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Evaluation of a Human Mission to Mars by 2033

Evan Linck
Keith W. Crane
Brian L. Zuckerman
Benjamin A. Corbin
Roger M. Myers
Sharon R. Williams
Sara A. Carioscia
Rodolfo Garcia
Bhavya Lal

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IDA SCIENCE & TECHNOLOGY POLICY INSTITUTE
1701 Pennsylvania Ave., NW, Suite 500 Washington, DC 20006-5805

About This Publication

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For More Information

Bhavya Lal, Project Leader
blal@ida.org, 202-419-3724

Mark J. Lewis, Director, IDA Science and Technology Policy Institute
mjlewis@ida.org, 202-419-5491

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Executive Summary

The NASA Transition Authorization Act of 2017 mandated that NASA "develop a human exploration roadmap…to expand human presence beyond low-Earth orbit to the surface of Mars and beyond, considering potential interim destinations such as cislunar space and the moons of Mars (U.S. Congress 2017, Section 432(b))." In response, NASA presented its current and notional plans for human space exploration in the *National Space Exploration Campaign Report* (Campaign Report), released September 24, 2018. In Section 435 of this Act, Congress also mandated that NASA contract with an independent entity to conduct a study that includes:

- The technical development, test, fielding, and operations plan using the Space Launch System (SLS), Orion, and other systems to successfully launch such a Mars human spaceflight mission by 2033
- An annual budget profile, including cost estimates, for the technical development, test, fielding, and operations plan to carry out a Mars human spaceflight mission by 2033
- A comparison of the annual budget profile to the 5 year budget profile contained in the President's Budget Request (PBR) for FY 2017 under 31 U.S.C. §1105

In August 2017, NASA asked the IDA Science and Technology Policy Institute (STPI) to conduct this independent assessment, specifically requesting that STPI use NASA's current and notional plans for human exploration as the basis for the spaceflight systems and timelines presented in this study. STPI produced a draft report in December of 2017. Because NASA's exploration program was refocused in 2018, STPI was asked to update the earlier report in September 2018. Additional research was conducted between September 2018 and January 2019. This report is the result of those efforts.

In its assessment, STPI drew on information from many sources, including the Campaign Report; discussions with NASA personnel and individuals from the space industry; peer-reviewed scientific literature; and other publicly available documents on NASA's current and notional plans for human space exploration, including the FY 2019 PBR and presentations to the NASA Advisory Council and its committees. STPI also utilized its own experts' insights on determinants and patterns of technology, scheduling, mission architecture, and cost risks for large, complicated projects incorporating new technologies.

An Overview of NASA’s Human Spaceflight Plans

In the Campaign Report, NASA has proposed plans for human spaceflight between now and the end of the 2020s. We use these plans as the point of departure to develop a schedule for an orbital human mission to Mars. Under current and notional NASA plans, the Gateway, a small human-tended station in orbit around the Moon, would be assembled in space between 2023 and 2026 for the purpose of providing a platform to study the lunar environment, gain deep space operational experience, and stage missions to the Moon and Mars. Human missions to the Gateway are to be launched using the SLS and the Orion Multi-Purpose Crew Vehicle (Orion). While not explicitly noted in current NASA plans or budget requests, the next step for a human orbital mission to Mars would be the formulation, design, fabrication, assembly, integration, and testing of the Deep Space Transport (DST), a vehicle that will take a crew to Mars orbit. After several years of in-space testing, the DST will depart on a 1,100-day crewed mission to Mars orbit.

Assessing Technology

Due to long development programs and ongoing testing, SLS and Orion present low technology risks to a Mars orbital mission.[1] Overall, the Gateway presents medium technology risk because certain technologies (e.g., xenon refueling and autonomous environmental monitoring) have not been previously demonstrated at the scale required by the Gateway. If additional modules are added, or mission requirements expand, the Gateway would face higher technology integration risk, especially for power, propulsion, and life support systems originally sized for a small Gateway. Integrating and testing Gateway elements, whether at its current scale or larger, face medium technology risk.

The DST requires several medium and high-risk technologies. Notably, an Environmental Control and Life Support System (ECLSS) that meets the performance and reliability requirements of the DST is currently at a low technology readiness level (TRL), although NASA plans to test an ECLSS with high oxygen reclamation rates on the ISS starting in 2022. Scaling systems from the Gateway (e.g., 500 kW solar electric propulsion system and reusable in-space engines) may be difficult, and thus presents a medium technology risk. Technologies to transfer cryogenic propellants and prevent unacceptable boil-off losses over long periods of time have also not yet been demonstrated at the scales needed for the DST and present a high risk. Integrating each system into a single bus would likely be high risk because a small change to one system could require a series of changes to the rest of the spacecraft due to the scale and interdependent nature of DST systems. Notional plans for a human mission to Mars rely on several other medium- and high-risk technologies (e.g., space suits suitable for repairs in deep space) to reach completion.

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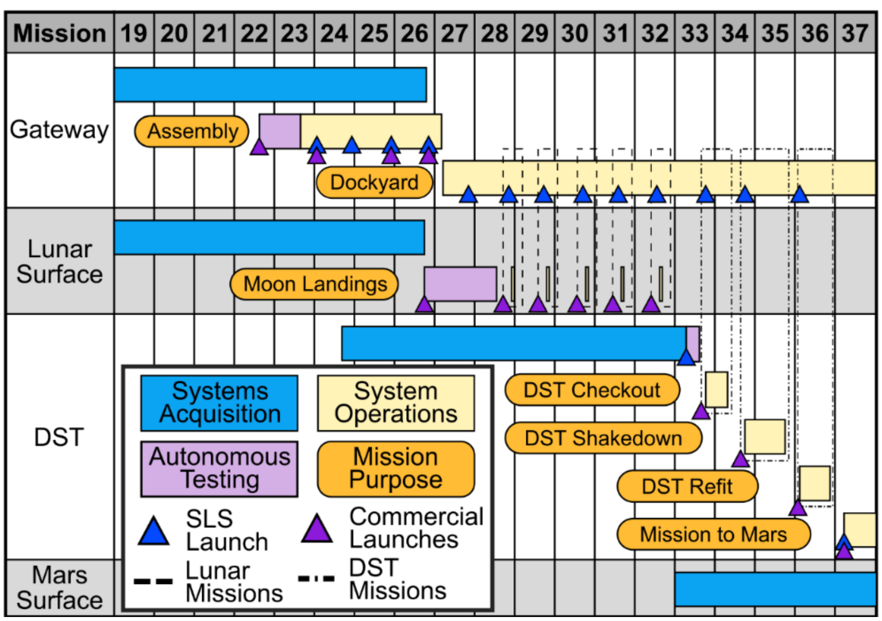
[1] For this study, STPI adopted the standard definition of risk as the severity of an event’s consequences combined with the event’s likelihood of occurrence.

Assessing Schedule

Under NASA's current and notional plans, four complex elements—SLS, Orion, Gateway, and the DST—need to be developed and completed to launch a human mission to orbit Mars. These technology developments would occur while NASA also designs and launches lunar landers and human astronauts to the Moon's surface. Figure ES-1 depicts a notional schedule for an orbital crewed mission to Mars orbit. We find that even without budget constraints, a Mars 2033 orbital mission cannot be realistically scheduled under NASA's current and notional plans. *Our analysis suggests that a Mars orbital mission could be carried out no earlier than the 2037 orbital window without accepting large technology development, schedule delay, cost overrun, and budget shortfall risks.* Further budget shortfalls or delays in the construction or testing of the DST would likely require the mission to depart for Mars in 2039 at the earliest.

The schedule developed in this report rests upon two critical assumptions based on the Campaign Report and discussions with NASA personnel. First, that NASA will choose the architecture of a human Mars orbital mission and begin systems development in 2024, which drives the development cycle of DST. Second, that there will be no more than one human mission to the Gateway annually, either to work aboard the Gateway, operate the DST, or to transfer to the lunar surface, which requires NASA to make trade-offs between focusing on lunar landings and preparing the DST for the mission to Mars.



Note: "Assembly" refers to the four missions dedicated to assembling the Gateway in lunar orbit; "dockyard" refers to the use of the Gateway as a staging ground for lunar and DST missions; the "DST checkout" is a mission to test and complete fabrication of the DST while docked at the Gateway; the "DST Shakedown" is a 1-year test flight of the DST in cislunar space; the "DST Refit" is a mission to refurbish the DST between the shakedown and the mission to Mars orbit.

Figure ES-1. Notional Schedule for Human Spaceflight through 2037

Assessing Costs

Under the assumption that the orbital mission to Mars would launch during the 2037 window, STPI constructed a set of cost estimates covering the full set of human space exploration activities over the 19-year period between FY 2019 and FY 2037. STPI estimates that the total cost for the development and operation of the core architectural elements for a human mission to Mars orbit (SLS, Orion, the Gateway, and the DST) between FY 2019 and FY 2037 may be up to $83 billion in FY 2017 dollars, including 10 to 30 percent reserves, but not including possible overruns. Including the costs incurred during the orbital mission through 2040, the total estimated cost of a human mission to Mars orbit is $87 billion in FY 2017 dollars, which is shown in Table ES-1.

Given that NASA's investment in SLS, Orion, and the Gateway will continue with or without the orbital mission to Mars, the additional cost beyond these elements, of just the orbital mission to Mars, is $45 billion in FY 2017 dollars, which includes the costs of SLS launches, Orion capsules, the DST and its supplies, and ground support during DST missions.

Although lunar landers, Mars surface systems, and other human spaceflight costs are not part of Mars orbital mission costs, budgets need to account for the spending. As shown in Table ES-2, our total estimated cost for human spaceflight from FY 2019 through FY 2037 runs $184 billion FY 2017 dollars.

Table ES-1. Cost Estimates (in billions of FY17 dollars) for Orbital Mars Mission

System	Costs through FY 2018	Projected System Costs (2019 onward)	Total System Costs
SLS	15.9	17.8	33.6
Exploration Ground Systems	3.0	2.7	5.7
Orion	14.9	10.7	25.6
Gateway		6.6	6.6
DST		29.2	29.2
Exploration Ground Systems Operations		16.2	16.2
Subtotal Orbital Mission to Mars through 2037	**33.7**	**83.2**	**116.9**
Cost associated with Mars Orbital Mission 2038–2040		3.7	3.7
Orbital Mission to Mars Total	**33.7**	**86.9**	**120.6**

Note: "SLS" and "Orion" lines include the costs of system development (including SLS Block 2 development) as well as the cost of launches associated with Gateway construction and the DST/Mars orbital mission), but not the SLS and Orion missions associated with lunar landings. "Costs associated with Orbital Mission 2038–2040" includes costs related to the SLS and Orion used for the return mission from the

DST and exploration ground system operations incurred between 2038 and the end of the orbital mission in 2040. Columns may not sum to the total listed due to rounding.

Table ES-2. Cost Estimates (in billions of FY17 dollars) for Exploration Systems through 2037

System	Costs through FY 2018	Projected System Costs (2019 onward)	Total System Costs
Orbital Mission to Mars Costs through 2037	33.7	83.2	116.9
Lunar landings		20.0	20.0
Mars Surface Systems		24.6	24.6
Other Human Spaceflight		55.9	55.9
Human Spaceflight Total	**33.7**	**183.6**	**217.4**

Note: Other Human Spaceflight includes costs associated with the ISS, low Earth orbit operations, human health research, other commercial lunar operations, and other technology development. Columns may not sum to the total listed due to rounding.

Mapping Costs to Estimated Budget

NASA was appropriated $20.7 billion for FY 2018 ($20.4 billion in FY 2017 dollars), of which approximately half was devoted to human spaceflight. If NASA continues to receive this amount annually—adjusted to account for inflation—between FY 2019 and FY 2037, it would have a cumulative $192.7 billion in FY 2017 dollars at its disposal for human spaceflight. If NASA were to receive a budget increase commensurate with annual real U.S. gross domestic product (GDP) growth of an anticipated 1.9 percent, available funds for human spaceflight over the 19-year period could be $233.8 billion in FY 2017 dollars, assuming that the share of the NASA budget devoted to human space exploration remains constant.

Comparing these estimates of the costs of systems needed for Mars and lunar exploration to prospective NASA budgets for human space exploration, we find aggregate funding under a flat budget scenario greater than aggregate costs ($184 billion, as shown in Table ES-2). If the human space exploration budget increases at the rate of real GDP growth, there may be sufficient funding for additional programs (e.g., more lunar landings, development of nuclear propulsion), or to mitigate the impact of cost overruns.

We compared annualized cost estimates associated with a human mission to Mars and the Administration's budget request, from FY 2019 to FY 2023. *Figure ES-2 shows that under flat budgets (blue dotted line), a 2037 start date for a mission to Mars is feasible; however, cost peaks will require activities, such as lunar landings, to be rescheduled to ensure that annual appropriations match development costs, which could have implications for the Mars orbital mission launch date. If lunar landings are a priority in the 2030s, construction of the DST could be delayed by 2 years, which would push the* *orbital mission to Mars to 2039. Under a budget that matches real growth (red dashed line), a mission to Mars is feasible in 2037 given NASA's current and notional plans. In this scenario, budgets always exceed expected costs by $1–6 billion FY 2017 dollars annually, allowing for additional exploration programs, especially after the peak cost years of the DST in the early 2030s.*

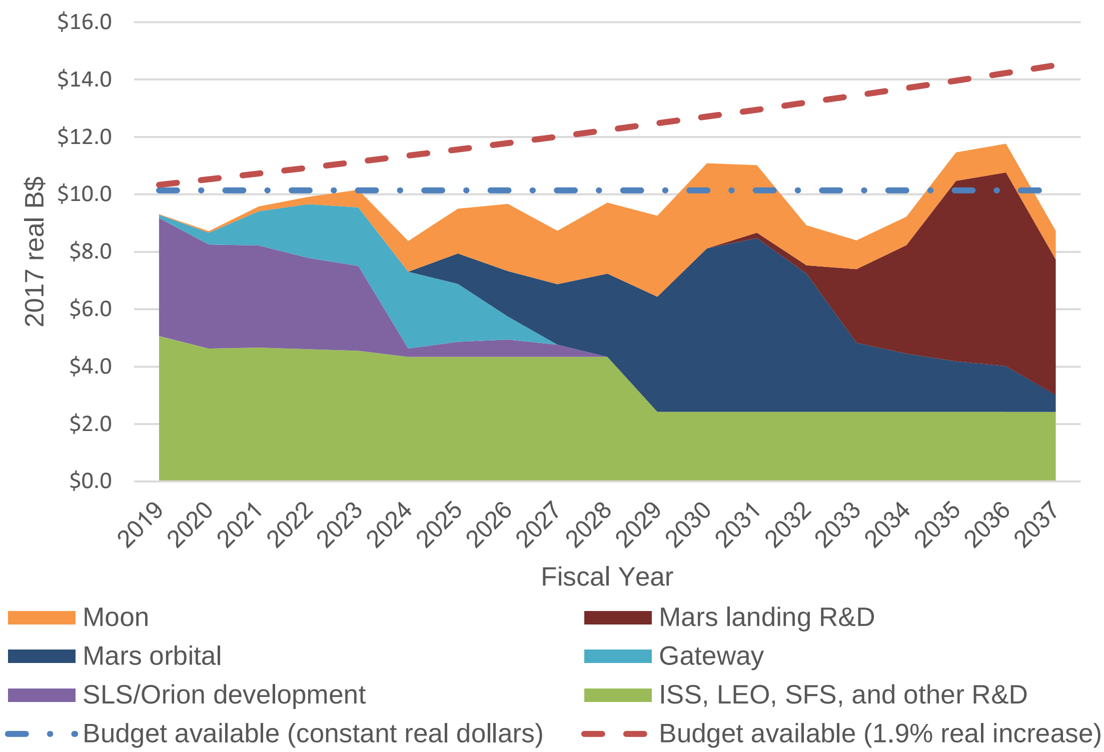


Figure ES-2. Comparing STPI-Estimated Costs of Human Exploration Activities with Budget Projections on Annual Basis

Assessing Risks to Human Health

Discussions with NASA personnel and a review of internal NASA planning documents and academic literature reveals that the understanding of human health risks associated with a 1,100-day human orbital mission to Mars is limited. Uncertainties remain with respect to threats to human health on an orbital mission to Mars that may not be fully understood prior to the mission given NASA's current and notional plans for ground-based research, ISS launches, Gateway and lunar surface operations, as astronauts would spend only short time periods in relevant environments. Additionally, the one-year DST shakedown cruise would occur so late that incorporating changes in design to mitigate risks based on information from the shakedown cruise would greatly increase schedule and cost risk for the mission to Mars orbit.

We found that NASA's current Human Research Program Integrated Research Plan to study human health risks associated with long-duration deep space spaceflight lacks sufficient detail in both evidence and strategy to justify the predicted timeline to develop risk mitigation strategies, or even estimate a realistic cost to retire the risks. Further, the document does not present a unified plan to prioritize NASA's approach to filling in gaps in knowledge, especially on the combined effects of radiation, low-or-micro-gravity, and isolation on astronauts. Accordingly, NASA's current approach to studying human health in deep space presents high risks to astronauts on a three-year mission to Mars.

Overall Assessment of a Human Mission to Mars

NASA's current plans call for parallel progress building a lunar infrastructure, while simultaneously developing a host of new deep space technologies, new and complex system-level capabilities, and new acquisition and institutional relationships. The Campaign Report, used as the basis of this report, contemplates no dramatic new funding. With such ambitious content and fixed funding, the only remaining variable is schedule.

STPI found that a 2033 departure date for a Mars orbital mission is infeasible under all budget scenarios and technology development and testing schedules, given NASA's current and notional plans. 2035 may be possible under budgets that match 1.9 percent real growth, but carries high risks of schedule delays due to complex technology development, testing, and fabrication schedules for the DST; may require reducing the scope of lunar missions; and reduces NASA's ability to mitigate risks to human health. We find that 2037 is the earliest the DST could feasibly depart for Mars assuming a small budget increase or smoothing budgets over two time periods in the 2030s, with 2039 being a more realistic timeframe if there are delays or budget shortfalls affecting the acquisition or testing of the DST.

Contents

1. Introduction

A. Purpose

Section 435 of the National Aeronautics and Space Administration (NASA) Transition Authorization Act of 2017 mandated NASA to contract with an independent entity to assess the technologies and the scheduling, costs, and budget profiles that would be associated with a human spaceflight mission to Mars to be launched in 2033.[2] NASA requested the Institute for Defense Analyses (IDA) Science and Technology Policy Institute (STPI) to conduct this assessment, and use NASA's current and notional plans for human spaceflight as the basis of the evaluation.

In this report, STPI provides an evaluation of the risks of such a mission associated with astronaut health, technologies, schedule, and cost. To assess the feasibility of launching an orbital human mission to Mars by 2033, the report constructs a likely timeline for such a mission based on NASA's proposed activities and schedules for human spaceflight systems, NASA standard operating procedures, and likely future NASA budgets. The report also maps anticipated annual costs against anticipated budgets to assess the feasibility of potential timelines.

B. Current U.S. Plans for Human Spaceflight to the Moon and Mars

The National Space Council (NSpC) and NASA have released several recent documents that elucidate U.S. plans for human spaceflight. We draw on these documents here to describe current and notional U.S. plans for human spaceflight that would lead to a mission to Mars orbit.

1. NASA's National Space Exploration Campaign

In September 2018, NASA released *The National Space Exploration Campaign Report* (Campaign Report), a high-level strategy document that establishes a spaceflight program for future human exploration of the Moon and, later, Mars. The Campaign Report responds to Space Policy Directive-1 (SPD-1) signed on December 11, 2017 (Trump 2017). In SPD-1, the President directed the NASA Administrator "to lead an innovative and sustainable program of exploration with commercial and international partners to enable human expansion across the solar system and to bring back to Earth new knowledge and opportunities. Beginning with missions beyond low Earth orbit, the United States will

2 Appendix A provides the full scope of the congressional mandate.

lead the return of humans to the Moon for long-term exploration and utilization, followed by human missions to Mars and other destinations." (Trump 2017).

Although the Campaign Report focuses on first conducting missions to the Moon, some of these missions are expected to be designed to enable human missions to Mars. To prepare for missions to Mars, the United States plans to transition human spaceflight activities in low Earth orbit (LEO) to commercial operators, put in place capabilities to support lunar surface operations and facilitate missions to Mars, return U.S. astronauts to the surface of the Moon, and demonstrate on the Moon the capabilities required for landing humans on Mars (NASA 2018a). To achieve these goals, NASA plans to construct a human-tended space station—the Gateway—that will orbit the Moon, and be used as a launching and return point for lunar landers as well as for elements of future Mars missions. The lunar surface will serve as a training ground and technology demonstration test site to prepare for future human missions to Mars.

The Campaign Report provides timelines for critical decisions and milestones related to human exploration of the Moon and Mars, including a human mission to the surface of the Moon by the end of the 2020s. Especially relevant to this evaluation, the report indicates that NASA will make decisions on the architecture for a human Mars orbital mission and the initial development of associated systems in 2024. NASA will determine the set of technologies in which it will invest and the timeline required for humans to land on the surface of Mars after 2024.

2. NASA's Notional Plans for a Human Mission to Mars

In addition to the Campaign report, NASA has presented a number of briefings to the public and the NASA Advisory Council regarding plans for a human mission to Mars. Below we draw on these briefings and several conversations with NASA officials about tentative plans for missions to Mars.

These plans set forth the following steps for human missions to Mars: (1) testing of advanced spaceflight technologies on the International Space Station (ISS); (2) cislunar flight testing of the Space Launch System (SLS) and the Orion Multi-Purpose Crew Vehicle (Orion); (3) construction and operation of the Gateway; (4) construction of a Deep Space Transport (DST) and in-space testing of the vehicle while docked to the Gateway during a "checkout mission"; (5) testing of the DST on a year-long flight beyond the Earth-Moon system, referred to as the "shakedown cruise"; and (6) a human orbital trip to Mars in the 2030s; followed by (7) human landings on the surface of Mars in the 2040s (Connolly 2017). We adopt these general steps as the basis of our schedule leading to a human orbital trip to Mars.

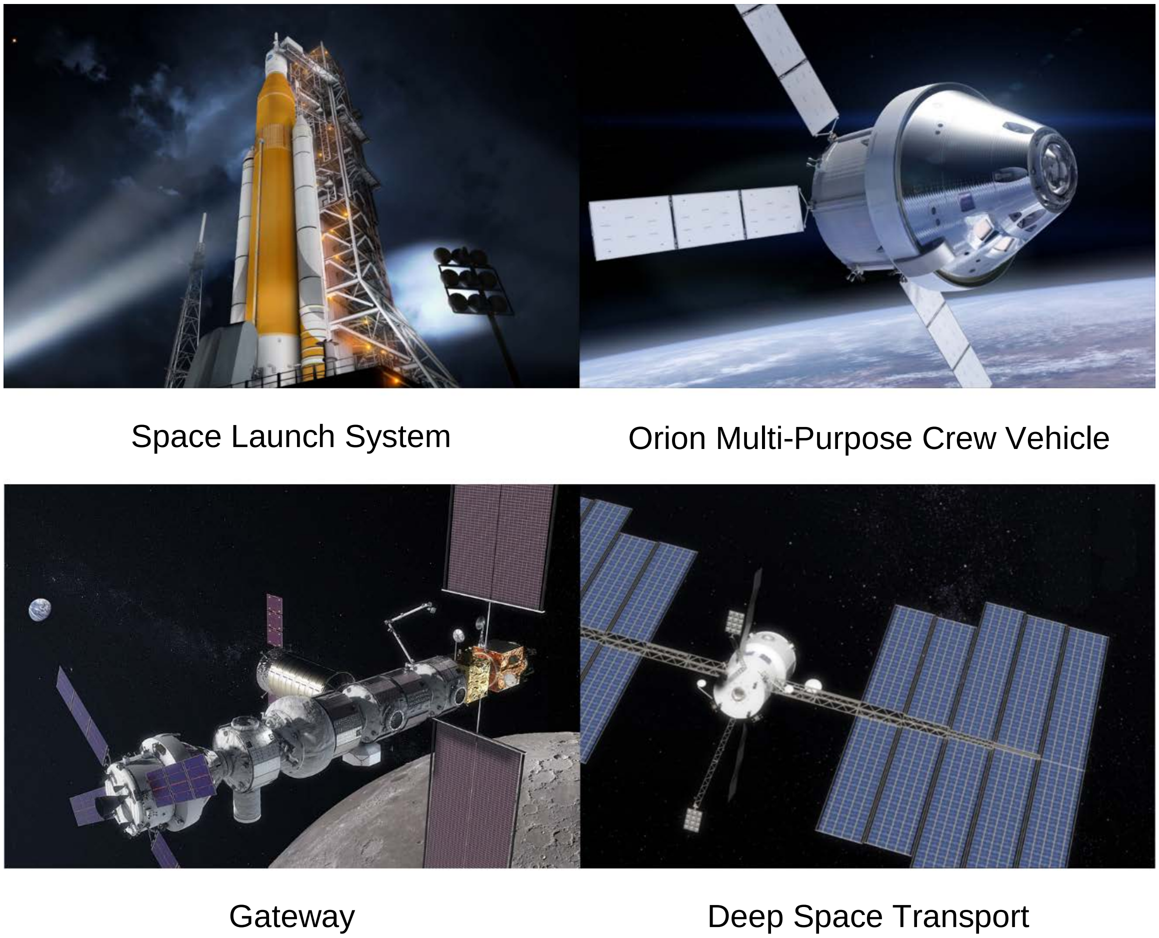
Notional NASA plans currently use SLS to launch most components of the Gateway, the entire DST, and all astronauts going to lunar orbit, the Moon, and Mars. Astronauts are carried to the Gateway and back to Earth in the Orion capsule. Trips to the lunar surface are to be made by three-stage and partially reusable lunar landers that dock with the Gateway. Like Orion, the DST is to carry four astronauts. Astronauts going to Mars are to be transferred to the DST from Orion.

The baseline human orbital trip to Mars is envisioned to involve a crew rendezvous with the DST in a high Earth orbit. The DST will then use a lunar gravity assist for Earth departure, which will augment a chemical burn. It will use solar electric propulsion to transit to Mars, but use chemical propulsion to enter into a Mars orbit. During the orbital trip, the crew will perform remote observations of Mars and its vicinity for 438 days (88 orbits). The DST will then depart Mars's gravity well using a chemical propulsion departure burn, but use electric propulsion to transit to Earth. Lunar gravity is used to assist recapture into the Earth's sphere of influence. Orion will then rendezvous with the DST, and bring the astronauts back to Earth (Connolly 2017). The crewed roundtrip to Mars is expected take approximately 1,100 days (about 3 years).

After the first mission, later trips are to focus on landing on the surface of Mars. Human landings on Mars may involve establishing a Mars surface field station using three robotic launches. Spacecraft using similar propulsion systems to that of the DST will transport and land supplies, the habitat, equipment for in-situ resource utilization (ISRU), and other equipment using robotic flights. The DST will then ferry four astronauts to Mars orbit following the same steps as during the earlier Mars orbital mission. However, once the DST reaches Mars orbit, the astronauts will use a lander to go to a modular habitat on the surface located near an ISRU unit. The astronauts will return to the DST in an ascent vehicle using propellant manufactured by the ISRU unit. After rendezvous, the DST will return to the Earth's sphere of influence, following the same steps as for the orbital mission. Three initial landing missions have been considered (Connolly 2017).

3. Major Architectural Elements

To the best of our information, NASA's current and notional plans for an orbital mission to Mars require four major architectural elements: SLS, Orion, Gateway, and the DST. As per NASA's request, we use these four systems as the basis of the architecture presented in this report. Some elements of the architecture are currently under development (e.g., SLS and Orion are to launch in 2020; prototypes of several Gateway modules have been built and initial modules are to be under contract in the near future). As this architecture represents a likely future for human spaceflight, STPI did not specifically consider alternative architectures to Mars (such as a direct trip to Mars without the Gateway or use of alternative propulsion systems). Some technology alternatives, however, are noted where relevant throughout the report. Artist renderings of each system are presented in Figure 1.



Source: NASA

Figure 1. NASA Renderings of Major Architectural Elements

a. SLS

As part of the 2017 NASA Transition Authorization Act, Congress specifically directed that NASA's plans for human exploration build on the use of SLS and Orion (U.S. Congress 2017, Section 432(b)). Therefore, although commercial launch systems will play a role in transporting logistics to cislunar space, all crewed missions are to use SLS and Orion. To support the large payload requirements of some of these missions, the SLS is to be developed in three stages, each incrementally increasing the vehicle's lift capacity. The first SLS model, Block 1, will consist of a core stage and boosters, both of which have been derived from Space-Shuttle-era rocket technology, with an upper stage based on the Delta IV's second stage. SLS Block 1 will be able to lift 70 metric tons to LEO. Following the notional schedule for planned upgrades, SLS Block 1B will replace the original second stage with the Exploration Upper Stage (EUS), increasing SLS's launch capacity to 105 metric tons to LEO. SLS Block 2 will upgrade the solid rocket boosters, increasing launch capacity to 130 metric tons to LEO.

NASA refers to crewed launches of SLS as Exploration Missions (EM). Cargo launches using SLS are not given this designation. NASA has notionally planned six EM SLS launches through 2026.

b. Orion

The four-seat Orion capsule will ferry astronauts to and from the Earth to Gateway and the DST. It will use an expendable service module (SM) developed in part by the European Space Agency (ESA) to provide power, propulsion, and life support, at least for the first two flights and likely the first four. Throughout the precursor missions leading to a human mission to Mars, NASA plans to make improvements to Orion. By its second crewed launch (currently scheduled for EM-3 in late 2023 or early 2024), NASA has stipulated that the SM must have the capability to move both the Orion capsule and Gateway habitat module for rendezvous with the Gateway Power and Propulsion Element launched on an earlier mission (EM-2). Future missions may take advantage of this cargo-tug capacity to transport airlocks and logistics modules. Orion will need to be able to be operated either manually or autonomously. For example, as the crew embarks or disembarks from their journey to Mars, Orion must be able to return from and travel to the DST without a crew.

c. Gateway

Final decisions on the design of the Gateway are expected to be made by 2019. Assembly is to begin in 2023 and the Gateway is to be fully operational by 2026 (NASA 2018a). The first return of U.S. astronauts to the surface of the Moon is planned to take place from the Gateway before 2029. The Gateway is to consist of eight modules: the power and propulsion element (PPE), an international partner habitation module, a U.S. habitation module, an airlock for extravehicular activity (EVA), a European System Providing Refueling, Infrastructure and Telecommunications (ESPRIT) module, an associated U.S. utilization module, a logistics package, and a robotic arm (Sloss 2018). Gateway will be the first human outpost beyond LEO, and will also provide a proving ground for the power and propulsion bus technology that the DST is to use. The Gateway has about a third of the habitable volume of the ISS. Current plans for the Gateway call for a life-support system that would be designed to sustain crews of four for a minimum of 30 days when assembly is complete with a stretch goal of up to 90-day stays. However, Gateway will only support crewed operations when Orion is docked.

The Gateway is to be parked in a near rectilinear halo orbit (Zimovan et al. 2017) around the Moon, providing future lunar surface missions access to areas of interest. Its propulsion system is to enable station keeping and orbital maneuvering and have the capability for refueling. The Gateway is to include a human health research laboratory to evaluate the human responses to the deep space mission environments and the technologies needed for human deep space spaceflight. It would also provide a waypoint for establishing mission operations requirements and procedures for deep space spaceflight. The Gateway would also serve as an in-space dockyard to assist in the construction and maintenance of the DST and as a transportation hub for potential missions to the lunar surface by U.S. Government, international, or commercial entities.

d. DST

The DST is currently a notional vehicle meant to carry a crew of four on a +1,000 day trip to Mars orbit and back to Earth. It is to consist of a habitat module and a power and propulsion module, which may use a hybrid solar electric/chemical design.[3] According to internal NASA plans, a hybrid propulsion system would use chemical thrusters to leave Earth and Mars orbits and solar-electric propulsion for deep space travel. The DST will carry all of its consumables (propellant, food, etc.) for the three-year mission. The DST's habitat module is notionally planned to have a volume of at least 100 cubic meters (the size of a large two-bedroom apartment), and support a crew of four for the 3-year mission, with private and public crew spaces, a galley, medical and exercise systems, and research stations (Connolly 2017). The DST's systems must operate with limited maintenance for the entire mission. The DST would be refurbished and refueled at the Gateway between trips. It is to have a lifetime of 15 years, and the ability to lie dormant for three. The 15-year lifetime would permit three missions to Mars (Connolly 2017) for the DST vehicles. Future uncrewed missions to Mars that will deliver cargo would use the same power and propulsion system as the DST.

C. Methodology and Data Sources

Following the congressional mandate in Section 435 of the 2017 NASA Transition Authorization Act, NASA requested that this report provide an assessment of a human spaceflight mission to Mars in 2033 by specifically assessing the following elements:

- The technical development, test, fielding, and operations plan using the SLS, Orion, and other systems to successfully launch such a Mars human spaceflight mission by 2033.
- An annual budget profile, including cost estimates, for the technical development, test, fielding, and operations plan to carry out a Mars human spaceflight mission by 2033.
- A comparison of the annual budget profile to the five-year budget profile contained in the President's Budget Request (PBR) for Fiscal Year (FY) 2017 under 31 U.S.C. §1105.

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[3] A nuclear thermal propulsion system may also meet this requirement.

NASA further requested that STPI use NASA's current and notional plans for human exploration as the basis for the major systems and timelines presented in this study, rather than developing its own mission architecture. To fulfill these tasks, STPI drew on information from internal NASA documents and discussions with NASA personnel and individuals from the commercial space industry. In addition to these interviews, we drew on publicly available government documents, such as NASA's 2015 Technology Roadmaps, NASA Inspector General and Government Accountability Office (GAO) reports, peer-reviewed scientific literature, and other publicly available information. Outside of the space literature, STPI also utilized literature that addressed determinants and patterns of technology, scheduling, and cost risks for large, complicated projects incorporating new technologies. Research for this report was conducted through January 2019.

Using these sources, we first identified specific technical requirements and conceptual designs in NASA's notional plans for a human mission to Mars. We also identified places where the information requested by Congress was unavailable or where proposed plans were internally inconsistent.

Our overall approach to this assessment has been to identify risks to completing a human mission to Mars, namely: human health risk, technology risk, schedule risk, cost risk, and budget risk. For this study, we adopt the standard definition of risk as the severity of an event's consequences combined with the event's likelihood of occurrence. We make qualitative assessments of these risks and assign systems, technologies, and plans relative rankings of low risk, medium risk, and high risk:

- Human health risks are the likelihood an astronaut will face an increased chance of death, decrease in life expectancy, or develop significant health problems caused by a specified environmental or mission condition during the course of space exploration.
- Technology risks stem from the difficulty of addressing remaining technical problems (e.g., specific challenges with subsystems or integration of spacecraft) and the likelihood a specific problem cannot be solved in time to meet current schedules.
- Schedule risks are the likelihood a delay in a system will impact the launch date of a mission to Mars or other missions as scheduled.
- Cost risks arise from the likelihood a program will face cost overruns.
- Budget risks are the likelihood the human space exploration portfolio as a whole will encounter budget shortfalls.

