

Surface Vehicle Atmospheric Considerations for Moon to Mars Exploration

Brian K. Alpert¹

NASA Johnson Space Center, Houston, TX, 77058, USA

Logan Kennedy²

NASA Marshall Space Flight Center, Huntsville, AL, 35808, USA

L. Daren Welsh³

The Aerospace Corporation, Chantilly, VA, 20151, USA

Adam Young⁴

HX5 LLC, Fort Walton Beach, FL, 32548, USA

Gregory L. Mercer⁵ and Daniel S. Baird⁶

NASA Communications Services (NCS), Huntsville, AL, 35816, USA

NASA and its Artemis commercial providers are continuing to address and mitigate flammability concerns at planned vehicle atmospheres on the lunar surface. Challenges include close integration between materials flammability, ignition control, fire mitigation, human physiology and performance, and spacesuit mobility and performance. Past NASA recommendations for vehicle atmospheres identified some of these challenges as open work, but they were not funded through completion. In winter 2022, NASA created a team dedicated to this problem, including all relevant stakeholders, to develop a strategy to quantify the integrated issue, reduce the severity of its impacts, and, if needed, provide alternative options to program management. This paper outlines key discussions, assumptions, interdependencies, analysis, and testing that led to the exploration atmosphere team's findings and recommendation of an optimized vehicle atmosphere and approach for early surface missions. These efforts not only shape the path to flight certification for those surface missions, but will improve the development and certification processes through updated materials flammability standards, vehicle configuration constraints, fire barrier effectiveness, ignition guidelines, and partial gravity impacts on flammability. Additionally, recent vehicle and spacesuit design efforts have allowed the team to challenge long-standing norms and assumptions to potentially provide more mission flexibility through improved fire suppression, elevated spacesuit operating pressures, and advanced vehicle environmental control systems. The team has also identified areas where standards or guidelines are insufficient for cumulative mission decompression sickness risk and partial gravity compensation factors. These efforts will lay the groundwork for future surface elements and missions to follow a similar process, reducing development time and flammability risk while providing clear guidance on a path to certification.

¹ EHP Synchronization Focal, HLS SE&I, JSC-XE2.

² EHP Suit Focal, HLS SE&I, MSFC-LP10.

³ Test Manager, EHP SE&I, JSC-DI.

⁴ Surface Mission Segment Lead, HLS SE&I, GRC-LSA0.

⁵ Strategic Communication, ESDMD SAO, HQ-BA0.

⁶ Strategic Communication, ESDMD SAO, HQ-BA0.

Acronyms and Nomenclature

Atmosphere	=	composition of gasses inside a habitable volume or spacesuit
Prebreathe	=	time spent in a higher oxygen concentration to reduce the dissolved nitrogen in the human body and avoid decompression sickness before an extravehicular activity
Shuttle	=	Space Shuttle
Station	=	International Space Station
Station Suit	=	ISS/Shuttle Extravehicular Mobility Unit
EHP	=	Extravehicular Activity and Human Surface Mobility Program
ESDMD	=	Exploration Systems Development Mission Directorate
EVA	=	Extravehicular Activity
HLS	=	Human Landing System Program
ISS	=	International Space Station
kPa	=	Kilopascals
MOC	=	Maximum Oxygen Concentration
NASA	=	National Aeronautics and Space Administration
NESC	=	NASA Engineering Safety Center
psi	=	Pounds per square inch
SAO	=	Strategy and Architecture Office
SCUBA	=	Self-contained Underwater Breathing Apparatus
SE&I	=	Systems Engineering and Integration
xEMU	=	Exploration Extravehicular Mobility Unit

I. Introduction

A safe, breathable atmosphere — the gasses inside a habitable volume or spacesuit — is an essential component of human spaceflight. Astronauts require breathable air while living and working in spacecraft and while venturing onto planetary surfaces during extravehicular activities. Maintaining a safe atmosphere is one of the most important functions of an environmental control and life support system.

