-sufficiency, enhancing resilience and efficiency in the construction process within a given functional context. Similarly, closed-loop resource systems developed in life-support programs, such as MELiSSA (Micro-Ecological Life Support System Alternative)³³⁶ by the European Space Agency, have been applied in terrestrial buildings for water management, wastewater treatment, and regenerative technologies. These examples demonstrate that solutions developed in space projects can be directly translated to specific elements of terrestrial architecture, supporting the improvement of functional and systemic self-sufficiency.

10.3. Complexity and Risks of High Levels of Autonomy

As the level of self-sufficiency increases, so does the complexity of technical and organisational systems. Higher SSRL levels are associated with greater investment costs, increased maintenance requirements, and the need for advanced resource management—often involving the use of innovative, experimental, and costly technologies. In practice, this means that full autonomy can only be achieved in specific contexts, such as extreme environments, research facilities, or critical infrastructure. For this reason, pursuing higher SSRL levels should be preceded by an economic analysis.

10.4. The Scale as a Systems model, From Building to Environment

Although the SSRL scale was defined at the level of a single facility, its internal logic demonstrates a gradual shift from thinking of a building as an isolated object to viewing it as part of a system, and eventually as a life-supporting environment. This tendency becomes particularly evident at the higher levels of the scale, where the boundary between architecture, infrastructure, and ecosystem becomes blurred. At the same time, the structure of a city as a multi-level system, encompassing numerous spatial, social,

³³⁵ ICON. (n.d.). ICON, 3D printing. Intelligent Machines Building Humanity's Future - ICON. <https://www.iconbuild.com/> (accessed: 04 February 2026).

³³⁶ European Space Agency. (n.d.). *MELiSSA - Closed Loop Compartments*. https://www.esa.int/Enabling_Support/Space_Engineering_Technology/Melissa/Closed_Loop_Compartments (accessed: 04 February 2026).

and economic connections, gives the concept of self-sufficiency a different meaning than in the case of a single facility. In this sense, the SSRL scale can serve as a starting point for further research encompassing district, city, or regional levels, using different criteria and analytical tools. A promising future research direction could be the extension of studies to larger systems, referring, for example, to space colonies, cities, or more complex structures, once such systems exist, even conceptually.

11. Conclusions

The conclusions presented in this chapter relate both directly to the research problem and objectives of the dissertation, as well as to the observations and relationships revealed through the analysis of space architecture, ICE environments, and selected case studies. In addition to conclusions regarding architectural self-sufficiency and its assessment through ARF factors and the SSRL scale, the dissertation also formulates synthetic and reflective conclusions concerning the role of architecture, the position of the architect, and the relationship between the facility and the infrastructural system in which it operates.

11.1. Architectural Self-Sufficiency and Future Resource Limitations

Contemporary design standards and urban systems enable the effective functioning of architecture within a model dependent on extensive external infrastructure, which in many contexts remains rational and economically justified. At the same time, an analysis of current environmental, social, and geopolitical trends indicates that the present level of resource security should not be considered permanent or guaranteed. According to forecasts by the Intergovernmental Panel on Climate Change³³⁷, the coming decades are expected to bring increasing extreme events, disruptions in water and energy availability, destabilisation of food systems, and heightened pressures from migration and urbanisation. These phenomena will directly affect the functioning of architecture, gradually forcing it to assume functions previously performed by external systems. In this context, architectural self-sufficiency can be understood as a strategy for preparing the built environment for conditions of limited resources, interruptions in infrastructure operation, and increased uncertainty.