All dollar figures in this report are in nominal dollars, unless otherwise noted. We use the U.S. Bureau of Economic Analysis's GDP Price Deflator to convert to any real dollar figures (U.S. Bureau of Economic Analysis 2018).

D. Organization of this Assessment

In Chapter 2, we consider the technological challenges confronting each of the major systems needed to enable a mission to Mars orbit in 2033. We identify and assess major challenges to designing and constructing each of these systems.

In Chapter 3, we assess the feasibility of the proposed timeline for launching an orbital mission to Mars. Drawing on the history of previous major NASA projects, we construct a schedule Gantt chart to identify critical points by when systems are likely to be completed. We use this schedule to assess the feasibility of a 2033 timeline.

In Chapter 4, we assess the potential costs of building these systems. Cost estimates for SLS, Orion, and exploration ground systems are based on NASA projections available from public documents. We developed our own cost estimates based on the costs of developing and constructing recent analogous systems, such as Orion, and on past NASA experiences with costs to develop complex human spaceflight systems for Gateway, DST, and systems needed for a Mars surface mission. We are unable to project the cost of retiring human health risks, and thus simply extend the current budget for the human research program indefinitely. Drawing on NASA's past experiences with spaceflight programs, we also identify and estimate the potential for cost overruns.

In Chapter 5, we develop scenarios encompassing the likely range of NASA's future funding levels between FY 2018 and FY 2037. We then develop scenarios for the share of these budgets that might be available for human space exploration—in particular, an orbital mission to Mars—and compare aggregate likely costs on systems for the Mars mission to cumulative likely appropriations available to NASA for human space exploration. We provide a comparison of annual projected budgets and costs for the entire period from FY 2018 to FY 2037. We also compare, in detail, the short-term expenditures that would be required to initiate a human mission to Mars in 2033 against proposed NASA budgets between FY 2018 and FY 2022.

In Chapter 6, we present our best understanding of the overarching challenges to maintaining human health in the transit, orbit, and return from Mars. We also describe NASA's research and development (R&D) efforts related to these challenges.

In Chapter 7, we summarize our assessment of major technology, schedule, and cost risks. It also contains our overall assessment of NASA's plans emerging from this analysis.

Appendix A reproduces the legislative mandate for this study. Appendix B includes a list of interviewees. Appendix C provides a list of the performance of NASA programs with regard to original cost projections. Appendix D contains a short discussion on calculating the risk of astronaut death on a mission to Mars using only observational data from previous spaceflight missions.

2. Technology Assessment

This chapter describes the requirements associated with each major technical system needed to complete a human orbital mission to Mars and then assesses technology risks associated with each requirement. Additionally, we describe other human exploration systems (including those related to NASA’s return to the Moon) that will be developed or used concurrently with the systems needed for a Mars orbital mission, as they will affect the budget available for activities directly related to the Mars mission.

For the technology risks identified in this chapter, a relative low, medium, or high ranking was assigned based on the potential hazards related to the difficult of remaining technical problems (e.g., specific challenges with subsystems or integration of spacecraft), the likelihood of a hazard’s occurrence, and the consequence of the hazard. Our judgements were per force qualitative because we lacked sufficient detailed information to quantitatively assess the likelihood and magnitude of the consequence for each hazard. For the subsystems of architectural elements that are close to operational status (e.g., SLS Block 1, Orion, and their ground systems), the hazard is that significant unexpected technical challenges arise that impact the development of a specified system; for subsystems of architectural elements that are still being designed (e.g., the Gateway, the DST, SLS Block 2), the hazard is that research and technology development fail to progress to the point where systems are flight-ready at critical decision points (e.g., preliminary design review or critical design review); for the architectural elements themselves (e.g., SLS, Orion, the Gateway, the DST), the hazard is a combination of the risk of constituent subsystems, and the difficulty of integration for the vehicle as a whole.

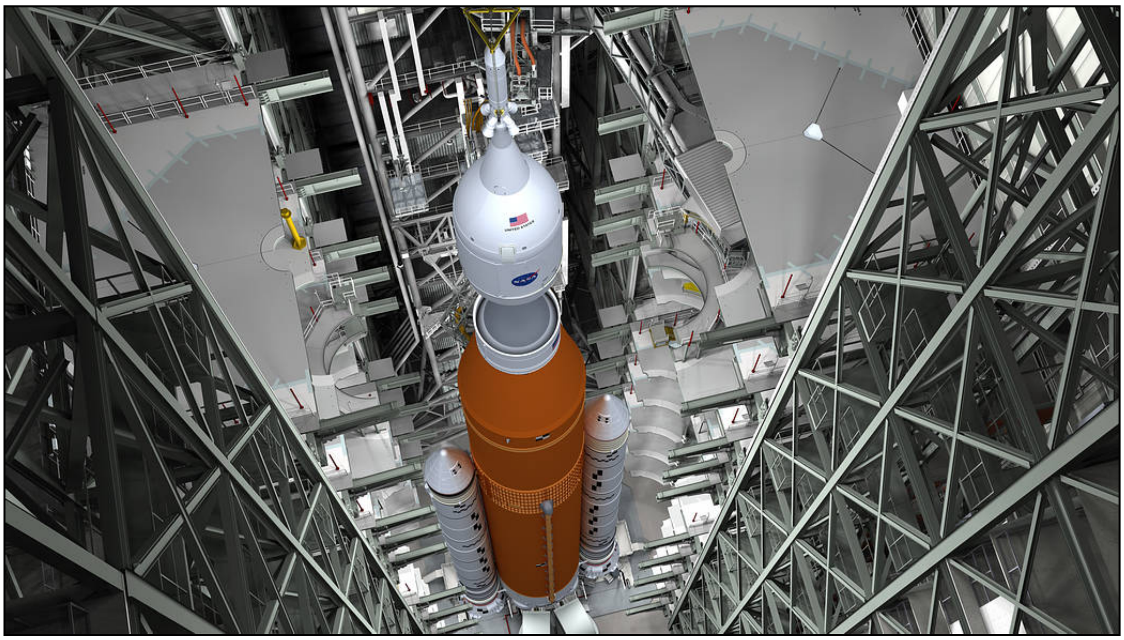
Following NASA’s current and notional architecture presented in Chapter 1, we grouped technologies into the four major sets of systems that will be needed for a human trip to Mars: Launch Systems and Related Vehicles, the Gateway, the DST, and Other Architectural Systems.

A. Launch Systems and Related Vehicles

NASA’s current and notional plans require several systems to launch and transport humans and cargo to lunar and Martian destinations. These include ground systems as well as systems for space. The major systems we examine under launch systems and related vehicles are SLS, Exploration Ground Systems (EGS), Orion, Logistics Modules, and Commercial Launch Vehicles.

1. SLS

Three versions of NASA's SLS are to be used during the precursor missions leading to a human mission to Mars. The first version, SLS Block 1, consists of a liquid-fueled core stage, two solid rocket boosters, and four Shuttle main-stage engines (renamed RS-25) for the first stage, and a launch vehicle stage adaptor (LVSA), the Interim Cryogenic Propulsion Stage (ICPS),[4] and a multi-purpose crew vehicle stage adapter (MSA) for the upper stage. The solid rocket boosters, RS-25 engines, and ICPS are based on existing technologies, whereas the MSA, LVSA, and core stage are new developments. SLS Block 1 is designed to lift 70 metric tons to LEO and 27 metric tons to trans-lunar injection (TLI).[5] Figure 2 shows a rendering of the SLS Block 1 in the Vehicle Assembly Building (VAB).



Source: NASA (2016c).

Figure 2. Artist Rendering of SLS Block 1

SLS Block 1B is to debut on EM-3, notionally slated for 2024 (see list of EMs in Figure 9). SLS Block 1B would replace the ICPS with the EUS and the LVSA with the Universal Stage Adaptor (USA). NASA has contracted with Dynetics to design and build the USA for SLS Block 1B (Warner and Russell 2017). The EUS would be a new system, although it would use four variants of the same engine as that of the ICPS. It passed

[4] The ICPS is based on the Delta IV's upper stage. It uses one RL-10 engine.

[5] The spacecraft will require another burn after arriving in cislunar space to close its orbit, resulting in a smaller final mass than the listed mass to TLI. Because the amount of fuel needed to enter a closed orbit around the Moon depends on the type of orbit, the final mass that SLS can send to lunar orbit cannot be specified without knowing the payload's specific orbit.

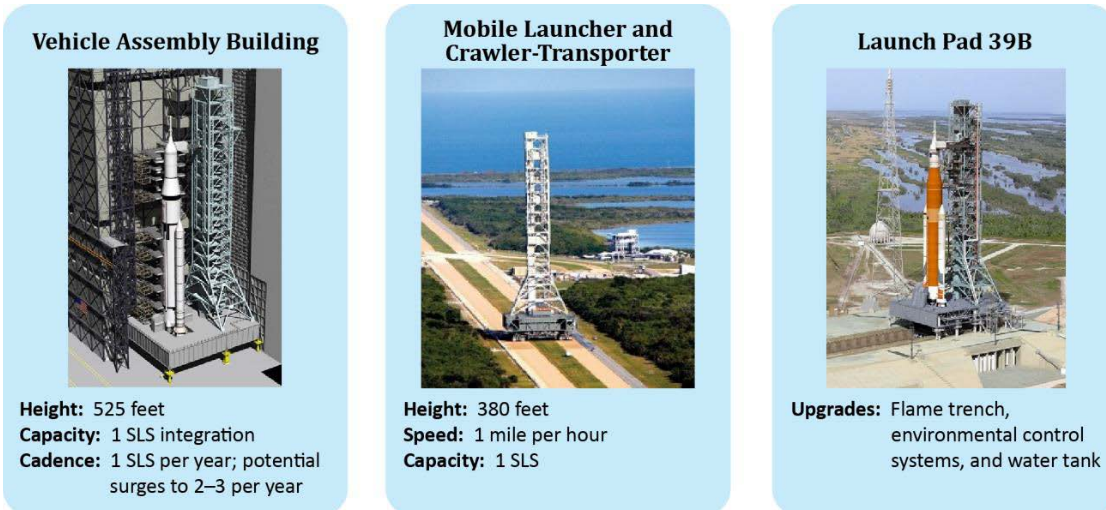
preliminary design review in January 2017. NASA has contracted with Aerojet Rocketdyne to produce the RL-10 engines necessary for the EUS in SLS Block 1B (NASA 2016b). These engines have been used in many previous missions on both the Delta IV and Atlas V with an almost perfect record (the Delta IV and Atlas V have each had one partial failure; Gunter's Space Page n.d. a, b). They would be used on the ICPS. The RS-25 engines are currently under contract; however, depending on the launch rate in the late 2020s, some expansion of production capacity may be required to support both the cargo and crewed vehicles. SLS Block 1B is projected to lift 105 metric tons to LEO and 34–40 metric tons to TLI.

SLS Block 2 is planned to first launch on EM-8 in 2028 once the existing eight flight sets of boosters are exhausted. It would replace the boosters from Blocks 1 and 1B with new boosters that increase lift capabilities to 130 metric tons to LEO and more than 45 metric tons to TLI. The Advanced Booster may consist of either an enhanced solid-fueled booster or a new liquid-fueled booster. Selecting either solid- or liquid-fueled boosters for the development of the Advanced Booster for the SLS Block 2 may require new technology or the development of new ground systems. For example, a liquid-fueled booster would require modifications of the Mobile Launcher to support liquid fueling (Bergin 2015). SLS Block 2 may require a larger cargo payload fairing for Mars missions depending on the Mars lander design, and Mars atmospheric entry and descent and landing technology selection.

2. EGS

The key systems under the EGS for the Mars mission are the VAB, the Mobile Launcher, the Crawler-Transporter, and Launch Pad 39B (see Figure 3), and two system integration software suites: Spaceport Command and Control System (SCCS) and the Ground and Flight Application Software (GFAS). All of these systems are under development or are being refurbished from Apollo legacy infrastructure at the Kennedy Space Center.

Following stage delivery to the VAB, the SLS would be assembled on the Mobile Launcher in the VAB at the Kennedy Space Center. The SLS would then be transported, using the Crawler-Transporter, to Launch Pad 39B, where the SCCS and GFAS would coordinate and automate interactions between Launch Control, SLS, Orion, and the Mobile Launcher. The VAB and the Mobile Launcher will need to be refurbished to account for the new height and weight of the EUS of SLS Block 1B (NASA Office of the Inspector General 2017c). Further refurbishments may be needed for the Mobile Launcher to accommodate SLS Block 2, depending on the design of the advanced solid rocket boosters. Depending on launch cadence, more than one Crawler-Transporter may be needed. Congress has allocated funds to build a second Mobile Launcher, which will be designed specifically to accommodate SLS Block 1B and Block 2, given that the launch cadence of SLS will require two SLS vehicles to be in production at the same time.



Source: NASA Office of the Inspector General (2017c).

Figure 3. Key Components of EGS

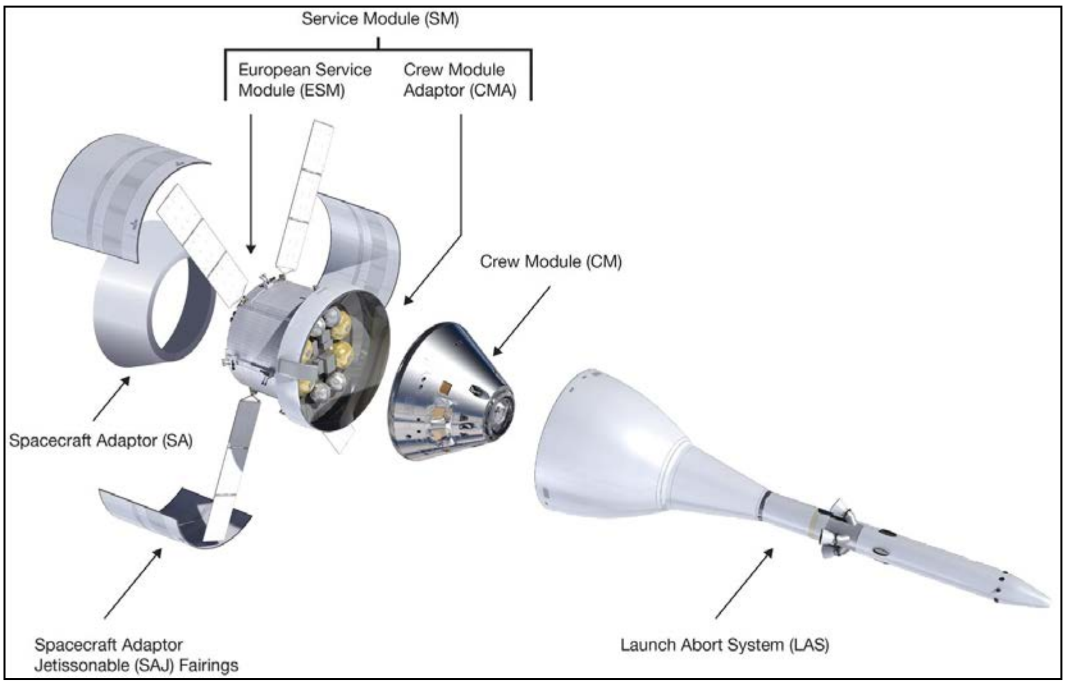
All buildings and systems in the EGS exist and are being refurbished to provide support for future SLS-based missions. Many of the refurbishment efforts are currently either complete or close to completion, leaving multi-element verification and validation as the main obstacle to flight readiness. Over the last 2 years, major recent accomplishments include refurbishing the Crawler-Transporter and the VAB, and developing the SCCS version 4.0. Both the refurbishment of the Mobile Launcher and Launch Pad 39B are on schedule to be ready for the SLS Block 1 launch.

3. Orion

Orion is intended to carry a crew of four astronauts for up to 21 days to destinations in deep space and bring them back to Earth. Its development began in the mid-2000s as part of the Crew Exploration Vehicle program under the Constellation program. In 2012, the project was transferred from the cancelled Constellation program to its own development program, the Orion Multi-Purpose Crew Vehicle (GAO 2016b). Following an uncrewed mission in the middle of 2020, and an initial crewed mission in 2022, Orion is expected to be used for crew transportation to and from the Gateway and the DST. All Orion missions are currently planned to launch on SLS.

As shown in Figure 4, Orion consists of a Crew Module (CM), a Launch Abort System (LAS), and an SM. The current version of the CM provides 8.9 cubic meters (316 cubic feet) of usable space. A heat shield on the underside of the CM protects the crew during reentry to Earth. The LAS ignites a solid rocket to propel the CM away from the SLS during an emergency.

The SM provides the CM life support, in-space propulsion, and power from solar panels (NASA 2017a). It consists of two subcomponents: the CM Adapter (CMA) and the European Service Module (ESM). The ESM is being developed under an international agreement with ESA, and is being built by Airbus Defence and Space. ESA is providing the ESM to NASA under a barter arrangement as part of its contribution to the ISS (NASA, n.d.). ESA is expected to produce the ESM at least through EM-4, though ESA is considering providing several more ESMs beyond the fourth (Foust, 2018c). It is expected that ESA will continue to produce the ESM for future missions, but this has not been confirmed.



Source: GAO (2016b).

Figure 4. Components of the Orion Multi-Purpose Crew Vehicle

In December 2014, a prototype Orion capsule was successfully launched on a Delta IV Heavy launch vehicle, leading to fixes for some Orion systems (GAO 2016b). For example, Orion’s heat shield had to be redesigned because cracks developed during the test. Additionally, the decision to redesign the heat shield arose from NASA’s concerns regarding manufacturability of the previous design.

NASA does not have the ground-based facilities to test a full-scale prototype of a new heat shield design. The NASA Aerospace Safety Advisory Panel has expressed concern over the lack of flight testing for other Orion systems, and has argued that EM-2 should remain in LEO until further testing of life support is complete since EM-2 would be the first flight test of the full Environmental Control and Life Support Systems (ECLSS) (GAO 2016b). To address this concern, NASA changed plans for EM-2: EM-2 is now to launch into a 24-hour period elliptical orbit to check the ECLSS and other systems before Orion and its service module conduct a trans-lunar injection burn to circumnavigate the Moon.

Many of Orion's components, such as the avionics system, are designed for reuse (GAO 2016b). Although reused systems would be refurbished and tested before launch, reuse of systems can sometimes increase technology risk. Conversations with Lockheed Martin officials revealed plans to gradually increase the degree to which parts from each Orion capsule are reused, which would lower the risks associated with reuse as experience builds over time.

4. Logistics Modules

Logistics modules will be required to transport cargo, both pressurized and unpressurized, to various destinations in space. These modules do not have to be human-rated, but will have to be able to dock with human-rated pressurized systems. We envision up to three different types of logistics modules to support future NASA missions.

The first and smallest logistics module would be commercial logistics modules, launched and operated by a commercial company outside of the cadence of SLS launches. NASA recently published a request for information (RFI) outlining some of the basic requirements for these modules. NASA envisions a cargo module with a total capacity of 7.6 metric tons of cargo, with up to 5 metric tons of that total capacity as pressurized cargo. The module would need to be able to have at least a three-year lifespan in deep space. According to interviews with NASA personnel, NASA assumes this capacity will provide sufficient cargo for a 90-day stay on the Gateway or the Moon of a crew of four. This logistics module would be used to ferry cargo for all missions to the Gateway to support all missions leaving from that point, including to the lunar surface and to Mars. The module would require all the systems necessary to travel autonomously from launch vehicle separation to docking at Gateway and final disposal, including propulsion, guidance, navigation and control, communications, and thermal management. It would also dock with the Gateway to increase habitat volume, and pick up and store trash and other waste products to be jettisoned from the Gateway. Future commercial logistics modules would also be designed to transfer propellant to the Gateway for use in lunar landers and the DST.

The second logistics module would be the small logistics module. These modules would be co-manifested with Orion on SLS launches. The schedule developed below calls for seven small logistics modules through the mission to Mars orbit. Their design would be based on existing pressurized modules and would not require their own navigation systems. A small logistics module could carry up to 13 metric tons of cargo to the Gateway, depending on the SLS block type. These modules would need to be designed for a longer lifetime and be able to withstand the radiation and micrometeoroid debris environment in lunar orbits if they dock with the station for extended periods of time to increase the habitable volume of the Gateway.

Another type of logistics module would be the large logistics module. Although it is not addressed in the current publicly available launch schedule, a large logistics module could ferry propellant and other logistics on a cargo SLS missions to the DST. The large logistics module, because of its size, would be a new design. Because the module would be the primary payload, it would require self-propulsion and guidance, navigation, and control capabilities. Since it would be the only manifested payload on an SLS flight, and the SLS can deliver 45 metric tons of cargo to TLI, we estimate that the total mass at the Gateway could be approximately 40 metric tons after maneuvering from TLI to near rectilinear halo orbit (NRHO) and docking with the Gateway. The large logistics module would require a major scale-up from the commercial logistics modules, though the same systems would be included for transfer to the Gateway, rendezvous, docking, and subsequent disposal. The schedule in this report does not call for any large logistics modules, instead relying on commercial and co-manifested logistics modules for resupply and propellant.

5. Commercial Launch Vehicles

NASA has expressed interest in using commercial vehicles whenever possible in its architecture. A new wave of commercial launch vehicles could be used to support and augment NASA’s missions to cislunar space and Mars. The Atlas V and Falcon Heavy launch vehicles have already successfully flown, and other rockets such as Blue Origin’s New Glenn, SpaceX’s Starship (formerly known as the Big Falcon Rocket), the United Launch Alliance’s Vulcan, and others provided by traditional U.S. and international aerospace companies could be used to support NASA efforts.

6. Summary—Technology Risks for Launch Systems and Related Vehicles

We find the technology risk associated with SLS Block 1 and 1B to be low, and with Block 2 as medium. SLS Block 1’s core stage requires novel welding techniques (Sloss 2017), but risks associated with these techniques should decline as manufacturers become more familiar with the process. The testing and integration required for flight-readiness of SLS Block 1 present a low technology risk. The development of the Advanced Booster for the SLS Block 2 presents the highest technology risk for SLS. However, because the United States’ aerospace industrial base has experience with solid- and liquid-fueled rockets, industry is unlikely to encounter technology challenges to building the Advanced Booster that carry more than a low-to-medium technology risk.

As NASA has notionally scheduled, and as will be discussed in Chapter 3, the first flight of SLS Block 1B (EM-3) would be a crewed flight. By scheduling crew on the first flight of a new system, NASA is implicitly accepting a higher risk for a technology that has not been previously flight-tested. This risk could be avoided by scheduling a non-crewed mission, such as the Europa Clipper mission, on SLS Block 1B before using it to launch astronauts. The schedule presented in Chapter 3 also uses the debut of the SLS Block 2 to launch crew on EM-8. To likewise reduce the risks to astronauts for this flight, NASA could use the first SLS Block 2 to launch the initial set of lunar landing systems, rather than launch each component separately on smaller commercial vehicles. This would, however, likely increase costs associated with lunar missions and require earlier development of the Advanced Boosters.

The refurbishments required of the key EGS buildings and systems are major, but are all currently near to or in the validation and verification stage. For this reason, we do not find major technology challenges to EGS and assess the technology risk for ground systems for launch as low.

Major systems for Orion are at high technology readiness levels (TRL),[6] and thus present low technology risk, as the capsule for EM-1 is undergoing integration and testing. Due to the inability to conduct more than one field test before crewed operations, Orion's heat shield represents a medium risk. Although most individual technologies may be low risk, we rank the testing and integration of Orion systems as medium risk.

Because the commercial and small logistics modules would be based on those currently used for the ISS, the technology risk is low, though the commercial modules will require additional propulsion capabilities to reach the Gateway. For logistics modules that would be attached to the Gateway for longer periods of time, additional design work would be needed, but these technology challenges are not fundamentally new and represent a low technical risk overall. However, the large logistics module would require a major scale-up from the commercial logistics modules. Consequently, we assess the technology risk of the large logistics module as medium. The use of the same systems for transfer to the Gateway, rendezvous, docking, and subsequent disposal, and the long timeline before the large logistics module is needed mitigate the technology risk associated with the large logistics module to some extent.

Commercial launch vehicles may be less reliable than launch vehicles built under traditional cost-plus contracting and mission assurance approaches, but the lower costs may more than make up for the increased risk of failure for uncrewed systems. There are risks

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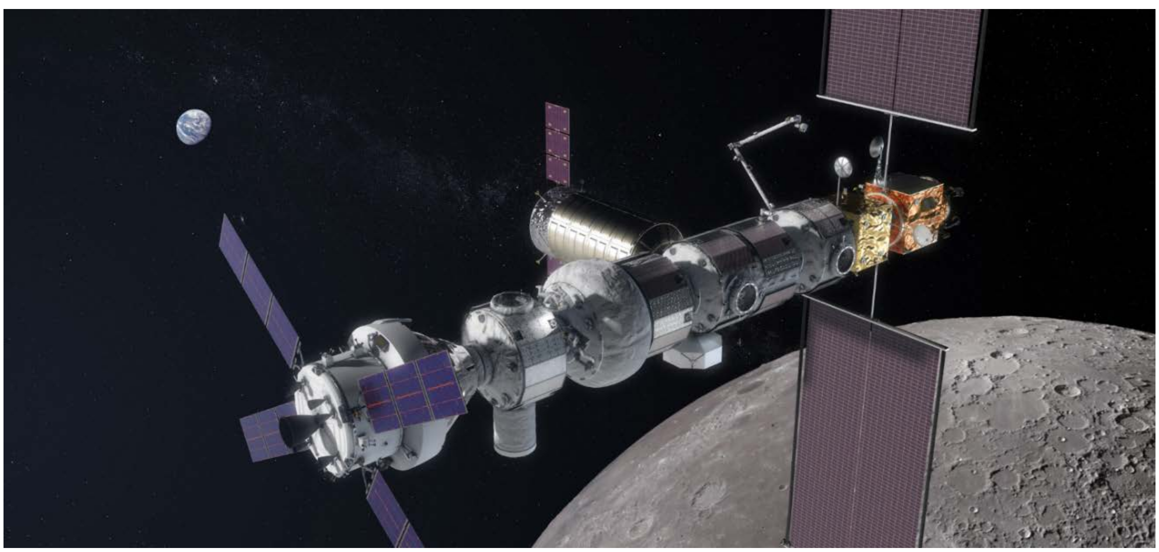
[6] We use the definitions for technology readiness levels as found in the NASA Systems Engineering Handbook that assign ratings from 1 to 9 to the state of a technology's maturity. TRLs 1–3 represent a technology undergoing early development from basic scientific principles through proof of concept; TRLs 4–6 represent a technology undergoing further development from component validation through system prototype testing and demonstration; and TRLs 7–9 represent a technology undergoing advanced development prototype testing and demonstration in space through successful mission operations (referred to as "flight proven") (NASA 2017d).

that some commercial launch vehicles in development will be delayed or fail to be completed, but two of these vehicles already exist, and there are other competing heavy-lift vehicles available that can supplement the capabilities of SLS and provide more flexible services.

B. Gateway

The Gateway is meant to serve as the hub for all human spaceflight activities in lunar orbits. It will have three major functions: 1) provide a base from which astronauts can perform science and deep space operations, including lunar surface teleoperations and evaluate surface samples from the Moon; 2) function as a transfer station for astronauts transiting to the lunar surface; and 3) operate as a transfer station for astronauts on their way to Mars. As of January 2019, the most recent publicly available documents show that the Gateway will ultimately consist of eight individual modules that will be assembled in a lunar NRHO. NASA plans for the capabilities of the Gateway to expand with each launch and module addition over the 2020s (Gerstenmaier and Crusan 2018). An artist's conception of the complete Gateway with an Orion capsule and a commercial cargo carrier docked is shown in Figure 5.

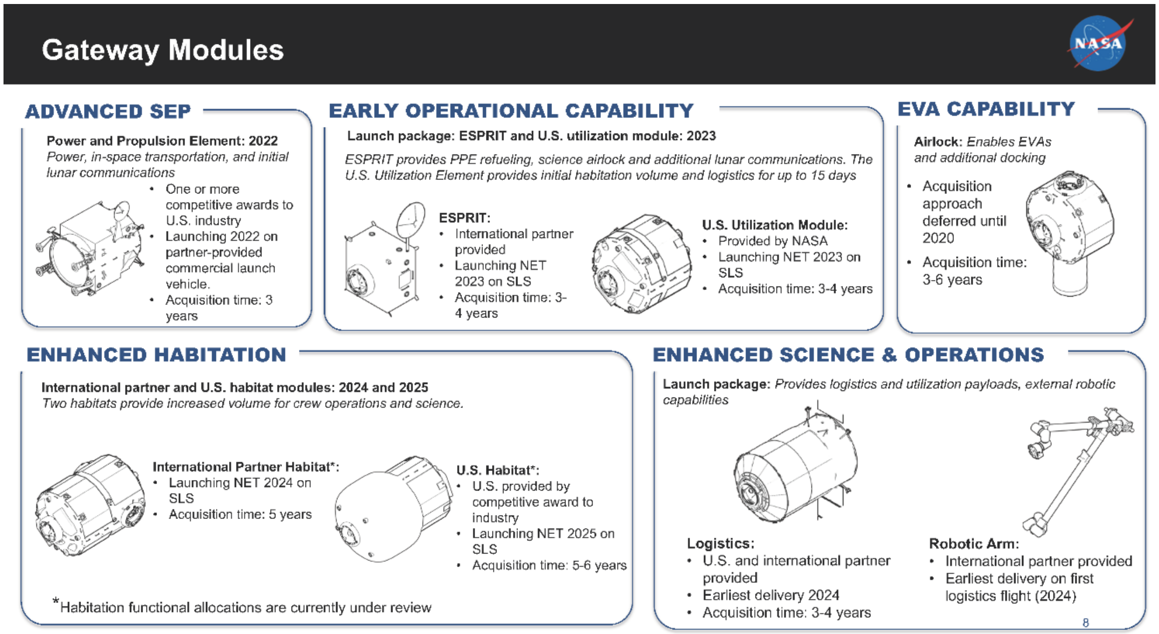


Source: Gerstenmaier and Crusan 2018.

Figure 5. The Gateway

The primary elements of the Gateway are the PPE; the U.S. Utilization module; the European ESPRIT module; an airlock; one or more habitation modules; a robotic arm; and additional logistics modules that are to be docked to increase habitable volume. A lunar sample return vehicle may also be eventually be built and docked at the Gateway, but planning for this possible mission is currently notional. The major functions and providers of each module are shown in Figure 6. Elements that enhance the functionality of the

Gateway, such as exercise equipment or scientific equipment for deep space human health assessments, will likely be delivered by commercial launch vehicles in logistics modules.



Source: Gerstenmaier and Crusan 2018.

Figure 6. Gateway modules and functions.

As Chapter 3 will elaborate, the Gateway assembly would be completed by 2026. By 2024, the Gateway is expected to support crew visits of up to 15 days by leveraging Orion's crew capabilities. Stays may be extended to 90 days when the U.S. and international habitats are delivered by the end of 2025. Longer duration stays on the Gateway will provide valuable data to support the Human Research Program by enabling longer astronaut stays in deep space. However, NASA does not plan to human-rate at least the first several Gateway modules without an attached Orion module (Hill 2017), as the lift capacity of SLS restricts Gateway elements' mass budget and Orion can provide many necessary crew support systems. This should save on the development costs of the Gateway modules, but it also means that the Gateway will only be able to support crewed operations when Orion is docked. In the sections below, we discuss the status of the technologies for each of the Gateway modules in order of assembly.

1. PPE

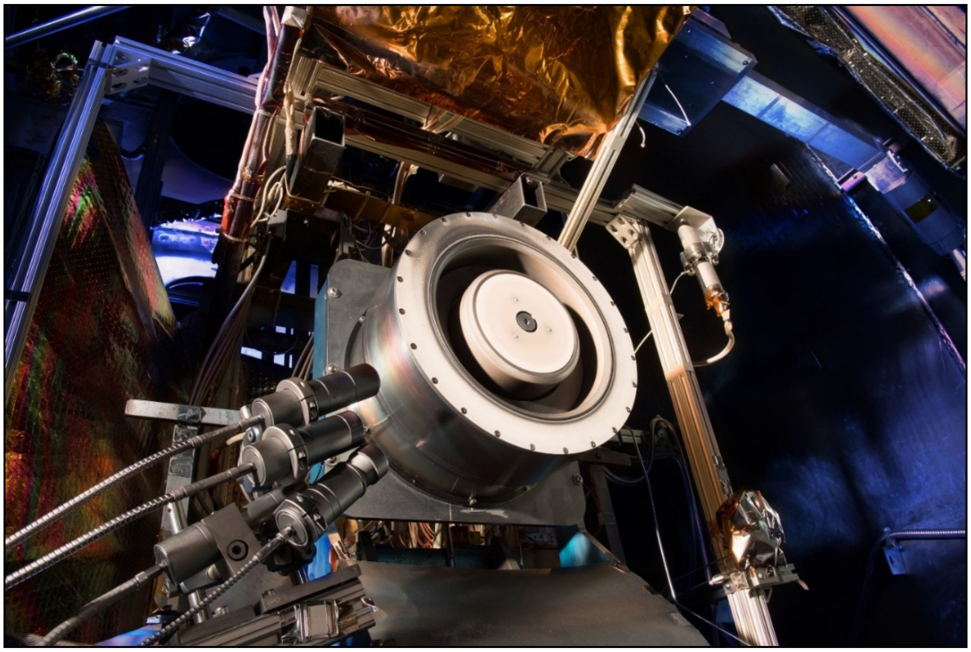
The PPE is an 8 to 9 metric ton power/propulsion element bus based largely on commercial satellite designs. Launched on a commercial vehicle, the PPE will use its 40 kW Solar Electric Propulsion (SEP) system to transfer from LEO to its operational lunar NRHO. The SEP system is powered by the PPE's 50 kW solar power system, which also provides up to 24 kW to the rest of the Gateway to support crew operations when the SEP system is not operating. The PPE will be a self-contained spacecraft, with thermal control; guidance, navigation, and control; a chemical reaction control system; and telemetry communications to enable the PPE to complete its journey to lunar orbit.

a. Propulsion Systems

The Gateway will use its 50 kW solar power system to drive a 40 kW SEP system. It will also have a small chemical propulsion system for reaction control. The SEP system on the Gateway will use four 13-kW Hall thrusters with xenon propellant (see Figure 7). The reaction control system is expected to use a standard hydrazine system that has already been extensively used for satellites and other space vehicles. Current requirements are for 23,000 total hours of operating lifetime (Herman et al. 2018). The reaction control engines must be able to operate as a system integrated with the SEP system, so the vehicle software will need to be written to accommodate the vehicle's dynamics with both systems operational.

The Hall thruster system will need to last at least 15 years to match the Gateway's minimum operational lifetime, although its operational life will depend on the amount of orbital maneuvering required. No ground testing of multiple 13 kW Hall thrusters is currently planned, nor has a facility for such testing been developed. Thus, currently there is no way to test for unexpected interactions between the conductive plasma plumes from the thrusters, which could lead to performance degradation.