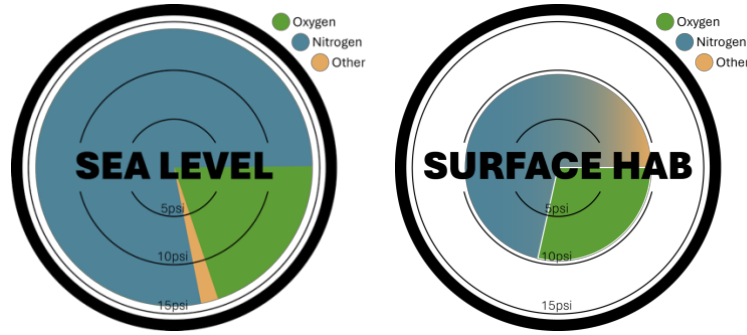


Figure 1. Graphical representation of sea level atmosphere and an example lunar surface vehicle atmosphere.

At sea level on Earth, the atmosphere exerts an average pressure of 14.7 pounds per square inch (psi, 101.3 kPa). The air is made up of approximately 78% nitrogen, 21% oxygen, and small amounts of other gasses [1]. Spaceflight systems maintain various pressures and gas ratios (primarily defined by oxygen concentration) to meet their specific needs.

For example, the International Space Station (referred to as “station” throughout this paper) maintains an atmosphere similar to sea level, but the station’s EVA suits operate under significantly less pressure and use exclusively oxygen. The reduced pressure makes astronaut mobility easier (i.e., by reducing the pressure differential with the vacuum of space), but that reduced pressure would not be habitable without the oxygen-rich environment. A higher oxygen concentration also increases fire risk (see the discussion of flammability below) therefore spacesuits use special materials and limit ignition sources to mitigate this risk.

NASA is currently evaluating the trade space for atmospheres across many different systems, all of which must work together to enable humans' exploration of the Moon and Mars. Selecting atmospheres and developing associated procedures (e.g., prebreathe protocols) requires the agency to balance a series of trade-offs to maximize safety and operational flexibility.

NASA Artemis requirements for sustained missions are targeting an average pressure of 8.2 psi (56.5 kPa) and a 34% oxygen concentration as one solution to those trade-offs. As discussed below, less is known about oxygen concentrations above 30% oxygen, leading to flammability concerns such that NASA teams have alternatively performed testing utilizing a vehicle atmosphere that stays below 30% (average pressure of 9.6 psi (66.2 kPa) and a 28.5% oxygen concentration) [2].

II. Key Factors

Vehicle and suit atmospheres must balance several key factors: crew physiology, spacesuit mobility, EVA duration, and flammability. Each affects the crew’s health, safety, and ability to achieve exploration objectives.

A. Flammability

Fire is one of the many hazards of spaceflight. Different atmospheric conditions can affect flammability; materials that might not be flammable under sea-level conditions could present a hazard at different pressures or oxygen concentrations. For example, the Apollo 1 fire was exacerbated by the increased flammability of materials inside the command module under its high-pressure, pure-oxygen atmosphere [3]. Generally, higher oxygen concentrations and/or higher oxygen partial pressures equate to a higher flammability risk. While the International Space Station operates around 21% oxygen, historically materials used onboard have been tested up to a maximum oxygen concentration (MOC) of 30% at sea level pressure to account for life support system control, error bands, etc [4]. As oxygen concentrations increase beyond 30% (or as partial pressure increases), some materials are less likely to pass

testing since they become more flammable. Materials to be used in the 34% atmosphere, have typically been tested up to a 37% oxygen concentration for the reasons mentioned above.

The desired atmosphere and materials used in the construction of spaceflight systems inform one another, with engineers balancing varying needs to create the safest possible environment. If a certain oxygen concentration or partial pressure is desirable, this may constrain materials selection. The selected atmosphere also dictates fire prevention and mitigation systems (i.e., ignition control and fire suppression).

NASA and its partners are investigating new materials (such as textiles) that are safer in a range of oxygen concentrations, which presents a variety of technical challenges. Even with better materials, flammability remains a concern when operating in high oxygen environments and will drive many EVA and spacecraft atmosphere design considerations, requirements, and operational procedures.

The reduced gravity on the lunar surface presents a unique challenge with respect to fire characteristics, such as extinguishment and propagation. A flame can extinguish if the cabin airflow is high enough that the reactants don't have time to react while the mixture is hot enough. This effect occurs more readily on Earth because the higher gravity causes higher flow velocities. Thus, a material that self-extinguishes in Earth gravity may continue to burn in lunar gravity. Additionally, since airflow is needed to sustain a minimum oxygen concentration for propagation, a smouldering flame in microgravity may not propagate in the absence of cabin ventilation. A smouldering flame in lunar gravity, however, might have sufficient natural airflow to promote the additional oxygen concentration needed to propagate [5].