It becomes particularly important in crises, such as natural disasters, prolonged blackouts, supply chain failures, or armed conflicts, where the ability of facilities to operate temporarily and autonomously determines user safety. This analysis highlights a field that can be defined as *security architecture*, architecture designed to function under

³³⁷ IPCC. (2023). CLIMATE CHANGE 2023 Synthesis Report. The Intergovernmental Panel on Climate Change.

conditions of threat, isolation, or temporary loss of access to basic resources and services. This category includes civil shelters, civil protection facilities, critical infrastructure, temporary post-disaster shelters, rescue facilities, and buildings intended for operation during prolonged humanitarian crises. In these applications, architectural self-sufficiency is not optional but a fundamental requirement for maintaining operational continuity and safeguarding life. Although the transfer of knowledge between space architecture and the military sector is historically evident (considering that as for the development of space, satellite, and rocket technologies is linked to defence), this aspect has not yet been sufficiently analysed in the architectural context. This dissertation demonstrates that the design logic developed in space environments (based on autonomy, redundancy, and the ability to function in isolation) can be directly applied to security architecture in both military and civilian scenarios. Space architecture and architecture in extreme environments provide universal design models for facilities that must operate under hazards, and unpredictability. Intentional and strategic improvement of architectural self-sufficiency thus can become a tool for achieving sustainable development goals but also for building resilience and safety in inhabited environments facing future crises.

11.2. Scaling Needs and Threats as a Key to Rational Self-Sufficiency

The dissertation concludes that self-sufficiency should not be understood as an absolute attribute, but as a multi-level response to specific scenarios or threats. Different contexts of architectural functioning (from stable cities to areas affected by climate crises, armed conflicts, or geographical isolation) generate varying requirements for system autonomy.

The SSRL scale allows the adjustment of the level of self-sufficiency to the scale of risk and needs, enabling the design of architecture:

- with low autonomy under stable conditions,
- with enhanced resilience in threatened environments,
- with high autonomy in extreme or crisis contexts.

This approach counteracts both the over-technologization of architecture and its insufficient adaptation to future challenges, highlighting the need for flexible and scenario-based design of the built environment.

11.3. Architecture as a Non-Static Adaptive System

The analysis of Architectural Resilience Factors (ARF) and the structure of the SSRL scale indicate that architectural self-sufficiency cannot be understood solely as a set of technical solutions. The study of space architecture shows that the built environment functions as an adaptive system, protecting users from external conditions while actively organising their activities. Under conditions of isolation and limited resources, architecture becomes a tool for regulating biological rhythms, social interactions, communication, and responses to emergencies. Space thus acts as an active component of the life-support system. Experiences from space and ICE environments also highlight the importance of perceptual and psychosocial factors, such as the legibility of spatial organisation, the ability to control privacy, and the deliberate use of colour, light, and sensory stimuli. These elements, often considered secondary in terrestrial architecture, prove to be critical in extreme conditions for system stability and user well-being. In this sense, architectural self-sufficiency encompasses both material systems and the environment's capacity to sustain quality of life.

11.4. Significance for Architectural Theory

From a scientific perspective, a significant contribution of this dissertation is the proposal of a new conceptual tool for analysing architectural self-sufficiency. The SSRL scale organises the complex issue of built environment autonomy by identifying qualitative thresholds, rather than attempting quantitative simplification, particularly challenging given the diversity and complexity of the built environment. By design, the SSRL scale enables comparative analyses between facilities of different functions, scales, and locations, and also provides a foundation for further research on self-sufficiency at scales beyond individual buildings, including neighbourhoods, cities, or regions. The dissertation also introduces and systematises emerging theoretical concepts, including architectural self-sufficiency, helping to clarify their definition and position within contem-

porary architectural theory. It was demonstrated in this work that ideas about space influences on the terrestrial solution can be implemented in architectural context as well.

11.5. Significance for Design Practice

Design decisions are strongly conditioned by diverse and extreme external factors, resulting in technically different solutions that nevertheless share common functional goals related to resource efficiency, resilience, and operational continuity. In contrast, psychosocial solutions are primarily shaped by the internal, built, and inhabited environment. These strategies show a high degree of similarity across different space habitats and analog environments, consistently addressing isolation, stress, privacy, social interaction, and circadian rhythm regulation. This indicates that while technical solutions must remain context-specific, psychosocial design principles are largely universal and highly transferable to terrestrial architectural practice.