A key requirement for the Gateway propulsion system is its capability for refueling, to support the long life of the mission in cislunar space. Refueling will be required for both the solar electric xenon propellant and the hydrazine reaction control system. Storable propellant refueling of the ISS has been demonstrated in space both by the European ATV and Russian Progress vehicles.



Source: NASA

Figure 7. Hall Effect Rocket with Magnetic Shielding (HERMeS) Thruster to Be Used for the SEP system on the Gateway and DST Vehicles

Over 50 spacecraft today use 1.3 to 4.5 kW xenon Hall thruster systems, so this technology, along with the associated thermal management subsystem, will require scaling from existing systems. Spacecraft today regularly process up to 9 kW of power for SEP while rejecting roughly 15 percent of the system input power as heat from either the power processor or thruster interfaces, so current thermal management systems could be scaled to meet the PPE needs.

NASA has made progress in developing more powerful Hall thrusters through contracts with propulsion manufacturers funded by the Advanced Electric Propulsion System (AEPS) and Next Space Technologies for Exploration Partnerships (NextSTEP) programs. The AEPS program, which was awarded to Aerojet Rocketdyne in 2016, is funding the development of the 13-kW Hall thruster system to be used in the Gateway and DST. Aerojet Rocketdyne plans to deliver flight systems in 2019, and has made substantial progress in meeting program requirements for efficiency and lifetime, although final demonstrations have not yet been completed and it is not clear if a full lifetime demonstration is possible prior to launch given the schedule constraints. Moreover, the effect of slight deficiencies in efficiency and lifetime on the Gateway mission would likely be small because the thruster is used primarily in the beginning of its mission and is only scheduled to perform minor orbit corrections over the rest of its lifetime.

Xenon refueling capability commensurate with the large propellant loads on the Gateway needs to be validated. Refueling rate requirements must be examined for their effect on other spacecraft systems such as attitude control. While NASA has plans to demonstrate cryogenic refueling on the ISS during phase 3 of the Robotic Refueling Mission (RRM) launched in December 2018, RRM3 does not include xenon transfer technologies as its predecessors did. Xenon properties are quite different from cryogens and vary considerably across the expected range of pressures.

b. Electric Power Systems

The PPE power system will be the first large-scale power system in deep space. It will be twice the size of the largest commercial satellite power systems, but only one quarter the size of the ISS array. It must generate sufficient electrical power for the 40 kW SEP system when required, as well as supply all the other Gateway modules and crew operations. The power system, when not under powered flight, will need to be able to provide up to 24 kW of power to the habitat, airlock, the Orion capsule, and external equipment (e.g., a Moon lander). The PPE power system is to consist of three interdependent subsystems: power generation, power management and distribution (PMAD), and energy storage. All of these subsystems are to be designed for a 15-year minimum lifetime (NASA 2017a); NASA will be considering options for enabling upgraded subsystems during and after this time.

Power generation: Electricity is to be generated by a 50-kW solar array, which is to be sized to ensure that sufficient power will still be available at the end of the 15-year vehicle life span (NASA 2017a). The solar panels will need to be lightweight, able to be stowed in small volumes to meet launch restrictions on mass and size, and be highly efficient and radiation tolerant for deep space operations. Arrays that meet these specifications, such as Northrop Grumman Innovation Systems' (formerly Orbital ATK) MegaFlex Array and Deployable Space Systems' Roll-Out Solar Array (ROSA), have already been tested in LEO, and are at a high TRL for LEO operations. However, before these systems can be used for long-duration human deep space missions, they must undergo long-term testing and be scaled to larger sizes.

PMAD: The Gateway PMAD will need to be more autonomous than the PMADs on current crewed systems. Currently, ground control manages the ISS's power system (NASA 2015a). However, many deep space robotic spacecraft, such as the Dawn SEP vehicle, have fully autonomous PMAD systems. The PMAD voltage range for the Gateway is expected to be similar to the ISS's voltage requirements. The benefits to optimizing the PMAD to enable peak-power-tracking approaches may be significant (i.e., reducing array size and thermal management requirements). While the PMAD system would need to be designed to act autonomously, it is well within the capabilities of today's technology.

Energy storage: In contrast to the ISS, which spends half of its orbit in darkness and therefore requires large batteries and oversized arrays to charge them, the Gateway is currently planned to spend almost all of its operating lifetime in sunlight. Nevertheless, some battery storage will be required to mitigate power fluctuations depending on the lunar transfer trajectory (e.g., during periods of an eclipse) as well as lunar orbit operations if other vehicles obscure the PPE arrays (e.g., during docking procedures). Rechargeable space- and human-rated lithium-ion batteries are already used on the ISS. Improving the lifetime and the specific energy of batteries would reduce the replacement rate and mass of the energy storage system, thus enhancing the overall mission architecture. Other battery improvements, such as low-temperature operability, would add flexibility to the engineering requirements of the spacecraft. Currently, NASA is planning to buy the Gateway's radiation-hardened batteries from the private sector to take advantage of advancements in the commercial market (Conversations with NASA officials).

2. Habitation Modules

The habitable volume of the Gateway will consist of three modules: the U.S. Utilization module, the U.S. Habitat, and the International Habitat. The total habitable volume of the Gateway when construction is finished should be approximately 125 cubic meters (about one-third the volume of ISS). The U.S. Utilization Module, when launched with the European ESPRIT module, would support a crew of up to four for an initial period of up to 15 days. It is not intended to be self-sufficient, and will rely heavily on the Orion systems for the crew. It will also be the likely attach-point for the robotic arm, which is to be a direct derivative of the ISS robotic arm, and is therefore technically well within known capabilities, though other modules will also have attach points for it.

The initial habitat phase will be followed by the U.S. and International Habitats. The habitats are required to support a crew of four at the Gateway for a minimum of 30 days and up to 90 days. Both U.S. and European suppliers have experience manufacturing, assembling and testing habitats for the ISS. As with the ISS, carbon dioxide and waste water are to be partially recycled. Additional air, food, and water are to be brought from Earth on logistics modules. The logistics modules or Orion would take away waste. The International Habitat is to have two additional docking stations for both surface excursion and cargo delivery vehicles. While all these capabilities are clearly required, the organization and operational procedures of the external access points (e.g., docking stations, airlocks, and robotic arm) are not completely clear from current conceptual designs.

In their final configuration, the Gateway habitats are to include the following sets of systems: habitation systems, ECLSS, environmental monitoring, safety and emergency response systems, and radiation safety technologies. Key subsystems within the ECLSS and habitation systems are atmosphere scrubbing technologies, water management, waste management, and crew health maintenance systems, such as exercise equipment. Key subsystems within the emergency response technologies are environmental sensors; fire detection, suppression, and recovery systems; protective clothing and breathing apparatus;

and remediation in the event of an emergency (e.g., fire, chemical spills). These systems are likely to employ technologies currently used on the ISS, though some may require scaling to the smaller volumes of the Gateway and greater levels of radiation hardening to account for the deep space radiation environment.

Because astronauts will visit the Gateway for 90 days or less, the Gateway ECLSS does not need to operate much more efficiently than existing systems on the ISS. NASA has described the Gateway as being able to support visitors from privately sponsored flights and from non-U.S. government users, but has not elaborated on the needs of these potential users. However, NASA's work toward developing interoperability standards (e.g., the international docking standard) would result in commonality across global partners and allow non-NASA users to utilize the Gateway.

3. ESPRIT Module

The European ESPRIT Module will include the external refueling interface, advanced lunar communications systems, science airlock, propellant storage, and thermal management. Other than the xenon refueling system, all of these systems employ established technologies used on other missions. Because the external refueling interface is planned for this module rather than the PPE, there will additional fluid interfaces to the PPE that will require careful design, but nothing outside established experience.

4. Airlock

Crews will enter Gateway through the Airlock Module, which also enables EVAs and additional docking. The Airlock would use systems that either are used on the ISS or incorporate incremental improvements from those currently on the ISS.

5. Other Subsystems and Components

In addition to the main modules described above, the Gateway will have a robotic arm and a Sample Return Vehicle. The robotic arm is to be a direct derivative of the ISS robotic arm, and therefore technically well within known capabilities. The reusable sample return vehicle would be capable of delivering small payloads to the lunar surface, and of bringing small samples from the surface to the Gateway. A small sample return vehicle would likely be expensive and difficult to acquire, and its presence is not essential for either the primary mission of the Gateway as a waypoint for further exploration missions or a future Mars mission.

The Gateway will also require thermal management systems, deep space navigation, autonomous rendezvous and docking, and other systems to fulfill the scientific or exploration mission of the crew (e.g., a lunar communications system and observation ports). Thermal management systems on the Gateway will maintain optimal operation temperatures for subsystems, including propellant storage and crew habitat. Heat exchange materials transport heat from the large SEP system (primarily the power processing units) to radiators for heat rejection. Radiators remove the heat produced by the power and propulsion systems, preventing the Gateway from overheating. Thermal management systems currently used on spacecraft are likely to be sufficient for Gateway operations. Advances in technology can reduce risk to astronauts and decrease the mass of thermal management systems, thus providing greater flexibility in design requirements. The ISS's thermal management system uses a double-loop heat transfer system, including one loop filled with ammonia, which is toxic to humans. A single-loop system that uses a non-toxic heat transfer material could decrease the mass of the system, improve efficiency, and reduce risk to crew. Although many promising thermal fluids have been identified, evaluating each fluid for the desired properties would take a substantial amount of time (NASA 2015a). A number of improvements in radiator technology (e.g., variable emissivity, variable geometry, and freezing point) would improve the performance of the Gateway thermal management system but would require additional technology development. Due to the heritage of thermal management systems on crewed spacecraft, we regard thermal management on the Gateway as low risk, although this rating would change if NASA were to adopt a more advanced, novel system.

NASA's Deep Space Atomic Clock (DSAC) program is on schedule to test hardware that could be used for future deep space navigation missions. While the timing technology required for autonomous lunar rendezvous and docking is not necessarily new, testing more advanced hardware that would feed forward into the DST is preferable in case mission requirements for timing for docking in Mars orbit change. A DSAC payload is scheduled to fly as part of the U.S. Air Force's Space Test Program 2 in March 2019.

One major difference between the ISS and the Gateway is the radiation environment, which has implications for the systems' structures (e.g., material effects) and electronics, as well as for astronaut and life support system exposure to deep space radiation. The latter will be discussed later in Chapter 6. Because astronaut stays on the Gateway are to be relatively short, NASA may choose not to develop human radiation safety technologies for the Gateway beyond those that have already been developed for the Apollo missions and for Orion. It should be noted, however, that the impacts of deep space radiation on microbes and pathogens in ECLSS subsystems is unknown, and warrants additional investigation.

6. EVA Systems (Specifically Spacesuits)

Spacesuits will be needed for deep space EVA on both the Gateway and the DST. The DST requires spacesuits that would need to last for the full 3 years of the human orbital mission, and have low maintenance requirements. Other EVA suits would be needed for Mars or lunar surface operations.

Although spacesuits are currently used on the ISS, experts we interviewed stated that the current generation of Shuttle-legacy suits are not suited to operations in deep space.

Some of these suits have had leaks and tears. Improvements in ease of donning and doffing, increased suit flexibility, ease of use, and reduced power requirements associated with environmental controls would facilitate longer EVAs.

Many of the technologies required to develop advanced EVA suits are currently at TRL 4 (NASA Office of the Inspector General 2017b). Space suits that would be worn for extended periods of time and are capable of being operated easily on the surface of the Moon or Mars would be even more challenging. Consequently, we consider the technology risk associated with spacesuits for deep space, the Moon, and Mars to have medium to high risk.

7. Summary—Technology Risks for the Gateway

We did not find major technology challenges to developing and constructing subsystems needed for the Gateway habitat or airlock modules because they, as well as other systems on the Gateway, are to use existing technologies. Some technologies, however, would be new, and would need to be integrated into a single spacecraft. No ground testing of multiple 13 kW Hall thrusters is currently planned, nor has a facility for such testing been developed. Thus, there is a medium risk of unexpected interactions between the conductive plasma plumes from the thrusters, which could lead to performance degradation.

An area that requires focus is autonomous environmental monitoring. A crew visiting the Gateway following an extended uninhabited period would be reliant on environmental sensors and diagnostics to verify that the atmosphere and the water and food are suitable for safe habitation. These technologies are being tested on the ISS, but have not yet been relied upon to the extent they will be on the Gateway. At present, the ISS is continuously inhabited, and atmospheric monitoring uses a regular sampling plan with some assessments still using laboratories on Earth. This arrangement would not be possible in all cases for the Gateway. Autonomous environmental monitoring presents a medium risk, though NASA has begun transitioning away from environmental monitoring that requires sample returns to systems capable of performing those analyses on-orbit.

Batteries that meet the requirements for deep space human-rated batteries (e.g., low temperature and long lifetime operations) are at low TRLs (NASA 2015a). If NASA requires such batteries, they would present a medium technology risk as they have not yet been fully developed and tested.

Other technology challenges may arise with regard to the smaller volumes available for some equipment (such as exercise systems), the deep space radiation environment, and fire detection and suppression systems, among others, since these components are to be modified from the ISS baseline systems.

C. DST

NASA has described the DST as consisting of a large habitation module integrated with a power and propulsion bus similar to a scaled up version of the Gateway's PPE with an additional chemical thrust system. The combined dry mass of the integrated system is expected to be 48 metric tons and habitable volume of at least 100 cubic meters (Connolly 2017). It should be able to travel from cislunar space to Mars and back in 3 years (1,000-plus days of crew time) without resupply (Connolly 2017). It is to be reusable for several missions with a lifetime of up to 15 years with refurbishment and refueling (Connolly 2017). The DST's power and propulsion system would use a hybrid propulsion system with 24 metric tons of propellant for the solar electric engines and 16 metric tons of chemical propellant for the conventional rocket engines, giving the DST a total wet mass of 88 metric tons.

1. Habitation Module

The DST habitation module would contain living quarters for the crew, an ECLSS that efficiently recycles exhaled carbon dioxide into oxygen and wastewater into potable water, and storage for food and medical supplies. It will have systems to monitor the environment and remedy problems as required. The module is to provide medical prevention and countermeasures against the potential hazards of the three-year mission. It will also house apparatus for exercising in microgravity.

Many of the technologies required for the DST are beyond the current state of the art on the ISS. Many technologies currently used on the ISS have a 2–3 year expected design lifetime (e.g., mean time before failure). For a three-year mission, many components would be reaching or exceeding their design lifetimes during the journey back to Earth. NASA will need to evaluate the non-operating lifetime of these systems to establish a protocol for stocking spares, and to assess the mass and system reliability implications. Since non-operating spares will be subject to deep space radiation, NASA will need to design DST technologies so that even after years of storage, spare parts will have the same operational lifetime as new parts that have not been in storage. NASA documents describe developing these technologies to the point that they can be launched to the ISS for testing in the 2018–2020 time frame, with selections in 2021 for an integrated ECLSS test on the ISS between 2022 and 2024 (Gatens 2016).

Closed-loop atmosphere technologies: Removing carbon dioxide from the spacecraft cabin atmosphere, and recycling it into oxygen depends on a number of interdependent functions. The ISS currently recycles carbon dioxide back into oxygen with 42 percent efficiency. According to internal NASA planning documents, the mission to Mars orbit would require 75 percent recycling efficiency or higher (Gatens 2016). In 2015, NASA considered closed-loop carbon capture and oxygen reclamation technologies that would achieve the targeted 75 percent recycling rate for oxygen to be at TRL 2 (NASA

2015a). Inability to meet this target recycling rate would likely increase integration risks since a larger mass of oxygen would be needed. ECLSS system reliability would also need to be improved, or a larger number of spare subsystems for ECLSS would be needed to be carried on each mission.

Closed-loop water management technologies: Closed-loop water recovery and management systems purify cabin humidity condensate and crew member waste so that the resulting potable water can be reused by the crew. Currently, the ISS recycles 90 percent of the water used on it. NASA has set a target of recovering 98 percent of all the water consumed on the DST. NASA has ongoing programs to develop this new technology (Kayatin 2017).

Habitation technologies: On the ISS, habitation systems include quarters for the crew, a galley, hygienic supplies, clothing and linens, and cargo transfer bags. Crew quarters provide a small private space for sleeping and relaxation. Dehydrated foods and beverages constitute the bulk of crew members' dietary intake, supplemented with fresh foods made available from periodic resupply missions. Limited refrigerated and frozen storage is available for foods that are not shelf stabilized. Laundering of clothing and linens is limited and rudimentary, involving substantial manual effort by crew members. Clothing and linen items contribute substantially to airborne particulate loads that require the crew to periodically clean cabin air filters.

Food currently consumed on the ISS has a one-year shelf life. Consuming only food with a long shelf life could result in the DST crew receiving insufficient nutrients. As of 2015, NASA had not assigned a TRL to foods with a long shelf life for use in space environments (NASA 2015a). NASA has, however, been engaged in studying the longevity of nutrients in food. It is drawing on the U.S. military's research and experience in the preparation of food that can be stored for as long as 3 years.

Medical technologies. Astronauts on the DST will need to be able to carry out their own medical diagnostics. Many medical diagnostic technologies for use on the DST were at low TRLs in the 2015 Technology Roadmap, including technologies for reuse and sterilization of medical equipment, the development of an integrated medical diagnostic equipment and software suite, and drugs with long shelf lives for multi-year missions (NASA 2015).

Without effective medical mitigation measures that can be employed in a spaceship environment, even routine medical issues that arise could become incapacitating or life-threatening. According to the 2015 NASA Technology Roadmaps, new technologies to mitigate the physiological effects of long-duration spaceflight are needed to address microgravity-induced challenges and isolation-induced performance issues. Many technologies remain at low TRLs as of the 2015 NASA Technology Roadmap, including integrated prevention and treatment for changes in vision, flexible remediation technologies (e.g., stem cell-based treatments), and low-footprint, effective exercise technologies (NASA 2015).

2. Propulsion Systems

According to a 2017 NASA presentation, the DST is to use a 300 kW SEP system consisting of 24 AEPSs along with a high-thrust chemical system consisting of 10 bipropellant engines, although a SEP-only variation is also being considered (Connolly 2017). The SEP system would be used in deep space for highly efficient, low thrust maneuvering, while the chemical system would be used in the vicinity of Earth and Mars when more impulse needs to be delivered in a shorter time to reduce gravity losses and trip time. The AEPS Hall thruster systems are to be the same design as those used on the Gateway.

According to conversations with NASA employees, NASA has not yet decided whether the chemical system would consist of hypergolic or cryogenic propellants, but NASA interviewees stated that NASA is strongly considering liquid oxygen (LOX)-methane (LCH_4) propulsion. While there is a large improvement in specific impulse if cryogenic propellants (LOX-LCH_4) are used rather than hypergolic propellants, cryogenic fluids would require additional developments in in-space cryogenic storage to minimize boil-off during the DST's long journey.

Either propulsion system will have to be refueled between missions using the large logistics modules. While refueling technologies would have been demonstrated on the Gateway, the scale of the DST refueling requirements is much greater and will be more challenging.

Based on conversations with NASA officials, NASA is open to alternative propulsion options such as nuclear thermal propulsion (NTP) if the technology becomes available. NTP could significantly reduce the travel time for a crewed journey to Mars over traditional chemical or electric propulsion methods. According to a recent NASA briefing, an NTP-driven DST could reduce the Earth-Mars transit times to 120 days for 540 day total Mars mission time (Houts et al. 2018). If the DST's development timeline is delayed to focus on cislunar activities, there may even be enough time and funding available to develop nuclear propulsion capabilities such that they could be a realistic option for the DST.[7]

3. Electric Power Systems

The DST will require an advanced electric power system capable of multi-year missions with minimal-to-no maintenance. It is to have a minimum design lifetime of 15

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[7] Experts at NASA and outside estimate the cost of a use-ready NTP system at $7-15 billion. Assuming funding availability, time to development is estimated at 8-15 years (or about $1 billion per year). The recurring costs of building, launching and disposing of NTP systems have not been estimated.

years. Current notional design specifications of the DST require up to 20 kW of power for the habitat module and twenty-four 13.3 kW Hall Thruster systems for the SEP system, which would draw up to 300 kW of power. Many of the DST's power systems would be designed using ISS heritage parts, and validated on the Gateway.

To provide adequate electricity for these demands, the DST is expected to employ a solar array that can generate 470 kW of electricity at the beginning of life in Earth orbit. This amount of electricity is over twice the peak power level generated by the ISS solar arrays, although with current technology, ISS-sized arrays could produce over 500 kW. Many solar arrays would be attached to a common backbone structure and controlled by ISS heritage rotary joints. Solar arrays are expected to degrade at 1.5 percent per year of operation. The DST SEP system would be built to throttle across the approximately 50 percent power degradation that would result from the combined effects of the 43 percent reduced sunlight intensity at Mars compared to Earth and radiation degradation stemming from the time spent on trips in deep space. Under this assumption, the solar arrays would have degraded to a power output of approximately 375 kW by the end of life. Power available from solar arrays that exceeds DST demand reduces the risk of individual panel failure to the DST. The structural dynamics of the solar array would need to be evaluated for integrity during a high-thrust chemical engine burn, rendezvous and docking, and occultation events that would cause large temperature gradients across the arrays. The DST arrays could be designed by scaling the Gateway's solar array technology or by adding more solar array wings in one of two configurations: the Northrop Grumman Innovation Systems' MegaFlex or the Deployable Space Systems' ROSA. However, scaling these systems may prove to be challenging.

The DST architecture enables the use of power systems similar to those of the Gateway but scaled to 10 times the power level. In interviews conducted in fall 2017, NASA was conducting a sensitivity analysis for the DST's PMAD operating voltage. The DST would likely either share the Gateway's voltage of 120 volts or have a higher voltage of 300 volts. The major PMAD system technology challenge would be managing the large currents, power levels, and thermal loads in the face of power transients during rendezvous and docking operations when solar array illumination may be sensitive to spacecraft rotation.

The DST PMAD system would also not be able to undergo extensive repairs during transit to Mars. Consequently, the power system would require long life-expectancy components that can withstand deep space radiation environments. They would need to be designed with significant redundancy. The PMAD system would require greater autonomous power system capabilities than the Gateway because communication delays to Mars can exceed 20 minutes compared to the delay time to the Moon of approximately 1 second. The PMAD, energy storage, and thermal control systems would need to be designed to operate with stability throughout power transients induced by variable solar array angles and occultation as well as radiator angles during rendezvous and docking operations.

The DST will require batteries for operation during eclipse when in orbit around Earth and Mars. While the SEP system will likely not operate during eclipse, all other systems will need to function. Although rechargeable batteries have been used in space applications, further research into long-lifetime, human-rated, radiation-tolerant rechargeable batteries would enable greater flexibility in the DST's engineering requirements. Designing the Gateway and the DST to use modular battery packs could facilitate switching batteries as technology improves.

4. Thermal Management Systems

According to interviews with NASA personnel, NASA notionally envisions that the DST would produce up to 32 kW of waste heat from the SEP system, several kilowatts of waste heat from the habitat, and, if cryogenic propellants for a LOX-LCH_4 propulsion system are used, 1.2 kW of waste heat from the chemical propulsion system. Transients in currents and power levels would result in significant fluctuations of thermal loads, requiring radiators to dissipate between 5–8 percent of the DST's rated power output. Consequently, the DST will require a thermal management system that is much more capable than the Gateway's and capable of managing these challenging dynamic thermal loads.

As notionally envisioned by NASA, the thermal management system would consist of a heat exchange system and radiators, with particular attention to the heat loads from the SEP system and the habitat. The DST's power and SEP systems would be much larger than the Gateway's, requiring a larger heat transportation and rejection system. Habitat heat loads are well understood based on experience from the ISS, although not in all the environments to which the DST will be exposed. DST radiators will also need to operate in several dynamic environments, including lunar orbit, deep space, Mars orbit, and transients induced by rendezvous and docking operations. Accordingly, variable emissivity from coatings or geometry of the radiators would increase mission options. Long-duration missions also require radiators to have a long lifetime and to be repaired during an EVA. Non-toxic thermal fluids could enhance crew safety while repairing the system.

If no improvements to thermal management systems are made, such as developing single-loop cooling systems, the DST can be designed with current technology, but the mass of the system would be higher than desirable. Other improvements to thermal management systems, although not required, would improve the mission architecture. For example, increasing the energy storage capabilities of heat exchange materials or passively insulating propellant tanks to eliminate propellant boil-off can reduce the mass of the overall system. Other advances (e.g., variable emissivity and geometry radiators) can enhance the performance of the DST.

5. Summary—Technology Risks for the DST

Overall, we rate the DST as having high technology risk, primarily because several key technologies require substantial development. Major challenges include extending the operational lifetime, and increasing the reliability of all the components, and increasing the sizes of systems, such as the SEP system, borrowed from the Gateway.

We consider the ECLSS as having the highest technology risk. While other technologies discussed here may be technically challenging and involve more variables, they have multiple development pathways, users, and applications outside of NASA's human exploration campaign, whereas few outside of NASA are currently interested in an ECLSS with requirements like the DST's. Furthermore, the performance of these other systems is likely to be well characterized before the first human missions, and the consequences of failure during the mission are lower compared to an ECLSS failure. Increasing reuse of air and water to the levels required, and the design of radiation hardened structures and electronics for the ECLSS will be challenging.

Due to the much larger number of Hall thrusters required for the DST than for the Gateway, NASA will need to evaluate the operation of many closely packed Hall thrusters to reduce unexpected plasma interactions. The facilities to test for such interactions have not yet been developed nor are they to be funded according to currently planned budgets. A PMAD system of this size poses other technical challenges, including thermal management and systems integration challenges. For these reasons, multiple Hall thrusters on the DST represent a medium technology risk.

If LOX-LCH_4 engines are to be used as the second component of the hybrid system, several remaining technological challenges will have to be overcome. Reusable in-space engines and propellant transfer technologies are currently not mature enough for the DST, but these risks are low given that similar engines and systems have already been demonstrated in multiple ground tests and are planned for use on lunar missions.

Although solar arrays with the area needed for the DST have been deployed on the ISS, the ISS deployment encountered significant difficulties. Deployment of 470 kW arrays would be a significant operational challenge and thus present a medium technology risk.

We consider thermal management systems for the DST habitat to be low risk. However, increased work on improved technologies could lead to mass savings, reductions in costs, or more powerful power and propulsion systems. However, the cryogenic systems needed for LOX and LCH_4 to stay in liquid form for 3 years, and achieve near-zero losses from boiling off pose a medium technology risk.

Subsystem design changes could result in the overall mass exceeding mission parameters. While mass creep can be acceptable for a small number of technologies, it becomes problematic when interactions between systems can cause the overall vehicle's mass budget to balloon. For example, if the ECLSS does not achieve the target recycling and recovery rates, it could cause a rise in consumables' mass, propulsion and power system mass, and propellant and propellant tank mass. If these parameters should grow beyond their assumed margins, more SLS missions may be needed to deliver enough supplies for each round-trip DST mission presenting a medium risk to the mission.

D. Other Architecture Systems

Our assessment only covers the time period until the planned launch of a Mars crewed orbital mission. Throughout the NASA literature, however, NASA discusses notional plans to develop lunar landers as part of its return to the Moon, and the conceptual development of these systems is underway. Similarly, to land on Mars by the early 2040s, technologies would need to be under development before the orbital mission is launched. Although the pace of development of these technologies does not need to affect the development of technologies for an orbital mission to Mars, their development will demand management and budgetary resources during the duration of the missions and programs evaluated in this report. For these reasons, we include a discussion of lunar landers and Mars surface systems here, and then again in the chapters on costs and budgets.

1. Lunar Landers

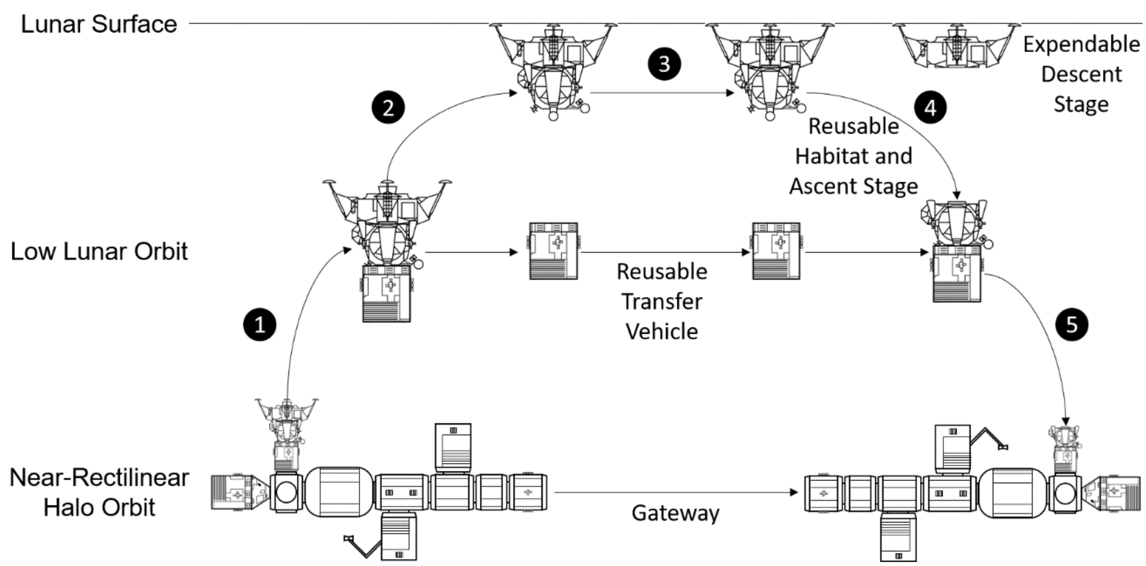
Several lunar landers are notionally planned. As per NASA documents and discussions, first, a small lander focused on science missions will be procured under the Commercial Lunar Payload Services (CLPS) program. Second, a medium-sized robotic lunar lander capable of placing 500–1000 kilograms on the lunar surface will be used for a least two science missions. Third, a human-scale descent module will be used once to test large-scale propulsion technologies that will be required for future missions. Fourth, a large expendable descent stage capable of placing payloads weighing 5,000–6,000 kilograms on the lunar surface will be designed based on the human-scale descent module. The expendable descent stage will be used for both cargo and crew missions, with different payloads on board depending on the mission.

The small CLPS landers will be used to place 10 to 30 kilogram science payloads at desired landing sites. Nine companies were recently selected for Indefinite Delivery/Indefinite Quantity contracts under this program: Astrobotic Technology, Deep Space Systems, Draper, Firefly Aerospace, Intuitive Machines, Lockheed Martin Space, Masten Space Systems, Moon Express, and Orbit Beyond. The landers are required to provide lunar surface "utilities" such as power, communications, and thermal management for the payloads. Even though these companies have been selected, there is little public information on the systems and technologies as these are proprietary. However, the technologies required for these landers are well within current capabilities.

The medium-sized robotic lunar landers are planned to be capable of placing 500 to 1000 kilograms on the lunar surface. One of the expected payloads is planned to be a science rover. This size lander is two to three times the mass landed by the Surveyor missions in the 1960s but is well within the capabilities of existing technologies. Many of the companies above have longer-term plans to develop mid-sized rovers.

Larger missions to the lunar surface are more challenging due to the masses required to land a crew of four on the surface and the desire to maximize the opportunities for commercial participation in lunar surface operations. While trade studies for lunar lander designs are underway (Crusan 2018), no design selections are expected until 2019, at the earliest. To stay within the commercial launcher delivery capabilities to Gateway while maximizing lander system reusability, a three-stage human-scale lander design has been proposed. This approach uses three architectural elements: the large expendable descent stage (described above), either an expendable lunar cargo carrier (for cargo missions) or a reusable habitat and ascent stage (for crewed missions), and a reusable transfer vehicle.

A “bat diagram” of this mission concept is shown in Figure 8. First, the reusable transfer vehicle will transport the expendable descent module and payload from the Gateway’s NRHO orbit to an appropriate low lunar orbit (1). From there, the expendable descent stage would descend to the surface carrying the payload (2). After landing, surface operations would begin (3). Robotic cargo landers would simply remain on the surface—eliminating the ascent capability adds several thousand kilograms to the delivered payload. Crewed landings would use the reusable habitat and ascent stage to transfer from the lunar surface back to the reusable transfer vehicle in low lunar orbit (4), which would then transport the crew back to the Gateway in NRHO (5).



Source for selected clip art: Morris, Steve. 2014. “Saturn V / Apollo Mission.” https://www.behance.net/gallery/15121165/Saturn-VApollo-Mission

Figure 8. "Bat diagram" of the proposed lunar landing architecture with Gateway

Both the tug and ascent stages are reused, but the descent stages would be expendable. The reusable tug and ascent stages could be refueled at Gateway. All three stages can be delivered to Gateway separately and dry (i.e., without fuel). Every landing mission would require delivery of a new descent stage and propellant for all three stages. Delivery of the descent stage and required propellant for a single round-trip lunar surface mission for a crew of four could be accomplished with two or three commercial cargo flights, depending on the exact capacity and manifesting of the descent stage and propellant.

Assuming that the reusable transfer vehicle, expendable descent stage, and reusable habitat and ascent stage all use storable bipropellants (NTO/MMH or NTO/N_2H_4), these requirements are within existing capabilities. Cryogenic propellant landers, including either LOX/N_2H_4, LOX/CH_4 or LOX/LH_2, will require further development of deep throttling engines capable of controlling landers during descent as well as cryogenic refueling technologies. Other lander systems, including the expendable cargo carrier for cargo missions and the reusable habitat and ascent stage would also employ existing technologies such as life support and communications systems. We assume that initial crewed missions to the lunar surface will be limited to 14-day stays.

While the development of lunar lander technologies and operations experience within a sustainable architecture with commercial resupply of propellant has some applicability to future Mars surface missions, the technology for the landers themselves does not easily transfer from the Moon to Mars. The Moon has a small gravity well and no atmosphere, while Mars has a slightly larger gravity well and an atmosphere that is uniquely challenging for transfer between Mars orbit and the surface; the atmosphere is too thin for parachutes to be effective enough to land without propulsive efforts, but too thick to easily ignite rocket engines while traveling backwards supersonically. Additional technical efforts to develop sustainable Martian landing vehicles will be required beyond these lunar landers and will be discussed in the next section.

The technologies required for a lunar landing architecture vary from low to medium risk. The in-space propellant transfer technologies required for the system are immature, though the Gateway buildup will help reduce this risk. The descent module and reusable tug are a low technology risk, and re-ignitable engine technology is advanced enough for this to be a small concern. The habitat and ascent module is a medium risk since no other vehicle has been designed to be reusable, land on and take off from a planetary surface, maintain a livable habitat, and dock with multiple vehicles in a single mission without maintenance, inspections, repairs, and refueling on the Earth.

2. Mars Surface Systems

Two types of landers would be needed for Mars cargo and crew. While the propulsion systems may be common between the two landers, the Mars entry requirements for the two vehicles would be quite different. The cargo mission would likely need to arrive at Mars at least 2 years before the astronauts to allow system emplacement and complete verification before the astronauts leave Earth orbit. This approach significantly reduces crew risk by having a fully operational habitat ready for the astronauts when they land. However, it would require highly precise landing technology since the crew must land close to, but not too close to, the established surface systems.

