DEFENSE, EMERGING TECHNOLOGY, AND STRATEGY PROGRAM

Parallel Burn

A Synchronized Push to the Moon and Mars

Varun Gupta
Georgia Reynolds
Alex Santangelo

HARVARD Kennedy School
BELFER CENTER
50 YEARS OF RESEARCH, POLICY, AND LEADERSHIP

JUNE 2025

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The Defense, Emerging Technology, and Strategy (DETS) program has a dual mission to

1. advance policy-relevant knowledge and strategy on the most important challenges at the intersection of security and emerging technology; and
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About the Authors

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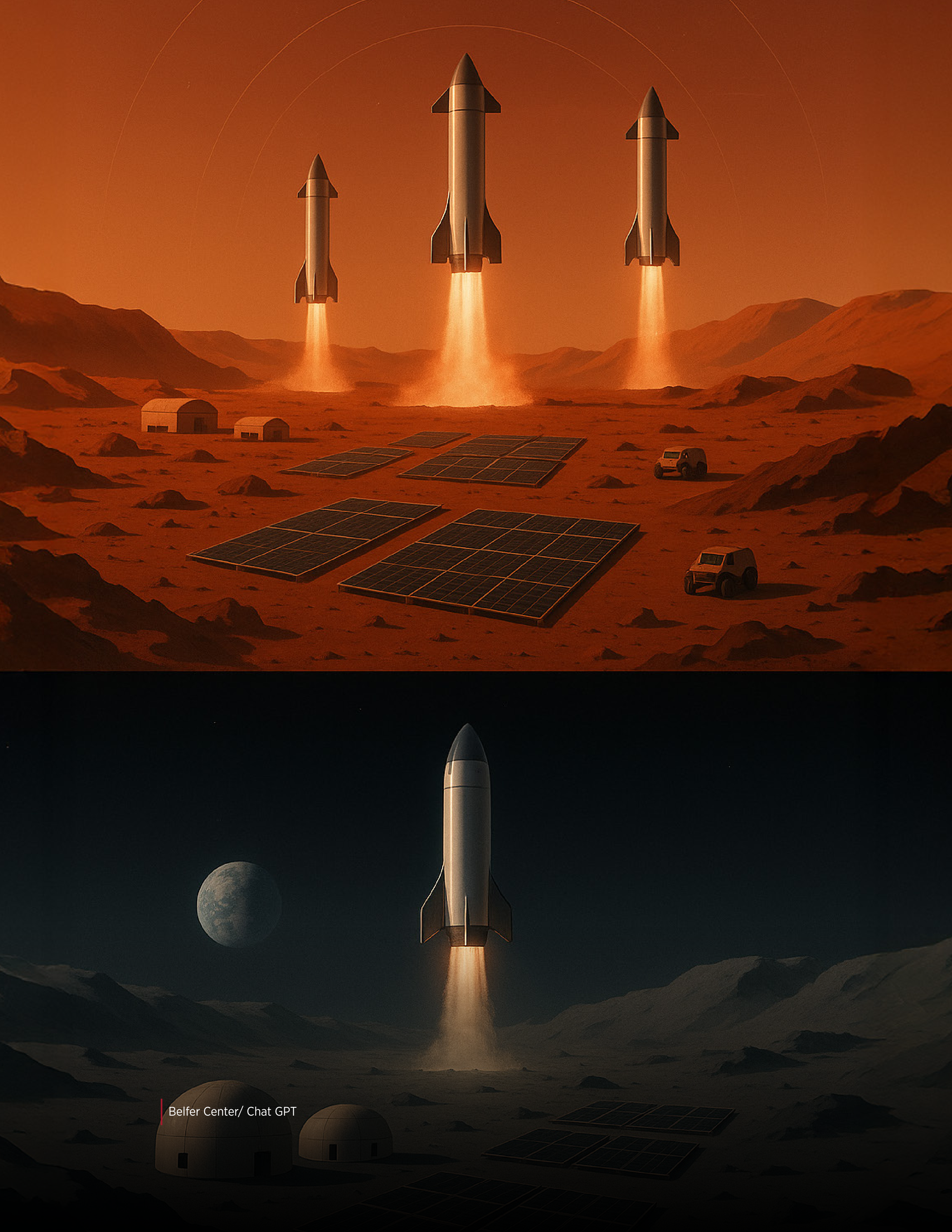

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Executive Summary

The Artemis program, launched in 2019, was designed to return humans to the Moon as a stepping-stone for future Mars missions. Since then, NASA has demonstrated meaningful progress, including a successful uncrewed test flight (Artemis I) and ongoing development of Orion, the Space Launch System (SLS), and SpaceX's Human Landing System (HLS). However, Artemis has suffered from persistent delays and high costs, particularly with the SLS and Gateway.

The Trump administration has proposed a dramatic recalibration: retiring legacy architectures like SLS and Gateway; accelerating Mars mission timelines; and pivoting to a commercial-first approach. Central to this strategy is the development of a new "parallel path" Mars mission architecture.

This report examines how the parallel path can be achieved by recommending a Mars program architecture and assessing how Artemis can be adapted to serve as a technology testbed. It outlines which capabilities are ready, which require urgent investment, and how NASA can better leverage commercial innovation. Notably, this dual-path approach utilizes Artemis missions to validate essential systems (e.g., orbital refueling, transit habitats, and in-situ resource utilization) before deploying them in Mars operations. This integrated approach not only supports a more efficient Mars timeline but also avoids duplication of effort and spending.

The analysis finds that several technologies (e.g., re-entry systems, life support, and surface power) are mature or near-ready. Others, such as Mars entry/landing systems, deep space habitats, and surface mobility, require further development and testing, ideally through Artemis follow-on missions. This roadmap enables a cost-conscious, resilient, and phased approach to human space exploration beyond low Earth orbit.

While recent changes, such as the withdrawal of Jared Isaacman as NASA administrator, may refocus the administration towards a Moon-first approach, it does not materially impact the recommendation of this report. The analysis in this report supports a human Moon landing before any Martian attempts but accelerates the Martian timeline by rapidly integrating learnings from a lunar program into a dedicated Martian program.

Recommendation 1: Phase out the costly SLS and Orion in favor of leveraging other private sector reuseable rockets like SpaceX's Starship, Blue Origin's New Glenn, or RocketLab. This report recommends that SLS should still perform critical Artemis Phase II and Phase III missions; however, it is a sunk-cost fallacy to continue SLS beyond Phase III if another private sector competitor can offer a more affordable and higher performing alternative. This report will detail its recommendations on what each future Artemis phase should aim to achieve, what technologies will be tested, and how it will help with informing the parallel Mars path.

Recommendation 2: Offload responsibility for Gateway to its international partners given that it has minimal synergies with Mars and is not critical to developing sustained lunar presence, which could be achieved with Starship or other competitors. Instead of Gateway and Artemis IV, this report recommends developing a vehicle that can land humans and cargo on the Moon without HLS and can return to Earth. This would require a vehicle like Starship, which is meant to carry out all phases of launch, landing, and relaunch.

Recommendation 3: After Artemis IV, conduct multiple moon missions with crews aboard new vehicles to further build out a sustained presence on the Moon, while also rigorously testing technologies that will be required for missions to Mars. It is critical to establish longer duration missions on the Moon to test technologies and methods that would be needed for a Mars mission in which astronauts would likely need to live on Mars for over a year, such as habitation modules.

Recommendation 4: Simultaneous with moon missions, a new 4-mission Mars program should be established (Ares Missions) that rapidly leverages technology demonstrations from the lunar program: 1) Entry, Descent & Landing, 2) Mars Return, 3) Base Buildup, 4) Crewed Landing. This architecture ensures that new technologies can be rapidly prototyped through Lunar missions before being deployed on costly and long Mars missions, accelerating America's timeline for boots on the Red Planet. Beyond their primary objective, these missions aim to create a sustained demand signal for the private sector that will encourage new technologies and capabilities for further deep-space exploration.