However, the conclusions drawn from the analysis indicate that space architecture provides a set of specific solutions that can be selectively implemented in terrestrial architecture as elements enhancing its self-sufficiency and resilience, without the need to achieve full autonomy of the facility.

Such solutions particularly include:

- **Additive technologies (3D printing)** used for the production of structural elements and enclosures with local materials, reducing dependence on external supply chains and construction costs (e.g., in social and emergency housing);
- **Water reuse systems**, including collection, filtration, and use for technical or sanitary purposes, are inspired by closed-loop cycles applied in life-support systems.
- **Local food production systems**, such as hydroponics and aquaponics in a closed loop, integrable with buildings or housing complexes, enhancing resource security and operational stability under limited infrastructure access;

- **Real-time monitoring and resource management**, enabling control of energy, water, and air, as well as rapid response to failures, directly translates solutions applied in space environments.
- **Spatial solutions supporting user well-being**, such as clear privacy zoning, sensory stimulus control, legible organisation of functions, and conscious use of colour and light, which in space architecture are treated as integral elements of life-support systems;
- **Modular and prefabricated building systems**, based on standardised, repeatable elements producible locally, allowing rapid assembly, disassembly, and adaptation of facilities to changing functions and environmental conditions. Inspired by the logic of space habitats, these solutions support architectural flexibility, long-term usability, and resilience to changes in usage scenarios without requiring a complete rebuild.
- **Emerging bio-solutions**, such as bioregenerative architecture integrating biological systems into buildings (e.g. oxygen production, water purification, biomass generation) and mycoarchitecture using mycelium-based bio-composites as construction materials.
- **Design thinking and logic**, emphasising the value and finiteness of resources, analysis of available connections with attention to costs, consequences, and risks. This introduces a design logic enforced by extreme environments.

It is worth noting that the SSRL scale can be particularly useful in the design of terrestrial facilities, especially those operating under threat, such as shelters and critical infrastructure. Its application could effectively support the design and decision-making processes for facilities such as the Merihaka Civil Defence Shelter in Finland,³³⁸ as it addresses the comprehensive functioning of the built environment in potential crises and resource-limited conditions, rather than focusing solely on individual technical so-

³³⁸ Buzovska, M. (2023). *Architecture of 100% readiness: How Helsinki transformed defensive structures into functional public space*. *Pragmatika*. <https://pragmatika.media/en/news/arkhitektura-100-hotovnosti-iak-helsinki-peretvoryly-zakhysni-sporudy-na-funktsionalnyi-hromadskyi-prostir/> (accessed: 04 February 2026).

lutions. The Merihaka shelter, under normal conditions, it functions as an extensive recreational and service space, including a swimming pool, skate park, and sports facilities. In a threat scenario, however, it can be converted into a facility capable of temporary, self-sufficient operation for 900,000 people. Its structure includes collective living spaces, sanitary facilities, filtered ventilation systems, structural protections, and basic resource storage, enabling the maintenance of safety and continuity of user functioning for a defined period without external support. This example demonstrates that the SSRL scale effectively addresses the needs of designing architecture prepared for rare but high-risk scenarios, where the facility's capacity for temporary autonomy and system resilience is of critical importance.

11.6. The New Role of the Architect in Designing Future Environments

Although defining a new role for the architect was not the primary aim of this dissertation, the results of the analyses revealed a significant relationship between the design of extreme environments and the evolution of architectural competencies. By examining self-sufficiency technologies, operational scenarios of space habitats, and architectural resilience factors (ARF), it became clear that contemporary architecture, both in extra-terrestrial and terrestrial contexts, requires a departure from traditional models of thinking of a building as a static object. Instead, there is a need to understand architecture as a complex, adaptive metabolic system operating under conditions of limited resources, variable environmental parameters, and high responsibility for user needs.