The astronauts would also need a Mars Ascent Vehicle (MAV) to return them to the orbiting DST at the end of their mission. Surface systems include the Mars habitat and all life support systems, all consumables (air, water, food), power and thermal management systems, propellant production, and any equipment required for surface mobility (rovers), EVA (appropriate space suits), and to conduct scientific investigations. If the MAV is to use in-situ propellant, the surface systems must include a full-scale propellant production capability landed 2 years before the astronauts arrive. The Mars habitat is likely to be similar to a space station module but designed for a gravity environment and able to survive planetary entry, descent, and landing. It might include greenhouses and methods for burial in regolith to reduce radiation exposure. A nuclear fission reactor (such as NASA's Kilopower System) is an option for generating power and heat, in addition to solar arrays (with batteries) that may work if the landing site is in the equatorial region. While very early conceptual studies of surface systems have been made, there is still considerable uncertainty.

All of the technologies needed for Mars surface operations are currently high risk (or even very high risk). In most cases, technological development is just beginning. Because of Mars's thin atmosphere and greater gravity than the Moon's, a Mars Descent Vehicle (MDV) that is capable of ferrying humans and landing them on Mars softly will be more challenging than landing on the Moon or Earth. Mars's atmosphere is too thin for sufficient reentry braking or for parachutes to be effective enough on their own, but thick enough that supersonic retrorocket technology will need further development and testing before it can reliably land heavy payloads on the surface softly.

The MAV poses several risks unless it is first tested without humans. NASA is likely to want to test a full-scale uncrewed mission of the MAV before placing astronauts on it. Technologies for in-situ resource utilization are still in their infancy. While the Mars 2020 rover will carry the Mars Oxygen In-situ Resource Utilization (MOXIE) experiment to produce oxygen from the Mars atmosphere for breathing and propellant, larger scale demonstrations are required on future surface missions before the technology can be relied upon for survival and return of astronauts to Earth. It is also not clear that MOXIE can be scaled to the right level for the operational mission. While R&D on a prototype is underway, designing, building, and operating a fission nuclear reactor on the surface of Mars would require many more years of technological development and maturation.

Rendezvous and docking in Mars orbit would be required to transfer crew from the DST to the MDV and from the MAV back to the DST. Launching from the surface of Mars and navigating to an orbital rendezvous point is also a mission-critical challenge that has never been attempted before. Without a demonstration of docking, possibly with a resupply vehicle, during the orbital mission, a crewed mission to Mars would not have had the opportunity to test such a maneuver in Mars orbit before attempting a landing.

E. Key Findings Related to Technology Risk

Due to long development programs and ongoing testing, SLS and Orion present low technology risks to a Mars orbit mission. SLS Block 2 Advanced Boosters presents a low-to-medium technology risk, depending on the design that is ultimately selected. Ground system upgrades and refurbishment are nearly complete, and future upgrades do not involve technology innovation, thus EGS presents low technology risk.

Currently, NASA notionally plans to launch crew on the first flight of SLS Block 1B (EM-3). Although conducting extensive ground testing can reduce the overall risk to astronauts, the notional schedule implicitly accepts a higher level of technology risk than would be the case if new systems were flight tested with uncrewed launches.

The Gateway presents medium technology risk because its current conceptual design largely builds on ISS-heritage technologies. Certain technologies (e.g., xenon refueling and autonomous environmental monitoring) present moderate risk because they have not been demonstrated previously at the scale required by the Gateway. However, if additional modules are added or mission requirements expand, the Gateway may face higher technology risk. In particular, power, propulsion, and life support systems are sized for a small Gateway. Increasing the complexity and size of the Gateway would require larger systems, which would add to technology risk. Integrating and testing Gateway elements, whether at its current scale or a larger, may face medium technology risk.

The DST requires several medium and high-risk technologies. Notably, an ECLSS that meets the requirement of the DST is currently at a low TRL. NASA plans to test an ECLSS with high oxygen reclamation rates on the ISS starting in 2022. Scaling systems from the Gateway (e.g., the solar array and propulsion system) is non-trivial and thus presents a medium technology risk. Additionally, minimizing boil-off of cryogenic propellant presents a medium-to-high technology risk. Integrating each system into a single bus is high risk because a small change to one system could require a series of changes to the rest of the spacecraft due to the scale and interdependent nature of DST systems.

Notional plans for a human mission to Mars rely on several medium- and high-risk technologies to reach completion. Although spacewalks on the Gateway and DST would be kept to a minimum, deep space spacesuits will be necessary for repairs. The next generation of spacesuits presents a medium technology risk that must be addressed in the near future if they are to be ready by the launch of the Gateway. Many technologies associated with a Mars surface mission are high risk, including a MAV, surface habitation, exploration systems, and in-situ resource utilization.

3. Schedule Assessment

As discussed in Chapters 1 and 2, under NASA plans, four complicated elements—SLS, Orion, the Gateway, and the DST—would need to be developed prior to a human mission to orbit Mars. During this same period, other human exploration systems, such as lunar and Martian landers, are likely to be developed. In this chapter, we first examine the proposed development schedule of key systems, or, when not publicly available, provide our own estimates. Next, we review NASA's announced and proposed schedules for human space exploration, which run through approximately 2028. Based on NASA's publicly released notional schedules, including those in presentations given to the NASA Advisory Council and in the *National Space Exploration Campaign*, and interviews with NASA personnel, we then developed a schedule leading to an orbital human spaceflight mission to Mars. Because schedules are also driven by the cost of systems and available budgets in addition to the progression of technology development, we discuss supporting cost and budget information for the schedule presented here in Chapters 4 and 5, respectively.

A. Development Schedules for Key Systems

1. SLS

As per NASA documents, the SLS is to be developed in three stages: Block 1, Block 1B, and Block 2. SLS Block 1 is planned to be used three times, starting in mid-2020 for EM-1, the first uncrewed test of SLS. As of the time of this publication, NASA plans to use this configuration of SLS for its crewed test EM-2, currently scheduled for September 2022, and the launch of Europa Clipper, notionally scheduled for 2023 based on interviews with NASA personnel.

Block 1B, which upgrades Block 1's upper stage, is planned to debut in 2024 with EM-3. Work on the new upper stage—the EUS—has been ongoing for several years, with development nearing critical design review (Foust 2018a). However, in recent months, NASA has asked Boeing to make modifications to EUS's design to increase performance, leading to a longer development timeline than initially scheduled. Based on conversations with NASA personnel, we set the readiness date of EUS and the launch of EM-3 in the first half of 2024. SLS Block 1B is expected to be used a total of five times, until the final set of the eight remaining sets of Shuttle boosters is expended on EM-7.

Subsequent SLS missions will use the Block 2 configuration with a new booster design. For this report, we assume a five-year development cycle for formulation and implementation of an advanced booster, with a readiness date of 2026.

Based on interviews, NASA expects to be able to reach a peak launch capacity of up to two SLSs per year and notionally plans to launch one crewed SLS annually, assumptions which we adopt for this report. Under the schedule developed in this report, NASA would launch SLS once annually (crewed or uncrewed), except for two periods when NASA may launch three SLSs (two crewed SLSs and one cargo SLS) within a two-year range in 2023–2024 and 2032–2033. NASA also expects every SLS procurement will require a five-year lead-time before launch.

Based on NASA's current and notional plans and the availability of other human spaceflight systems (e.g., the Gateway, lunar landers, or the DST), we developed a set of notional missions for SLS launches through the mission to Mars orbit. Figure 9 shows the notional launch schedule of SLS used in this report between now and 2037. We discuss these missions and the justifications for their schedules in detail in relevant sections below, but we briefly list them together here to complete the discussion of SLS's schedule. EM-1 and EM-2 are the uncrewed and crewed tests of SLS and Orion, respectively. EM-4 through EM-6 are associated with the assembly of the Gateway. As discussed in Section C of this chapter, under NASA's notional plans, the DST would not be available for launch until 2033, as such our schedule assigns EM-7 through EM-12, which would take place from 2027–2032, to lunar activities. As discussed in Section B.2 of this chapter, the first lunar landing is notionally scheduled to take place in 2028 on EM-8, meaning that the launch opportunity in 2027 reserved for EM-7 does not have a notionally planned purpose. This mission could, for example, be used to test lunar landing systems or conduct a 90-day mission to the Gateway. The DST would launch on a cargo SLS in 2033 and travel autonomously to the Gateway. EM-13 would be a crewed mission to the Gateway to test DST systems and complete any in-space fabrication of the DST during the "checkout" mission. EM-14 would be the one-year "shakedown" test of the DST in lunar orbit. EM-15 would refit and refurbish any systems necessary before the departure of the DST to Mars orbit on EM-16. The last mission in Figure 9, EM-17, would launch an uncrewed Orion in 2040 to bring astronauts back from the DST to Earth.

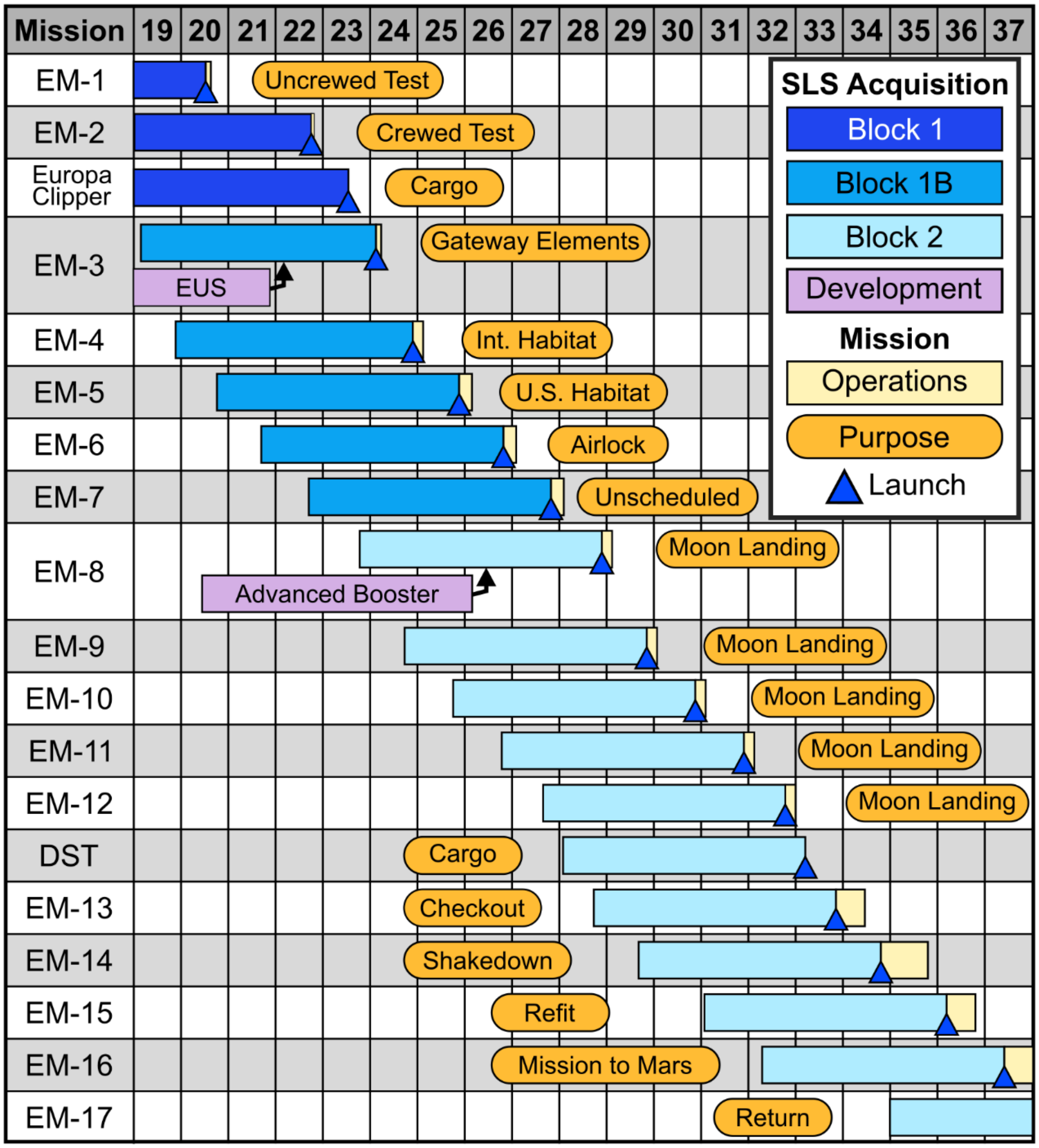


Figure 9. Notional Schedule of SLS Launches and Their Purpose through 2037

2. EGS

As of March 2018, the EGS, including the Vertical Assembly Building, Crawler-Transporter, Mobile Launch Platform (ML), and SCCS GFAS, were scheduled to be ready for EM-1, which at the time was set for launch in 2019 (Hill and Smith 2018). Since the development and delivery of the core stage of SLS is the most important driver of EM-1's schedule, and since EM-1's launch date is now scheduled for mid-2020, EGS should be ready before EM-1's planned launch date.

In May 2018, Congress appropriated funds to build a second mobile launcher able to support SLS Block 1B and Block 2 launches. In NASA's request for proposals for the system issued in July 2018, NASA set the period of performance for the contract to be 44 months (NASA 2018b). With the contract award expected in February 2019, a second mobile launch platform is expected to be ready by the end of 2022. In the schedule presented in this report, we assume ML-1 will undergo refitting to accept SLS Block 1B and Block 2 after the last notional launch of SLS Block 1 in 2023 for the Europa Clipper mission. We assume this process will take 33 months, as called for in NASA's previous plan (Smith 2018a), and will be ready in 2026.

3. Orion

Orion has been repeatedly delayed, most recently because of delays in receiving the ESM from Airbus. Under the Constellation program, after missing initial deadlines, the first launch of Orion was scheduled for no later than 2015 (GAO 2009b). An uncrewed Orion capsule is now to be launched on SLS Block 1 in mid-2020. The first crewed Orion capsule is to be launched on SLS Block 1 by 2022. Orion capsules can be produced at a cadence of one per year, with the ability to ramp up the schedule to two or three a year. The crew module, avionics, and other parts of Orion may be able to be reused. Under our assumptions concerning schedule, one Orion capsule is produced or refurbished every 2 years with work underway on two at the same time, assumptions that provide slack for the schedule.

4. Gateway

As shown in Figure 10, the Gateway is to be built and launched in several phases. NASA's broad agency announcement for the first operational module, the PPE, was released in September 2018. Contracts for the system are to be awarded in March 2019. The broad agency announcement calls for launch of the system no later than September 2022 and 1 year of in-space testing prior to handover to NASA (NASA 2018c). The PPE is to be launched on a commercial launch vehicle in 2022.

The next elements to be launched are the European ESPRIT module and the U.S. Utilization Module. These elements would be co-manifested on EM-3, notionally scheduled for the first half of 2024, based on interviews with NASA personnel. NASA presentations state acquisition time of both of these systems to be 3 to 4 years (Gerstenmaier and Crusan 2018).

The Gateway is to have two crew habitats, one provided by international partners and one by the United States, each with a 5–6 year acquisition period. Notional schedules have the International Habitat launching first, but no earlier than 2024, and the U.S. Habitat launching no earlier than 2025 (Gerstenmaier and Crusan 2018), which we adopt for our schedule here. Interviews with NASA personnel revealed that these plans are flexible, and that the launch order of the habitats may be switched.

Other Gateway components include an airlock, a robotic arm, and a sample return vehicle from the lunar surface. NASA expects the airlock to take 3–6 years for acquisition and to be launched on EM-6 (Gerstenmaier and Crusan 2018; Gerstenmaier 2018), which we notionally schedule for 2026.[8] The robotic arm is to be launched on the first logistics flight to the Gateway, scheduled for 2024. Based on NASA presentations, we assume the sample return mission from the lunar surface will occur in 2025.

The Gateway will also host expendable logistics modules used for temporary storage and waste disposal for when the crew is aboard. In October 2018, NASA released a RFI on logistics modules for the Gateway. NASA expects the acquisition time for such modules to take 3–4 years (Gerstenmaier and Crusan 2018). From interviews with NASA personnel, each logistics module will be able to hold enough cargo for 90 days of crew activities aboard the Gateway. As such, for this report, we assume one logistics module will be launched in 2024, 2025, 2026, 2027, 2029, and 2031, and two modules will be launched in 2033, 2034, 2035, and 2036 to support crew operations on the Gateway. Modules will either launch aboard commercial vehicles or be co-manifested with Orion capsules when SLS has no other payload. We assume the development of both the commercial logistics module and the SLS co-manifested logistics module will start in FY 2020 and take 4 years.

[8] Alternatively, NASA may delay the launch of the Gateway airlock in order to launch the reusable lunar habitat and ascent stage aboard SLS on EM-6. For this report, we assume that the reusable habitat and ascent stage for lunar landings would be launched on a commercial vehicle.

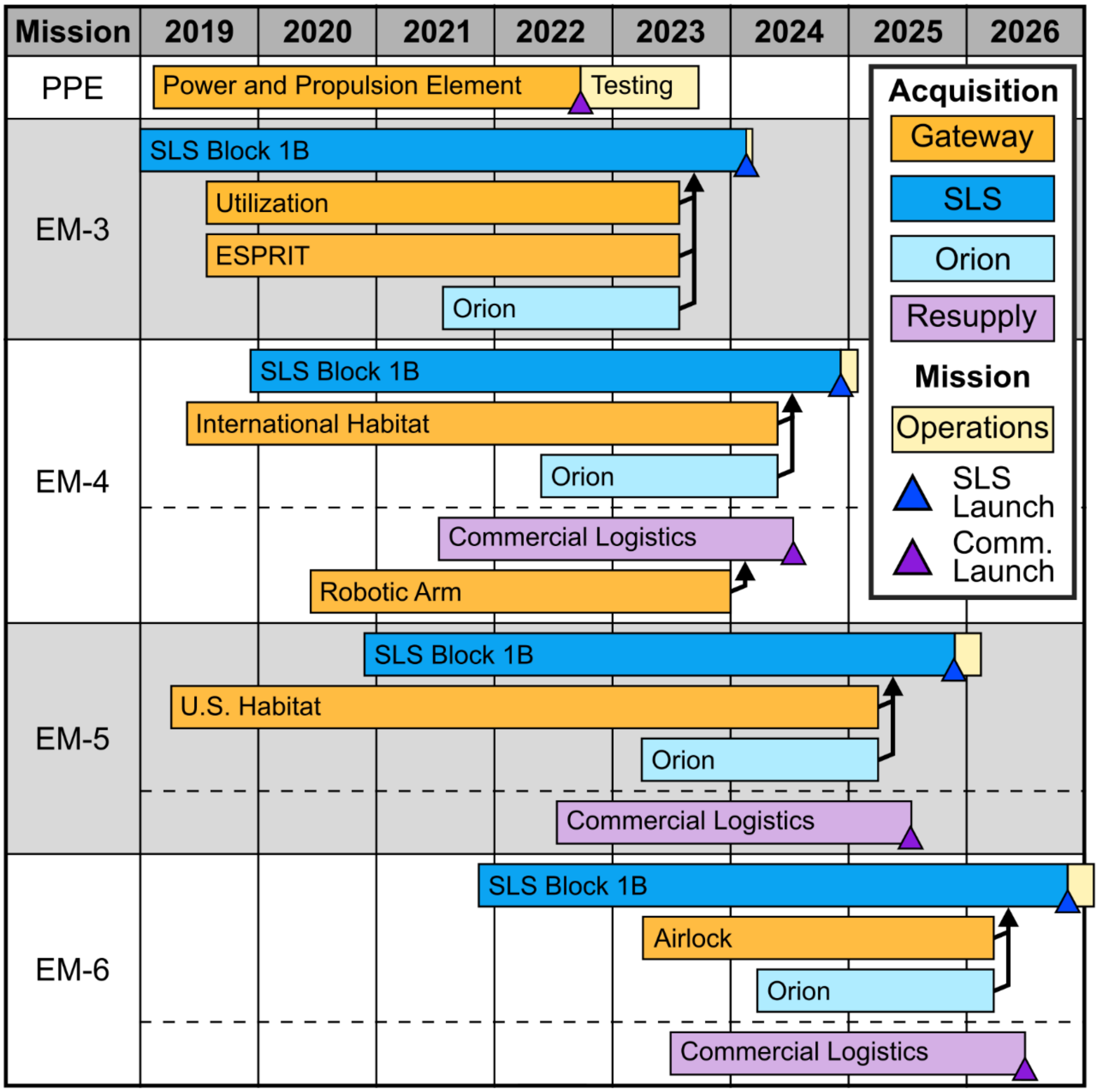


Figure 10. Notional Development and Assembly Schedule of the Gateway

5. Lunar Landers

Based on NASA's announced and notional schedules, conversations with NASA personnel, and assumptions for future NASA needs, our schedule requires multiple architectural elements for lunar crew and cargo landing systems: a medium-sized lander, a human-scale descent module, a large expendable descent stage, a reusable habitat and ascent stage, a large expendable cargo carrier, and a reusable transfer vehicle.[9] The medium-sized lander would be launched twice: once in 2022 and again in 2025. The

9 Other small lunar landers would be built as part of the CLPS program, but as they are funded and used by the science mission directorate, we do not include them here.

human-scale descent module, a technology testbed for lunar lander technologies, is to launch in 2024. Here, we assume this descent module would be used as the basis of the large expendable descent stage. We estimate that both of these would require 4 years for development, and that procuring subsequent landers would take 3 years.

In this report, we assume that a crewed lander would be a three-stage system: a reusable transfer vehicle that would ferry the lander to and from the Gateway to low lunar orbit, an expendable descent module, and a reusable habitat and ascent stage, which can support the 14-day surface stays for a crew of four. These systems would each be transported to the Gateway by commercial launch vehicles.[10]

We estimated the development and procurement timelines for each architectural element based on the relative complexity of the components. The reusable transfer vehicle would take 4 years to procure, whereas the reusable habitat and ascent stage would take 5–6 years to design and build. The expendable descent stage would be based on the technologies used in the human-scale descent module, and would take 4 years to design. Subsequent expendable descent stages would take 3 years each to procure. Each lunar landing would also require two to three commercial fueling missions to refuel the reusable architectural elements and possibly the expendable descent stages.

The large expendable cargo carrier would likely take 3 years to procure. This system would not debut until the third Moon landing. As an assumption in this report, it would carry $100 million worth of cargo, such as a lunar rover, which we estimate would require a four-year lead-time. This system would also be carried by a commercial launch vehicle.

6. Deep Space Transport

Unlike the Gateway, the notional DST would be designed to launch as an integrated spacecraft, so the propulsion and habitat would never be fully separate systems. Based on NASA best practices and interviews with NASA personnel, we created a notional project lifecycle for the DST. Due to the complexity of the DST and knowledge gleaned from designing and building the Gateway, the DST's Pre-Phase A would last 2 years. Following project approval, the DST formulation phase (Phase A through preliminary design review) would take 2 years. The DST implementation phase—starting with Phase C (final design and fabrication) through system assembly, integration, and testing—would span 6 years. The DST would then be delivered for integration into SLS at least 6 months prior to launch. Following launch, the DST would undergo several years of in-space testing and refurbishment at the Gateway and around the Moon prior to its first mission to Mars. Based on interviews with NASA personnel, the DST is planned to be reused for at least three

[10] Alternatively, NASA may delay the launch of the Gateway airlock in order to launch the reusable lunar habitat and ascent stage aboard SLS on EM-6. For this report, we assume that the reusable habitat and ascent stage for lunar landings would be launched on a commercial vehicle.

missions to Mars. We assume a minimum of 1 year would be required for refurbishing the DST between trips to Mars. As indicated in Chapter 2, use of an NTP system could cut transit time to Mars by 30 percent or more.

B. Announced and Proposed Spaceflight Plans

1. LEO Operations

The Trump Administration has announced plans to stop directly funding the ISS in 2025. Interviews with NASA personnel revealed that NASA's notional plans expect a space station, whether the ISS or a commercial platform, in LEO post-2024 for extended human health research and technology development. Previous STPI research suggests that an alternative to the ISS will not be available during this time without large subsidies provided by NASA (Crane et al. 2017). Additionally, NASA's international partners support extending the ISS to at least 2028 (Foust 2018b). Accordingly, in this report, we assume the ISS will be operated until 2028. In the following years, we assume that NASA will continue sending astronauts to private space stations and offering subsided transportation to the operators of these space stations. Currently, NASA is offering $900 million in subsidies over 5 years for LEO commercialization efforts with the hope of having a commercially viable platform by the mid-2020s.

2. Lunar Exploration

NASA's primary focus for human spaceflight in the 2020s is the Moon. Starting in 2022, NASA plans to begin assembly of the Gateway in lunar orbit. Over the course of the 2020s, NASA will purchase or build a series of lunar landers. In this report, we assume NASA will purchase one small lander from the CLPS program annually and two mid-sized landers in 2022 and 2025.

For crew landing systems, NASA is currently conducting trade studies on possible architectures. For this report, we assume NASA will choose a three-stage lander architecture—composed of a reusable transfer vehicle for in-orbit movement, a reusable habitat and ascent stage, and an expendable descent stage (see Figure 8)—as this architecture enables the greatest use of commercial launch vehicles and propellant delivery services. From public presentations, NASA has proposed launching a human-scale descent module technology testbed in 2024, and conducting a human-class end-to-end test of the landing system in 2026, which we take to mean testing the reusable transfer vehicle and habitat and ascent stage that would be used in subsequent human landings, along with the final version of the expendable descent module. For this report, based on public statements by NASA Administrator Jim Bridenstine and NASA Associate Administrator for Policy and Strategy Tom Cremins, we set the first human lunar landing in the second half of 2028 (Bonn 2018; Smith 2018b).

3. Mars Exploration

NASA has not announced a notional timeline for human exploration of Mars. In this report, we base our notional timeline for Mars exploration using the timeframe of two decisions listed in the Campaign Report, in which NASA states it will “decide on architecture of human Mars orbital mission and begin associated systems development” in 2024 and “determine set of technology investments and timeline required to achieve human landing on the surface of Mars” post-2024 (NASA 2018a).

C. Focus on Mars in the 2030s

Based on the announced plans and system development schedules listed above, we have developed a notional schedule leading to the earliest feasible date of a human orbital mission to Mars, as shown in Figure 13, below. Two major assumptions drive our schedule. First, NASA has stated it plans to “decide on architecture of human Mars orbital mission and begin associated systems development” in 2024 (NASA 2018a), which drives the development cycle of DST in the schedule presented in this report and which we fit other human spaceflight activities (e.g., lunar landings) around. Second, based on conversations with NASA officials, NASA plans to launch one human mission to the Gateway annually, to either work aboard the Gateway, operate the DST, or to transfer to the lunar surface, which forces NASA to make trade-offs between focusing on lunar landings and preparing the DST for the mission to Mars.[11]

We employed these assumptions to create a schedule for the first crewed orbital mission to Mars. We take the first assumption to mean that the decision to construct the DST would be announced as part of the FY 2025 PBR in early 2024, and that Phase A would begin at the start of FY 2025 (in the second half of calendar year 2024). This implies that the two-year Pre-Phase A begins in 2022. The DST’s formulation phase would last until 2026, and final design would conclude in late 2028. Fabrication, assembly, vehicle integration, and ground testing would take place over the following 4 years, and the DST would be delivered for integration into SLS in the second half of 2032.

The DST would be launched on a cargo version of SLS Block 2 in 2033, and travel to the Gateway. Based on notional plans for DST missions NASA publicly released in 2017, and from discussions with NASA personnel, three DST missions would take place prior to its first mission to Mars. The DST’s in-space testing schedule is driven by our second assumption that NASA plans to launch one human mission to the Gateway annually, as this forces DST testing missions to take place at a slower cadence than possible. In our schedule, after transiting to the Gateway, a crew would check out the DST,

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[11] Our schedule makes one exception to the second assumption. According to NASA documents and conversations with NASA personnel, EM-3 is notionally planned to launch at the end of 2023 or early 2024. In this report, we list the date as 2024. Our schedule calls for EM-4 to launch at the end 2024.

and install various subsystems in the latter half of 2033. In the second half of 2034, the DST would depart on a one-year shakedown mission to validate all systems in deep space before returning to the Gateway. Another mission would be launched in the first half of 2036 to refurbish and refuel the Gateway. Each of these missions would be supported by co-manifesting cargo on SLS along with commercial logistics and propellant missions as needed. Figure 11 shows the notional timeline of development and testing for the DST.

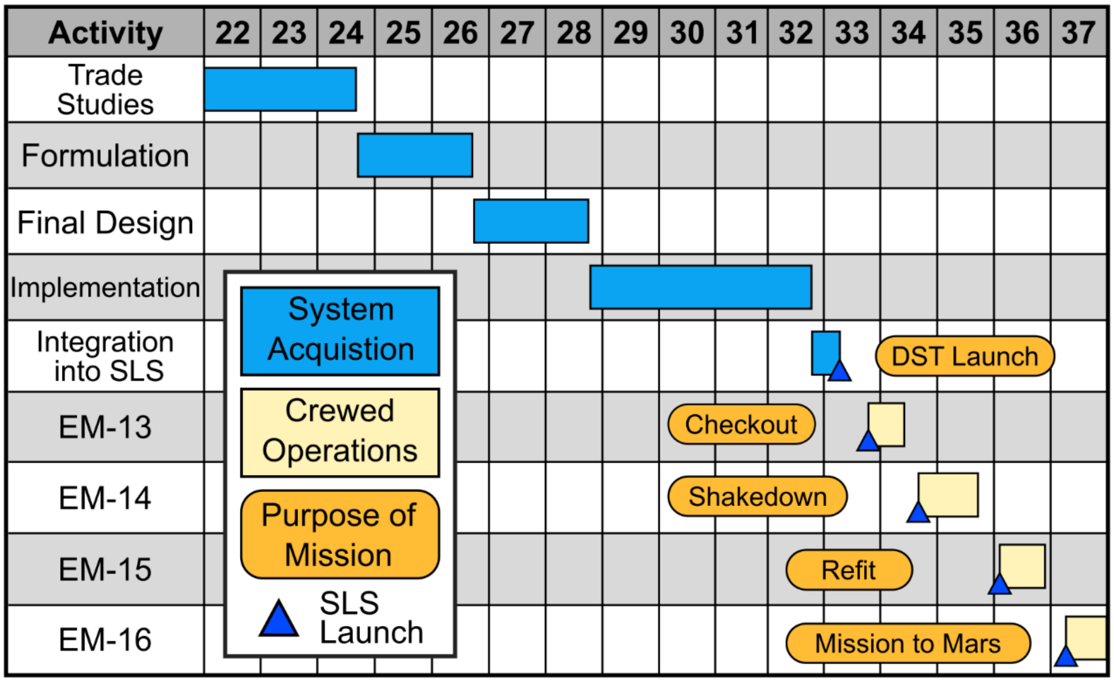
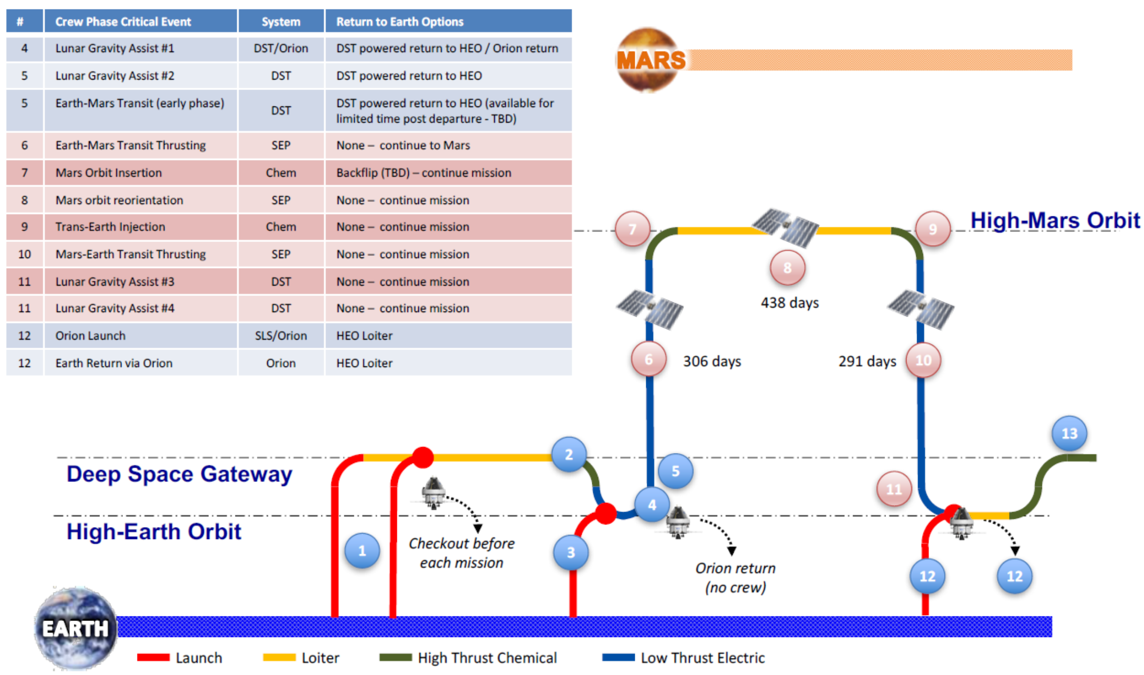


Figure 11. Notional Schedule of the development and testing of the DST through 2037

Because the next available opportunity for a low-energy transit to Mars is in 2037, our schedule calls for the first human mission to Mars orbit in 2037. Figure 12 is taken from a publicly available NASA presentation (Connolly 2017), and shows a "bat diagram" of the notional mission concept of operations for the DST on its first mission to Mars orbit. An important aspect of this notional concept is that after a checkout mission, the DST travels autonomously from the Gateway's NRHO orbit to a high-Earth orbit, where a crewed Orion vehicle rendezvouses with the DST to transfer the crew before traveling out of Earth's gravity well and towards Mars.[12]

[12] Other mission concepts for the orbital mission to Mars could include visiting Mars's moons, Phobos and Deimos.