A Parallel Path to the Moon and Mars

"To get to Mars, you have to land on the Moon, they say... Any way of going directly without landing on the Moon? Is that a possibility?"[1]

- President Donald J. Trump, 2019

Artemis Program Background

Since the Apollo 17 mission in 1972, humans have not yet returned to the Moon. In 2004, President Bush made several key decisions in his Vision for Space Exploration that have helped shaped the trajectory of NASA's growth and focus. He announced the plan to retire the Space Shuttle program, focused on completing the International Space Station (ISS), and called for returning to the Moon and eventually going to Mars.[2] Since then, NASA has had several different space explorations efforts: Constellation (2004-2010, targeted lunar surface and Mars); Journey to Mars (2015-2018, targeted cislunar space, asteroid, and Mars); and most recently, Moon to Mars (2018 to present, targeting lunar surface and Mars).[3] In 2010, the U.S. passed the NASA Authorization Act of 2010 which specifically directed NASA to develop a heavy-lift rocket and crew capsule for cis-lunar space and beyond low-Earth orbit (LEO) which would later become the Space Launch System (SLS) and Orion spacecraft.[4]

In 2017, President Trump announced through a memorandum known as Space Policy Directive 1 to remove any mention of asteroid landings and declare a focus on moving beyond LEO to return humans to the Moon for long-term exploration and utilization, followed by human missions to Mars and other destinations.[5] In 2019, the Artemis program was officially launched by NASA with the express

1 Politico (@politico), "Elon Musk tells investors that SpaceX could land humans on Mars in 2024. NASA says 2033 is more realistic," X (formerly Twitter), July 19, 2019, https://x.com/politico/status/1152268834683797504.

2 NASA. "Vision for Space Exploration." Last modified July 2023. https://www.nasa.gov/history/vision-for-space-exploration/.

3 The Planetary Society. "Artemis, NASA's Moon Landing Program." Accessed May 7, 2025. https://www.planetary.org/space-missions/artemis.

4 National Aeronautics and Space Administration Authorization Act of 2010, Public Law 111–267, 124 Stat. 2805 (2010). https://www.congress.gov/bill/111th-congress/senate-bill/3729.

5 Trump, Donald J. "Presidential Memorandum on Reinvigorating America's Human Space Exploration Program." White House, December 11, 2017. https://trumpwhitehouse.archives.gov/presidential-actions/presidential-memorandum-reinvigorating-americas-human-space-exploration-program/.

goal of achieving a human Moon landing by 2024, while simultaneously working toward sustainable lunar exploration in the mid-to late 2020s.[6] Additionally, Artemis was crafted with the understanding that it would pave the way for the U.S. to build the capabilities necessary to get astronauts to Mars, which is referred to as the ”Moon to Mars” exploration approach. Artemis would be a proving ground of deep-space technology and human-led exploration that would inform efforts for Mars exploration.

In 2022 through the CHIPS and Science Act, Congress passed the NASA Authorization Act of 2022 which explicitly authorized funding for the Moon to Mars Program and upcoming Artemis missions.[7]

Artemis Program Phases and Components

The Artemis program was divided into four phases and was designed so that each phase built upon the success and lessons learned from the previous phase. Due to a series of technical challenges and safety concerns, the Artemis program has met many delays and cost overruns. Artemis did not meet its original goal of landing astronauts on the Moon by 2024, but it plans to do so by early 2026.[8] Below is a more detailed description and timeline of the planned Artemis missions. Later, this report will examine how the Trump administration plans to reimagine the Artemis program and Mars missions while also offering recommendations on how to pursue this dual-path strategy.

Artemis I: In 2022, the SLS rocket and Orion spacecraft were launched around the Moon and back to Earth. SLS is a super heavy-lift rocket that is taller than the Statue of Liberty, ~15% more powerful than the original Saturn V launcher that first took astronauts to the Moon, and is developed by Boeing and Aerojet Rocketdyne, while Lockheed Martin is the lead contractor for Orion. [9] It was an uncrewed mission that proved that the rocket and spacecraft could work safely in deep space and pave the way for future crewed missions to Mars.

6 NASA. Artemis Plan: NASA's Lunar Exploration Program Overview. September 2020. https://www.nasa.gov/wp-content/uploads/2020/12/artemis_plan-20200921.pdf.:contentReference[oaicite:2]{index=2}

7 ASME.org. "First NASA Authorization in Five Years Included in CHIPS and Science Act." ASME, August 29, 2022. https://www.asme.org/government-relations/capitol-update/first-nasa-authorization-in-five-years-included-in-chips-and-science-act.:contentReference[oaicite:2]{index=2}

8 Longo, Alex. "NASA Accelerates Artemis 2 by Two Months." AmericaSpace, March 22, 2025. https://www.americaspace.com/2025/03/22/nasa-accelerates-artemis-2-by-two-months/.

9 NASA. "Artemis Partners." Last modified May 2025. https://www.nasa.gov/artemis-partners/.

Artemis II: This mission will carry four astronauts around the Moon via the SLS and Orion spacecraft; however, it will not land on the Moon. This phase is important for testing life support, navigation, and communication systems with a crew onboard. It was recently announced that it will take place in February 2026, two months earlier than previously discussed.

Artemis III: Two astronauts will land near the Moon's South Pole where there are large deposits of water ice that could potentially be processed and utilized for fuel on later missions. This mission is planned to be 30 days long, with about a week of it spent on the surface of the Moon. It is currently slated for late 2027. For sequencing of the mission, the Human Landing System (HLS) developed by SpaceX will be pre-positioned in Near-Rectilinear Halo Orbit (NRHO) around the moon. The Orion spacecraft will launch via the SLS in a separate launch. Orion will then rendezvous with HLS in orbit around the Moon where the crew will transfer to HLS while Orion remains in orbit. Like an elevator, the HLS will land the crew on the Moon for its mission and then will bring the crew back to Orion. The crew will then transfer to Orion to return back to Earth.

Artemis IV and beyond: Date is still undetermined. Artemis IV is intended to be the beginning of the building of a small space station called Gateway around the Moon in NRHO. Gateway is a collaborative effort between NASA and other international partners like the Canadian Space Agency (CSA), the European Space Agency (ESA), and the Japan Aerospace Exploration Agency (JAXA).[10] Gateway would allow for testing how humans can live away from Earth for longer periods, and in theory act as a staging point for missions to future Mars and Moon operations. Beyond Artemis IV, more Moon landings would occur to further build out Moon infrastructure and conduct technology testing to help plan and inform future Mars missions.

10 NASA. "Gateway." Last modified May 2025. https://www.nasa.gov/mission/gateway/.

Pushback on Artemis by the Trump Administration

Despite Artemis being established by President Trump in his first presidency, he has shown in his second term a much more pessimistic view on Artemis and embraced Mars as the biggest priority. There is strong evidence that Elon Musk, who owns SpaceX and was one of Trump's most trusted advisors, has had a strong influence on Trump's desire to divert more resources to Mars.[11] In addition to influence from Musk, some speculate that Trump sees Mars as an opportunity to enter the space pantheon while simultaneously outcompeting China much like JFK with the Soviets. There are also very strong budgetary reasons to reassess Artemis and its associated systems, such as SLS, Orion, and Gateway.

Various reports by NASA's Office of the Inspector General have shown that SLS has ballooned in costs and delays,[12] with the Trump White House claiming in its recent topline budget request that SLS "costs $4 billion per launch and is 140% over budget."[13] Among other proposed cuts to NASA programs, President Trump seeks to phase out SLS and Orion after three flights and outright terminate Gateway. In turn, he plans to allocate more funding and redirect savings towards other commercial heavy-lift launch solutions and Mars focused missions. This move by Trump will find many opponents on both sides of the aisle in Congress and may be difficult to unwind given that the Artemis program is written into existing law mentioned earlier in this report. In fact, the reconciliation text released by the Senate Commerce Committee specifically funds SLS and Orion through Artemis V, but this may change as negotiations progress.[14] Space policy experts interviewed for this report believe that despite Trump's stated desire to

11 Fung, Brian, and Micah Maidenberg. "Elon Musk's Mission to Take Over NASA—and Mars." The Wall Street Journal, March 30, 2025. https://www.wsj.com/business/elon-musk-nasa-mars-space-travel-d3978a7b.

12 Foust, Jeff. "NASA's Inspector General Predicts Continued Cost Growth for SLS Mobile Launch Platform." SpaceNews, August 28, 2024. https://spacenews.com/nasas-inspector-general-predicts-continued-cost-growth-for-sls-mobile-launch-platform/.

13 Executive Office of the President, Office of Management and Budget. Fiscal Year 2026 Discretionary Budget Request. Washington, D.C., May 2, 2025. https://www.whitehouse.gov/wp-content/uploads/2025/05/Fiscal-Year-2026-Discretionary-Budget-Request.pdf.