B. Crew Physiology

A spacecraft or spacesuit must keep crew members safe and healthy for the duration of their mission, including providing enough oxygen and managing exhaled gasses like carbon dioxide. Oxygen is essential to the human body, while excessive carbon dioxide can be toxic. However, even oxygen requires the right balance; too little oxygen can cause hypoxia, while too much oxygen can cause oxygen toxicity. If nitrogen is present in the vehicle atmosphere, it can cause decompression sickness so it is advantageous to remove as much of it as possible from the body (denitrogenation) before performing an EVA.



Figure 2. Engineers test lunar spacesuits being developed by Axiom Space in the Neutral Buoyancy Laboratory at NASA's Johnson Space Center in Houston [14].

Currently, NASA standards for oxygen partial pressure limit how hypoxic the atmosphere can be for crew operation. The standards are based on historical flight and test data; however, the data is limited and does not attempt to quantify degradation of health or performance from extended hypoxia exposure or adjusted hypoxia limits. The NASA community is actively performing research to further explore acceptable hypoxia limits.

A spacecraft or spacesuit's environmental control and life support system must control the above factors to maintain crew safety and comfort. Spaceflight systems must also control, among other parameters, the rates of pressure changes, as rapid changes in pressure can cause physiological damage, including to the ears and lungs.

C. Operational Timeline

Unlike recent objectives on station expeditions, where the goal is to enable science (which is largely conducted inside the vehicle) and EVAs are utilized mostly for replacements and repairs, the primary goal of a surface mission is to perform EVAs. While the majority of task durations on an EVA day are defined independently of the vehicle (private medical conferences, sleep, battery charging and configuring of suits and tools), the EVA preparation time includes prebreathe (the denitrogenation protocol mentioned above) which depends on vehicle atmosphere, oxygen saturation levels, etc [6]. Prebreathe gives the body time to expel dissolved nitrogen to help avoid decompression

sickness (colloquially known to SCUBA divers as “the bends”). Symptoms of decompression sickness can range from minor joint pain to neurological damage [7]. Lower vehicle pressures can reduce prebreathe time by reducing the initial amount of dissolved nitrogen in the body but they usually require higher oxygen concentrations (higher flammability risk) to prevent hypoxia. Minimizing prebreathe time will directly lead to more EVA time.

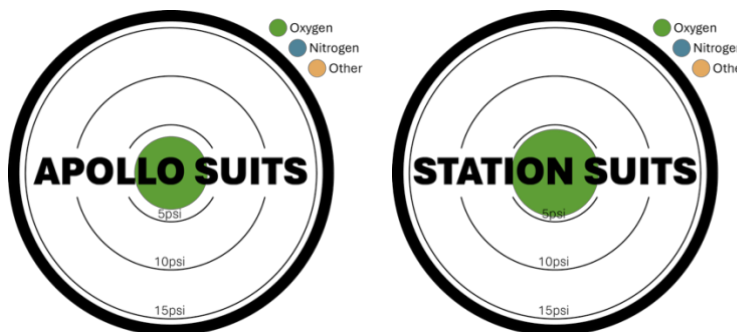


Figure 3. Graphical representation of Apollo spacesuit atmosphere and Station US spacesuit atmosphere.

D. Suit Mobility

Spacesuits often use a different atmosphere than spacecraft and habitation systems. Higher atmospheric pressures make spacesuits more rigid (i.e., less flexible and more physically demanding to operate), require stronger brackets and other hardware to increase material strength (and mass), and increase wear and tear on hardware. For this reason, it is beneficial to operate spacesuits at the lowest possible pressure. To avoid hypoxia mentioned earlier, these lower pressure spacesuits must operate at higher oxygen concentrations.

Spacesuits worn by Apollo astronauts operated at a pressure of 3.75 psi (25.8 kPa) and 100% oxygen. The Extravehicular Mobility Unit used during the Space Shuttle program and aboard the International Space Station (referred to as “Station Suit” throughout this paper) maintains a pressure of 4.3 psi (29.6 kPa), while the Russian-made Orlan spacesuit, also used aboard the space station, maintains a slightly higher pressure of 5.7 psi (39.2 kPa). Both systems operate with a 100% oxygen atmosphere [8].