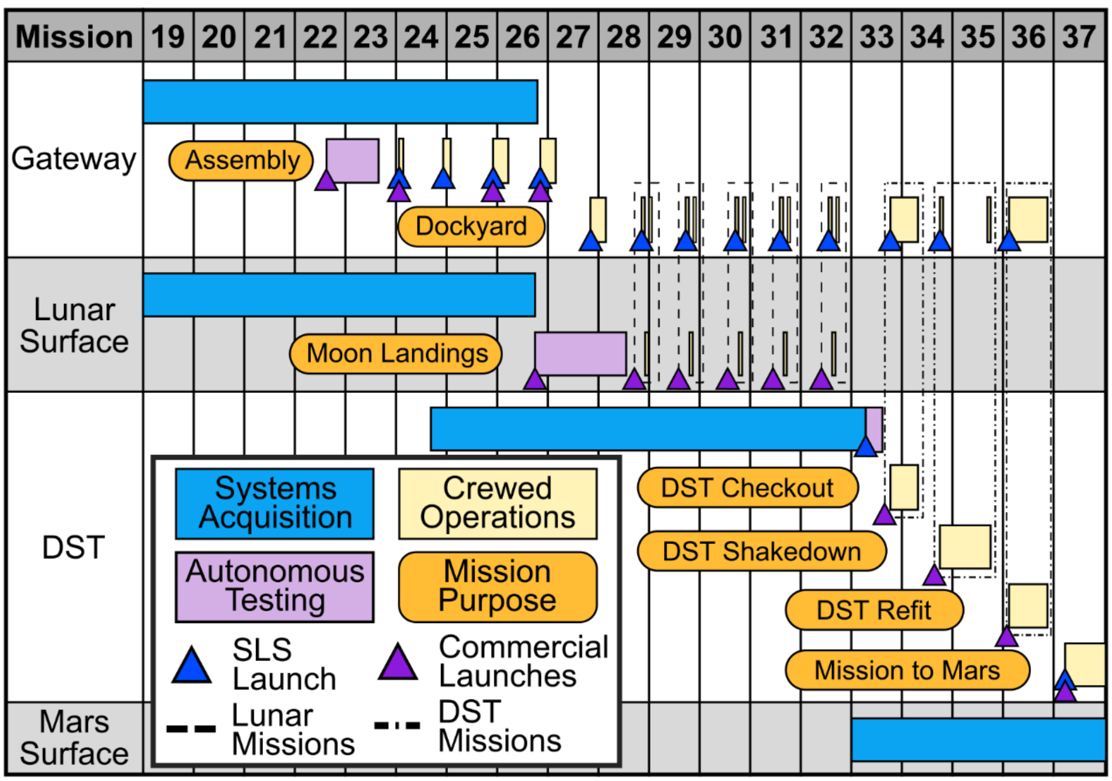
#	Crew Phase Critical Event	System	Return to Earth Options
4	Lunar Gravity Assist #1	DST/Orion	DST powered return to HEO / Orion return
5	Lunar Gravity Assist #2	DST	DST powered return to HEO
5	Earth-Mars Transit (early phase)	DST	DST powered return to HEO (available for limited time post departure - TBD)
6	Earth-Mars Transit Thrusting	SEP	None – continue to Mars
7	Mars Orbit Insertion	Chem	Backflip (TBD) – continue mission
8	Mars orbit reorientation	SEP	None – continue mission
9	Trans-Earth Injection	Chem	None – continue mission
10	Mars-Earth Transit Thrusting	SEP	None – continue mission
11	Lunar Gravity Assist #3	DST	None – continue mission
11	Lunar Gravity Assist #4	DST	None – continue mission
12	Orion Launch	SLS/Orion	HEO Loiter
12	Earth Return via Orion	Orion	HEO Loiter

Source: Connolly 2017

Figure 12. Notional Schedule of the first mission to Mars

After returning in 2040, the DST would be refurbished again at the Gateway and depart for a Mars landing mission as early as 2041, for the first human landing on Mars. As this study focuses on an orbital mission to Mars, and not on the first Mars landing, we only develop a notional architecture for Mars landings to account for the potential impact the costs of these surface mission systems would have on projected budgets (discussed in Subsections 2.D.2 and 4.D.2). After returning approximately 3 years later, the DST would be refurbished at the Gateway before departing on one final mission to Mars.

One consequence of our assumption that NASA can support one human mission to the Gateway each year is that there are six human mission slots open from 2027–2032—as the DST is unable to launch until 2033—which we assign to Moon landing missions. As noted above, based on public statements by NASA officials, we set the first human lunar landing in the second half of 2028 (The Hill 2018; Cremins 2018) on EM-8. In order to meet this deadline and test the system in space, our schedule assumes that the full lunar landing system would be tested during a NASA human-class end-to-end test in 2026. The lunar lander would undergo any required in-space checkouts in the second half of 2027 during EM-7. To fit with NASA's announcements, EM-8 in 2028 would be the first lunar landing mission. In total, we schedule five lunar landings from 2028 to 2032. For the final three launches in 2030, 2031, and 2032, we assume a cargo lander would bring an additional $100 million worth of cargo, such as a lunar rover. These six landings (one autonomous and five crewed), would require the support of 29 commercial launch vehicles to deliver lander modules, supplies, and propellant. After the launch of the DST in 2033, NASA deep space human exploration focuses on preparing for an orbital mission to Mars, as discussed above. However, based on NASA's current program to support the development of commercial space stations in LEO to take over LEO operations following the retirement of the ISS, we assume that the United States will support commercial lunar surface activities following the end of NASA's landings. As such, we allot for the support of commercial activities on the lunar surface following the last NASA lunar landing in 2032. Ultimately, our report assumes that the scope of NASA's lunar activities will depend on available budgets, as discussed in Chapter 5. Figure 13 shows the notional schedule of all major NASA missions through 2037 developed for this report.



Note: "Assembly" refers to the four missions dedicated to assembling the Gateway in lunar orbit; "dockyard" refers to the use of the Gateway as a staging ground for lunar and DST missions; the "DST checkout" is a mission to test and furnish the DST while docked at the Gateway; the "DST Shakedown" is a 1-year test flight of the DST in cislunar space; the "DST Refit" is a mission to refurbish the DST between the shakedown and the mission to Mars orbit.

Figure 13. Notional Schedule of Major Architecture Elements Leading to a Human Mission to Mars by Year

D. Schedule Risks to a Human Mission to Mars

Under the schedule described above, a mission to Mars depends on the readiness of each of the interdependent elements of NASA's human exploration architecture—SLS, EGS, Orion, Gateway, and the DST. Here, we describe possible schedule risks for major architectural elements.

1. SLS

Development of SLS is already running behind the originally stated schedule. This delay is not unusual for the development of complex technologies. Its predecessor, the Ares launch vehicle under the Constellation program, was also repeatedly delayed (GAO 2009b). While there is a risk that the first SLS launch of Orion may be delayed again, it is unlikely that the delay would be long enough to affect the timing of the launch of either the Gateway in 2024, or the DST in 2033. As noted above, NASA has asked the developer of the EUS, Boeing, to make changes to its design that could lead to schedule delay. However, the debut of Block 1B, originally scheduled for early 2023 on EM-2, is now planned for EM-3, which would likely occur in early 2024. As such, the risk of major schedule delays for the construction of the Gateway due to SLS Block 1B development is low.

Following an initial procurement program for solid- and liquid-fueled booster concepts in 2012, NASA decided to focus on upgrading the upper stage of SLS before upgrading boosters (Kyle 2017). Advanced booster programs, whether solid-fueled or liquid-fueled, would need to start around 2020 to ensure that the new boosters are ready for an initial mission in 2027. NASA had made no design decisions regarding SLS Block 2’s expanded boosters as of November 2018. Even if a delay occurred in development of Block 2, as the Gateway will be completed using SLS Block 1B and the need-by-date for Block 2 to launch the DST is not until the end of 2032, Block 2 development poses a low risk.

As NASA increases the cadence of SLS launches over the 2020s, it is likely to increase efficiency in production through practice. As such, SLS-readiness is a low risk to delay a Mars mission from a schedule perspective.

2. EGS

Although the current refurbishments of ground systems for EM-1 are complete or nearly complete, because the ground systems are the integration bed for SLS and Orion, any delays in SLS or Orion result in delays in the validation and verification process for ground systems. This is especially true for the ground software systems, which have already experienced delays (NASA Office of the Inspector General 2016). However, because ground systems are nearly complete, the validation and verification process presents a low risk to an EM-1 launch date.

Refurbishing Mobile Launcher 1 is necessary to support SLS Block 1B and SLS Block 2. NASA has announced that refurbishment of the Mobile Launcher for SLS Block

1B would take 33 months to complete, including validation and verification (Berger 2017). Congress has allocated funds to construct a second Mobile Launcher. As noted above, NASA's request for proposals for Mobile Launcher 2 calls for its completion by the end of 2022. In the schedule presented in this report, we assume the first mission to use Mobile Launcher 2 would be EM-3 in 2024 and that Mobile Launcher 1 would undergo refurbishment after the launch of Europa Clipper in 2023, with a need-by-date at the end of 2026 so that NASA has two platforms from which to support both EM-7 and the launch of the lunar lander system in mid-2027. Under these assumptions, the construction or refurbishment of both Mobile Platforms has reserve time to allow for some schedule slippage. Although there may be delays in either program, like with the SLS, any schedule slippage is unlikely to delay the launch of the DST in 2032.

3. Orion

Orion continues to encounter technical problems, such as requiring a redesigned heat shield after the 2014 prototype test to address cracking and manufacturability concerns, which has led to program delays. The only opportunity for a flight test of this new design is on EM-1 since there are no ground-based facilities to test a full-sized prototype of the new design. If problems occur with this new design, further program delays could occur. Development and construction of the Orion module has a history of schedule delays, but with the pushback of EM-1 to the middle of 2020, Orion poses low risk to further delays for its first mission. The GAO notes, however, that the delayed EM-1 may cause delays in Orion production for EM-2 (GAO 2018).

Completion and delivery of the ESM has been repeatedly delayed. The ESM will use updated Orbital Maneuvering Engines for primary propulsion, which NASA is requalifying and supplying (GAO 2017b). There are a limited number of these engines, and as such, more must be produced or another engine procured. Production should start about 7 years before the new engines are needed for EM-6 (notionally scheduled for 2026) to allow time for the new line and production of the additional engines to be completed. NASA released a RFI on service module engines in February 2018 (Gebhardt 2018). All the other engines on the service modules and CMs are variants of engines used for other vehicles so their production schedule likely would not face problems.

Despite delays in the Orion program, further delays pose low risk to a human mission to Mars in the 2030s.

4. Gateway

As noted above, in September 2018, NASA released a request for proposals for the Gateway PPE. The PPE's solar arrays, solar electric propulsion, and refueling capabilities are more advanced than those deployed on existing spacecraft. Technology development over the past several years has greatly reduced the risk that required technologies would be unavailable when needed. As of November 2017, Aerojet Rocketdyne has been contracted to produce a flight-qualified Hall thruster system by April 2019 (Anderson and Rachul 2016). Two different suitable solar arrays, Northrop Grumman Innovation Systems' MegaFlex Array and Deployable Space Systems' ROSA, have been flight tested. The Robotic Refueling Mission 3 launched to the ISS in December 2018, and is to validate cryogenic refueling technology. Unforeseen engineering challenges integrating each of these elements into a single bus may cause delays. However, NASA's current plan for procurement calls for the launch of the PPE in September 2022, to be followed by a year of testing prior to handover to NASA. If a problem is found during testing or the system is delayed in launch, the development timeline of the Gateway may be affected.

According to NASA, the Gateway habitat's major systems, such as the ECLSS, will likely be based on ISS heritage systems, reducing the likelihood of schedule delays due to unexpected problems with technology. The development of habitat prototypes is currently ongoing through the NextSTEP program. For the Utilization module and the U.S. habitat module to be ready for launch, they must be completed by the first half of 2023 and late 2024, respectively. As such, acquisition programs for these systems must begin in the near future (approximately in 2020) or the construction of the Gateway will be delayed.

Other systems (e.g., the airlock module and the external robotic arm) present low technology risks and are unlikely to face long delays. International partners are to build a habitat module of Gateway and the external robotic arm. Based on the historical record, negotiating international partner agreements tends to increase schedule risk. On average, it takes 2 years to negotiate an agreement. Relying on international partners for critical technology may result in NASA not having oversight and control of a subsystem on the critical path.[13] As an example, Orion's ESM has experienced significant delays. If similar delays occur for a Gateway module, NASA may not have full functionality of the Gateway until after 2026. However, as the Gateway is notionally scheduled to be complete 6 years before the launch of the DST, any schedule problems on the Gateway pose low risk to a human mission to Mars.

5. DST

Technology development and integration pose the major schedule risks for the DST. According to the 2015 Technology Roadmap, "the Human Exploration and Operations Mission Directorate prefers the technology to have a higher maturity [TRL 7+] prior to

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[13] "Critical path" in this chapter refers to the sequence of tasks that determines the minimum time needed to complete an objective. Other tasks may be prerequisites for starting a task, but they can experience some delay before threatening the end date of the whole mission. "Critical path" should not be confused with the phrase "critical technologies," which are required before the mission can be complete but may not necessarily be the sole task responsible for holding up a chain of events, or "critical design," which is sometimes used interchangeably with the phrase "detailed design."

incorporation into the flight program." (NASA 2015a), meaning prototypes of the technologies should be tested in relevant environments prior to preliminary design review at the end of the formulation period. In Subsection 2.C, we discussed the DST's technological requirements and technology risks. Below we discuss technology development timelines for critical technologies for the DST that would carry high risk to the DST program if their testing has not completed by the end of the DST's formulation period (notionally scheduled above for the end of 2026).

NASA plans to test the advanced ECLSS that would be used on the DST onboard the ISS starting in 2022 (Crusan and Gatens 2017). If testing does not finish by the time the ISS is notionally planned to be retired in 2025, testing would need to be moved to the Gateway.[14] Other technologies for the DST habitat that must be tested alongside advanced ECLSS prior to inclusion into the DST program include habitat radiation safety technologies, fire safety technologies, and crew health equipment, which can all be tested aboard the Gateway if ISS testing is not completed in time. In some instances, testing of certain critical technologies for habitation could occur during DST Final Design, provided they do not affect the launch and operations of the DST (e.g., deep space EVA suits or crew health equipment); these systems would be launched at a later date with crew and logistics.

Likewise, several key power and propulsion technologies will also need further development before they can be included in the DST. These include deep space autonomous rendezvous and proximity operations systems; in-space cryogenic fluid transfer (both for chemical propellants as well as electric propellants like xenon); re-ignitable LOX-methane engines; and advanced thermal management technologies, such as near zero boil-off cryogenic fluid storage and single-loop cooling systems. Although we do not rank these technologies as high risk, several—specifically zero boil-off cryogenic fluid storage, re-ignitable LOX-methane engines, and in-space cryogenic fluid transfer—could require 5-year development programs to sufficiently mature (NASA 2015a). The Gateway PPE mission will serve as an important validation of the thruster and power systems, given the similar design heritage, as well as deep space rendezvous and proximity operations. The PPE is scheduled to complete testing in late 2023. In-space cryogenic transfer and storage technologies will be demonstrated on the Gateway during the first years of its operations, though these systems may not have all of the properties the DST requires. As the design of the DST is expected to draw heavily from technologies used on the Gateway, if a technology is found to underperform on the Gateway, DST development may be delayed.

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[14] In this report, we assume the ISS will be in service through 2028.

Several DST-specific technologies, including the large solar arrays and multi-unit Hall thruster configurations, would benefit from testing to build confidence in the technology prior to DST's Final Design phase. While the testing periods of these technologies would be short, the facilities required for testing these technologies do not exist yet. Facilities for testing large solar array deployment and multi-thruster plume interactions may take 1.5–3 years to build; another 6 months to 1 year would be required for testing. Although the Gateway will use several 13 kW Hall thrusters, which will help build confidence in the longevity of the individual thrusters, it may not be able to mimic the conditions the DST power and propulsion system will undergo or provide adequate information on thruster plume interactions for the thruster configuration that will be used on the DST.

Beyond technology development and testing, other potential issues provide sources of schedule risk. For example, the decade of human health research in deep space on the Gateway, the lunar surface, and the shakedown of the DST may reveal unexpected effects on human health from microgravity and relatively higher radiation environments than that in LEO. If these effects are severe enough, the DST may need to be redesigned to mitigate these complications.

The schedules proposed in this report have the DST ready to launch on a mission to Mars by the second half of 2036. As the next transit opportunity from Earth to Mars occurs in 2037,[15] significant delays in the development, construction, or testing of the DST may cause the DST to miss the 2037 launch window. The next opportunity to begin a mission to Mars would be in 2039.

According to NASA's plans, the DST would be refurbished at the Gateway following every mission. Because the DST is designed for three round-trip Mars missions, it would require refurbishment sometime in the early 2040s after returning from the first Mars landing mission. However, the 2017 Gateway PPE RFI noted that the PPE must have a minimum lifetime of 15 years (NASA 2017a). If the Gateway were retired before the final DST refurbishment in the 2040s, alternative dockyard solutions would be required. Otherwise, schedule delays would occur.

E. Other Considerations

1. Key Components and Support Systems

Many technologies and ground systems need to be developed and built before the critical design phases of the DST and Gateway can begin. Critical technologies that are

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[15] The exact dates of the transit opportunity depends on the characteristics of the DST's propulsion system and total mass.

required for these architectural elements need to be developed, tested, and matured before they are included in the detailed design. For example, testing the Hall thruster systems to ensure that they can last for the duration of the trip has already begun so that the Gateway propulsion bus can be ready to launch in 2022. Other subsystems, most notably the ECLSS, require significant development and extended testing to meet DST system requirements. Attempting to insert undeveloped technologies into the critical design phase before they have finished being tested can lead to major schedule risks. Delays in technology maturation—due to a lack of suitable facilities for testing or a lack of foresight to schedule those developments—could push those elements onto the critical path. Technologies that pose the highest risk to schedules are discussed throughout Chapter 2.

2. Technology Testing Facilities

Space technology development programs often must start more than 10 years ahead of when they are to be fielded because of long design lifecycles and testing times. Although technology development programs typically range from 2–5 years, some programs that involve multi-year continuous testing, such as ECLSS and SEP propulsion systems, can take longer. Key concerns include the long development cycles for advanced radiators, among other technologies. New facilities, such as large vacuum chambers needed to test clusters of Hall thrusters, a state-of-the-art arc jet facility to test new heat shields, and a validation test facility for large solar array deployment, do not appear to be part of current budget plans. Construction on such facilities would need to start in the next several years to be ready to test technologies needed for the DST.

3. Parts Procurement

Most of the hardware required for the Gateway and DST must be manufactured to space specifications and radiation-hardened for multi-year deep space operation. Items of this nature may require up to 2 years lead time before they can be delivered. Delays in procuring these parts, if they are not ordered far enough in advance, could lead to substantial schedule delays.

4. Commercial Plans

NASA's Campaign Report stated that NASA will take advantage of commercial systems that can be used for human exploration as they become available. In particular, NASA has expressed interest in using heavy-lift commercial launch vehicles that will become available in the mid-to-late 2020s, including SpaceX's Falcon Heavy, the United Launch Alliance's Vulcan, and Blue Origin's New Glenn. As such, the schedule presented in this report uses over 40 commercial launch vehicles between 2022 and 2037 to transport supplies, propellant, and some vehicles—including lunar landers—to the Gateway and DST. As NASA increases the cadence of commercial launches to the Gateway, either for logistics modules, landing vehicles, or fuel modules, should other heavy-lift vehicles not come to market by the mid-2020s and commercial vehicle production rates remain low, NASA may need to launch cargo on dedicated SLS flights.

Some companies, such as Blue Origin, have also proposed building systems that NASA notionally plans to build, such as lunar landers. The availability of such systems may free NASA to focus its some of its resources on systems it is uniquely situated to build, such as the DST. However, reliance on commercial companies to build critical systems may cause delays in NASA's human spaceflight plans if the companies' business cases for the systems do not close, and developments are ended or delayed. This would in turn require increasing NASA's reliance on SLS, which could dramatically increase costs for human spaceflight presented in Chapter 4.

5. International Plans

NASA plans to rely on foreign partners for major parts of the Gateway, such as the ESPRIT module and a habitation module, the Orion service module, and for some launch capacity. Although these partnerships bring benefits, such as shared mission costs and improving relationships with allies, relying on international partners reduces NASA's ability to control or oversee critical mission systems.

6. Unexpected Events

The schedule presented in this report does not account for potential schedule delays caused by large unexpected events. A wide diversity of events could cause prolonged delays for the human spaceflight programs. For example, continuing resolutions could prevent starting new projects at critical times; lower than expected budgets or cost overruns of one program could require NASA and Congress to make trade-offs between programs or lengthen program timelines; government shutdowns could halt development and acquisition of critical systems that ripples throughout multi-year programs; and world wars could result in targeted destruction of key U.S. launch sites that would take years for a civil space program to recover from.

Unexpected challenges in subsystem development or manufacturing processes (e.g., welding techniques used for SLS) could require a program to re-evaluate the design of its system. Natural disasters, such as hurricanes at coastal NASA facilities, could delay critical component development, testing, or acquisition as program sites recover. Anomalies or accidents that occur on human spaceflight missions, especially those that result in the loss of human life, may delay further activities for months or even years as the accidents are investigated and faulty systems are redesigned.

F. Feasibility of a Mission to Mars Before 2037

The schedule developed for this report was based on NASA's current and notional plans and two critical assumptions introduced above: that NASA will choose the architecture of a human Mars orbital mission and begin systems development in 2024; and that there is one human mission to the Gateway annually, either to work aboard the Gateway, operate the DST, or to transfer to the lunar surface. In this section, we briefly evaluate the feasibility of an earlier departure date for an orbital mission to Mars if we forego the two assumptions listed above.

For either a 2033 mission or a 2035 mission, NASA would have to run lunar landings and DST testing concurrently or reduce the scope of lunar missions. More pressing, however, is technology development for the DST, as the critical path for a mission to Mars depends on the readiness of the DST. As noted in Subsections 2.C and 3.D.5, the DST relies on many technologies that require further development before they can be incorporated into the DST's final design.[16] The testing schedules of these technologies thus drive the earliest date NASA can begin the final design and implementation phase of the DST.

In the schedule presented in this report, we notionally expect the DST final design phase to begin in the last quarter of 2026 in order to begin a mission to Mars orbit in 2037. For a mission to Mars to begin in 2033, the dates of key milestones would need to be moved up 4 years. Notably, this would require critical technologies to have finished testing by 2022. As discussed in Subsection 3.D.5, several technologies, including advanced ECLSS, zero boil-off cryogenic storage, re-ignitable LOX-methane engines, multi-unit Hall thrusters, and those tested on the Gateway PPE (e.g., in-space cryogenic fluid transfer), will not have finished testing by this period, which dramatically increase technology and schedule risks for the DST and could force the DST design to be revised if any one of these technology testing programs reveals problems. Additionally, based on the schedule for the DST presented in Subsection 3.A.6, in order to launch an orbital mission to Mars in 2033, Phase A development for the DST would need to begin at the start of FY 2020 (October 1, 2019), a milestone which would likely be missed, as trade studies must be conducted first. Shrinking the DST's formulation and implementation timeline by violating NASA's standard operating procedures for system development would lead to very high technology, schedule, and cost overrun risk. As such, a mission to Mars orbit in 2033 is infeasible from a technology development and schedule perspective.

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[16] According to the 2015 Technology Roadmap, "the Human Exploration and Operations Mission Directorate prefers the technology to have a higher maturity [TRL 7+] prior to incorporation into the flight program." (NASA 2015a), meaning prototypes of the technologies should be tested in relevant environments prior to preliminary design review at the end of the formulation period.

For a mission to Mars orbit to begin in 2035, the next available orbital window after 2033, final development of the DST will likely need to begin by the end of 2024. Due to the concurrent development and construction of the Gateway and DST, a 2035 launch date would hold high schedule risk due to increased demand for fabrication and testing facilities. Depending on technology development and demonstration timelines, several technologies could be the driver of the DST's critical path. For example, re-ignitable LOX-methane engines, in-space cryogenic fluid transfer, and zero boil-off storage for cryogenics may all require five-year development and testing programs before they are mature enough for inclusion into the DST program. This in turn requires these programs to begin within the next year. If problems arise with the advanced ECLSS during demonstration on-board the ISS starting in 2022 or with technologies demonstrated on early Gateway elements, redesigning and testing these technologies could delay the start of the DST's final design phase. Likewise, delays in the Gateway program could cascade into the DST development if critical technology demonstrations do not occur prior to the DST final design phase.

Additionally, several technologies that will be scaled up from those on the Gateway, such as multi-unit Hall thrusters and the large solar arrays, may require new ground facilities to be built for testing. Construction of these facilities may need to begin in the next 2–3 years to allow sufficient time for testing. Finally, improvement in some technologies—such as composite structures, radiation safety, and other advanced thermal management systems, including deployable or freezable radiators or advanced radiator coatings—could enable mass savings or increase crew safety; the longer these types of technologies have to mature, the more robust the DST program will be. Accordingly, a 2035 mission to Mars orbit may be possible from a technology development and schedule standpoint, but brings with it high schedule risks. If any one of numerous technology development or demonstration programs are delayed, the development of the DST would also be delayed. Any prolonged delays in DST development or acquisition could push the mission to Mars to the next available orbital window in 2037.

G. Key Findings

Using the two major NASA assumptions in this report—that NASA will not begin Phase A of the DST until the second half of 2024, and that there will be one crewed Orion mission to the Gateway, lunar surface, or DST annually—a 2033 mission to Mars is infeasible (see Figure 13 for the earliest feasible schedule for a mission to Mars). By the end of 2033, NASA would only have started testing the DST during the checkout mission (and the DST shakedown and refit would not yet have taken place). Using these assumptions, we find that the earliest an orbital mission to Mars could depart is 2037.

Even the 2037 date is not without risks. Complex, multi-year projects involving the development and integration of new technologies, such as the elements required for a human mission to Mars and its precursor missions, frequently encounter schedule delays.

Many factors lead to these delays: technologies that fail to be developed as quickly as planned, suppliers who encounter problems in manufacturing key components, prime contractors who struggle to integrate disparate systems into a working whole, and changes in requirements after critical design features have been decided. Schedule delays in funding, designing, building, or testing the DST on the ground or in space of more than a year would likely result in the mission to Mars departing in 2039 or later.

If the development of the DST is allowed to begin earlier, this conclusion does not change. The DST requires numerous medium and high-risk technologies that will take at least 4–5 years to mature to the point that they could be included in the flight program, which in turn drives the development cycle of the DST. For a 2033 mission to Mars, final design of the DST would need to begin by the end of 2022, meaning many precursor technologies will not be ready by their need-by date. Shrinking the DST formulation and implementation periods to try to meet a 2033 mission date would bring very high technology and schedule risks to the program. For a 2035 mission, many critical technologies could be demonstrated by their need-by date in 2024. However, prolonged delays in any one of many technology development programs would delay the development of the DST. As such, although a 2035 mission date may be possible from a technology and schedule perspective, it would be a high-risk program that would be likely to slip to the next orbital window in 2037. Accordingly, 2037 is likely the earliest feasible date for the departure of the DST to Mars orbit.

4. Cost Assessment

This chapter provides estimates of the costs of the major systems described in the technology chapter.[17] These cost estimates provide Congress and the Administration an approximation of the overall costs of the Mars orbital mission described in Chapter 3, as well as the costs of other activities related to human space exploration such as lunar landings. As our notional schedule through the launch of the Mars orbital mission ends in 2037, STPI constructed a set of cost estimates covering the full set of human space exploration activities over the 19-year period between FY 2019 and FY 2037. In addition to these overall cost estimates, this chapter presents the cost basis for the budgetary analysis in Chapter 5, which maps costs to schedules, permitting estimates of annual costs. The costs associated with the orbital mission to Mars, however, will not end with the launch of the DST on its 1,100-day journey as ground systems will need to monitor to astronauts' progress and a SLS and Orion will need to be launched upon the DST's return to retrieve the astronauts. We therefore separately estimated these costs associated with operating the orbital mission, which will be incurred between 2038 and 2040.

We use three methods to estimate costs. For systems like SLS and Orion that are nearing the end of development, we use the amounts budgeted by NASA for the completion of these systems. However, we critically compare those budgets with estimates by the NASA Inspector General and others to assess whether budgeted funds cover all likely future costs. For the Gateway, we draw on a variety of sources to estimate the costs of each of the eight modules and launch costs to build and service that system. For DST, we draw on an analogous system, Orion, to project potential future costs. In addition to these estimates of the costs of the four major systems, we also estimate potential costs of other human exploration systems that NASA is likely to fund from its budget over the course of the period before the launch of a human orbital mission to Mars. These systems include the costs of notional lunar landing missions and the systems that will need to be developed and funded for a human landing on Mars shortly after the orbital mission is completed. NASA's human exploration budget will have to fund these systems and hence need to be included in the budget analysis. For our cost-to-date figures in this chapter, we drew numbers from the historical actual authorization columns in the FY 2010 to FY 2019 PBRs for NASA.

[17] The estimated costs of individual systems listed in this chapter may not sum to the total estimated cost of missions due to rounding. All dollar figures in this chapter are in nominal dollars, unless otherwise noted. We use the U.S. Bureau of Economic Analysis's GDP Price Deflator to convert to any real dollar figure (U.S. Bureau of Economic Analysis 2018).

We chose to use actual authorizations throughout this chapter as these numbers provide a standard source of cost information for each program. Because the PBR provides annual numbers, we were able to convent them to constant price dollars.

A. Launch Systems and Related Vehicles

1. SLS

a. Projected costs

Between FY 2011 and FY 2018, NASA spent $14.4 billion in FY 2017 dollars on SLS (NASA Budget Estimates 2010a, 2011, 2012, 2013, 2014, 2015b, 2016a, 2017b, and 2018, drawn from historical actual authorization columns for SLS). If costs are included for those parts of the cancelled Constellation program upon which SLS has drawn (calculated from NASA Office of the Inspector General 2017c, 51), the total cost of SLS as of the end of FY 2018 was $15.9 billion FY 2017 dollars.[18]

In the President's FY 2019 budget, the Office of Management and Budget (OMB) has budgeted $10.8 billion for SLS between FY 2019 and FY 2023, $10.0 billion in constant FY 2017 dollars. Budgeted amounts for SLS include one SLS Block 1 flight, the development cost and one flight of SLS Block 1B, plus predicted expenditures on post-2023 SLS flights through FY 2023. However, due to Congress funding a second mobile launcher in the FY 2018 budget, NASA's notional plans have changed since the release of the President's Budget to reschedule EM-2 to 2022 as a SLS Block 1 flight. We account for this by assigning the costs of EM-2 on top of the budget presented in the President's Budget in our annualized costs presented in Chapter 5. NASA will also need to pay for the development costs for Block 2. As SLS Block 2 has not been baselined, STPI estimates that Block 2 will necessitate another $2 billion in FY 2017 dollars.

Once SLS is operational, NASA estimates that the cost of each SLS launch will be on the order of $0.7 billion to $1 billion in FY 2017 dollars. For our analysis, we assume that NASA will launch 18 SLS flights in support of human exploration through 2040.[19] 12 of

[18] The total cost of SLS as of FY 2018 adds the cost of the SLS Program during the Constellation Program transition year of FY 2011 ($1.5 billion, per NASA Office of the Inspector General 2017c, 51) to the overall cost of the SLS Program per NASA budget estimates ($14.4 billion FY 2017 dollars). Because NASA operated on continuing resolutions for much of FY 2018 and FY 2019, and Congress passed the FY 2018 budget at the end of March 2018 with $539 million more for EGS (including a new mobile launcher) and SLS than the FY 2018 PBR requested, we included these additional appropriations in the FY 2019 budget.

[19] Discussions with NASA personnel suggested that NASA might use a SLS Block 1 to launch the Europa Clipper mission in 2023. As this mission would be a science mission, we assume the costs of this SLS launch would not be borne by human exploration accounts, and as such do not include it in our cost or budget analyses.

these flights are in support of the mission to Mars, either through testing SLS and Orion, launching the Gateway, or launching and testing the DST. The remaining six flights are in support of lunar landings. Based on the changes to NASA's notional launch plan noted above, we assume that the remaining costs associated with EM-1 and the construction of SLSs for EM-3, EM-4, EM-5, and EM-6 through 2023 are accounted for in the FY 2019 PBR. We use the estimated cost of an SLS flight ($0.7 billion to $1 billion in FY 2017 dollars) for the cost of each of the remaining SLS flights (EM-2, parts of EM-4 and EM-5, EM-6 through EM-17, and the launch of the DST). Between FY 2019 and FY 2037, the 12 flights related to the Mars orbital mission will cost an estimated $17.8 billion to $20.2 billion in FY 2017 dollars.[20] Adding these figures to funds already spent yields total program lifetime costs for SLS related to the mission to Mars of $33.7 billion to $36.1 billion in FY 2017 dollars.[21] We use the lower estimated cost ($17.8 billion FY 2017 dollars) for SLS throughout the report.

SLS launches associated with the lunar missions (EM-7 through EM-12) are expected to cost a total of $4.2 billion in FY 2017 dollars using the lower estimated cost for SLS. We account for this cost in Subsection 4.D.1 with the other costs of lunar missions.

b. Cost risks

In an October 2018 report, the NASA Inspector General concluded that based on Boeing's current expenditure rate, NASA will need to increase the contract value for the SLS by $1.2 billion for the first two flights (NASA Office of the Inspector General 2018). In addition, NASA has not established baseline commitments and life-cycle costs for SLS Block 1B and SLS Block 2. Consequently, we perceive the risk that remaining costs for SLS missions related to Mars would cost more than $20.2 billion in FY 2017 dollars between FY 2019 and the launch of the Mars human orbital mission as high.

Estimates of future launch costs of $700 million to $1 billion in FY 2017 dollars per launch are somewhat lower than launch costs of Saturn V, estimated at $1.25 billion in FY 2017 dollars (calculated from Williams 2016) or the Space Shuttle, estimated at $1.4 billion in FY 2017 dollars (calculated from Pielke and Byerly 2011). Based on the cost history of Saturn V and the Space Shuttle, the costs per SLS launch could run 25 percent higher than our high-end estimate.

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[20] As EM-17 is to take place in 2040, we assign 33 percent of EM-17's cost to take place through FY 2037. Adding $10 billion based on the President's Budget plus $2 billion for Block 2 plus $5.7 billion to $8.2 billion in additional launch costs yields $17.8 billion to $20.2 billion, all in FY 2017 dollars.

[21] Adding past expenditures of $15.9 billion to $17.8 billion and $20.2 billion yields $33.7 billion to $36.1 billion FY 2017 dollars.

2. EGS and Space and Flight Support (SFS)

a. Projected costs

NASA spent a total of $3.0 billion in FY 2017 dollars on EGS through FY 2018 (NASA Budget Estimates 2010a, 2011, 2012, 2013, 2014, 2015b, 2016a, 2017b, and 2018). According to the President's FY 2019 Budget and NASA appropriations for FY 2018 (NASA 2018; U.S. House of Representatives 2018), an additional $2.7 billion in FY 2017 dollars will be spent on EGS through 2023, which includes the expenditures on a second mobile launcher.[22]

According to the President's FY 2019 budget, NASA will spend $4.2 billion in FY 2017 dollars on SFS between FY 2019 and FY 2023. We argue that labor and other cost efficiencies and the eventual retirement of the ISS will make it possible for NASA to provide ground support for SLS and Orion, followed by the Gateway, and eventually the DST without incurring more costs for SFS than planned for FY 2023, which is $955 million or $855 million FY 2017 dollars. Therefore, we assume that NASA will continue to spend $855 million FY 2017 per year between FY 2024 and the Mars orbital mission, which we assume launches in FY 2037, for total SFS costs for those 14 years of $12.0 billion FY 2017 dollars.[23] The total cost between FY 2019 and FY 2037 would then be $2.7 billion in capital costs plus $16.2 billion in operating costs, for a total cost of $18.9 billion FY 2017 dollars.

b. Cost risks

Most of the cost risks for EGS and SFS stem from the possibility of schedule overruns in various technologies (especially software verification and validation) due to additional delays in SLS/Orion deliveries. EGS software development has already put pressure on EM-1's launch date due to SLS/Orion delays and software implementation issues pushing up software verification and validation costs (NASA Office of the Inspector General 2016). The SCCS was already 77 percent over the projected budget in 2016. Software and other integration issues present cost risks to major architectural elements, especially since NASA will have to update SCCS before EM-2 to implement mission data collected from EM-1 (NASA Office of the Inspector General 2016).