During the research, it became particularly evident that architecture in extreme environments simultaneously serves structural, environmental, energy, and psychosocial functions. For example, in space habitats are understood as life-support systems in which the cycles of energy, water, air, and matter are integrally linked to human needs. This approach requires the designer to possess skills that go beyond the traditional architectural toolkit, including an understanding of environmental processes, the integration of closed-loop technologies, and the creation of spaces responsive to user behaviour and perception.

An important finding that emerged during this research is that designing under conditions of limited resources changes the very meaning of the concept of “architecture.” In such situations, a building becomes a tool operating at the interface between humans and the environment, regulating resource flows and stabilising internal conditions. Consequently, the architect must assume some competencies traditionally associated with environmental engineering to effectively manage the relationships between technical, ecological, and human systems.

The results of this dissertation show that, in the future, the architect will need to act as a designer of integrated life-support environments, understanding both the physiological and psychosocial needs of users as well as the dynamic nature of resource cycles. This implies the necessity of developing an interdisciplinary design practice in which the architect assumes the role of mediator between technology, humans, and the environment. In space habitats, this is a matter of survival. Still, similar principles are becoming increasingly relevant in the context of terrestrial architecture, particularly in the face of climate change, rising energy costs, and the growing importance of buildings with low or zero resource consumption. This secondary, yet key, research finding indicates that designing self-sufficient structures is not limited to selecting technologies but involves redefining the role of the architect as a designer of systems in which form, function, and metabolism constitute an inseparable whole. This approach opens new directions for the development of future architecture, in which the architect’s competencies include both shaping space and co-creating environments capable of adaptation, regeneration, and resource balance. Experiences from space architecture demonstrate that designing under extreme conditions leads to a fundamental shift in perspective, it teaches humility toward resources, responsibility for the user, and systems thinking in which every element matters. In such conditions, architecture ceases to be a field for free expression and becomes a life-sustaining environment, where there is no room for excess or design illusions.

12. Summary

The research questions posed in this dissertation have been addressed:

- The environmental, technological, and social factors that determine the level of self-sufficiency in extreme environments include, above all, the degree of extremity of the external and internal environment, the availability and possibility of local resource acquisition and recovery, the level of autonomy and serviceability of technical systems, as well as human-related conditions. These include the number and structure of users, the duration and objectives of use, and habitability, understood as the ability of an environment to sustain long-term human functioning in isolation.

Based on the conducted analyses, it was shown that the level of self-sufficiency of architecture in extreme environments is determined by a complex configuration of environmental, technological, and social factors, rather than by individual design or technological solutions. As demonstrated in Chapter 5, the character and degree of extremity of the external and internal environment are of key importance, encompassing both physicochemical conditions and the conditions of human functioning in confined spaces. The case study analysis presented in Chapter 7 and the compilation of ARF factors (Chapter 8) showed that a critical element determining the level of self-sufficiency is the availability of resources and the possibility of their local acquisition and recovery, particularly concerning water, energy, air, and food. Directly related to this is the level of autonomy of life-support systems, the degree of closure of resource cycles, and the capacity for maintenance, repair, and reconfiguration of technical systems, which affects the facility's ability to operate over long periods under limited external support. At the same time, it was shown that technological factors cannot be analysed independently of the human factor. As noted in Chapter 5, particularly 5.4, the level of self-sufficiency is significantly influenced by the number and structure of users, the duration of the mission or facility use, and the operational objectives adopted. A key element is also habitability, understood as the ability of the built environment to provide conditions that support long-term human functioning in isolation, including psychophysical com-

fort, psychosocial stability, clarity of spatial organisation, and the capacity to adapt to environmental constraints.

- ➔ It has been demonstrated that experiences from space architecture and analog space missions can support the development of architecture resilient to extreme conditions on Earth through the transfer of design strategies, technologies, and spatial organisation solutions, enabling built environments to function under conditions of limited resources, high risk, and long-term isolation.