Higher suit pressures operating with this 100% oxygen atmosphere can reduce prebreathe time by reducing the amount of nitrogen that crew members must expel, thus also enabling longer EVA durations, but they also reduce suit flexibility and mobility. Data from suited EVA performance testing, repeated at multiple suit pressures, can inform a cost function characterizing the impact of suit pressure increase to crew workload, fatigue, and task duration. This cost function can be compared to the prebreathe protocol options, informing a risk trade. Spacesuit engineers and mission planners must strike a careful balance between the risk of decompression sickness, the operational burden of prebreathe, and suit mobility.

NASA and its commercial partners are currently developing and testing the Exploration Extravehicular Mobility Unit (xEMU) spacesuit for Artemis missions. NASA is testing the xEMU’s performance using a variety of atmospheres, between 4.3 psi (29.6 kPa) to 8.2 psi (56.5 kPa) [9]. Future spacesuits designed for EVAs on planetary bodies have different mobility requirements than spacesuits designed only for microgravity. The design and atmosphere considerations may also vary by destination (i.e., EVAs on Mars may have different mobility requirements than lunar EVAs.)

III. Considerations for Moon to Mars Exploration

The Moon to Mars Architecture includes many human-rated systems, such as the Orion spacecraft, the Human Landing System, the Pressurized Rover, spacesuits, and surface habitats. These elements bring together many different providers and partners. To explore the Moon, including building a Moon Base, and journey to Mars, astronauts will need to be able to work seamlessly across different elements, creating the need for compatible atmospheres.

A. Atmosphere Transition Considerations

Spacecraft that dock or berth in cislunar space, like the Orion spacecraft, Gateway, and the Human Landing System, must be able to maintain similar atmospheres to enable crew to transition between them. Similarly, habitation assets on the lunar surface will need to maintain suitable atmospheres to enable astronauts to transition to spacesuits for EVAs.

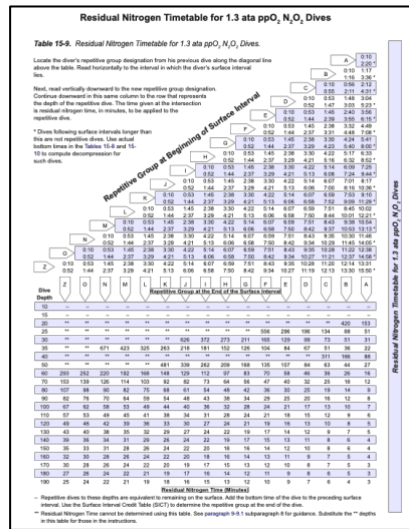


Figure 4. Example dive table from the U.S. Navy Diving Manual [13]. SCUBA divers use dive charts like this one to plan for safe dives given considerations include water pressure, dive time, and tank air mixture. (Credit: U.S. Navy)

outline a suite of safe pressures, oxygen concentrations, and prebreathe times to help astronauts and mission controllers plan EVAs that meet a variety of exploration needs. Decompression sickness is a complex event that combines the presence of a gas phase in the tissues (venous gas emboli) with human perception of pain. Therefore, probabilistic models about decompression sickness and presence of venous gas emboli require a large amount of test data to validate those models [12].

B. System Design Considerations

Atmosphere requirements also have flow-down effects on overall system design and pre-flight testing. In an architecture that uses multiple systems (e.g., launch vehicles, landing vehicles, habitation modules) built by different providers, ensuring compatible atmospheres will be a key design concern. Spacecraft will need to monitor and adjust gas ratios to maintain the desired balance. Improvements to accuracy and reliability of spacecraft ECLSS sensors and gas injection can result in smaller oxygen concentration excursions which could decrease the boundaries for material flammability testing (i.e., more materials might pass). Maximum pressure requirements can also affect the design and mass of a system's structures.

Spacesuit pressures will also need to balance prebreathe requirements with factors such as astronaut fatigue, mobility, and suit life cycle (i.e., wear and tear on the spacesuit). These architectural considerations, including the characteristics of the intended destinations, will dictate many design choices.

Another factor for system design consideration should be commonality among multi-system architectures, where practical. System design and operational choices made independently, such as atmosphere set points, resulting pre-breathe protocols, and even fire mitigations, could result in additional mission operational complexity in terms of crew and ground operator training.