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[22] Because NASA operated on continuing resolutions for much of FY 2018 and FY 2019, and Congress passed the FY 2018 budget at the end of March 2018 with $539 million more for EGS (including a new mobile launcher) and SLS than the FY 2018 PBR requested, we included these additional appropriations in the FY 2019 budget.

[23] $0.855 billion per year times 14 years between FY 2024 and FY 2037 plus the $4.2 billion budgeted for ground support from FY 2019 through FY 2023.

Due to the upgrade from Block 1 to Block 1B, the Mobile Launcher and Vehicle Assembly Building will need to be refurbished to accommodate the height and weight changes in SLS (NASA Office of the Inspector General 2017c, 20). The introduction of Block 2 will entail additional costs for EGS since the Mobile Launcher and Vehicle Assembly Building will need additional modifications to account for the increase in launch vehicle height. These refurbishments introduce cost risk. NASA currently plans to purchase a second Mobile Launcher to mitigate this risk. This Mobile Launcher was included in the FY 2018 budget. NASA may also need to refurbish Mobile Launcher 1 for a high cadence of SLS launches.

Our assumption that SFS will remain constant through 2037 also introduces cost risk. NASA will be simultaneously providing ground support for the Gateway and the DST. These missions may severely tax the current staff of SFS, leading to the need for additional resources to cope with these simultaneous activities.

3. Orion

a. Projected Costs

The Orion program had cost $4.7 billion under the Constellation Program (GAO 2016b). An additional $10.2 billion in FY 2017 dollars was spent on the program through FY 2018 (NASA Budget Estimates 2010a, 2011, 2012, 2013, 2014, 2015b, 2016a, 2017b, and 2018). Through FY 2018, Orion had a total cost of $14.9 billion in FY 2017 dollars. Going forward, the President's Budget allocates $5.3 billion in FY 2017 dollars for Orion for EM-1 and EM-2, plus partial construction costs of Orion for EM-3, EM-4, and EM-5.

One non-NASA expert interviewed for the study estimates that after EM-2, it would cost $600 million to $700 million per refurbished Orion capsule—for an average of $650 million—and $1 billion for each new Orion capsule for each subsequent launch. Alternatively, NASA has targeted each launch to cost from $400 million to $650 million for each capsule, depending on the extent to which capsules can be reused and how much refurbishment would cost. As such, NASA's estimates differ from our figures based on expert estimates by –$250 million and –$350 million, respectively.

ESA will be providing NASA the SMs for Orion as part of its contribution to support the ISS. We assume that ESA will pay for the cost of SMs as their contribution to future human spaceflight programs through at least the orbital mission to Mars. The first ESA ESM and part of the second ESM cost a total of €390 million ($488 million using the 2014 euro/dollar exchange rate) (de Selding 2014). Subsequent ESMs are contracted at €200 million apiece ($236 million) (Agencia EFE 2017). If ESA does not provide SMs going forward, NASA would need to cover this cost ($236 million for each SM).

Based on cost overruns for the Orion program through FY 2018, we have chosen to use the expert-provided higher estimates of $650 million per refurbished Orion capsule and $1.0 billion per new capsule for our analysis. As discussed in Chapter 3, we assume that NASA will fund 15 flights of Orion after EM-2 through 2037, of which 9 would be related to the Mars mission and 6 would be related to lunar missions.[24] Conversations with Lockheed Martin, the manufacturer of the Orion capsule, revealed that although Orion capsules are planned to be increasingly reused over the lifetime of the program, the rate of reuse is unknown but will likely be less than half through the mission to Mars. As such, in order to develop cost estimates for Orion procurement for this report, we make the assumption that 10 of the 17 Orion capsules would be new and the remaining 7 would be refurbished, which represents a program with little reuse initially. This rate of reuse leads to an average of $850 million per Orion. Under this assumption, the costs of Orion capsules for the flights related to the Mars orbital mission outside of the FY 2019 PBR are estimated to be $5.4 billion through 2037 in FY 2017 dollars; if all Orion capsules are new, the cost estimate rises to $6.4 billion.[25]

Summing budgeted amounts from FY 2019 through FY 2023 and the cost of Orion for the additional nine launches in support of Gateway and DST related to the Mars mission through FY 2037 yields a total projected cost for Orion from FY 2019 to the launch of the Mars mission of $10.7 billion to $11.7 billion in FY 2017 dollars.[26] Six more Orion vehicles would be used to support lunar missions, costing between $5.1 billion and $6.0 billion in FY 2017 dollars.

b. Cost Risks

A GAO analysis found that the Orion program faces a potential cost overrun of between $258 million and $707 million through the end of the current contract in December 2020 (GAO 2016b). Lockheed Martin, Orion's prime contractor, was found to be expending its management reserve funds at a higher rate than NASA and Lockheed Martin had expected. Orion program personnel believe that it is unlikely that Lockheed will continue to draw at the higher rate, and therefore expect that current reserves will be sufficient (NASA Office of the Inspector General 2017c). Lockheed expects costs to

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24 For our cost estimate here, we only include 25 percent of the cost of the Orion for EM-17 in our estimate through 2037, as EM-17 is to launch in 2040, meaning that most of the costs incurred for this Orion will take place after 2037.

25 11 flights at $850 million per capsule equals $9.4 billion. 11 flights at $1 billion per capsule equals $11.0 billion. However, as part of the cost for five flights and remaining development is captured in the FY 2019 PBR and as some of the cost for the Orion for EM-17 is beyond 2037, total expenditures between FY 2024 and FY 2037 are $5.4 billion at the low estimate and $6.4 billion at the high estimate.

26 $5.29 billion in capital costs plus $5.42 billion for additional modules at an average $850 million results in $10.7 billion in FY 2017 dollars; $5.29 billion in capital costs plus $6.38 billion in new capsules yields $11.7 billion FY 2017 dollars.

complete the Orion contract to be between $360 million and $772 million more than budgeted (GAO 2016b). The high-end estimate is 14 percent of budgeted program costs through FY 2023. Because of this potential cost overrun, we evaluate the cost risk for Orion as medium.

4. Commercial Logistics Modules and Launch Vehicles

The Gateway is to be resupplied using small logistics modules that would fit underneath Orion on top of the SLS and commercial logistics modules launched on commercial rockets. As discussed in Subsection 3.A.4, we assume that NASA will contract for seven commercial supply missions to the Gateway for crew operations aboard the Gateway, in addition to the seven logistics modules that are co-manifested on SLS. NASA has also stated that the Gateway PPE is to be launched on a commercial vehicle.

We used Orbital ATK's (now Northrop Grumman Innovation Systems) costs of developing its Cygnus capsule that supplies the ISS—$300 million—as an estimate of the cost of developing a small commercial logistics module (Clark 2013). We assume that the cost of purchasing each commercial capsule after development costs would be the same as the cost of SpaceX's Dragon capsule. We estimate that each supply mission using commercial logistics modules will cost $71 million for the modules and $90 million for the launch.[27] The cost of launching such a module to the Moon was estimated as the cost of launching of Falcon Heavy, which is $90 million, according to SpaceX (SpaceX n.d.).

For our estimate, we account for the cost of the four commercial logistics missions related to crewed operations and outfitting of the DST while docked with the Gateway with the rest of the costs related to the DST in Subsection C.1; likewise, we provide a rough estimate for the total cost of supplying the DST for long-duration missions, including cost of transportation, in Subsection C.1. The total costs of the remaining three commercial logistics modules not accounted for in the DST or the Gateway's total cost is $214 million for three modules plus $300 million for development. Adding in the cost of launch the three modules and the Gateway PPE ($360 million for four launches), gives a total of $874 million FY 2017 dollars for commercial logistics modules and launch vehicles not accounted for elsewhere in this chapter.

In addition to supplies for the Gateway, propellant will need to be transported to the Gateway to refuel lunar landers and the DST. We assume that the propellant will be transported by commercial spacecraft at a cost of $90 million per launch, the cost of a

[27] The $71 million figure for the module cost was calculated by dividing the total value of SpaceX's resupply cost contract with NASA of $1.6 billion by 12 (the number of resupply missions for which SpaceX has contracts), yielding an average cost per mission of $133 million and then subtracting the cost of the launch of a Falcon 9, listed at $62 million on the SpaceX website (SpaceX n.d.), yielding a cost per module of $71 million.

Falcon Heavy, that the first refueling module will cost $200 million to develop and build, and that subsequent modules will cost $50 million. Each launch will carry up to 15 metric tons. We account for the costs of propellant for lunar landers in Subsection D.1 along with the other costs for lunar missions and the costs of propellant for the DST in Subsection C.1.

B. Gateway

1. Projected Costs

As noted in Chapter 2, the Gateway is to consist of eight modules: a power and propulsion element, the European ESPRIT, the associated U.S. utilization module, an airlock, an international partner habitat, a U.S. habitat, a logistics package, and a robotic arm. Cost estimates for these prospective designs are not yet available. STPI has constructed a rough estimates of the potential costs of the Gateway using data and estimates about component costs. Table 1 lists the Gateway modules, cost estimates, and sources for those estimates. It does not include the costs to NASA's foreign partners for the modules that they are assumed to supply: ESPRIT, the international habitat, and the robotic arm.

The cost for some of these elements was estimated using analogs from the ISS and the commercial communications satellite industry. To estimate costs for the propulsion and energy module, STPI used analogous costs from the communications satellite industry. STPI's estimate of $600 million for the U.S utilization module includes a low capability ECLSS system and logistics to enable 15-day stay times. The high capability ECLSS system is contained in the international partner and U.S. habitats. We looked at two cost analogs for the U.S. habitat module: Destiny, the U.S.-built scientific module on the ISS, and Kibo, which was built by Japan. In 2000, Destiny cost $1.38 billion or $1.91 billion in FY 2017 dollars (calculated from Leary 2001). Kibo cost $3 billion dollars in 2007 when it was readied for launch or $3.5 billion in FY 2017 dollars (calculated from Malik 2007). Because Kibo is substantially larger than the Gateway is expected to be, and incorporates a number of additional subsystems, we chose the cost of Destiny for our analogue for the U.S. habitat.

Because Destiny did not have a communications module, we added this cost. Krikorian, Emmons and McVey (2005) have provided a range of estimated costs for a deep space communications system for a crewed spacecraft. We took the average of their high and low most probable estimates, and converted them into FY 2017 dollars for our estimate of $92 million for communications. We assume integration costs would be 20 percent of total subsystem costs for the module for a total cost for the U.S. habitation module of $2.4 billion FY 2017 dollars.

Table 1. Estimated Cost of the Gateway

System	Cost (Millions of FY 2017 Dollars)	Source
Power and propulsion	$600	Internal STPI estimate
ESPRIT	$10[a]	NASA
Utilization module	$600	Internal STPI estimate
Airlock module	$222	Calculated from Stenger (2001)
International Habitat	$10[a]	NASA
U.S. Habitat Module	$2,407[b]	
Habitat	*$1,914*	Calculated from Leary (2001)
Communications	*$92*	Calculated from Kerkorian et al. (2005)
U.S. Habitat Integration	*$401*	20% of habitat module costs
Logistics module	$300	Cost of Cygnus module
Robotic arm	$10[a]	NASA
Space suits	$250	Average of interviewee estimates
Total	**$4,409**	
Reserve	$1,323	30% of total cost (NASA standard)
Total cost of Gateway	**$5,732**	

[a] NASA assumes it will incur $10 million in costs to coordinate with the foreign space agencies providing these systems.

[b] This number is the total of the subsystems and integration under "U.S. Habitat": $1,914 + $92 + $401= $2,407.

Note: The *italicized* numbers in the table are subsystem costs.

Airlocks on the ISS are estimated to have cost $164 million (Stenger 2001), or $222 million FY 2017 dollars. We use that number here. Space suits for operations in deep space are estimated to cost between $200 million and $300 million, according to experts engaged in developing space suits. We took the average of these two figures for our estimate: $250 million in FY 2017 dollars. For the cost of small logistics modules co-manifested on SLS, we used the development cost for commercial logistics modules of $300 million. Additionally, we use the estimated cost of the commercial logistics module as the cost of a logistics module that is co-manifested on SLS ($71 million). However, we account for these costs as part of the mission costs for lunar landings and the DST. While almost all the cost of the modules supplied by international partners is covered by them, we have allocated $10 million to NASA for each foreign-procured module for management of all Gateway module interfaces and quality control coordination requirements.

NASA best practice is to provide a financial reserve of 30 percent for complex projects. Adding a 30 percent financial reserve of $1.3 billion yields a total cost estimate of $5.7 billion in FY 2017 dollars (Table 1). Launch, operating costs, and commercial resupply are captured in the estimates for the SLS, Orion, and other systems above.

2. International Contributions

In Table 1 above, we only provide estimates of NASA's costs of coordinating with foreign providers of ESPRIT, the international habitat, and the robotic arm. ESPRIT and the international habitat are assumed to be built by the European Space Agency with support from the Japan Aerospace Exploration Agency (JAXA) for the international habitat. The robotic arm is assumed to be manufactured by Canada. Because the costs of these modules are not being covered by NASA, we do not include them in our analysis. They will be substantial, however. We assume that ESPRIT will cost at least as much as the U.S. logistics module, or $300 million. The international habitat is likely to cost at least as much or more than the U.S. habitat, which is $2 billion. The first robotic arm constructed by Canada cost about $100 million; subsequent robotic arms have cost about $150 million each (Canada Connects n.d.). We assume that a similar arm for the Gateway would also cost $150 million. All told, foreign partners are likely to contribute an additional $2.5 billion to the construction of the Gateway.[28]

3. Cost Risks

According to NASA documents, Gateway is to be designed with existing technologies, will be much smaller than the ISS, and will be intermittently inhabited by astronauts, and then only in conjunction with Orion. A robust U.S. initiative for lunar exploration is likely to place more demands on the Gateway, or at least lead to more visits by astronauts. More robust demands on Gateway are likely to lead to adding capabilities, triggering design changes. Design changes are a major driver of cost increases. Although the extent to which a more robust lunar mission for human exploration would raise costs is unknown, the risk of sizable cost increases for Gateway is high.

4. Costs of Additional Missions

The costs of transporting astronauts using SLS and Orion impose constraints on expanding the number of exploration flights beyond the one per year envisioned. Once the Gateway is completed, the cost of a trip to the Gateway (assuming a short-term stay without lunar exploration) would be $1.62 billion (the cost of a supplying the Gateway is $71 million if the logistics module is co-manifested on SLS, while the cost of an SLS/Orion

[28] $300 million for ESPRIT plus $2 billion for the international habitat plus $150 million for the robotic arm equals $2.45 billion.

flight is $1.55 billion), of which 96 percent is the cost of astronaut transportation using SLS and Orion.[29]

An alternative approach to increasing astronaut residence time on the Gateway would be to extend the stay of astronauts who had already been launched on an SLS/Orion flight (e.g., astronauts sent on a lunar mission to return to the Gateway for an additional period to test the sufficiency of radiation protection and medical systems installed there for long-term flights in preparation for DST launch). To support such a mission, NASA would need to resupply the Gateway on a regular basis, as is currently done with the ISS. Assuming that a supply module carries 90 days of supplies, extending a crew's stay to one full year would require three additional commercial flights to supply consumables. As a resupply module costs $71 million and a commercial flight $90 million, the additional cost would be $484 million.

C. Deep Space Transport

1. Projected Costs

The design of the DST is far more conceptual than the Gateway, as NASA currently does not plan to select an architecture for the vehicle until 2024. This in turn brings high uncertainty to estimating the cost of the DST program. For example, based on NASA's notional plans, the DST would be launched fully assembled on SLS, likely a SLS Block 2 with higher lift capacity. However, a number of factors could require the DST to be launched in multiple parts and be assembled in space, which would influence the cost of the program. For instance, many critical components for the DST are still at low TRL and have uncertain mass requirements, which could lead to mass budget overruns; discoveries in the human health program on the effects of long-term radiation could require adding greater than expected radiation shielding; using SLS Block 1B to the launch the DST—due to the possibility of long-term delays in the SLS Block 2 or the requirement to launch the DST during the late 2020s to meet a 2033 mission—would reduce the available mass budget for the DST were it to be launched in a single piece.

Because of these uncertain design factors, rather than conducting parameterized cost assessments of different possible permeations of the vehicle's design, we instead chose to use the cost of the Orion program as a proxy to produce an order of magnitude cost estimate of the DST, as the Orion program is the most analogous recent NASA program. Although the DST and Orion have major differences, they also have many similarities. Similarities include a full panoply of systems designed for deep space: propulsion, ECLSS, and communications. Compared to Orion, differences on the DST include the much larger

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[29] $1.55 billion is 96 percent of $1.62 billion.

habitation module, an ECLSS that is designed to use a high degree of recycling rather than be replenished, no heat shield, large propellant capacity, and a large solar electric propulsion system.

Accepting the similarities and the differences of the two spacecraft, we have used the total development costs of Orion as our basis to estimate the cost of the DST. Including costs incurred under Constellation and budgeted amounts for FY 2019 through FY 2023, as discussed above, total development costs of Orion are likely to be $20.2 billion in FY 2017 dollars.[30] We use this figure as our estimate of the cost of designing and constructing the DST.[31] Due to the high technical risks for the DST discussed in Chapter 2, we add a financial reserve cushion to this number of 30 percent, generating an estimate of $26.3 billion. In addition to the development and construction costs for the DST, we have added $2 billion for propellant and cargo delivery to the DST for the 12-month shakedown cruise and for the human orbital trip to Mars,[32] using the cargo and propellant modules developed for the Gateway and lunar landers, discussed in other sections of this chapter. For supplying crew operations of the DST while docked with the Gateway, we add another $931 million for four supply missions using small logistics modules launched on commercial launch vehicles[33] and four co-manifested small supply modules on SLS flights. We estimate the total cost of DST to be $29.2 billion in FY 2017 dollars, which includes all development, assembly, in-space testing, and supply vehicles necessary for DST operations leading up to the orbital Mars mission, including a one-year shakedown cruise. This figure does not include launch costs for the DST or for astronauts (those are accounted for in the section

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[30] Development costs for Orion include $4.7 billion from the Constellation program, $10.2 billion from FY 2010, the year Constellation was terminated, to FY 2018, and $5.3 billion in budgeted costs from FY 2019 to FY 2023 for a total of $20.2 billion.

[31] Alternatively, mass-based cost comparison models are typically used for first-order cost estimates of space programs. A simple linear comparison of Orion's initial design, development, test and evaluation phase cost estimate through EM-2 ($3.9 billion in FY 2006 dollars, or $4.7 billion FY 2017 dollars; Braukus, Dickey, and Humphries) multiplied by the ratio of the notional mass of DST to Orion (roughly 4.6:1) leads to an estimate of $21.7 billion for the DST, which is similar to our estimated cost of DST before factoring in reserves and efforts beyond initial launch. However, Orion's history of cost overruns may make the Orion program unsuitable as the basis for a mass-based cost comparisons, as its baseline cost established in 2015 through EM-2, not factoring in the money spent during the Constellation program, is $11.3 billion FY 2015 dollars (GAO 2016b), or $11.7 billion in FY 2017 dollars. Using the simple linear mass-based cost comparison above on the 2015 baseline leads to a cost estimate of $53.8 billion in FY 2017 dollars.

[32] As the DST is a notional vehicle, we cannot evaluate the exact amount of supplies it will require, and thus this $2 billion represents a rough estimate of the cost of supplies, furnishings (e.g., exercise, scientific, or medical equipment), propellant, and transportation of each that must be incurred to prepare for a mission to Mars.

[33] As noted above, we estimate that each supply mission using small modules will cost $71 million for the modules and $90 million for the launch. We multiply the sum of $71 million and $90 million, which is $161 million, by four, the number of logistics modules to be delivered to cislunar orbit for DST to arrive at the figure of $645 million.

on the costs of SLS above) or the terrestrial operations cost (which have already been included in our estimates of the cost of ground support operations) for the supply missions, checkout, shakedown, refit, or the orbital mission.

2. Cost Risks

At this point, the DST conceptual design poses a large number of cost uncertainties and risks. NASA has not yet defined the vehicle requirements and performance margins so that technology gaps and required development program risks can be better quantified. In particular, radiation protection, measures to forestall or mitigate human health issues (e.g., diagnostics and treatment systems), ECLSS performance and reliability requirements, chemical propulsion system selection (LOX/LH_2, LOX/LCH_4, or hydrazine), low boil-off cryogenic storage technologies, refueling technology, and solar array deployment have not been fully addressed or are at low levels of technology readiness. Difficulties in surmounting technology hurdles may well drive the vehicle cost above the baseline estimate.

D. Other Architecture Systems

The costs listed in above sections represent the costs associated with an orbital mission to Mars. While lunar landers and Mars surface systems are not part of Mars orbital mission costs, the budgets presented in Chapter 5 must account for all spending through the Mars orbital mission in 2037. As such, below we develop cost estimates for the notional lunar and Mars surface missions described in Chapters 2 and 3.

1. Lunar Landing Mission Costs

Lunar landing mission costs consist of the landers themselves, and the costs of delivering the landers, astronauts, and associated propellant and consumables. As noted in Chapter 2, four types of lunar landers are planned for the coming decade: a small lander for science missions, a medium-sized robotic lander, a human-scale robotic cargo lander, and a large expendable descent stage capable of carrying four astronauts or a large cargo carrier to the lunar surface. The first two types of landers are to be competitively bid by NASA.

Table 2. Estimated Costs of Lunar Missions, Millions of FY 2017 Dollars

System	Development Cost	Cost per additional unit	Number of units	Total Cost
Medium-sized lander	$200	$100	2	$300
Rover for medium-lander	$100		1	$100
Human-scale descent module	$500		1	$500
Crew landing system				
Reusable transfer vehicle	$500		1	$500
Reusable habitat and ascent stage	$1,000		1	$1,000
Expendable descent stage[a]	$0	$200	6	$1,200
Cargo landing system[b]				
Expendable cargo carrier	$200	$100	3	$400
Expendable descent stage	$300	$200	3	$700
Human rover		$100	3	$300
Refueling modules for landers	$200	$50	18	$1,050
Subtotal costs of lunar landers				$6,050
30% Reserve				$1,815
Subtotal costs of lunar landers with 30% reserve				**$7,865**
Launch costs of SLS		$700	6	$4,200
Costs of Orion operations		$850	6	$5,100
Costs of transport for landers, propellant, and cargo		$90	29	$2,610
Cost of small logistics modules		$71	3	$214
Subtotal costs of launches for lunar missions				**$12,124**
Total cost of lunar landing missions				**$19,989**

[a] The crew landing system uses the same expendable descent module as the cargo landing system, so no development costs for this element are incurred under this category.

[b] The cargo landing system uses the same reusable transfer vehicle as the crew landing system, so no development or procurement costs for this element are incurred under this category.

Note: The cost of the first unit of each system is assumed to be captured under development costs.

We did not attempt to estimate the likely costs of procuring small landers or small lander services, as these are likely to be paid for by non-human exploration accounts at NASA. We do estimate the likely costs of the other three landers. In each case, we first estimate development costs, which include the cost of the first unit. We then estimate the costs of each additional unit after the first unit. The estimates, which were all made by STPI, are based on Apollo or other analogous systems.

We assume that the crewed landing system is partially reusable, and that both the crew and cargo landing systems use a reusable transfer vehicle to transfer from the Gateway to low lunar orbit prior to descent and landing. In this case, only one reusable tug is required: the cargo and crew landing systems would be phased to preposition all required surface systems for each crewed landing. As the habitat and ascent stage would support astronauts for short-duration missions on the Moon, and the missions in this report would be up to approximately 14 days, we do not include the costs of developing long-duration lunar habitats in our analysis. In addition to the costs of developing and building these systems, we include the costs of six SLS and six Orion launches. We break out these launches from those included in the section on SLS above, because they are part of NASA's lunar exploration program; they are not integral to the missions to Mars. Likewise, as the notional lunar missions presented in this report rely on 29 commercial launch vehicle missions to carry lander modules, propellant for the landers, and other supplies, we list costs associated with these commercial missions here. Table 2 shows our estimates of these costs.

As can be seen, the cost of lunar landings will be substantial, running $20.0 billion FY 2017 dollars. These costs consist of $7.9 billion for developing and building landers, $9.3 billion for the costs of launching SLS and Orion for lunar landing missions, and $2.8 billion in launches to provide propellant for the landers and other supplies.

Breaking out costs by mission after development, the first two lunar missions (including the SLS/Orion astronaut launch costs, the costs of the expendable descent module and associated supplies for a lunar mission, the cost of the commercial flights, and the Gateway resupply cost) would each cost $2.44 billion. The cost of a lunar exploration mission involving cargo along the lines of lunar missions 3–5 is $3.05 billion, of which half ($1.55 billion) is the cost of astronaut transportation using SLS and Orion.

2. Mars Surface Systems

a. Projected Costs

While the first human mission to the surface of Mars is not expected to take place until the 2040s, many Mars surface systems must be pre-placed on the surface 1–2 years before the human landing mission to ensure that everything is operational before the crew departs from Earth. Because much of this development would have to be completed during the years leading to a human orbital mission to Mars, the potential impact of the costs of these surface mission systems on projected budgets needs to be assessed.

We follow a notional Mars surface architecture discussed in internal NASA documents for this assessment. We assume that there would be two cargo landings to deliver the surface habitat, surface power systems, in-situ propellant production and storage, surface mobility system (rover), and surface science equipment. Each of these cargo landers would be delivered to Mars using a cargo DST. A third cargo DST would deliver the Mars Crew Landing/Ascent Vehicle (MCLAV) to Mars orbit, where it would remain until the crew arrives on a fourth DST. The MCLAV would consist of a Cargo Lander for which the “cargo” is the MAV. After arriving in Mars orbit, the crew would transfer to the MCLAV for the trip to the surface, where the surface systems would already be operational, awaiting the crew’s arrival. Once on the surface, the crew would immediately commence fueling the MAV from the surface propellant manufacturing plant as the crew conducts surface missions. The MAV is therefore available soon after landing to return the crew to the DST should problems arise on the surface.

Development of this equipment would have to begin in the late 2020s to be ready for a human landing on Mars in the early 2040s. Most of these elements would incorporate highly complex, yet-to-be-developed technologies. We found no estimates of the costs of all the individual elements during our research, so we developed our own rough estimates based on comparable systems or engineering assessments of possible vehicles. This approach enabled us to provide a complete framework for future, more detailed cost estimates while fulfilling our mandate to provide an overall budget assessment. Our rough costs for the landing, surface, and ascent elements are as follows:

- **Mars cargo lander.** The challenges associated with landing on Mars are far greater than landing on the Moon because of a thin Martian atmosphere, a need for greater flight autonomy, and higher gravity. We estimate that the design, manufacturing, and integration of a Mars cargo lander would cost $2 billion in FY 2017 dollars, with another $3 billion FY 2017 dollars R&D program required before program initiation, for a total cost of $5 billion FY 2017 dollars. We assume that there are two variants of the lander with identical entry, descent, and landing systems, one for cargo and one for crew. We assume that two cargo landings would be required before the first crew landing. The cost of each additional Mars cargo lander is assumed to be $500 million FY 2017 dollars.
- **Mars crew lander and ascent vehicle.** We assume that this vehicle would use the same entry, descent, and landing propulsion system as the cargo lander, with the MAV and crew quarters being the “cargo” for this vehicle. The technical feasibility of this approach has not been directly verified but appears to be consistent with recent MAV studies. We assume that the ascent stage would use a smaller version of the descent propulsion system and leverage all the flight heritage life support hardware developed for Orion for a short “taxi” journey from the Mars surface back to the crew DST vehicle for return to Earth. Development and manufacturing cost of the MAV and crew quarters on the cargo lander is estimated to be $3.5 billion FY 2017 dollars. Adding the cost of a Mars

cargo lander ($500 million FY 2017 dollars) brings the total cost for the first Crew Lander and Ascent Vehicle to $4 billion FY 2017 dollars.

- **Surface habitat.** We assume the surface habitat uses the same systems as the DST habitat (due to their similar requirements), which will have already been developed but will need to be modified to account for the high g-loads to which the surface habitat will be subjected during landing and to surface dust. We assume no new technologies other than those needed for the DST habitat. We assume the total additional costs of development and construction to be $3 billion FY 2017 dollars.
- **Surface power system.** There are two primary options for surface power: solar or nuclear. Solar power systems would suffice for locations close to the equator. We assume a cost of $3 million FY 2017 dollars per kilowatt (three times what in-space systems require), with a peak power capability of 100 kilowatts, or $300 million FY 2017 dollars for the solar power system and energy storage batteries. For landing sites farther away from the equator, nuclear power systems would be required, for which we use $500 million FY 2017 dollars per 10 kilowatt for the system based on the costs of the Kilopower Reactor, for a total of $2 billion FY 2017 dollars for a 40 kilowatt surface system.
- **In-situ propellant production system.** We assume this system would cost $1.2 billion FY 2017 dollars to develop, build, and integrate. Because the propellant manufacturing would have to start (if not be completed) before the first crew landing, a separate long-term propellant storage system would have to be included in the propellant production system, along with propellant transfer lines that could be connected to the MAV propellant tanks.
- **Surface mobility.** We assume that a surface rover will cost about $1 billion FY 2017 dollars to develop and that it will leverage the ECLSS used for Orion.
- **Surface science.** We allocated $400 million FY 2017 dollars for equipment development for surface science.
- **Surface suits for the crew.** We allocate $200 million FY 2017 dollars for development of space suits for the crew to use on the surface of Mars.

Table 3 shows the estimated cost of the Mars surface mission, using STPI estimates for the cost of each system and subsystem. All of these systems will need to be developed, manufactured, assembled, tested, and launched before the crew returns from the Mars orbital mission if the Mars surface mission is to depart shortly after the return of that mission. Under this approach, three cargo DST vehicles are launched within 2 years after the launch of the orbital mission (2039) to allow time for the complete fueling operation. They depart in the same year—two with landers and the third with the Mars crew lander, which remains in orbit until the crew arrives. From Table 3, a rough estimate of the total cost of the cargo landing and surface systems is $17.3 billion FY 2017 dollars, assuming that a nuclear surface power system is used. Adding in a 30 percent reserve and the cost of three cargo DSTs, our estimate of the total cost of the Mars surface systems is $24.6 billion. However, feedback STPI received from NASA suggests this figure could be dramatically higher, which could require delaying the first Mars landing to 2043 or later. These rough cost estimates of large expenditures highlight the need to include surface mission systems in budget planning documents for a human orbital mission to Mars.

Table 3. STPI Estimated Cost of the Mars Surface Mission

System	System Cost (Millions of FY 2017 Dollars)
Mars cargo lander	$5,500[a]
Development	$5,000
Production	$500
Mars crew lander	$4,000[b]
Development	$3,500
Production	$500
Surface Habitat	$3,000
Nuclear power system	$2,000
Space suits	$200
In-situ propellant production	$1,200
Surface mobility	$1,000
Surface science	$400
System cost	**$17,300[c]**
30% Reserve	$5,190
Cargo DSTs	$2,100
Total	**$24,590**

[a] This number is the cost of the subsystems under “Mars cargo lander”: $5,000 + $500 = $5,500.

[b] This number is the cost of the subsystems under “Mars crew lander”: $3,500 + $500 = $4,000.

[c] This number equals the subsystem plus system cost total $5,500 + $4,000 + $3,000 + $2,000 +$ 200 + $1,200 + $1,000 + $400 = $17,300.

Note: The *italicized* numbers in the table are subsystem costs.

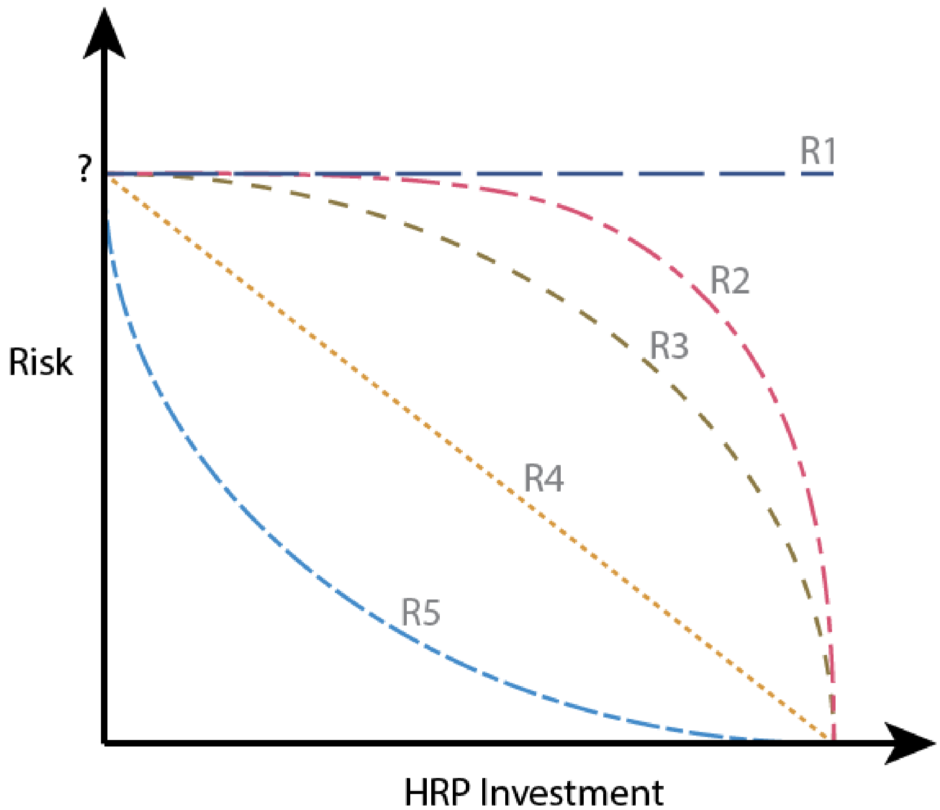
b. Cost Risks

In this assessment, we assume that no ascent vehicle demonstration missions are required before the first crewed mission (the cargo landings would demonstrate all other aspects of the mission) and that the ascent vehicle is not pre-placed on the surface but rather arrives with the crew. If a demonstration mission is required or if the ascent vehicle needs to be pre-placed, it would, of course, have major effects on the schedule and the budget.

E. Human Research Program

Research before the first trip to Mars orbit would be undertaken to better understand the risks facing astronauts going to Mars, and at least through 2030, inform design decisions for the DST. Once the orbital mission is launched, funding would be used to track and understand the physiological changes of each astronaut.