14 U.S. Senate Committee on Commerce, Science, and Transportation, Coast Guard Mission Readiness and Other Provisions Act, S. l.c., 124th Cong., amended Senate bill, introduced 2025, Washington, DC: U.S. Government Publishing Office, 2025, accessed June 11, 2025, https://www.commerce.senate.gov/services/files/AD3D04CF-52B4-411F-854B-44C55ABBADDA.

land on Mars, he is not putting as much of an emphasis and priority on space as he did in his previous term.[15] It is still early to tell, but experts believe that as Trump devotes more energy on immigration, tariffs, and regional conflicts, that space will further wane in importance to the Trump agenda.

The Trump Administration's Views on Artemis and Moon to Mars

Jared Isaacman who is a longtime friend and customer of Musk, was initially tapped by Trump to become the NASA Administrator; however, at the time of publishing of this report, he was abruptly removed before his Senate confirmation vote.[16] Furthermore, the White House has not offered a reason for its decision, but, the media has speculated that it may be because of Isaacman's previous political donations to Democratic candidates.[17] Since the Trump administration has not yet named a new nominee and the firing seems to stem from political reasons rather than policy differences, this report assumes that the statements made by Isaacman during his Senate testimony are largely reflective of the Trump administration's views regarding Artemis and space sector.

Jared Isaacman advocated for a dual-path strategy that pursues lunar and Martian missions concurrently rather than sequentially. He emphasized that the Moon and Mars "don't have to be a binary decision," arguing that Artemis lunar missions and Mars exploration can share technologies like reusable heavy-lift launch systems and in-situ resource utilization (ISRU) to reduce costs and accelerate timelines.[18] While Isaacman supported the current Artemis architecture, specifically SLS

15 Elsbeth Magilton and Frans von der Dunk, interview by author, April 22, 2025

16 Jeff Foust, "White House to Withdraw Isaacman Nomination to Lead NASA," SpaceNews, June 1, 2025, updated 6 a.m. Eastern, accessed June 11, 2025.

17 Wall Street Journal. "Trump Drops Musk Associate Jared Isaacman as Nominee for NASA Chief." May 31, 2025

18 Kuhr, Jack. "Isaacman Charts a Parallel Course to the Moon and Mars." Payload, April 9, 2025. https://payloadspace.com/isaacman-charts-a-parallel-course-to-the-moon-and-mars/.

and Orion, for near-term lunar missions, he called SLS “outrageously expensive” and envisioned transitioning to commercial rockets (e.g., SpaceX’s Starship, Blue Origin’s New Glenn) for sustainable lunar and Mars operations.[19] He viewed SLS as the “fastest way” to beat China to the Moon, but insisted that NASA must shift focus to researching and developing next-generation technologies that are “near impossible”, like nuclear propulsion, which he viewed as essential for future Mars missions.[20] He also wanted to prioritize fixed-cost contracts instead of cost-plus contracts that were used for SLS and previous NASA missions because cost-plus often resulted in delays, cost overruns, poorer quality. Overall, the Trump administration prioritizes cost efficiency, commercial partnerships, speed, and mission focus.

19 U.S. Senate. Committee on Armed Services. Responses to Questions for the Record Submitted by Senator Josh Hawley to Mr. Jared Isaacman. 118th Cong., 1st sess. Washington, D.C.: U.S. Government Publishing Office, 2023. https://www.armed-services.senate.gov.

20 U.S. Senate. Committee on Commerce, Science, and Transportation. Responses to Questions for the Record Submitted by Democratic Senators to Mr. Jared Isaacman. 118th Cong., 1st sess. Washington, D.C.: U.S. Government Publishing Office, 2025.

Defining the Mission Architecture

"And we will pursue our manifest destiny into the stars, launching American astronauts to plant the Stars and Stripes on the planet Mars."[21]

– President Donald J. Trump, 2025

A Mars Mission Architecture – The Ares Missions

Given the refocus of key administration officials on an accelerated, and parallel, path to Mars, a new mission architecture must be created. This architecture must take advantage of process and technology developments from the Artemis program and rapidly integrate them into Mars missions that will be sequentially launched during each transfer window.

The proposed mission architecture is called the Ares Missions, based off the Greek counterpart to Mars in mythology and symbolizing unyielding drive and courage in the face of danger.

Important Disclaimers

We do not yet know what commercial opportunities will ultimately look like on Mars. At this stage, no clear market exists for private capital to sustainably support exploration. Because of that, the U.S. government will take the lead by offering firm-fixed-price indefinite delivery, which are indefinite quantity contracts to industry, and will build on the successful model used for Artemis,[22] Commercial Crew,[23] and Cargo. This provides predictable milestones, keeps costs in check, and incentivizes innovation, while ensuring public goals remain central.

This plan assumes the use of SpaceX hardware for its current availability. But the architecture is not exclusive. Fixed-price contracts would be open to any company that can meet the technical milestones, and competition would be encouraged at

21 Donald J. Trump, The Inaugural Address, The White House, January 20, 2025, https://www.whitehouse.gov/remarks/2025/01/the-inaugural-address/.

22 U.S. Government Accountability Office, NASA: Assessments of Major Projects, GAO-24-106256 (Washington, D.C.: Government Accountability Office, March 2024), https://www.gao.gov/assets/d24106256.pdf.

23 NASA, Commercial Crew Program Overview, last modified March 2024, https://www.nasa.gov/humans-in-space/commercial-space/commercial-crew-program/commercial-crew-program-overview/.

every phase. Having multiple providers capable of orbital refueling, cargo delivery, or eventually crew transport makes the system more resilient and less dependent on any single player.

Given the long lead times and uncertain timeline for Mars, what we can offer industry is a clear, sustained demand signal. Companies know that if they build the capability, there will be real missions waiting. That certainty, paired with milestone-based payments and government-backed goals, creates a stable runway for private investment, even in the absence of a commercial market on Mars itself.

The four-mission architecture provides a strong path to land humans on Mars within the next decade. It is not intended to establish a permanent presence, but rather to demonstrate the key technologies and validate operational and systems concepts needed for human exploration of Mars. Each mission serves a distinct purpose, enabling step-by-step risk reduction across critical domains like propulsion, entry-descent-landing, surface systems, and in-situ resource utilization. This plan does not presume that long-term habitation or colonization is immediately viable. Instead, it prioritizes safe return of humans from Mars and a clear demonstration that such missions are technically achievable, logistically feasible, and repeatable.

This report intentionally chose a commercial-first approach, enabling NASA and its partners to leverage the rapid innovation cycles and capital deployment of the private sector, while retaining guaranteed demand, government oversight, and public accountability. By building on momentum from Artemis, this architecture prioritizes incremental, testable demonstrations aligned with each 26-month Mars transfer window.

The mission dates are based on transfer windows that open when Earth and Mars are in ideal orbital positions roughly every 26 months.[24]. Any delay for mission milestones would push out the dates of each mission by this amount of time.

While private commercial entities may attempt their own launches in addition to the Ares missions described below, they would not be funded through government grants or contracts as described. Companies like SpaceX have expressed their

24 NASA Ames Research Center, Trajectory Browser, accessed May 7, 2025, https://trajbrowser.arc.nasa.gov/traj_browser.php?maxMag=25&maxOCC=4&chk_target_list=on&target_list=Mars&mission_class=oneway&mission_type=rendezvous&LD1=2029&LD2=2040&maxDT=1.5&DTunit=yrs&maxDV=7.0&min=DT&wdw_width=-1&submit=Search#a_load_results.

intent to conduct their own deep space exploration by deploying their own private capital.[25]

The mission architecture is summarized below.

Ares I: Mars Entry, Descent, Landing (EDL) Demo & Landing Site Selection (2028/2029)

A single, fully fueled spaceship is sent to Mars to test the ability to land large payloads using supersonic retro propulsion and Martian aerobraking. This uncrewed mission validates vehicle integrity under Mars atmospheric entry, descent, and landing conditions and transmits engineering and environmental data. It helps identify a viable future base location near accessible water ice and lays out initial infrastructure for a base.