The analysis of space and analog environments (Chapters 5, 7, and 9) showed that these solutions enable architecture to function under conditions of limited resources, high risk, and isolation. At the same time, research on habitability confirmed the importance of integrating technical and psychosocial factors in the design of environments intended for long-term use (Chapter 5.4). These conclusions were formalised in the form of ARF factors and the SSRL scale, enabling the systematic transfer of knowledge and solutions from space architecture to the context of terrestrial architecture (Chapters 8, 9, 11.5).

- ➔ It has been shown that it is possible to develop a multidimensional scale that allows for the comparison and classification of architectural facilities according to the degree of integration of autonomous systems, while simultaneously taking into account environmental, technological, and psychosocial factors, as well as the varied temporal horizons of built environment functioning.

As demonstrated in Chapters 8 and 9, the analysis of Architectural Resilience Factors (ARF) made it possible to identify key areas of architectural functioning in extreme environments and organise them into a coherent analytical structure. On this basis, an original Self-Sufficiency Readiness Level (SSRL) scale was developed, with successive levels reflecting an increasing degree of integration of autonomous systems and the transition from resource dependence to enhanced operational autonomy. A pilot application of the scale is presented in Chapter 8.5.

- ➔ Based on the analysis of space architecture as a model of extreme self-sufficiency, the dissertation formulated conclusions for the development of the scientific

discipline of Architecture and Urban Planning, as well as for sustainable development strategies, such as:

- The necessity of treating architecture not as a static object, but as an adaptive system capable of responding to changing environmental, resource, and user conditions (Chapter 11.3);
- The need for a gradual and scenario-based approach to self-sufficiency, adapted to the scale of risk, duration of use, and environmental context, rather than striving for absolute autonomy (Chapter 11.2);
- The importance of integrating technological, environmental, and psychosocial factors as a foundation for designing resilient and durable architecture over the long term (Chapters 5.4, 8);
- The author's definition of self-sufficiency (Chapter 8.4), taking into account technological, spatial, and psychosocial factors;
- The integration of solutions for design practice (Chapter 11.5) provides a set of possible interventions influencing the level of self-sufficiency of facilities, as well as an expanded set of factors derived from solutions applied to individual case study facilities (Chapters 7 and ARF: Chapter 8).

The doctoral dissertation achieved its overarching goal, which was the identification and categorisation of solutions ensuring self-sufficiency in extreme environments (ARF). Based on these, an integrated assessment model, SSRL (Self-Sufficiency Readiness Level), was developed for the advancement of autonomous, resilient, and independent architecture. This model enables systematic analysis, comparison, and deliberate shaping of the self-sufficiency level of the built environment, depending on context, scale, and the temporal horizon of use (Chapters 8, 9).

All specific objectives were also achieved.

- The relationships between the characteristics of extreme environments and the degree of integration of self-sufficient systems in space architecture and facilities operating under extreme terrestrial conditions were examined, demonstrating that the level of self-sufficiency is directly linked to the environmental context, duration of use, and the scope of risk and system autonomy (case study, Chapter 7).
- Technological and design solutions developed in the context of extreme architecture were identified and analysed, allowing the organisation of recurring adaptive strategies applied in response to resource, environmental, and operational constraints (Chapters 7 and 8).
- Directions for knowledge and technology transfer between space and extreme architecture and terrestrial architecture were indicated within the framework of spin-off and spin-in phenomena, confirming the possibility of adapting selected strategies and solutions to Earth conditions, particularly in hazardous, crisis, and resource-limited environments (Chapter 11.5).
- Architectural resilience and self-sufficiency factors (ARF - Architectural Resilience Factors) were identified, forming the basis for the analysis of solutions applied in extreme environments and enabling systematic comparison of facilities of different scales, functions, and levels of implementation (Chapter 8).
- An original assessment scale, Self-Sufficiency Readiness Level (SSRL), was developed, based on ARF and adapted for the multidimensional evaluation of architectural self-sufficiency, allowing classification and assessment of the degree of integration of autonomous systems in environmental, technological, and psychosocial terms (Chapter 8.4).
- Guidelines and recommendations for the development of future self-sufficient architecture were formulated, based on experiences from space architecture and the results of ARF and SSRL analyses, indicating directions for designing resilient, adaptive architecture capable of long-term functioning under conditions of limited resources and increased uncertainty (Chapters 9, 11.5).