To the best of our knowledge, NASA has no plans to increase spending on the Human Research Program, which was $140 million in FY 2017 and in FY 2018. The PBR for FY 2019 asks for $140 million annually through 2023 in nominal dollars (NASA 2018). Producing a useful estimate of the costs associated with understanding and mitigating the risks to humans on a 1,100-day mission to Mars would require an understanding of the relationship between funding and risk reduction, as this relationship can dramatically change the level of funding required buy down risk (see Figure 14). In some specific health risk research areas that are currently more advanced, such as renal stone formation and immune response, NASA may have enough information to estimate future costs based on current progress. However, in most health risk areas identified in Chapter 6 below and in the overall risk to humans, data does not exist to allow for accurate calculations and the development of reasonable cost models. Because STPI does not have enough data to begin to develop accurate models for the cost of addressing and retiring human health risks, we therefore assume that funding for the Human Research Program (HRP) is $140 million in inflation-adjusted FY 2017 dollars in FY 2024, and then stays at this annual level indefinitely. This number may be lower or higher than the necessary amount of funding required to address the gaps in human health research discussed in Chapter 6.



Note: The question mark represents an unknown amount of risk for a given topic at the start of research. The amount of funding needed to retire the risk is the area under each curve. R1: risk remains constant regardless of research investment; R2: risk remains constant until a critical threshold of research investment; R3: risk gradually decreases as a function of research investment; R4: risk mitigation is perfectly correlated with research investment; R5: research investment results in decreasing marginal rates of risk reduction.

Figure 14. Illustrative Figure Demonstrating Change in Risk as a Function of HRP Investment for Five Sample Risk Regimes

F. Other Costs

NASA's human exploration budgets will include some items, such as operating and maintaining the ISS, in addition to the costs described above. We describe these other items and their associated costs here.

1. International Space Station

Currently, the Trump Administration plans to end direct support of the ISS by FY 2025. However, NASA personnel have told STPI that NASA requires a space station in LEO through at least 2028 to meet mission needs for extended human health research and technology development that would be unmet by the capabilities offered on the Gateway, and that NASA plans to support a platform in LEO through at least this time. Previous STPI research suggests that an alternative to the ISS will not be available during this time without large subsidies provided by NASA (Crane et al. 2017). As such, large cost savings would likely not manifest even if NASA ended support of the ISS in 2025.

To be conservative, we assume that the ISS continues to operate through 2028. In the FY 2019 NASA budget request, NASA expenditures for FY 2023 are budgeted at $1.45 billion in support for the ISS and $1.81 billion for space transportation (NASA 2018). Deflating those figures into FY 2017 dollars yields $1.30 billion and $1.62 billion FY 2017 dollars, respectively, $2.92 billion FY 2017 dollars in total. We assume that expenditures for operations and transportation to the ISS remain at this FY 2023 level through 2028. We assume that spaceflights to LEO for astronaut training and other activities will continue after 2028. Accordingly, we project that expenditures on space transportation and other activities in LEO will fall, but will still run $1 billion FY 2017 dollars annually after 2028.

2. Commercial Lunar Activities

Based on NASA's current program to support the development of commercial space stations in LEO to take over LEO operations following the retirement of the ISS, we assume that the United States will support commercial lunar surface activities following the end of NASA's landings in 2032. As such, we assumed that NASA would allocate $1 billion in FY 2017 dollars annually for the support of commercial activities on the lunar surface starting in FY 2033, for a total of $5 billion in FY 2017 dollars.

3. Advanced Exploration R&D projects

We assume $130 million per year in FY 2017 dollars will be spent on long-term, unassigned Advanced Exploration Systems R&D projects. This figure was derived from deflating the $144.7 million budgeted for Advanced Exploration Systems R&D projects for FY 2023 in the President's FY 2019 NASA Budget Request into FY 2017 dollars (NASA 2018).

4. Space Technology Mission Directorate

We assume that the Space Technology Mission Directorate will provide $300 million per year in FY 2017 dollars for long-term, unassigned R&D projects in support of human spaceflight.

5. Funds for the Commercialization of Space

The President's FY 2019 Budget Request includes $150 million for FY 2019 for the commercial development of LEO rising to $225 million in FY 2023 (NASA 2018). We assume that the funding stream between FY 2019 and FY 2023 is sufficient for the commercial development of LEO, and that no additional funds are provided after FY 2023.

G. Total Costs

1. Cumulative Costs for Human Exploration

96 percent of the costs associated with an orbital trip to Mars occur prior to the DST leaving for Mars, scheduled for 2037 in this report. The remaining four percent is split between the 3 years of the orbital mission, and is composed of the costs incurred during the mission.[34] As such, when discussing cumulative budgets versus cumulative costs in Chapter 5, including FY 2038, FY 2039, and FY 2040 would obfuscate the actual available budget for an orbital mission to Mars. Accordingly, we divide our analysis of total costs into two sections: the total costs associated with an orbital mission to Mars through 2040, and the total costs of human spaceflight through FY 2037.

Table 4 shows historical and total projected costs for a human orbital mission to Mars and precursor missions by system. Our estimate of total future costs for a human orbital mission, assuming lower launch costs for SLS, is $87 billion in FY 2017 dollars. *The cost of the orbital mission to Mars beyond the development of SLS, Orion, and the assembly of the Gateway is $44.6 billion in FY 2017 dollars.*[35] Averaging the costs related to a Mars orbital mission incurred through FY 2037 ($83 billion FY 2017 dollars) across the 19 years between FY 2019 and FY 2037 leads to an average annual cost of approximately $4.4 billion FY 2017 dollars; the average annual cost during mission years is $1.2 billion FY 2017 dollars. Adding in costs that have already been incurred through the end of FY 2018, the total cost for an orbital mission to Mars and its precursor missions through FY 2040 is $121 billion FY 2017 dollars.

Table 4. Estimated Costs of the Orbital Mars Missions

	Millions of FY 2017 Dollars		
System	System Costs through FY 2018	Projected Future System Costs	Total System Costs
SLS development[a]	$15,875	$10,049	$25,924
SLS Block 2 development		$2,000	$2,000
SLS launches outside of development costs ($700 million per launch)[b]		$5,705	$5,705
Orion development[c]	$14,910	$5,289	$20,199

[34] This includes 66 percent of the SLS and 75 percent of the Orion for EM-17, plus 3 years of ground support, for a total of $3.7 billion.

[35] This includes 6 SLS launches ($4.2 billion), 5 Orion capsules ($4.3 billion), the DST and supplies ($29.2 billion), and 8 years of ground support ($6.9 billion), for a total of $44.6 billion in FY 2017 dollars.

		Millions of FY 2017 Dollars	
Orion launches outside of development costs ($850 million per launch)[b]		$5,423	$5,423
Human exploration ground systems	$2,961	$2,737	$5,698
Exploration ground systems operations[b]		$16,187	$16,187
Commercial logistics modules and launch[d]		$874	$874
Gateway[e]		$5,732	$5,732
DST		$29,190	$29,190
Subtotal Orbital Mission to Mars through 2037	**$33,746**	**$83,186**	**$116,932**
Cost associated with Mars Orbital Mission 2038–2040[f]		$3,711	$3,711
Orbital Mission to Mars Total	**$33,746**	**$86,897**	**$120,643**

[a] Contains the expenditures for EM-1, EM-3, EM-4, EM-5, and EM-6 between FY 2019 and FY 2023.

[b] FY 2019 through FY 2037.

[c] Contains the expenditures for Orion acquisition between FY 2019 and FY 2023.

[d] Four commercial launches, and three commercial logistics modules and their development are not accounted for in other lines.

[e] Does not include launch costs.

[f] Includes costs related to EM-17 and exploration ground system operations incurred between 2038 and the end of the orbital mission in 2040.

For our budget comparisons in Chapter 5, Table 5 shows the total costs of human spaceflight through 2037, including estimated costs of lunar landing missions and a human surface mission to Mars. The costs of the lunar mission presented in this report beyond the development of SLS, Orion, and the assembly of the Gateway is $25.2 billion in FY 2017 dollars.[36] Including the cost of development and operation of SLS, Orion, the Gateway, and the lunar landing missions, the total projected cost of meeting Administration goals to return to the Moon by the end of the 2020s would be $62 billion.[37]

Our total estimated cost for human spaceflight from FY 2019 through FY 2037 runs $184 billion FY 2017 dollars. Including costs already incurred through the end of FY 2018 yields a total cost through FY 2037 of $217 billion FY 2017 dollars. Averaging the total

36 This includes 6 SLS launches ($4.2 billion), 6 Orion capsules ($5.1 billion), lunar landers, propellant, supplies, and commercial transportation ($10.7 billion), 6 years of grounds support ($5.2 billion), for a total of $25.2 billion in FY 2017 dollars, and comprises EM-7 through EM-12.

37 The remaining $37 billion is the cost of the development, construction, and operations of SLS, Orion, and Gateway and ground system operations through EM-6.

estimated cost between FY 2019 and FY 2037 (19 years) leads to a total human spaceflight cost of approximately $9.7 billion per year.

Table 5. Total Estimated Costs of Human Spaceflight through 2037

	Millions of FY 2017 Dollars		
System	**System Costs through FY 2018**	**Projected Future System Costs**	**Total System Costs**
Orbital Mission to Mars Through 2037 (Table 4)	$33,746	$83,186	$116,932
Lunar landers [2019–2032]		$7,865	$7,865
Launch costs of lunar landing missions [2025–2032]		$12,124	$12,124
Mars surface systems [2030–2037]		$24,590	$24,590
Human Research Program [2019–2037][a]		$2,660	$2,660
Other human spaceflight costs [2019–2037][b]		$53,210	$53,210
Human Spaceflight Total through 2037	**$33,746**	**$183,635**	**$217,381**

[a] Estimated expenditures for HRP is based on inflation adjusted projection of FY 2017 and FY 2018 budgets and the FY 2019 requests. As discussed in Subsection 5.E, STPI did not do specific analysis to estimate the total amount of funds needed to address and retire human health risks. As such, this number may be lower or higher than the necessary amount of funding required to address the gaps in human health research discussed in Chapter 6.

[b] Includes LEO operations, subsidies of commercial lunar operations, other R&D.

2. Annualized Costs

While the average expected cost for human spaceflight is about $9.7 billion a year, these costs are not spread evenly across the years. To estimate the amount of money spent per year for the development of a piece of hardware, given an estimated total budget and time for development, we developed cost curves for development of major systems based on established systems engineering principles (NASA 2017d). We assumed that the cost of acquisition of additional units for a piece of hardware that has already gone through the development lifecycle would have a different budget curve. For 3- and 5-year acquisition cycles (representing Orion and SLS vehicles, respectively), we assumed that the bulk of the costs would come towards the end of the acquisition cycle compared to the development cycle. Figure 15 shows our assumptions for the spread of development costs for 3-, 4-, 5-, and 8-year project development cycles and acquisition cost curves for 3- and 5-year acquisition cycles as well as which major architectural elements follow each curve, based on Chapter 3. The sum of the points on each curve is equal to 1, representing the full cost of a program.

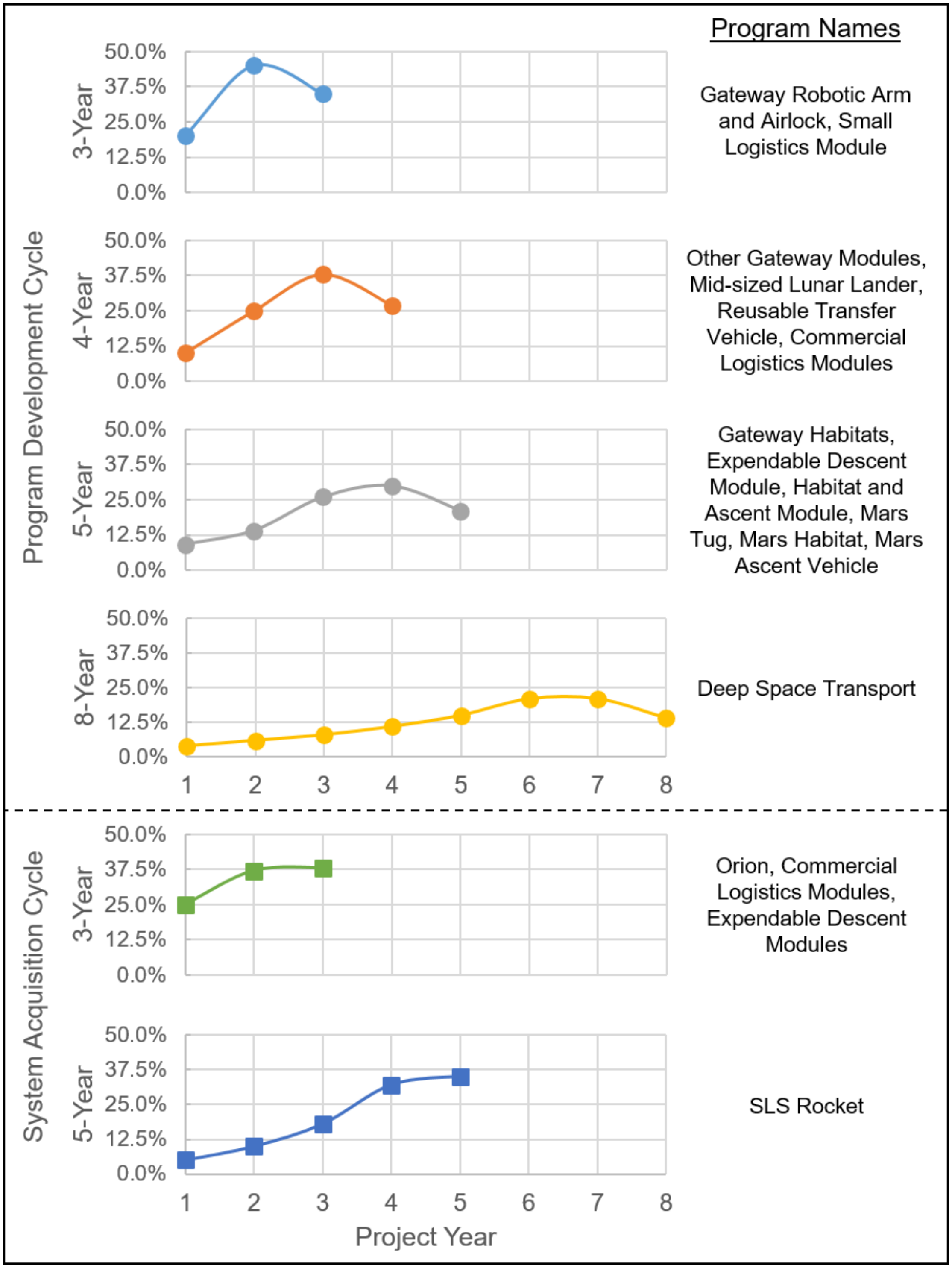


Figure 15. Cost Curves for Development and Acquisition of Major Architectural Elements

Overlaying these development and acquisition curves for major systems along with the costs operations and other programmatic expenses discussed above onto the schedule presented in Chapter 3 allows us to construct annualized expected cost of human spaceflight through FY 2037. Figure 16 shows the annualized costs for human spaceflight divided into six major categories: development of SLS and Orion; development, construct, and assembly of the Gateway; development, construction and operations of the DST (Mars orbital mission); robotic and human missions to the Moon; R&D related to Mars landings; other costs associated with human space exploration. In the next chapter, we reconcile the costs presented in this chapter with projected NASA budgets for human exploration.

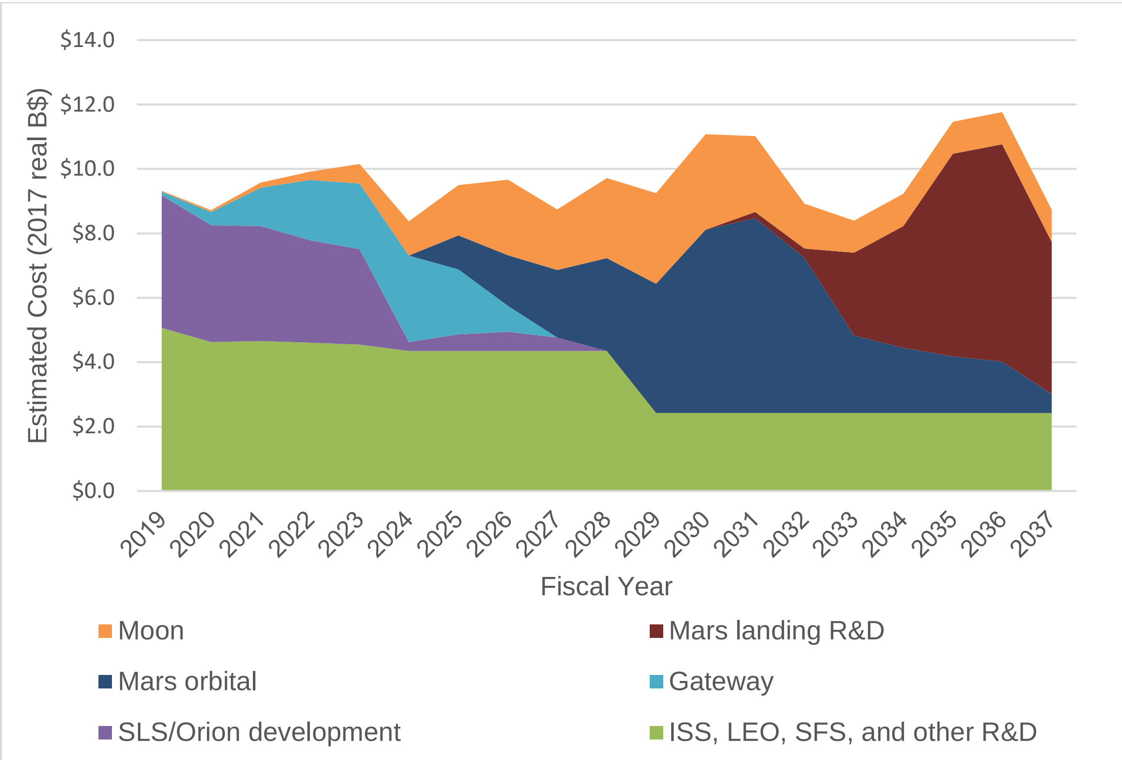


Figure 16. STPI-Estimated Costs of Human Exploration Activities on an Annual Basis

H. Risk of Cost Overruns

1. NASA's Past Record on Predicting Costs

Historical mission complexity and timelines can provide a useful guide to assess whether a mission or activity is likely to be accomplished within a specified schedule. Many NASA programs have experienced unexpected developments (including launch failures), technical challenges, cost overruns and significant schedule slips, as measured from initial contract/program start to launch and/or full capability.

- Space Shuttle: 9 years (1972–1981)
- Hubble Space Telescope: 13 years (1977–1990)
- Space Station: 17–27 years

- Orion: 13 years (estimated, 2006–2019 expected delivery)

To better understand the cost risks of major architectural elements for a human mission to Mars and its precursor missions, we reviewed cost overruns from past NASA projects. We used a Congressional Budget Office (CBO) Study of NASA projects up to 2004 (CBO 2004) and a series of GAO reports on assessments of selected large-scale projects at NASA from 2009 to 2017 (GAO 2009a, 2010, 2011, 2012, 2013, 2014b, 2015, 2016a, and 2017b) to develop cost overrun data for NASA projects (Figure 17). These projects represent both large and small missions, and were baselined under several different cost estimating policies. For our analysis, we split the documented projects into four groups: near-Earth satellites, human-space-flight-oriented programs, deep space programs, and programs related to launch vehicles. We concluded that the programs most relevant to NASA's plans for human exploration are the deep space and human-space-flight-oriented programs. The individual cases are listed in Appendix C.

Of the 30 deep space programs, 18 (60 percent) experienced cost overruns. The average overrun for these 18 programs was 46 percent with a standard deviation 56.5; the large standard deviation reflects the very large overruns of some programs like the James Webb Space Telescope. For programs oriented towards human spaceflight, we find that three out of the four programs (75 percent) experienced cost overruns with an average overrun of 66 percent. Because of the small number of programs oriented towards human spaceflight, we combined the deep space and human-space-flight-oriented programs that had experienced cost overruns. The average overrun of these 21 programs was 49 percent, although there is a statistically significant decline over time in the overrun percentage.[38]

[38] Linear regression of overrun against time for the 21 missions shows a decline of the overrun rate of 2.4% per year ($p < .05$). For the full set of 84 missions considered in Figure 17, the overrun rate was modeled to decline at 2.6% per year ($p < .01$).

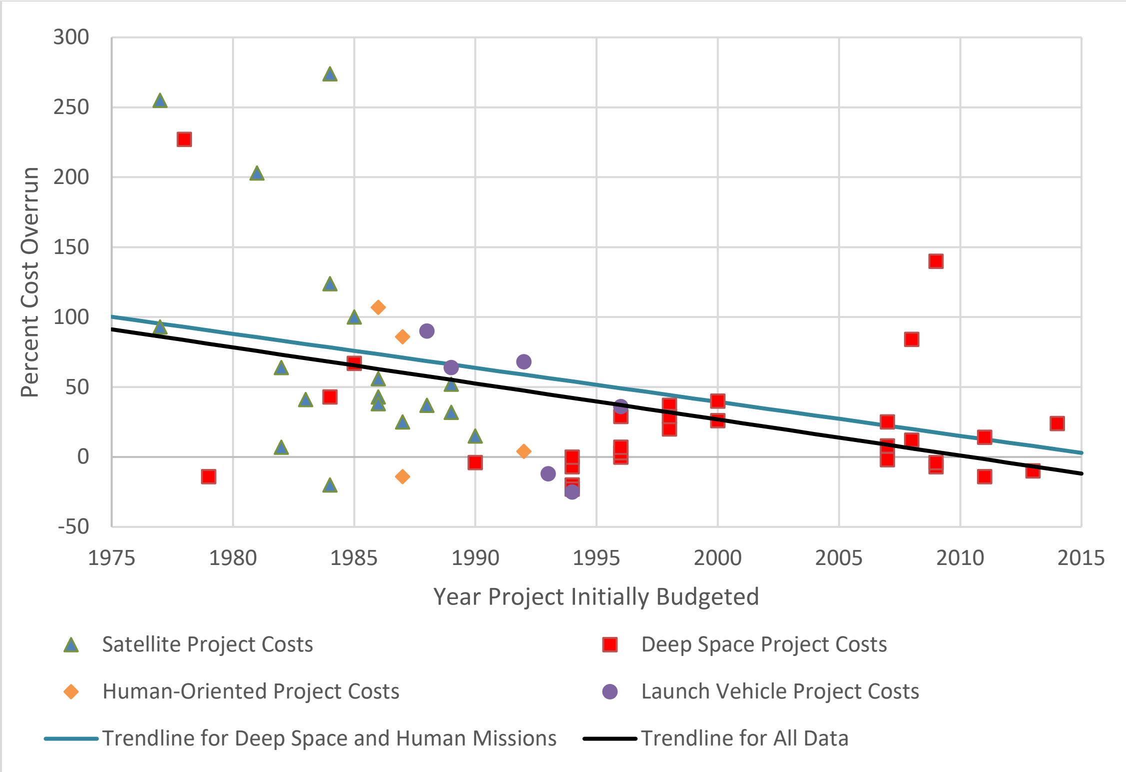


Figure 17. NASA Cost Overruns by Project Type

The National Research Council conducted a study of a possible Mars missions entitled Pathways to Exploration (NRC 2014). In their analysis, they use a 50 percent reserve to account for the risks of cost overruns. We note that the 49 percent figure cited above is almost identical to the NRC's number.

2. Implications for Cost Risk

As noted above, we argue that the risks of substantial, additional cost overruns for launch systems and related vehicles are low. However, for the other systems, Gateway and DST in particular, risks could be large. Taking the average of 49 percent cost overage calculated above and multiplying it by our estimate of total program costs for the Gateway of $5.7 billion FY 2017 dollars yields a potential total cost of $8.5 billion in FY 2017 dollars. Based on the historical record, the risk of additional costs of this magnitude is not unrealistic.

However, in discussions, NASA has noted that in 2009, agency-wide cost estimating practices were changed, and has seen significant reductions in cost overruns. Although few flagship missions have been baselined after this point, the time trend data suggests that the effects of improving practices over time have been significant. Our 49 percent estimate is intended to represent a reasonable worst-case estimate, reflecting the possibility that due to the complexity of designing spacecraft for human exploration cost over-runs revert to their historical average rather than their current levels.

The cost model for DST development is based on the current cost estimate for the Orion program ($20.2 billion), which already includes historic cost overruns in the Orion program. As such, adding an additional 49 percent for possible cost overruns for DST may be inappropriate, as it would double count some of Orion's cost overruns. We note, however, that taking Orion's original baseline cost estimate of $3.9 billion (Braukus, Dickey, and Humphries 2006) and comparing it to the current cost estimate of $20.2 billion gives a total cost overrun of 418 percent. This large percentage increase is the result of many factors (e.g., program cancellations). Although not all of these factors may apply to the DST, because the DST would be a similarly complex spacecraft, and currently has uncertain mission requirements, possible cost overruns could be as large.

In light of the number of highly complex elements needed for a human mission to the surface of Mars, the potential risk to that estimate is especially large. Applying the historical average cost overrun of 49 percent to this figure generates a potential overrun estimate of $36.7 billion in FY 2017 dollars, which reflects the cost risk associated with developing, constructing, and integrating these elements.[39]

[39] $24.6 billion times 149 percent, reflecting past average cost overruns of 49 percent, yields a potential cost of $36.7 billion.

5. Comparing Costs with Available Budgets

This chapter first estimates NASA budgets between FY 2019 and FY 2037, the year of the start of the Mars orbital mission,[40] under two scenarios suggested by NASA: (1) overall budgets that remain flat in inflation-adjusted dollars and (2) overall budgets that rise at the rate of growth in U.S. gross domestic product (GDP) in inflation-adjusted terms as projected by the CBO.[41] We then estimate the share of these budgets that might be available for human exploration. We sum these prospective budgets over the FY 2019 to FY 2037 time period, and compare them with the likely research, development, testing, and capital and operational costs of the exploration systems components estimated in Chapter 4. Next we match potential annual budgets to needed annual expenditures for the exploration schedule laid out above. As stipulated for this study, we conclude with a comparison of our projected annual expenditures to the five-year budget profile contained in the FY 2019 PBR for NASA. Although the legislation mentions the FY 2017 budget, because the FY 2017 PBR has been superseded by the final FY 2018 appropriations passed by Congress, we have chosen to compare our annual budget profile to that of the final FY 2018 budget. Our sources are publicly available NASA budget documents and FY 2018 appropriations language, cited in the following sections.

A. Future NASA Budgets

1. Projected Aggregate NASA Budgets

NASA was appropriated $20.7 billion for FY 2018, which corresponds to $20.4 billion in FY 2017 dollars. In our first scenario, we assume that NASA's overall budget remains static in inflation-adjusted dollars from FY 2019 to FY 2037 at this amount. Cumulatively, this assumption yields total funds available to NASA of $387.9 billion in

[40] 96 percent of the costs associated with an orbital trip to Mars occur prior to the DST leaving for Mars, scheduled for 2037 in this report. The remaining 4 percent is split between the 3 years of the orbital mission and is composed of the costs incurred during the mission, which includes part of one SLS, part of one Orion, and 3 years of ground support. As such, when discussing cumulative budgets versus cumulative costs, including FY 2038, FY 2039, and FY 2040 would obfuscate the actual available budget for an orbital mission to Mars. Additionally, as this report focuses on missions through the Mars orbital mission, we did not develop budgets for later missions past 2037. Accordingly, we present budgets only through FY 2037 in this report.

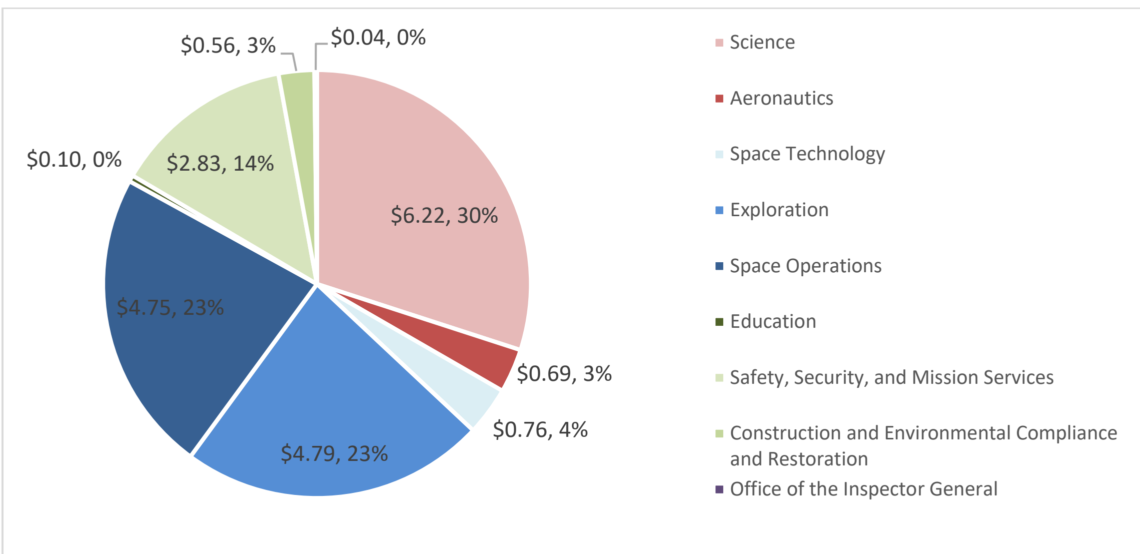
[41] All dollar figures in this chapter are in nominal dollars, unless otherwise noted. We use the U.S. Bureau of Economic Analysis's GDP Price Deflator to convert to any real dollar figures (U.S. Bureau of Economic Analysis 2018).

FY 2017 dollars between 2019 and 2037. In the second scenario, we assume that GDP grows at an average annual rate of 1.9 percent (CBO 2018), and that NASA's inflation-adjusted budget grows at this same rate. Under this scenario, cumulative funds available to NASA between FY 2019 and FY 2037 total $470.7 billion in FY 2017 dollars.

2. Share of Budgets Devoted to Human Spaceflight

a. NASA accounts currently associated with human spaceflight

To estimate the shares of NASA's prospective budgets that might be used for human space exploration, we included funding associated with "Exploration," "Space Operations," and half of the "Space Technology" categories as supporting the activities related to human spaceflight.[42] In FY 2018, these accounts represented approximately half of NASA's budget (see Figure 18).[43] Another one-third of NASA's budget was directed to Science, Aeronautics, and Education activities. The remainder of its budget was devoted to its Safety, Security, and Mission Services (which includes the costs of NASA's centers and facilities), Construction and Environmental Compliance and Restoration, and Inspector General accounts.



Source: U.S. House of Representatives 2018.

Note: Half of Space Technology ($0.38 billion) + Exploration ($4.79 billion) + Space Operations ($4.75 billion) = $9.9 billion, which is 48 percent of NASA's budget.

Figure 18. NASA Spending in FY 2018

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42 We assume that half of Space Technologies is spent toward human exploration and the other half toward science missions.

43 For comparison, in the FY 2019 President's Budget Request, the accounts related to human space exploration represented 53 percent of NASA's budget.

b. Projecting possible funds available for human exploration

In this subsection, we explore two scenarios for future funds available to NASA for its exploration plans. In both scenarios we assume that funding for human exploration is separated from funding for other NASA Directorates and budget lines—should NASA's requirements for aeronautics expand in the mid-2020s, for example, any funds would need to be reprioritized from planetary science investments rather than human exploration-related accounts. The first scenario assumes that NASA's budget remains constant in real terms between FY 2019 and FY 2037, and that the share of NASA funding devoted to accounts potentially relevant to a human exploration remains fixed at its share in FY 2018 (and other recent years), at 50 percent. In that case, total funding available to NASA for exploration-related accounts would be $192.7 billion in FY 2017 dollars over the period FY 2019–2037 (See Table 6). The total funding available between FY 2019 and FY 2033 in FY 2017 dollars would be $152.1 billion.

The second scenario assumes that NASA's budget grows in real terms at 1.9 percent per year (the rate of growth in GDP assumed by the CBO) and that the share of NASA funding devoted to exploration-related accounts remains fixed at 50 percent of the total. In that case total funding available to NASA for exploration would be $233.8 billion in FY 2017 dollars over the FY 2019–2037 period, including $177.4 billion available through 2033 (See Table 6).

Table 6. Funding Availability, FY 2019–FY 2037

Budget Assumption	Scenario 1	Scenario 2
Funding available for NASA	FY 2018 appropriated funds, constant purchasing power	Annual increase at rate of real GDP growth
Share of funding for human exploration	FY 2018 level	FY 2018 level
Cumulative NASA funding FY 2019-2033	$306 billion	$357 billion
Cumulative funding for human exploration FY 2019–FY 2033	$152 billion	$177 billion
Cumulative NASA funding FY 2019–FY 2037	$388 billion	$471 billion
Cumulative funding for human exploration FY 2019–FY 2037	$193 billion	$234 billion

Note:

Scenario 1 assumptions: NASA's budget remains constant in real terms between FY 2018 and FY 2037 and the share of NASA's funding devoted to accounts potentially relevant to exploration remains fixed at its share in FY 2018 (and other recent years), at 50 percent.

Scenario 2 assumptions: NASA budget grows in real terms at 1.9 percent per year. The share of NASA's funding devoted to exploration-related accounts is fixed at 50 percent of the total.

It should be noted that these assumptions suggest a more expansive budget for NASA's exploration missions than had been assumed in the National Academies' 2014 report *Pathways to Exploration: Rationales and Approaches for a U.S. Program of Human Space Exploration*. That report assumed a budgetary baseline of $8 billion in FY 2013 dollars, and considered constant real expenditures of $8 billion to be its more aggressive budgetary scenario with an alternative scenario of constant nominal dollars (NRC 2014). STPI's analysis is based upon NASA's current budget and budgeting scenarios, and we recognize that a return to the more austere NASA budgets of earlier in the decade would require considerable reductions in any estimates of the total funds available to NASA for human exploration.

B. Comparison of Projected Costs to Projected Human Spaceflight Budget

1. Comparison of Cumulative Cost to Cumulative Available Budget

The annualized costs developed for this report are based on adding the cost curves for each program shown in Subsection 4.G.2. Of course, in real programs, the actual percentage of total cost expended in a given year may vary from what we assumed for this report as some amount of expenditures can be adjusted and rescheduled to account for other programs running concurrently. Likewise, annual budgets may shift for a variety of reasons. As such, comparing total cumulative cost to total cumulative available budgets enables analysis of whether there is enough available funding for the programs envisioned in NASA's current and notional plans and in this report. Below, we examine whether sufficient funds for human spaceflight would be available if the orbital mission to Mars left in 2037 or in 2033.

a. Comparison of Cumulative Cost to Available Budget for a 2037 Mission

NASA human spaceflight is projected to cost $184 billion FY 2017 dollars between FY 2019 and FY 2037. Comparing cumulative costs developed in the preceding chapter against aggregate budgets presented in Table 6 indicates that if NASA budgets for human space exploration remain flat in constant dollars ($193 billion FY 2017 dollars), aggregate funding through FY 2037 easily covers aggregate costs ($184 billion FY 2017 dollars) and can handle five percent cost overruns for activities associated with human spaceflight.