Technology	Ares 1 (2028/2029) *EDL Demo & Site Recon*
Launch & Propulsion	Launch 1 spaceship to Mars
Orbital Refueling	LEO refueling test
Transit Habitat	None
Entry / Landing System	Supersonic retropropulsion demo
Life Support & Habitat	None
Power (Ground)	Basic solar for lander ops
Surface Mobility	None
ISRU	None
Comms / Navigation	Direct-to-Earth Communications

Ares II: Round-Trip Spaceship Test & Infrastructure Drop (2031)

Multiple spaceships are launched. One is sent with enough in-space refueling support to land on Mars and then return to Earth, validating the spaceship as both descent and ascent vehicle. Others are likely used to refuel the returning spaceship and are discarded. The remaining spaceships deliver essential systems like In-Situ Resource Utilization (ISRU)[26] units, power sources, initial habitats, and autonomous rovers for scouting terrain and ice. This phase initiates the permanent surface base buildout and contains remote monitoring that feeds into design iterations on Earth for future missions.

25 Anthony Cuthbertson, "SpaceX to Launch Starship in Critical Test of Elon Musk's 2026 Mars Plan," The Independent, May 26, 2025, https://www.independent.co.uk/space/starship-launch-latest-spacex-mars-b2757919.html.

26 NASA, Overview: In-Situ Resource Utilization, last modified October 2023, https://www.nasa.gov/overview-in-situ-resource-utilization/.

Technology	Ares 2 (2031) *Return Test + Core Systems*
Launch & Propulsion	Multiple spaceships incl. 1 round-trip return
Orbital Refueling	Multiple tankers refuel return-capable spaceship
Transit Habitat	Limited uncrewed spaceship cabin ops
Entry / Landing System	Multiple cargo landings + return spaceship landing to Earth
Life Support & Habitat	Cargo habitats delivered for surface prep
Power (Ground)	Solar arrays + test small fission unit
Surface Mobility	Scout rovers for terrain, ice survey
ISRU	Sabatier reactor + ice detection systems
Comms / Navigation	Mars relay sats deployed for ops

Ares III: Base Build-Up & Return System Redundancy (2033)

A large fleet of spaceships deliver a massive wave of cargo, including backup ISRU systems, life support stockpiles, radiation shelters, rovers, and habitat modules. Some spaceships perform automated Mars ascent and return flights to prove the architecture's reliability for crew extraction. This mission ensures robust redundancy and prepares Mars to safely support humans for over a year.

Technology	Ares 3 (2033) *Base Build-Up & Redundancy*
Launch & Propulsion	Large fleet of spaceship launches (cargo, demo return flights)
Orbital Refueling	Operational refueling scale-up
Transit Habitat	Optional cargo-transit testing, simulated crew test
Entry / Landing System	More spaceship landings validate reusability
Life Support & Habitat	Multiple units; redundancy for human safety
Power (Ground)	Grid expansion; backup units
Surface Mobility	Pressurized long duration crew vehicles, logistics bots
ISRU	Fuel production (O_2/CH_4) for return, water production
Comms / Navigation	Full comms net

Ares IV: First Human Mars Landing (2035)

A human crew launches aboard a spaceship for a conjunction-class mission[27] (about 500 days on the surface). They land at the pre-established base, use ISRU-produced fuel and oxygen, and live off systems deployed in earlier missions. The crew conducts scientific research, surface exploration, technology testing, and

27 Damon F. Landau and James M. Longuski, Trajectories for Human Missions to Mars, Part I: Impulsive Transfers, Purdue University, West Lafayette, Indiana, 2006, https://engineering.purdue.edu/AAE/research/Groups/longuski/Software/NOMAD/Papers/MTraj1.pdf.

long-duration habitation testing, then returns on a landed and refueled spaceship, marking the first successful human Mars round trip.

Technology	Ares 4 (2035) *First Human Landing*
Launch & Propulsion	Crewed spaceship to/from Mars (conjunction)
Orbital Refueling	Required for both outbound & return legs
Transit Habitat	Human-rated systems for 6–9 month trip
Entry / Landing System	Human spaceship landing (EDL proven at scale)
Life Support & Habitat	Full-time human use of habitat system
Power (Ground)	Continuous ops (ISRU, heating, life support)
Surface Mobility	Full surface mobility for crew
ISRU	Used for fuel + life support during stay
Comms / Navigation	Human ops coordination; Earth data uplink

Re-imagining Artemis in the Trump Era

This report concurs that reform of the Artemis program is necessary in order to accelerate missions to Mars and to phase out the extremely costly SLS and Orion in favor of leveraging other private sector innovation like SpaceX's Starship, Blue Origin's New Glenn, or Rocket Lab's Neutron. Critics warn that abrupt transitions risk destabilizing international partnerships and previous progress, but proponents counter that commercial agility combined with NASA focusing on future technologies is better than the status quo of delays and cost overruns. Furthermore, SLS will still perform critical Phase II and Phase III missions. Although the government has already plowed $23 billion into SLS, it is a sunk-cost fallacy to continue SLS beyond Phase III. This report will detail its recommendations on what each future Artemis phase should aim to achieve, what technologies will be tested, and how it will help with informing the parallel Mars path.

Central to this recalibration is retiring the SLS and Orion after Artemis III and replacing them with reusable commercial rockets like SpaceX's Starship. This report also recommends offloading responsibility for Gateway to its international partners given that it has minimal synergies with Mars and is not critical to developing sustained lunar presence, which could be achieved with Starship or other competitors. Instead of Gateway and Artemis IV, this report recommends developing a vehicle that can land humans and cargo on the Moon without HLS and can return back to Earth. This would require a vehicle like Starship, which is meant to carry out all phases of launch, landing, and relaunch. Following Artemis missions would focus on establishing longer duration missions on the Moon to test technologies and methods that would be needed for a Mars mission in which astronauts would likely need to live on Mars for over a year, such as habitation modules.

Artemis Phase II and III: Proceed as currently planned in order to be the first to return to the Moon ahead of China, and make use of technology that is already further along in the development cycle. Below are the technologies that will be utilized and tested during these missions.

Technology	Artemis II as planned (2026)
Launch & Propulsion	Launch SLS and travel via Orion to orbit moon and return to Earth
Orbital Refueling	None
Transit Habitat	Four pilots for 10 days in Orion
Entry / Landing System	Orion reentry
Life Support & Habitat	None
Power (Ground)	None
Surface Mobility	None
ISRU	None
Comms / Navigation	Direct-to-Earth Communications

Technology	Artemis III as planned (2027)
Launch & Propulsion	Launch SLS and travel via Orion to HLS. Launch HLS from Moon to Orion
Orbital Refueling	HLS orbital refueling in LEO
Transit Habitat	Two pilots for 30 days
Entry / Landing System	HLS landing on Moon, Orion reentry to Earth
Life Support & Habitat	Approximately 1 week on Moon with HLS as habitat
Power (Ground)	Basic solar and batteries in HLS
Surface Mobility	Spacesuits
ISRU	Identify and sample water ice
Comms / Navigation	Direct-to-Earth Communications, Utilize Earth GNSS

New Artemis IV: Encourage private industry to develop a vehicle that can seamlessly land on the Moon and return to Earth without utilizing an intermediary like Orion and HLS. This would be conducted without a crew. This report targets 2028; however, companies like SpaceX are already attempting to conduct these types of tests, so it may be pulled forward. This would be a key enabler of then including astronauts on these missions to further test out critical technologies for the Ares mission.

Technology	New Artemis IV (2028)
Launch & Propulsion	Launch new craft and travel directly to Moon
Orbital Refueling	Likely required prior to landing on Moon
Transit Habitat	Unmanned monitoring of life support systems
Entry / Landing System	Craft lands on the moon; reenters and lands on Earth
Life Support & Habitat	Unmanned monitoring of life support systems
Power (Ground)	Solar and batteries
Surface Mobility	None
ISRU	None
Comms / Navigation	Direct-to-Earth Communications

Follow-On Artemis Missions: Conduct multiple moon missions with crews aboard new vehicles to further build out sustained presence on Moon while also rigorously testing technologies that will be required for Ares missions. Although all technologies are important to test, most vital in these phases will be sustaining long-term presence in space, such as transit/ground habitation and ISRU, since human missions to Mars will require staying on planet for potentially over a year.[28]

Technology	Follow-On Artemis Missions (2029-2034)
Launch & Propulsion	Launch new crafts and travel directly to Moon
Orbital Refueling	Frequent LEO refueling for large payload delivery to Moon
Transit Habitat	Long-duration testing in LEO or lunar orbit
Entry / Landing System	Capability and endurance testing
Life Support & Habitat	Long-duration habitat testing
Power (Ground)	High efficiency solar power + fission unit test
Surface Mobility	Long duration surface transport vehicles with life support
ISRU	Begin pilot experiments to extract useful resources (water, fuel, etc.,)
Comms / Navigation	Lunar relay satellite net

Integration of New Artemis & Ares

This report will go into further detail on the state of specific technologies in the next section, however this section shows that for each major technology category, the mission architecture has been designed such that each technology category has been tested on an Artemis mission before being launched on an Ares mission. The

28 Damon F. Landau and James M. Longuski, Trajectories for Human Missions to Mars, Part I: Impulsive Transfers.

number in the chart indicates which mission phase it will be tested. This has been summarized in the chart below.