The research confirmed the validity of the proposed theses:

It was demonstrated that space architecture, analog space missions, and facilities in extreme environments constitute a key source of design, technological, and operational knowledge that can be directly applied to the development of self-sufficient architecture on Earth (Thesis 1).

It was shown that architectural resilience and self-sufficiency factors (ARF) serve as a tool for systematically assessing the degree of integration of autonomous systems in both architecture operating under extreme environmental conditions and in facilities designed for everyday use under standard terrestrial conditions (Thesis 2).

An original Self-Sufficiency Readiness Level (SSRL) scale was created, which is an effective tool for the multidimensional assessment of the self-sufficiency level of facilities, enabling comparison, classification, and identification of potential directions for the development of technologies and design strategies (Thesis 3).

It was demonstrated that technologies and design strategies developed for space architecture play a significant role in shaping future sustainable development models and increasing the resilience of terrestrial architecture to future challenges, such as climate change (Thesis 4).

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Appendix

Appendix A - ARF Strategy Criticality Matrix

ARF		Name of the component	A	B	C	sum
ARF 3	3.2	Protection against environmental hazards	5	5	5	15
ARF 5	5.1	Basic functions	5	5	5	15
ARF 2	2.1	Stabilization of physiological living conditions	5	4	5	14
ARF 2	2.3	Regulation of internal microclimate	5	4	5	14
ARF 3	3.3	Resistance to failure of single components	5	5	4	14
ARF 1	1.1	Water recirculation	5	5	4	14
ARF 1	1.3	Local energy production	5	5	4	14
ARF 2	2.2	Maintenance of indoor environmental quality	4	5	4	13
ARF 1	1.5	Local food production	3	5	5	13
ARF 7	7.2	Automation of systems	4	4	4	12
ARF 3	3.1	Adaptable operational spaces	5	5	2	12
ARF 5	5.4	Clarity of spatial layout and operational order	3	5	4	12
ARF 5	5.3	Universality and multifunctionality of architectural structures	3	5	4	12
ARF 6	6.2	Privacy control and regeneration	2	5	5	12
ARF 7	7.3	Capability for autonomous and continuous operation	3	5	4	12
ARF 1	1.2	Water storage	5	4	3	12
ARF 1	1.4	Energy storage	5	4	3	12
ARF 4	4.2	In-situ repair and maintenance	5	4	2	11
ARF 4	4.1	Scalability and phasing of development	4	5	2	11
ARF 4	4.3	Rapid implementation of structures under limited resources (in-situ)	5	4	2	11
ARF 6	6.1	Stabilization of biological rhythms	3	3	5	11
ARF 5	5.5	Regulation of social interactions	2	3	5	10
ARF 7	7.1	Reduction of logistical dependence on external supply	3	5	2	10
ARF 5	5.2	Additional functions	1	3	5	9
ARF 6	6.4	Enhancement of sense of control and identity	1	2	4	7
ARF 6	6.3	Perceptual environmental quality	1	2	4	7



- 1 – marginal significance
- 2 – low / supporting significance
- 3 – moderate significance
- 4 – high significance
- 5 – critical significance (necessary condition)

- (A) Survival
- (B) Operationality
- (C) Well-being

“The key is we are not passengers on Spaceship Earth.

We are the crew.”

- Ron Garan, NASA, *The Orbital Perspective*