C. Operational Considerations

NASA has extensive experience with microgravity spacewalks (e.g., in low Earth orbit). Engineers and mission planners have a thorough understanding of human physiological responses in these conditions and use atmospheres that maximize comfort, health, and safety.

The transition between different systems and atmospheres is an operational consideration the architecture must address. As mentioned above, a prebreathe period is usually needed to prepare for an EVA, with the prebreathe duration depending upon the magnitude of the difference in atmospheres between spacecraft and spacesuit.

Because surface assets may operate at different atmospheres and EVA cadences will vary, there is no one-size-fits-all prebreathe protocol. A lengthy prebreathe period can limit EVA opportunities; a short prebreathe enabled by higher suit pressures can increase the risk of crew fatigue and injury. NASA aims to minimize prebreathe time to maximize astronaut utilization opportunities (e.g., conducting science or technology demonstrations while EVA) while ensuring crew safety [10].

Ultimately, NASA would like to develop protocols similar to those outlined on SCUBA dive tables, which help divers calculate safe dive depths and times that minimize the risk of decompression sickness. The development of this DCS risk estimation tool is known as the Aerospace Estimation Tool for Hypobaric Exposure Risk (AETHER) [11]. This approach would

NASA has far less operational experience in partial gravity (i.e., only from the lunar landings of the 1960s and 1970s). As the agency gains more practical experience in partial gravity, atmospheres (e.g., for the Human Landing System, spacesuits) may change to optimize for the effects of partial gravity on the human body and surface assets.

D. Mars-Forward Considerations

While many lunar systems are extensible to Mars exploration, environmental differences between the two planetary bodies may prompt design differences. Operating in Mars's atmosphere, which exerts less pressure than Earth's atmosphere but more than the Moon's vacuum conditions, may call for different atmospheres in habitation systems and spacesuits. Flame blow-off factors will be different in martian gravity and the on-back mass and center of gravity of the spacesuit will have an even more pronounced impact on crew fatigue during spacewalks.



Figure 5. Astronauts Practice Next Giant Leap for Artemis. NASA astronaut Doug “Wheels” Wheelock and Axiom Space astronaut Peggy Whitson test the mobility of Artemis spacesuits conducting movements and tasks similar to those necessary during lunar surface exploration on Artemis missions [15].

IV. Conclusion

There is no one-size-fits-all solution for vehicle and suit atmospheres. Realizing a multi-partner architecture that minimizes risk and maximizes utilization time requires NASA to develop robust, flexible systems that can operate in and interface with a variety of systems. Rather than the agency dictating specific atmospheres or setting operational requirements, it is imperative that NASA awards contracts and adjudicates standards with their providers with this flexibility in mind.

As the agency grows its experience in partial gravity operations, it will refine its approaches and this knowledge gain will enable an enduring presence at the Moon Base and humanity's first journeys to Mars.

A. Early Artemis architectures

For the first missions to land astronauts on the Moon in over 40 years, NASA and its Artemis commercial providers are developing multiple architecture options to enable surface EVAs.

Table 1. Early Artemis mission architecture variables related to surface EVAs.

Vehicle Atmospheric Variables	Option 1	Option 2
Vehicle Pressure	8.2 psi	9.6 psi
Vehicle MOC	37%	30%

Physiological Variables	Option 1	Option 2
Partial Pressure of Inspired Oxygen	2.46 psi	2.22 psi*

Suit Atmospheric Variables	Option 1	Option 2
Suit Pressure	4.3 psi	5.2 psi†

Utilizing the variables in Table 1, NASA has evaluated multiple prebreathe protocols for use on the early Artemis missions

Table 2. Early Artemis mission architecture examples.

	Vehicle Pressure	Vehicle MOC	PiO2	Suit Pressure	Prebreathe Time
Architecture 1	8.2 psi	37%	2.46 psi	4.3 psi	~50 min‡
Architecture 2	9.6 psi	30%	2.46 psi	5.2 psi	~50 min

B. Key Takeaways

- Vehicle and suit atmospheres are a key factor for crew health and safety, providing the gas mixture that crew members breathe. When selecting an atmosphere, NASA must consider risks like fire and decompression sickness, while maximizing spacesuit mobility and EVA duration.
- Exploration systems will need to provide safe and compatible atmospheres, enabling crew members to live and work in space while transitioning between elements.
- While NASA has a great deal of experience in microgravity, operating in a partial gravity environments like on the Moon to Mars may have different effects on human physiology that the agency must understand.
- NASA will manage atmospheres for the Artemis campaign and Mars missions based on many considerations and trade-offs, including exercising flexibility to use a range of atmospheres for different use cases.