Technology	Mission	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
Launch and Propulsion	Artemis		III	IV	V+						
	Ares			I			II		III		IV
Orbital Refueling	Artemis		III	IV	V+						
	Ares			I			II		III		IV
Transit Habitat	Artemis	II	III	IV	V+						
	Ares								III		IV
Entry / Landing System	Artemis		III	IV	V+						
	Ares			I			II		III		IV
Life Support & Habitat	Artemis		III	IV	V+						
	Ares						II		III		IV
Power (Ground)	Artemis		III	IV	V+						
	Ares			I			II		III		IV
Surface Mobility	Artemis		III	IV	V+						
	Ares						II		III		IV
ISRU	Artemis				V+						
	Ares						II		III		IV
Comms / Navigation	Artemis	II	III	IV	V+						
	Ares						II		III		IV

Artemis	Ares
Partial Test	Prep Materials
Complete Test	Required Materials

Launch and Propulsion

The first Ares mission will require a tested and reliable launch vehicle and spaceship to arrive to Mars. Given SLS is not intended for or currently capable for Mars missions,[29] major tests of the launch and propulsion technologies for the Ares missions occurs in Artemis III with the launch of HLS from earth on top of a Starship Booster. HLS will then be refueled in LEO by Starship tankers, travel to the moon, park itself in lunar orbit until Orion docks, land on the Moon, and

29 Eric Berger, "Long-time Advocate of SLS Rocket Says It's Time to Find an 'Off-Ramp'," Ars Technica, February 2025, https://arstechnica.com/space/2025/02/long-time-advocate-of-sls-rocket-says-its-time-to-find-an-off-ramp/.

later boost back up to lunar orbit to dock with Orion.[30] This will test all the critical launch and propulsion systems that will be needed for the first Ares mission.

Orbital Refueling

The first Ares mission requires proven and reliable orbital refueling. While Artemis II does not conduct any orbital refueling, Artemis III requires it for HLS transfer from LEO to lunar orbit.[31] Once LEO orbital refueling has been tested consistently across the Artemis missions, it will be ready for the first Ares mission.

Transit Habitat

A long-duration transit habitat is not needed for an Ares mission until Ares IV, but it will begin testing in an uncrewed Ares III. Artemis II and III begin some of the testing required for building a Mars-ready transit habitat that can shelter crew for the months long journey to the red planet.[32] The transit habitat on Orion must provide life support, protect crew from radiation and serve as living quarters for the ten day journey. Vehicles created for Artemis IV and V+ will further develop the transit habitat for an eventual Mars mission with long duration tests conducted on the transit vehicles. This will be critical for the eventual human mission to Mars in Ares IV.

Entry / Landing System

The first Ares mission will require proven and reliable entry/landing systems. Given the exclusive use of Orion for Artemis I-III, little will be learned about the reentry profiles for the Mars capable vehicles. This will be fully tested in Artemis IV when the vehicle reenters Earth via a trans-Earth injection.[33] This system will need to be tested ahead of the first Ares mission to Mars.

30 Catherine E. Williams, “Artemis III: NASA’s First Human Mission to Lunar South Pole,” NASA, January 13, 2023, https://www.nasa.gov/missions/artemis/artemis-iii/.

31 Jeff Foust, “SpaceX Making Progress on Starship In-Space Refueling Technologies,” SpaceNews, April 27, 2024, https://spacenews.com/spacex-making-progress-on-starship-in-space-refueling-technologies/.

32 “Orion Spacecraft - NASA,” accessed May 8, 2025, https://www.nasa.gov/reference/orion-spacecraft/.

33 SpaceX. “Updates.” SpaceX. Accessed May 9, 2025. https://www.spacex.com/updates/.

Life Support and Habitat

Long-duration life support and habitats are not needed until Ares IV. However, materials for building habitats aim to be sent as soon as Ares II to prepare for human arrival. Some testing of life support and ground habitat will begin during Artemis III[34] and IV with one week on the moon with Artemis III and a longer stay for Artemis IV with unmanned monitoring of life support systems. However, future Artemis missions will be critical for long-duration habitat testing that will be needed[35] before the first Ares manned mission (Ares IV).

Power (Ground)

Ground power will be needed as soon as Ares I. While Artemis III and IV expand on already proven solar panels and batteries, it is still to be seen if solar can provide enough energy alone to support the energy demands for long-duration stays on Mars, especially during storm-like periods. Future Artemis missions should aim to explore the potential for small-scale fission technologies that can be transported to the Moon and eventually Mars.[36] However, solar panels and batteries should suffice for Ares I-IV.

Surface Mobility

Spacesuits[37] and basic surface mobility will be required for Ares IV, but early delivery of this machinery[38] in Ares II and III can help prep the Martian surface for human arrival and serve as testing for larger transport systems than current rovers. Artemis 3 will contain lunar spacesuits; however, no rover is currently planned for the Artemis I-IV missions. Artemis V+ missions should contain testing for critical pressurized and non-pressurized rovers that could be used on Mars.

34 NASA. "Orion Components." Last modified February 27, 2024. https://www.nasa.gov/reference/orion-components/.

35 Alexander A. Tikhomirov et al., "Biological Life Support Systems for a Mars Mission Planetary Base: Problems and Prospects," Advances in Space Research 40, no. 11 (2007): 1741–1745, https://doi.org/10.1016/j.asr.2006.11.009.

36 Ramin Skibba, "Mars Colonies Will Need Solar Power—and Nuclear Too," WIRED, May 5, 2022, https://www.wired.com/story/mars-solar-nuclear-power/.

37 NASA. "Spacesuits." Last modified February 27, 2024. https://www.nasa.gov/humans-in-space/astronauts/spacesuits/.

38 "NASA's Artemis III: First Human Mission to the Lunar South Pole." YouTube video, 3:45. Posted by NASA, March 15, 2025. https://www.youtube.com/watch?v=N0f-QkEVU7U.

In-Situ Resource Utilization (ISRU)

ISRU is a critical technology needed for Ares IV and will need a full proof of concept and validation in Ares III with testing in Ares II. Existing, unmanned, Mars missions plan for ISRU testing but larger scale machinery will be needed for a manned landing.[39] Artemis missions I-IV do not contain any ISRU but Artemis V+ missions should make this a major focus to ensure preparation for the Ares missions specifically for ice / water mining.[40]

Comms / Navigation

Ares I-IV will require communications that allow information sharing back to Earth to enable iteration of technologies for future missions. This can be done with existing high-gain antenna, but bandwidth and short, daily comms windows present challenges. Ares IV should aim to have an established Martian satellite web in place for human communications.[41] While Artemis I-IV do not build out this system and instead continue evolution of DTE comms and utilization of GNSS services,[42] Artemis V+ should aim to establish a lunar satellite web as a test for a Martian replica.

39 NASA. "Mars Oxygen In-Situ Resource Utilization Experiment (MOXIE)." https://www.nasa.gov/space-technology-mission-directorate/tdm/mars-oxygen-in-situ-resource-utilization-experiment-moxie/.

40 NASA, Add-on to Large-Scale Water Mining Operations on Mars to Screen for Introduced and Alien Life, January 4, 2024, https://www.nasa.gov/general/large-scale-water-mining-operations-on-mars/.

41 NASA. "The Mars Relay Network Connects Us to NASA's Martian Explorers." Last modified February 16, 2021. https://www.nasa.gov/centers-and-facilities/jpl/the-mars-relay-network-connects-us-to-nasas-martian-explorers/.

42 Katherine Schauer, "NASA Successfully Acquires GPS Signals on Moon," NASA, March 4, 2025, https://www.nasa.gov/directorates/somd/space-communications-navigation-program/nasa-successfully-acquires-gps-signals-on-moon/.

Technology Status

Development of the technologies needed for future Mars missions has already begun, but has it been directed to critical technologies? And how ready are they?

Launch and Propulsion

The launch sector has had the largest recent development through private sector competition. Across ULA, BlueOrigin, SpaceX, and NASA's SLS, there is significant capacity to take payloads to LEO. Appendix 1 compares the different launch options across companies. This is a relatively mature industry and existing NASA programs and contracts sufficiently manage development.

The next stage of launch development is increasing the capacity into LEO and trans-lunar injection orbit. This is represented by SpaceX's Starship and NASA's SLS Block 1B. Both rockets have experienced significant delays in development, pushing out Artemis timelines and raising questions about Mars timelines. Further, as SLS is phased out, development of SLS Block1B should cease. This creates a significant bottleneck in the Mars mission architecture around Starship.

Starship has yet to successfully complete a full flight, undertaking its ninth test and failure in May 2025.[43] Developed in 2019, original timelines had Starship ready in 2021, but this has proved to be an overestimation. SpaceX is still outwardly confident that Starship will be operational by the end of 2025, discussing plans for a 2026 uncrewed Mars mission.[44] With SpaceX's culture of rapid development, this ambitious goal may be possible. However, without a fully functioning prototype, the readiness for a Mars mission is at a TRL ~6-7.

NASA has done some preliminary investigation into nuclear propulsion. Nuclear thermal propulsion could significantly shorten Mars transit times, reducing crew exposure to deep space radiation, but remains at TRL 3 with no in-space test and uncertain budgetary prioritization.

43 "SpaceX," SpaceX, accessed May , 2025, http://www.spacex.com.

44 "Elon Musk Says First SpaceX Mission to Mars Will Launch next Year," March 15, 2025, https://www.bbc.com/news/articles/cx2g88y52y8o.

System	Function	Developer	TRL	Notes
Starship (Super Heavy + Ship)	Launch to LEO and TLI	SpaceX	6–7	Multiple tests flown; full mission profile unproven. Dependency for Artemis/ Mars.
Nuclear Thermal Propulsion	Faster interplanetary transit	NASA / DARPA	3	DARPA DRACO planned, no space test. Attractive but non-essential for early Mars mission.

Orbital Refueling

A critical element of Starship's large trans-lunar injection orbit capacity is its anticipated orbital refueling. This allows the Starship to launch into LEO and then be refueled by a second Starship "tanker" carrying excess fuel.[45] While some limited in-orbit propellant transfers have occurred (e.g., hydrazine transfers to ISS satellites), Starship's scale and complexity are unprecedented. Each Mars-bound Starship may require six to eight tanker launches for full refueling in LEO, compounding schedule and launch cadence challenges.[46] This LEO rendezvous is another ambitious goal SpaceX seeks to achieve before its intended 2026 flight.

System	Function	Developer	TRL	Notes
Starship-to-Starship Propellant Transfer	Enables TLI after LEO launch	SpaceX	4	Critical but untested; requires multiple launches and precision docking.

Transit Habitats

Transit habitats are the astronauts' home for the duration of the segments from the Earth-to-Moon or Earth-to-Mars. Critically, this module must protect provide life support, protect from radiation, and serve as living quarters for the mission duration.While there is commercial drive for LEO space stations, it is unlikely for this drive to extend to transit habitats in the medium-term.

The Orion spacecraft built by Lockheed Martin is set to take humans from Earth to the Moon in Artemis II. This successfully completed a full-scale test during the uncrewed Artemis I mission. One option for the Mars transit habitat is a modified Orion capsule, but there is a significant difference between the approximately 21-day Artemis II mission and the multi-year Mars transit journey.

45 "SpaceX."

46 "SpaceX."

Long-duration space missions on the ISS have provided data for potential Mars missions and allowed research into critical technologies including crew health and performance systems. While in transit, the crew must continue to exercise to prevent muscle atrophy. This is particularly important on a Mars mission where upon arrival crew will be needing to complete extended physical activity on the surface.

Radiation is of particular concern for missions beyond LEO. Research experiments on Orion for Artemis I sought to investigate the effect of the radiation trapped in the Van Allen Belts that are part of the Earth's magnetosphere.[47] More generally, the deep space radiation environment seen on missions to the Moon or Mars is significantly different from that experienced by the ISS in LEO.

The Orion spacecraft is a mature, tested craft that is ready to undertake Artemis II when delayed launch systems catch-up. For this lunar mission, it is at TRL 9.

However, it is unclear if the Orion capsule continues to be the right fit for a Mars mission. Instead, a commercially developed transit habitat could be considered. This would have the same requirements and concerns as the Orion capsule, but it would be extended for the longer-duration flight. A non-Orion transit habitat is not in development currently making it very early stage TRL ~ 3-4.

System	Function	Developer	TRL	Notes
Orion Capsule (for lunar transit)	Crew transit (Earth-Moon)	NASA / Lockheed Martin	9	Fully tested in Artemis I; ready for Artemis II. Too small for Mars.
Non-Orion Transit Habitat	Long-duration Mars transit	TBD (NASA or commercial)	3–4	No current design or prototype. Needs radiation shielding, autonomy, and life support.

Entry/Landing Systems

For the Artemis missions, the lunar landing system is developing from the Orion capsule and the SpaceX Human Landing System (HLS), the first of which is mature and the second is wholly untested. Re-entry to Earth's atmosphere for the Artemis missions uses Orion's heat shielding. On top of being a mature technology used throughout ISS crew missions, this system has been tested in Artemis I, making it TRL 9.

47 "Orion Spacecraft - NASA."

The HLS, however, is not established. SpaceX was awarded a development contract for this system, which is included in Artemis III to bring crew from the orbiting Orion spacecraft to the lunar surface and back.[48] SpaceX's HLS develops on Starship spacecraft and utilizes a retro-propulsion system to decelerate the craft by firing the engines towards the surface. While prior Mars missions have demonstrated different mature landing systems (such as hypersonic parachutes), these are unlikely to be able to scale to meet requirements due to mission architecture.[49] Thus, the HLS is utilizing a relatively untested system. The HLS will be a crewed system requiring a soft landing on lunar regolith, which adds an additional level of complexity to SpaceX's challenge. To make this system ready for Mars, Earth and lunar testing will both be critical to the rapid development cycles SpaceX operates within. NASA has not publicly identified contingency architectures should HLS face Artemis IV delays or underdeliver.

The HLS is an untested component that relies on an operational Starship before further testing can occur, sitting at a TRL ~ 4-5. NASA's reliance on Starship for launch and HLS introduces programmatic risk, as delays or setbacks from a single commercial partner could cascade across the Mars architecture.

System	Function	Developer	TRL	Notes
Orion Re-entry System	Earth atmospheric return	NASA / Lockheed	9	Tested in Artemis I and other missions.
SpaceX HLS	Lunar descent and ascent	SpaceX	4–5	Based on Starship; relies on retro-propulsion; no test yet.

Life Support and Habitat

Life support systems that will be critical for Mars surface habitats are likely to be based upon the incredibly mature ISS systems. This is the case for Orion. The systems that provide air revitalization, recycle waste, and control temperatures are all based on the heavily tested ISS systems. However, as mission durations increase and the spacecraft moves further from Earth, the importance of reducing resupply needs grows. Technology development to improve oxygen and water recovery,

48 "NASA, SpaceX Illustrate Key Moments of Artemis Lunar Lander Mission - NASA," November 20, 2024, https://www.nasa.gov/directorates/esdmd/artemis-campaign-development-division/human-landing-system-program/nasa-spacex-illustrate-key-moments-of-artemis-lunar-lander-mission/.

49 Ashley M Korzun and Karl T Edquist, "DEVELOPMENT STATUS OF POWERED DESCENT FOR HIGH-MASS MARS ENTRY, DESCENT, AND LANDING SYSTEMS," n.d., https://ntrs.nasa.gov/api/citations/20220008299/downloads/FAR_fullpaper_Korzun_vFINAL.pdf#:~:text=Table%202,storage%20or%20viable%20ISRU%20production.

reliably grow food, and improve radiation shielding will be essential to improving the life support and habitat systems.[50]

While there are mature elements, no Mars habitat hardware exists beyond concepts, TRL ~ 3-5.