* A PiO2 of 2.22 psi is being evaluated as a mildly hypoxic atmosphere but is not yet approved.

† A suit pressure of 5.2 psi is being evaluated as an elevated suit pressure but is not yet approved.

‡ The Architecture 1 protocol is based on modeling and indirect testing, but has not yet been tested.

Acknowledgments

The authors would like to recognize the work of the Exploration Atmosphere Issue Resolution Team members. Since the winter of 2022, this team has worked with NASA commercial providers Axiom, Blue Origin, SpaceX, international partner ESA, and the NASA Engineering Safety Center (NESC). Together they reviewed historical lessons learned and identified key process updates and design trades needed to make NASA's return to the lunar surface successful, while safely maximizing the duration of EVAs.

References

- [1] National Oceanic and Atmospheric Administration, "The Atmosphere," 2 July 2024. [Online]. Available: <https://www.noaa.gov/jetstream/atmosphere>. [Accessed 3 March 2026].
- [2] C. Anchondo, P. Masi and C. Briggs, "Creating the Test Environment for Exploration Habitats," in *53rd International Conference on Environmental Systems*, Louisville, KY, ICES-2024-128.
- [3] National Aeronautics and Space Administration, "Report of Apollo 204 Review Board," 5 April 1967. [Online]. Available: <https://www.nasa.gov/wp-content/uploads/static/history/Apollo204/summary.pdf>. [Accessed 3 March 2026].
- [4] D. Hirsch, "An Approach to the Flammability Testing of Aerospace Materials," NASA Technical Reports Server, 20120010633, 2012.
- [5] E. Johnson and P. Ferkul, Interviewees, and G. Jordan, Interviewer, "Moon Material Flammability," *Houston We Have A Podcast*, 23 May 2025. [Podcast]. Available: <https://www.nasa.gov/podcasts/houston-we-have-a-podcast/moon-material-flammability>. [Accessed 1 May 2026].
- [6] National Aeronautics and Space Administration, "APPENDIX H: Human Landing System Attachment A01 HLS Con Ops v1.0 Release 1.3," 1 May 2020. [Online]. Available: <https://sam.gov/workspace/contract/opp/7e3ad9e2ec964008a7f419ae8a8511a4/view>. [Accessed 4 March 2026].
- [7] NASA, "Decompression Sickness (DCS) Risk Mitigation," OCHMO-TB-037, Rev C, 2023.
- [8] K. Lange, B. Duffield, F. Jeng and P. Campbell, "Exploration Spacecraft and Space Suit Internal Atmosphere Pressure and Composition," in *2005 Bioastronautics Investigator's Workshop*, Galveston, TX, 2005.
- [9] National Aeronautics and Space Administration, "Exploration Extravehicular Mobility Unit (xEMU)," 7 October 2019. [Online]. Available: <https://www.nasa.gov/image-article/exploration-extravehicular-mobility-unit-xemu/>. [Accessed 3 March 2026].
- [10] S. McFarland, D. Campbell and R. Rhodes, "NASA Advanced Space Suit Pressure Garment System Status and Development Priorities 2025," in *54th International Conference on Environmental Systems*, Prague, Czech Republic, ICES-2025-385.
- [11] NASA, "CO2 Chamber Services - 80NSSC25913595Q," SAM.gov, 2025.
- [12] J. Conkin, "Probability of Decompression Sickness and Venous Gas Emboli from 49 NASA Hypobaric Chamber Tests with Reference to Exploration Atmosphere," National Aeronautics and Space Administration, NASA/TP-2020-220529.
- [13] U.S. Navy, "U.S. Navy Diving Manual, Revision 7," Commander, Naval Sea Systems Command, 2016.
- [14] National Aeronautics and Space Administration, "Twitter," 8 July 2025. [Online]. Available: https://x.com/NASA_Johnson/status/1942709546977567116/photo/1. [Accessed 3 March 2026].
- [15] SpaceX, "Astronauts Practice Next Giant Leap for Artemis," NASA Image and Video Library, 5 March 2024. [Online]. Available: <https://images.nasa.gov/details/hls-crew-elevator-demo-20240503-dsc00138>. [Accessed 3 March 2026].