System	Function	Developer	TRL	Notes
ISS-Derived Life Support (for Orion)	Atmosphere, water recycling	NASA / ESA	8–9	Mature but optimized for LEO and short duration.
Mars Surface Habitat	Long-duration surface habitation	TBD	3–5	Only concepts exist. Needs testing for autonomy, resupply independence, and shielding.

Power (Ground)

The NASA 2024 Moon-to-Mars architecture calls for primary fission power on Mars.[51] The rationale for this is that, while mature, solar arrays do not operate at night, cannot provide reliability during Martian storms, and are susceptible to dust accumulation. In contrast, NASA is pursuing a multi-tens-kilowatt nuclear fission reactor that can run constantly and tolerate the Martian dust. This is a step up from the mature radioisotope thermoelectric generators deployed on the Curiosity and Perseverance rovers that generate hundreds of watts. At the multi-tens-kilowatt level this technology is still at a TRL ~ 3-4, with a demonstration planned for 2025.

System	Function	Developer	TRL	Notes
Fission Surface Power	Continuous surface power	NASA	3–4	Demo planned by 2025. Needed for night/dust resilience on Mars.
Solar Arrays (baseline)	Power generation	NASA / commercial	8–9	Used on ISS and lunar landers; vulnerable to dust accumulation on Mars.

Surface Mobility

Surface Mobility allows crew to leave the lander and explore the Lunar or Martian surface. There are two major technologies in this area: spacesuits and rovers.

50 NASA. "Orion Components." Last modified February 27, 2024. https://www.nasa.gov/reference/orion-components/.

51 NASA, "2024 Moon to Mars Architecture Concept Review," accessed May 9, 2025, https://www.nasa.gov/wp-content/uploads/2024/12/acr24-mars-surface-power-decision.pdf.

Axiom has been contracted to develop spacesuit for Artemis and initial testing occurred in 2024.[52] Spacesuit technology is reasonably mature, but Axiom has focused on increasing joint mobility for crew.[53] These improvements will directly translate to future Mars missions.[54]

Rovers allow crew to extend their field of exploration and research. NASA has issued a competitive program for unpressurized lunar rover development, Lunar Terrain Vehicle (LTV) program). In 2024, three companies were selected to undertake feasibility studies: Intuitive Machines, Lunar Outpost, and Astrolab.[55] In addition to the unpressurized rovers, NASA has signed a joint agreement with JAXA to develop a pressurized lunar rover to further extend exploration range.[56] These are still in the design stage, making the TRL ~ 2-3.

Significant work will need to occur in order to have surface mobility prepared for testing during the Artemis 3 mission. While this is not the current bottleneck, if Starship meets its proposed timelines for HLS, the LTV may become the bottleneck for the mission.

Many of the key challenges present for crewed lunar rovers transfer to Mars, including dust mitigation, autonomous navigation, and reliable power. Thus, it is understandable that NASA would wait to undertake a serious feasibility study for Mars until initial testing has occurred for the Moon, with a current TRL ~1-2.

System	Function	Developer	TRL	Notes
Exploration space suit	Protecting crew outside craft	Axiom	~7	Initial Earth testing begun for Artemis.
LTV – Unpressurized Rover (Lunar)	Local crew mobility	Intuitive Machines, Astrolab, Lunar Outpost	2–3	In feasibility/design stage.
JAXA/NASA Pressurized Rover	Extended lunar mobility	JAXA + Toyota	2–3	Early co-development phase.
Mars Crewed Rover	Martian surface exploration	TBD	1–2	No defined program; would benefit from lunar data.

52 "Axiom Space Tests Lunar Spacesuit at NASA's Johnson Space Center - NASA," accessed May 9, 2025, https://www.nasa.gov/image-article/axiom-space-tests-lunar-spacesuit-at-nasas-johnson-space-center/.

53 "Axiom Suit — Axiom Space," accessed May 9, 2025, https://www.axiomspace.com/axiom-suit.

54 "Spacesuits - NASA," accessed May 9, 2025, https://www.nasa.gov/humans-in-space/astronauts/spacesuits/.

55 "NASA Moves Forward with Development of LTV | APPEL Knowledge Services," post, April 30, 2024, https://appel.nasa.gov/2024/04/30/nasa-moves-forward-with-development-of-ltv/.

56 "NASA, Japan Advance Space Cooperation, Sign Agreement for Lunar Rover - NASA," accessed May 9, 2025, https://www.nasa.gov/news-release/nasa-japan-advance-space-cooperation-sign-agreement-for-lunar-rover/.

In-Situ Resource Utilization (ISRU)

ISRU is a tool to reduce the payload carried on a Mars mission by using local Martian resources for life-support, propellent, or construction instead of bringing that material from Earth. This makes ISRU a non-critical component of the minimum viable product, but a potential way to reduce loads and extend future Mars missions. Lunar ISRU is largely non-transferrable for Mars missions due to major differences in Lunar and Martian regolith and atmosphere.

Mars ISRU of oxygen is somewhat mature, with a prototype (MOXIE) being sent to Mars on the Perseverance Rover in 2020.[57] This system produced O2 from the Martian CO_2 atmosphere. It was a small proof-of-concept demonstration and a module approximately 100x would be required for a life support system. It is a promising demonstration of the technology, with a TRL ~ 6-7.

Lunar water ice mining is a parallel ISRU capability under early development. NASA's VIPER rover (Volatiles Investigating Polar Exploration Rover), previously scheduled for a 2024 launch, was expected to explore the Moon's south pole to identify and map subsurface water ice deposits.[58] While VIPER has since been canceled, interest remains high in lunar ice extraction for life support and propellant generation (via electrolysis into hydrogen and oxygen). However, lunar ice is contained in fine grains intermixed with lunar regolith. Ice deposits are located in permanently shadowed regions, requiring specialized thermal mining and extraction systems. Lunar water mining remains at a low TRL ~2–3 as no demonstration has yet been conducted in-situ.

Importantly, the technologies developed for lunar water ice mining are not directly transferrable to Mars. Mars ice tends to be concentrated in thick subsurface layers or polar caps. Unlike the Moon, Mars offers a thin atmosphere and seasonal variation, which affects sublimation and mechanical properties. These systems, designed for lunar regolith excavation and ice handling, are unlikely to be transferrable for Martian operations.

57 "This Is One Mars Rover With MOXIE - NASA Science," April 5, 2019, https://science.nasa.gov/resource/this-is-one-mars-rover-with-moxie/.

58 "VIPER - NASA Science," May 13, 2023, https://science.nasa.gov/mission/viper/.

System	Function	Developer	TRL	Notes
MOXIE – Oxygen from CO_2	Life support / propellant	NASA	6–7	Flown on Perseverance rover; proof of concept, small scale.
Lunar Water Ice Mining	H_2O for life support/fuel	TBD	2–3	No in-situ demo; VIPER cancelled; requires cryogenic extraction in shadowed regions; not Mars transferrable.
Martian Water Ice Mining	H_2O for life support/fuel	TBD	1–2	Conceptual only; no mission has demonstrated water extraction on Mars.

Comms/Navigation

Lunar and Martian missions utilize NASA's established Deep Space Network (DSN) for command, telemetry and navigation. While the DSN operates Earth based antenna, the Mars Relay Network (MRN) is an international constellation of satellites orbiting Mars to facilitate this communications path on the other end.[59] This is how NASA communicates with and controls its existing Mars rovers. Improvements to the DSN for Artemis missions would inherently benefit a Mars mission as well. However, the most critical improvement needed for a Mars mission would need to be to both DSN and MRN, increasing capacity as the scale of Mars missions is set to rapidly increase.

System	Function	Developer	TRL	Notes
Deep Space Network (DSN) / Mars Relay Network (MRN)	Comms and telemetry	NASA / ESA	9	Operational and mature; will need scaling or redundancy for crewed Mars missions.

59 "Mars Relay Network - NASA Science," February 17, 2025, https://science.nasa.gov/mars/mars-relay-network/.

Recommendations

Recommendation 1: Redirect focus to more cost effective reusable commercial systems

Starting with Artemis IV, NASA should transition to reusable commercial systems due to their cost-effectiveness and high-performance. As these systems have integrated launch, landing, and return capabilities this would provide additional benefits by reducing mission complexity between SLS, Orion, and HLS.

Recommendation 2: Move Gateway capabilities and tests to end-to-end vehicles

Gateway enables lunar missions but does not uniquely contribute to Mars missions. Instead, Mars technology demonstrations (e.g. life-support, radiation testing) would be better served conducted on end-to-end vehicles which will be utilising these technologies on long-duration Mars missions. Shifting focus from Gateway to these craft will better serve accelerated timelines proposed in this paper.

Recommendation 3: Use Artemis as a technology demonstration for Mars

Use Artemis IV–VII missions as technology demonstration platforms for Mars-relevant systems. Flight demonstrations should be prioritized for technologies that are not yet at TRL 6, including:

- Orbital refueling: Validate Starship-to-Starship cryogenic fuel transfer in LEO.
- Transit habitats: Begin uncrewed cislunar habitat missions to test radiation protection and closed-loop life support.
- Surface power: Accelerate development and testing of compact fission surface reactors, with a target demonstration on the Moon or cislunar orbit by 2027.
- ISRU: Advance and scale oxygen and methane production systems based on MOXIE data.
- Mars EDL systems: Invest in terrain-relative navigation, retropropulsion testing, and hazard avoidance under lunar analog conditions.

Recommendation 4: Establish a Phased Ares Mission Built Around Technology Readiness

In parallel with ongoing Artemis missions, NASA should launch a dedicated, four-mission Mars program designed to directly leverage maturing technologies from Artemis and provide a structured pathway toward a crewed Mars landing. Each Ares mission should build upon the flight demonstrations and operational knowledge gained during Artemis IV–VII, translating those into Mars-specific systems, timelines, and design decisions. The Ares sequence should follow a timeline driven by technology readiness:

1. Ares I: Mars Entry, Descent & Landing (EDL) Demonstration and Site Reconnaissance (2028–2029)
    - Demonstrates: Supersonic retropropulsion, Mars aerobraking, LEO refueling
    - Delivers: EDL data, terrain and ice site reconnaissance
    - Infrastructure: Basic solar power and direct-to-Earth comms
2. Ares II: Round-Trip Flight Validation and Infrastructure Deployment (2031)
    - Demonstrates: In-space refueling at scale, Mars return capability
    - Delivers: Sabatier reactors, ice detection systems, solar + fission power, surface cargo habitats
    - Infrastructure: Mars relay comms, autonomous terrain scouting
3. Ares III: Base Build-Up and System Redundancy (2033)
    - Demonstrates: High-frequency cargo delivery, automated return flights
    - Delivers: Life support redundancy, pressurized mobility, ISRU scale-up (O_2/CH_4), surface power grid
    - Infrastructure: Simulated long-duration crew systems, logistics automation
4. Ares IV: First Human Mars Landing (2035)
    - Demonstrates: Human-rated Mars EDL, conjunction-class stay (~500 days)
    - Delivers: Fully integrated human operations with habitat, mobility, and ISRU
    - Infrastructure: Earth-Mars data uplinks, deep-space transit habitat

Further Considerations:

Public policy development will be an essential component of increased civil space activity. This could include:

- Codifying a dual-path Moon-to-Mars architecture in a revised NASA Authorization Act, formally linking Artemis and Ares objectives.
- Setting clear expectations for phasing out SLS and Orion after Artemis III to improve fiscal sustainability and focus on reusable systems.
- Increasing transparency around TRL tracking, schedule risks, and mission dependencies to support public understanding and congressional oversight.

The US led Artemis accords are an important element of the Artemis program but looking beyond the Moon further consideration could be given to the legal framework necessary for Mars. This could include:

- Building on the Artemis Accords to establish an international consensus on Mars resource use and ISRU protocols, particularly for fuel and oxygen production.
- Clarifying legal roles and responsibilities for surface infrastructure ownership and access, especially in missions involving commercial and international partners.
- Advancing a U.S. legal interpretation of the Outer Space Treaty that enables responsible commercial use of in-situ resources consistent with peaceful exploration

Appendix

Figure 1: Comparison of different launch vehicles considered for Artemis.[60]

	Vulcan Centaur with Heavy Booster	New Glenn	Falcon Heavy	SLS Block 1	SLS Block 1B	Starship with Super Heavy Booster
Vehicle Maker	United Launch Alliance	Blue Origin	SpaceX	NASA	NASA	SpaceX
Upmass to Low Earth Orbit	27 metric tons	45 metric tons	64 metric tons	70 metric tons	105 metric tons	100+ metric tons[b]
Upmass to Trans-Lunar Injection	12 metric tons	See note[a]	16 metric tons	27 metric tons	37 metric tons	100+ metric tons[b]
Planned Features	Designed for affordability	First Stage reusable minimum of 25 times; human rated	Partially reusable; not human rated	Capsule partially reusable; human rated	Capsule partially reusable; human rated	Fully reusable; human rated
Anticipated Launch Readiness Date	2022	See note[a]	Operational	Late 2021	2026	Late 2021

Source: NASA OIG depiction of Agency program and company information.

[a] In response to a NASA OIG request, Blue Origin declined to provide information about the New Glenn rocket. Data displayed in the table is from publicly available sources and has not been confirmed with the company.
[b] Starship upmass capabilities to low Earth orbit and trans-lunar injection require multiple launches and in-space refueling.

60 "NASA'S MANAGEMENT OF THE ARTEMIS MISSIONS - November 15, 2021," November 15, 2021, https://oig.nasa.gov/wp-content/uploads/2024/02/IG-22-003.pdf.

Figure 2: Chronological Order of Ares + Artemis Missions

Technology	Artemis II as planned (2026)	Artemis III as planned (2027)	New Artemis IV (2028)	Ares 1: *EDL Demo & Site Recon (2028/2029)*	Follow-On Artemis Missions (2029-2034)	Ares 2: *Return Test + Core Systems (2031)*	Ares 3: *Base Build-Up & Redundancy (2033)*	Ares 4: *First Human Landing (2035)*
Launch & Propulsion	Launch SLS and travel via Orion to orbit moon and return to Earth	Launch SLS and travel via Orion to HLS.	Launch new craft and travel directly to Moon	Launch 1 spaceship to Mars	Launch new crafts and travel directly to Moon	Multiple spaceships incl. 1 round-trip return	Large fleet of spaceship launches (cargo, demo return flights)	Crewed Starship to/ from Mars (conjunction)
Orbital Refueling	None	HLS orbital refueling in LEO	Likely required prior to landing on Moon	LEO refueling test	Frequent LEO refueling for large payload delivery to Moon	Multiple tankers refuel return-capable spaceship	Operational refueling scale-up	Required for both outbound & return legs
Transit Habitat	Four pilots for 10 days in Orion	Two pilots for 30 days	Unmanned monitoring of life support systems	None	Long-duration testing in LEO or lunar orbit	Limited uncrewed spaceship cabin ops	Optional cargo transit testing, crew test	Human-rated systems for 6–9 month trip
Entry / Landing System	Orion reentry	HLS landing on Moon, Orion reentry to Earth	Craft lands on the moon; Earth reentry	Supersonic retro-propulsion demo	Capability and endurance testing	Multiple cargo landings + return to Earth	More spaceship landings validate reusability	Human Starship landing (EDL proven at scale)
Life Support & Habitat	None	Approx. 1 week on Moon with HLS as habitat	Unmanned monitoring of life support systems	None	Long-duration habitat testing	Cargo habitats delivered for surface prep	Multiple units; redundancy for human safety	Full-time human use of habitat system
Power (Ground)	None	Basic solar and batteries in HLS	Solar and batteries	Basic solar for lander ops	High efficiency solar power + fission unit test	Solar arrays + test small fission unit	Grid expansion; backup units	Continuous ops (ISRU, heating, life support)
Surface Mobility	None	Spacesuits	None	None	Long duration surface transport vehicles with life support	Scout rovers for terrain, ice survey	Pressurized long duration crew vehicles, logistics bots	Full surface mobility for crew
ISRU	None	Identify and sample water ice	None	None	Begin pilot experiments to extract useful resources (water, fuel, etc.,)	Sabatier reactor + ice detection systems	Fuel production (O_2/CH_4) for return, water production	Used for fuel + life support during stay
Comms / Navigation	Direct-to-Earth Commun-ications	Direct-to-Earth Commun-ications	Direct-to-Earth Commun-ications	Direct-to-Earth Commun-ications	Lunar relay satellite net	Mars relay sats deployed for ops	Full comms net	Human ops coordination; Earth data uplink

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