If the human space exploration budget increases at the rate of real GDP growth, budget resources through FY 2037 ($234 billion FY 2017 dollars) would be equal to costs even if costs overrun the base cost of $184 billion FY 2017 dollars by approximately 30 percent.

b. Comparison of Cumulative Cost to Available Budget for a 2033 Mission

Were NASA to attempt to complete the set of scheduled activities (e.g., ISS, Gateway construction, lunar landings, and DST construction and testing) in time to meet a 2033 transfer window for the mission to Mars, cumulative costs ($172 billion FY 2017 dollars)[44] would exceed cumulative budgets ($152 billion FY 2017 dollars) assuming a budget with constant purchasing power, although there would be sufficient cumulative funds ($177 billion FY 2017 dollars) to complete the scheduled activities in time for a 2033 launch window were NASA to receive budget increases commensurate with real economic growth (see Table 6).

2. Comparison of Annual Cost Profile to Budget Profile

While cumulative budgetary resources are approximately equal to or exceed cumulative costs, that is not always so when costs and budgets are distributed across years. Figure 19 overlays the annual cost profile constructed from the schedule in Chapter 3 and the cost estimates in Chapter 4 on STPI's two human spaceflight budget scenarios.

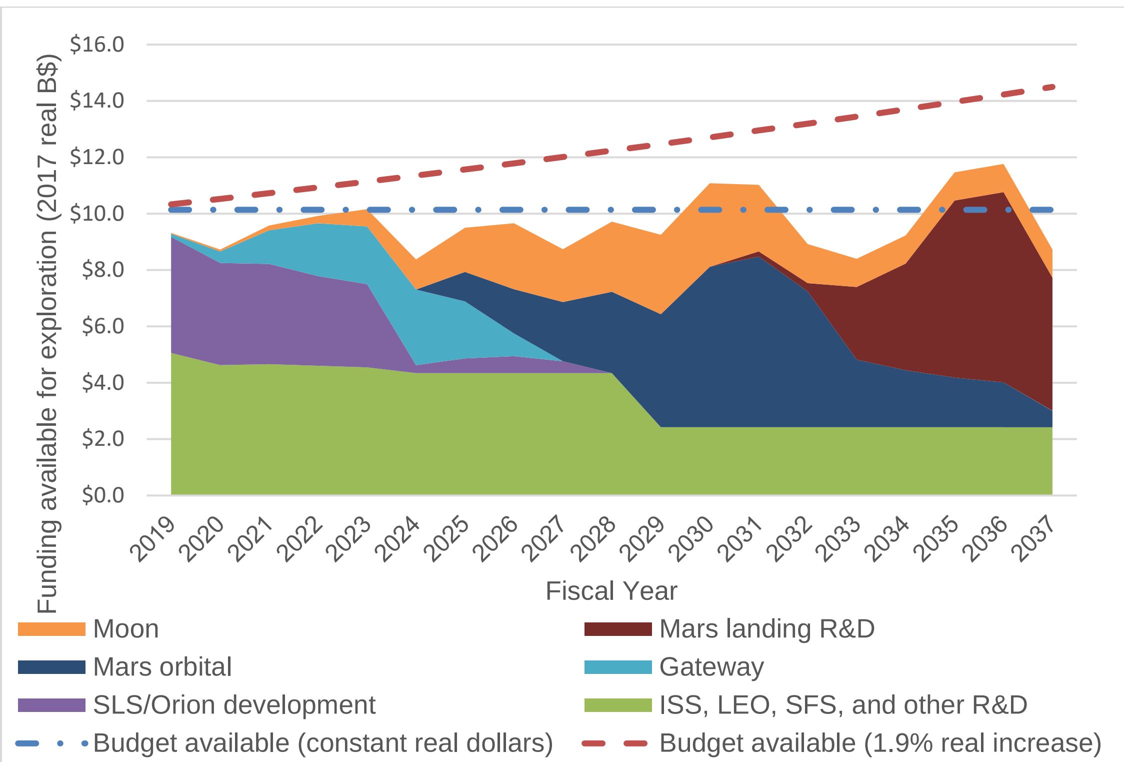

Figure 19. Comparison of STPI-Estimated Costs of Human Exploration Activities with Budget Projections on an Annual Basis

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[44] This number includes everything listed in Tables 4 and 5, except for fixed annual costs for human exploration from FY 2034 through FY 2037 (e.g., supporting LEO operations, SFS, annual R&D).

Under the flat budget scenario, a mission to Mars in 2037 is feasible but only if budgets can be smoothed during peak cost periods or the campaign to the Moon is scaled back. As can be seen, there are individual years (FY 2030–2031, at the peak of construction cost estimates for the DST and while Moon landings are occurring annually, and FY 2035–FY 2036, at the peak of procurement costs for Mars surface systems) where estimated costs exceed budgetary resources by approximately $1 billion per year. In each of these cases, there is sufficient budget in the years directly before and after these periods (i.e., FY 2029 and FY 2032; FY 2034 and FY 2037) that if programmatic costs could be spread over slightly longer periods, a flat budget will approximately meet or exceed costs in every year. However, if programmatic spending cannot be flattened, this budget shortfall could be fully mitigated by reducing the scope of lunar surface activity (such as reducing the number of lunar landings and not supporting establishment of commercial lunar activities) and delaying a human landing on Mars. Alternatively, if lunar landings are a priority in the 2030s, construction of the DST could be delayed by 2 years, which would push the orbital mission to Mars to 2039.

Under the flat budget scenario, in FY 2023 (at the peak of the cost of Gateway procurement), in FY 2025–26 (as the Gateway is completed and lunar R&D is at its peak) and in FY 2028–2029 (during Moon landings and near the peak of DST costs) costs are approximately equal to budgets. In no year is there a cumulative shortfall (i.e., where estimated cumulative costs up to that year exceed estimated cumulative budgets up to that year) in either the flat budget or the real growth scenario.

Under a real growth budget scenario, annual budgets always surpass annual costs by $1–6 billion FY 2017 dollars. Accordingly, a mission to Mars in 2037 is feasible under this scenario, even with cost overruns. As noted above, there is an excess of $50 billion FY 2017 dollars over the course of FY 2019 to FY 2037. This extra funding could be used for such activities as developing lunar habitation systems or increasing the number of missions to the Moon, which would require more than one crewed SLS mission annually.

3. Comparison of Costs with FY 2019 PBR

STPI was also asked to compare our estimates of the costs associated with a human mission to Mars with the Administration's budget request for FY 2017, extending to FY 2021. Because during the course of this research the Administration has issued its FY 2019–FY 2023 budget request, we chose to compare our cost profile with the FY 2019 NASA budget request to provide a more up-to-date comparison between projected budgets and costs. Table 7 shows budget categories that we assume incorporate all human space exploration programs.

The budget figures in Table 6 differ from those used in our analyses in Table 7. First, the budget figures in Table 7 are in nominal dollars. In contrast, we have used constant FY 2017 dollars for our cost analysis. Second, the budget uses different cost categories than does STPI. STPI has built up its cost estimates by system. We provide separate cost estimates for Gateway and DST. Third, we only include part of spending on Exploration Research and Technology (ER&T) in our analyses of the costs of human spaceflight since some of ER&T's activities support technology development for activities other than those related to human exploration.

Table 7. FY 2019 Budget Request: Projections for FYs 2019–2023

	Millions of Dollars (Nominal)				
Account	**2019**	**2020**	**2021**	**2022**	**2023**
Exploration Research and Technology (Exclusive of the Human Research Program)	862.7	772.7	772.7	772.7	772.7
Orion Development	1,163.5	1,137.7	1,134.2	1,117.8	1,117.8
SLS Vehicle Development	2150.0	2,062.9	2,165.1	2,131.0	2,276.0
Exploration Ground Systems	895.0	589.9	520.8	458.7	451.9
Human Research Program	140.0	140.0	140.0	140.0	140.0
Gateway	504.2	662.0	540.0	558.9	459.1
Advanced Cislunar and Surface Capabilities	116.5	146.0	163.7	300.0	320.3
Exploration Advanced Systems	313.0	260.7	240.6	186.1	144.7
SMD Missions Related to Exploration	268.0	268.0	268.0	268.0	268.0
Commercial LEO	150.0	150.0	175.0	200.0	225.0
ISS Program	1,462.2	1,453.2	1,471.2	1,466.2	1,451.2
Space Transportation	2,108.7	1,829.1	1,858.9	1,829.2	1,807.3
SFS	903.7	841.4	888.2	934.9	954.6
Total	**11,037.5**	**10,313.6**	**10,338.4**	**10,363.5**	**10,388.6**

Source: NASA (2018, BUD-1–BUD-5). "Exploration Advanced Systems" line for FY 2019 includes $44.8M in facilities construction costs.

Note: Because NASA operated on continuing resolutions for much of FY 2018 and FY 2019, and Congress passed the FY 2018 budget at the end of March 2018 with $539 million more for EGS (including a new mobile launcher) and SLS Vehicle Development than the FY 2018 PBR requested, we included these additional appropriations in the FY 2019 budget.

Table 8 transposes the budget numbers into categories analogous to STPI's cost estimates. After recombining lines into higher-level categories, we find that the President's FY 2019 budget includes $19 billion over the five-year period to complete development of launch systems, $22 billion for ISS and ground-based support, and nearly $11 billion for technology development.

Table 8. FY 2019 Budget Request: Projections for FYs 2019–2023

2019 PBR	Billions of Nominal dollars					
	2019	**2020**	**2021**	**2022**	**2023**	**Cumulative**
SLS + Orion + Ground Systems	$4.2	$3.8	$3.8	$3.7	$3.8	$19.4
ISS + Space Transportation + Space and Flight Support + Commercial LEO	$4.6	$4.3	$4.4	$4.4	$4.4	$22.2
Technology (including Gateway and Lunar Exploration Systems)	$2.2	$2.2	$2.1	$2.2	$2.1	$10.9
Total (in Nominal Dollars)	**$11.0**	**$10.3**	**$10.3**	**$10.3**	**$10.3**	**$52.5**
Total Expressed in Constant 2017 Dollars	**$10.7**	**$9.8**	**$9.6**	**$9.4**	**$9.2**	**$48.7**

Source: NASA (2018, BUD-1–BUD-5).

Note: As noted in Table 7, SLS and Exploration Ground Systems costs for FY 2019 depart from the PBR, reflecting additional funds appropriated in the NASA FY 2018 final appropriation for ground systems construction.

Comparing these numbers with STPI's cost estimates, Table 9 shows that our cost estimates are close to the five-year cumulative budget request projections ($47.7 billion in estimated costs, as compared with $48.7 billion in inflation-adjusted funding). Note that the President's 2019 budget request reduces NASA's overall exploration-related budget in inflation-adjusted dollars over time. The decay in NASA's purchasing power, coupled with STPI's estimates of peak Gateway costs in 2022–2024, leads to an estimate of a gap in FY 2022 of $0.5 billion and in FY 2023 of $1.0 billion.

Table 9. STPI Estimates of Costs of Human Spaceflight in the Context of the Exploration Campaign: Projections for FYs 2019–2023

STPI Estimates	Billions of FY 2017 Dollars					
	2019	**2020**	**2021**	**2022**	**2023**	**Cumulative**
SLS + Orion + Ground Systems	$4.2	$3.7	$3.8	$3.6	$3.4	$18.7
ISS + Space Transportation + Space and Flight Support + Commercial LEO	$4.6	$4.2	$4.2	$4.2	$4.1	$21.4
Technology (including Gateway and Lunar Exploration Systems)	$0.5	$0.8	$1.6	$2.1	$2.6	$7.6
Total Cost	**$9.3**	**$8.7**	**$9.6**	**$9.9**	**$10.2**	**$47.7**
Total Budget Available	**$10.7**	**$9.8**	**$9.6**	**$9.4**	**$9.2**	**$48.7**
Difference	**$1.4**	**$1.1**	**$0.0**	**-$0.5**	**-$1.0**	**$1.0**

Note: Individual budget categories should not be directly compared between Table 8 and Table 9, as one reflects nominal dollars and one constant dollars. Only the totals lines should be compared directly.

The categories used to categorize NASA's budgets in Tables 8 and 9 are slightly different from the categories used in Figure 19, which allocate resources to missions, so the two should not be compared directly. NASA's budgets consider all SLS and Orion development part of a single budget category, while the analysis shown in Figure 19 assigns some of the spending on SLS and Orion in FY 2022 and FY 2023 towards the purchase of the vehicles that will launch Gateway components.

As noted in Table 7, SLS and Exploration Ground Systems costs for FY 2019 depart from the PBR, reflecting additional funds appropriated in the NASA FY 2018 final appropriation for ground systems construction.

C. Feasibility of a Mission to Mars Before 2037

The schedule developed for this report was based on NASA's current and notional plans and two critical assumptions: that NASA will choose the architecture of a human Mars orbital mission and begin systems development in 2024; and that there is one human mission to the Gateway annually, either to work aboard the Gateway, operate the DST, or to transfer to the lunar surface. In this section, we briefly evaluate the feasibility of an earlier departure date for an orbital mission to Mars under available budgets if we forego the two assumptions listed above. In pre-2037 mission scenarios, trade-offs would need to be made that reduce the scope of human exploration activities presented in this report.

No budget scenario with the current configuration of the Gateway accommodates an orbital mission to Mars departing in 2033. Based on the schedule for the DST presented in Subsection 3.A.6, in order to launch an orbital mission to Mars in 2033, Phase A development for the DST would need to begin at the start of FY 2020 (October 1, 2019). Even under a real growth budget scenario that ends support of the ISS in FY 2025 and forgoes all lunar landings, NASA would face multiple years of budget shortfalls during the concurrent assembly of the Gateway and development of the DST (Figure 20). Additionally, as discussed in Subsection 3.F, technology development schedules for critical DST technologies will not have been completed by their need-by date for a 2033 mission, requiring reducing the DST's acquisition timeline. However, shrinking the DST's formulation and implementation timeline by violating NASA's standard operating procedures for system development would exacerbate budget shortfalls under this scenario throughout the mid-2020s and lead to very high technology, schedule, and cost overrun risk.

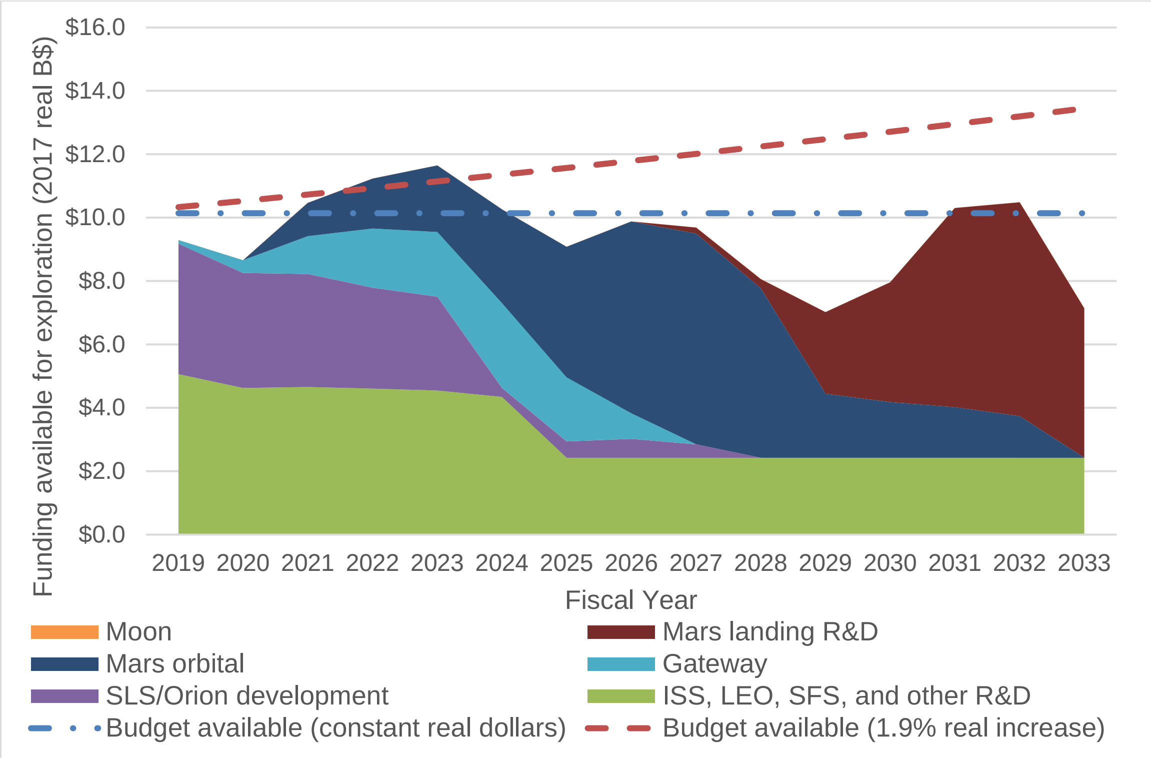


Figure 20. Comparison of Budgets to Costs of Human Spaceflight Leading to a 2033 Mars Orbital Mission

For the DST to leave for Mars by 2035, the next available orbital window after 2033, development of the DST must begin by FY 2022, which likely requires Pre-Phase A trade studies to begin in 2019 (see Subsection 3.A.6 for the DST's notional development schedule). As noted above, NASA requires a LEO platform through at least 2028 for extended human health research and technology development; ending funding for the ISS before 2028 likely would not lead to sufficient cost savings nor meet NASA mission needs. Figure 21 shows the effects of shifting all activities related to Mars orbit and Mars surface missions forward by 2 years.

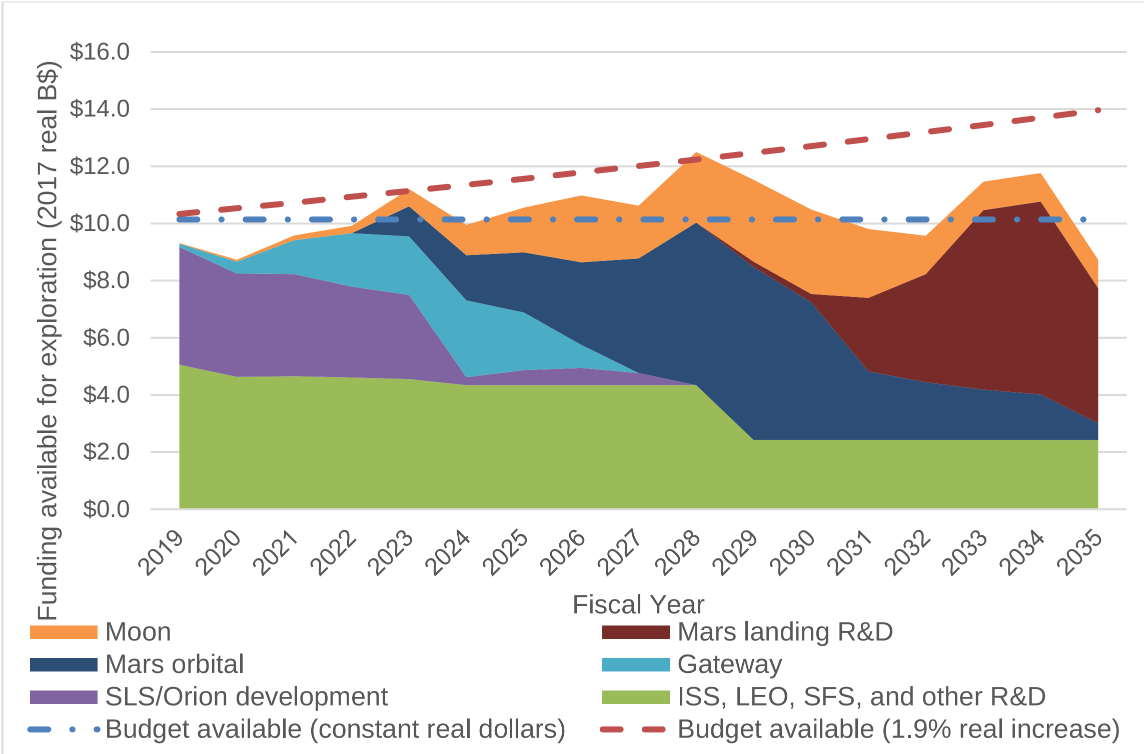


Figure 21. Comparison of Budgets to Costs of Human Spaceflight Leading to a 2035 Mars Orbital Mission

Under a flat budget, annual budgets approximately meet or exceed annual costs for missions leading to an orbital mission to Mars. However, funding would be insufficient to develop and operate both the DST and human lunar landing systems concurrently. To launch a mission to Mars orbit in 2035, most development of human lunar landers would need to be delayed until the late 2020s after the peak costs of acquiring the DST are over. This in turn means that human landings would not be possible until the mid-2030s at the earliest. However, if NASA were to return to the Moon during the mid-2030s, development of Martian surface systems would be slowed, delaying the first human landing on Mars. Accordingly, a 2035 mission to Mars would be infeasible under the flat budget scenario without significant changes to the notional lunar program.

Under a real growth budget scenario, annual costs approximately equal annual budgets. Lunar landings may need to be delayed to mitigate potential budget shortfalls in FY 2028. If NASA is unable to launch more than one crewed SLS annually, in order to meet the testing schedule of the DST, NASA would need to reduce the scope of lunar landings, potentially conflicting with current Administration priorities. Even under a real growth budget scenario, attempting a 2035 launch date for a mission to Mars would heighten technology, schedule, and costs risks listed in earlier chapters, and decrease NASA's ability to research human health risks and develop strategies to mitigate them. Additionally, if cost overruns of either lunar or Martian programs were to occur in the late

2020s, there would not be slack in the budget to mitigate increase costs, likely pushing the mission to Mars back to 2037. Although budgets may be sufficient under a real growth budget scenario, as noted in Subsection 3.F, a 2035 mission to Mars would be high risk from technology and schedule perspectives under NASA's current and notional plans.

D. Key Findings

Comparing cumulative costs developed in Chapter 4 against aggregate budgets, even if NASA budgets for human space exploration remain flat in constant dollars, STPI found that available funding should be sufficient for activities associated with the exploration campaign as long as NASA pursues a 2037 launch window for the DST's first Mars mission. If NASA receives funding above and beyond the rate of inflation, it could have funding for enhanced exploration (e.g., more Moon landings, funding of nuclear thermal propulsion). For a mission to Mars in 2033, cumulative funding under a flat budget would be insufficient to meet the costs of missions described in this report, whereas cumulative funding under a real growth budget scenario would be sufficient.

Although cumulative funding is comparable to cumulative costs through FY 2037 even in the flat budget scenario, in years when the costs of specific systems peak (e.g., 2030–2031 for the DST), under flat budgets NASA may need to reschedule or cancel some activities to ensure that annual appropriations cover development costs. In order to keep the 2037 start date for the mission to Mars orbit, NASA would have to scale back the scope of lunar or other missions. If NASA cannot reprogram costs associated with the peak of DST construction and chooses to keep the same level of lunar activity as presented in this report, the mission to Mars would need to be pushed back to 2039.

Under budgets that are commensurate with 1.9 percent real growth, budgets are always comparable to or exceed predicted costs. As such, this scenario allows NASA to begin a Mars orbital mission in 2037 and have a remaining $50 billion in FY 2017 dollars for enhanced exploration activities.

The current NASA budget under the FY 2019 PBR is sufficient in the aggregate to fund technology development activities for lunar exploration and the development of the Gateway during the FY 2019–FY 2023 period described in the FY 2019 PBR, although shortfalls may occur late in the budget period as NASA's purchasing power declines under the 2019 PBR—due to the 2019 PBR reducing NASA's overall exploration-related budget in inflation-adjusted dollars over time—and Gateway costs approach their peak.

6. Human Health Factors

Human spaceflight involves an increased risk of death associated with all aspects of launch, mission, and return, and the increased risks of negative health consequences from spaceflight over the short- and long-term. Further, maintaining a minimum level of health is necessary for completing the tasks required for successful human space exploration. Over the nearly six decades of human spaceflight, NASA has carefully set health standards for astronauts to prevent and mitigate negative health consequences and minimize the risk of death related to space travel. These standards are based on knowledge of more than 30 space-related health risks and on research on known and potential space-related health risks (NASA 2018d).

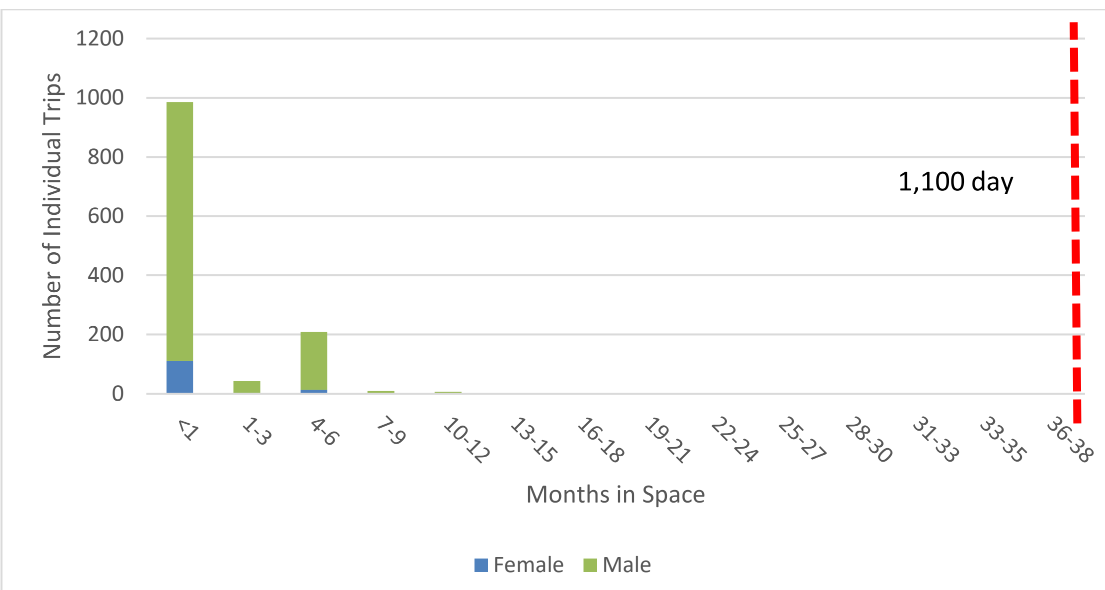
While no astronaut has died from health-related causes during normal in-space operations—only in accidents in tests, upon launch, or reentry—an extended mission of around 1,100 days (Connolly 2017) or longer (Frisbee & Hoffman, 1996) to Mars introduces potential risks to astronauts' health that are unprecedented in human experience. As will be discussed in Appendix D, relying solely on observations that no astronaut has yet died from natural causes in space provides limited insight into the health risks that astronauts would face in undertaking the planned 1,100-day Mars mission.

Although acknowledging that maintaining human health during long-duration exploration is a challenge, the NASA mission planning documents that STPI reviewed did not include enough information from which to completely determine either the risks to human health or the parameters NASA has used in assessing those risks. This chapter points out some of the gaps in knowledge that must be addressed to understand the risks to humans in a human mission to Mars, and some potential implications that uncertainties in our knowledge of the risks of spaceflight pose for the success of the planned missions. Often lost in the discussion of architecture and the technological issues surrounding habitats and life support systems is the reality that actual humans will rely on this technology. This chapter frames some of the issues that may pose challenges to human health during an extended mission to Mars and is meant to complement the other risk assessments in this report.

A. Available Data

Over the course of spaceflight history, humans have spent a combined total of more than 50,000 days in space (NASA 2018i; Becker and Janssen n.d.). The median duration of these flights has been 10 days, with the only human missions to deep space being short-duration Apollo missions to the Moon. While the ISS has provided opportunities to study some aspects of the effects of longer-term space travel on human health, the number of individuals who have spent longer than half-a-year in space is small, limiting our knowledge about the effects of these stays on human health.

As of December 2018, 124 individuals had completed time onboard the ISS for stays ranging from 48 to 340 days. The majority of individual stays have lasted between 4 to 6 months (NASA 2018h, 2018i) with a predominantly male crew. Only six American astronauts have accumulated more than one-year equivalent in space, including only one woman, Peggy Whitson. Among all American astronauts, Whitson has spent the most time in space (665 days). Her longest stay was 288 days (NASA 2018h). Scott Kelly completed a 340 consecutive-day stay on the ISS in 2015 (NASA 2018h). Cosmonaut Gennady Padalka has spent 878 days in space. His longest consecutive mission was 198 days (NASA 2010b). Valeri Polyakov completed the longest consecutive day space station stay (438 days) in 1994–1995 on the Mir space station. Cumulatively, he spent 678 days in space (NASA 2010b). While useful, cumulative data do not provide as much relevant information as data collected over consecutive days as astronauts recover on Earth in the time between missions. As Figure 22 illustrates, NASA has considerable experience with astronauts spending fewer than 30 days in space—primarily in LEO. Few individuals have spent more than 30 days in space, and as of 2018 no one has spent more than 15 months in space, let alone the time corresponding to a potential 1,100-day (nearly 37 month) Mars orbital mission, represented by the red dotted line.



Source: NASA 2018h; NASA 2018i; Becker and Janssen n.d.; CSIS 2018

Note: Multiple trips taken by the same individual are counted as separate individual trips. The red dotted line marks a hypothetical 1,100-day trip to Mars.

Figure 22. Available Data by Astronaut Months in Space

Despite the 50,000 days astronauts have spent in space, trying to extrapolate the results of previously conducted research to a three-year mission to Mars orbit presents a number of problems, as Earth's magnetic field screens out much of the radiation to which astronauts would be exposed in a deep space journey (Sihver et al. 2015). As such, researchers have used the results of animal model studies and information derived from studies of terrestrial radiation events to estimate cancer risks and other morbidity and mortality risks associated with space travel. For example, given the uncertainties associated with extrapolating current knowledge to a Mars mission, Cucinotta et al (2018) have calculated that the upper 95 percent confidence interval around the risk of death from exposure to radiation and from cardiovascular damage could exceed 10 percent in both male and female astronauts, with uncertainty ranges broader for female astronauts.[45] Although such models help characterize human health risks, reducing or retiring human health risks will require further research in relevant environments.

B. Unique Deep-Space Exploration Health Issues

Considerable progress has been made over the approximately 20 years of experience on the ISS in identifying the risks to human health from the space environment. Based on these data, NASA has identified 32 key health risks, 232 gaps in knowledge, and 1097 tasks to complete to fulfil the gaps in knowledge in the *Human Research Program Integrated Research Plan* and accompanying human research roadmap website (referred to collectively in this report as the human research roadmap) (NASA 2018d; NASA 2018g). The human research roadmap focuses on the key known risk factors that have been directly observed (e.g., renal stone formation, bone and muscle loss) while others are more theoretical based on evidence derived from non-space health risks or extrapolated to fit the extreme conditions of an extended duration mission to Mars (e.g., radiation exposure, inadequate nutrition).

The current NASA human research roadmap signals NASA's intent to continue its reliance on the ISS to help understand human health risks associated with deep space exploration. However, the ISS does not provide a representative environment for deep space exploration nor the conditions that would be encountered on an extended orbital mission to Mars. Mission durations on the ISS are significantly shorter than the planned mission to Mars. The effect of exposure to galactic cosmic and solar radiation, extent of isolation, and the cumulative impact of around 3 years in space are key issues associated with a human mission to Mars that are either difficult or impossible to address on the ISS.

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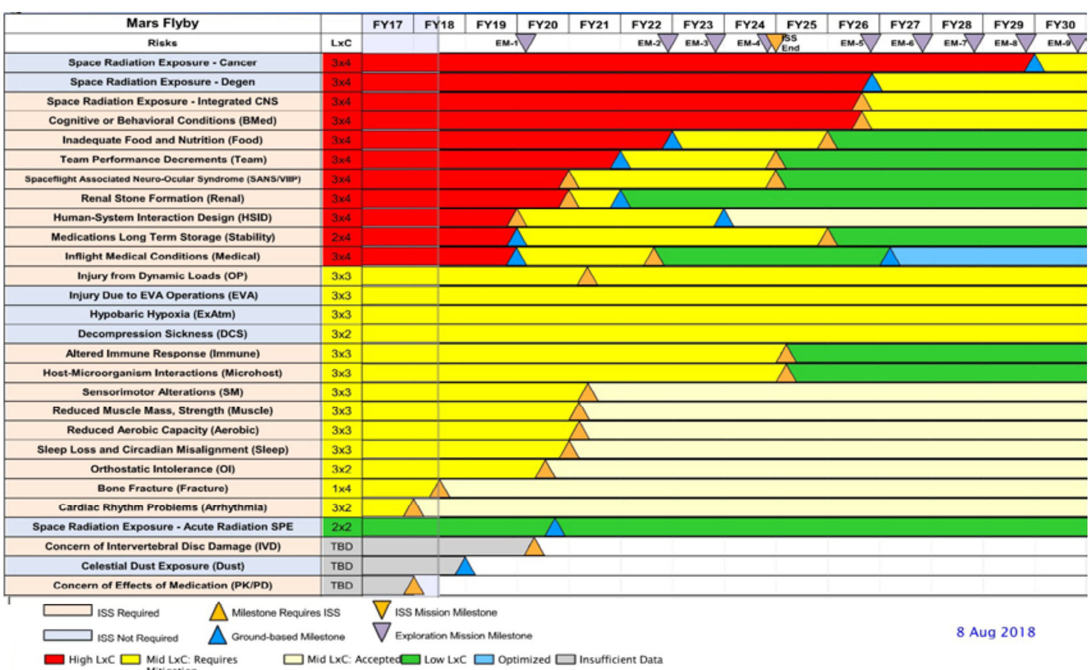
45 The authors calculated exposures based on a 940-day mission of which 540 days would be spent on the Martian surface, while 400 days would be spent in transit, where radiation risks are higher. The authors also note that their analysis is limited to a subset of the risks astronauts might face. The analysis does not attempt to distinguish acute risks astronauts might face during a mission from chronic, lifetime, risks.

Furthermore, the short duration missions on the Gateway, although in deep space, will be too short to provide sufficient information regarding the long-term reaction of the human body to the deep space environment. NASA will need to prevent or mitigate the human health risks from deep space radiation, long spells in microgravity, and the degree of isolation. To accomplish these goals, NASA will need to understand the health risks associated with these conditions that either are not represented on the ISS or that may accumulate over an extended mission or manifest after current data would allow for identification.

The latest available Human Research Program Requirements Document (NASA 2015c) and the current Human Research Program Integrated Research Plan (NASA 2018d) do not explicitly plan for a 1,100-day mission to Mars. They do, however, as noted above acknowledge risks related to long-duration, deep space exploration. The most recent reference to the Human Research Program's priorities was presented in December 2018 at the Human Exploration and Operations Committee of the NASA Advisory Council's (HEO NAC) meeting (Scimemi 2018). Public NASA presentations suggest that there may be some unresolved health risks by the time of the first mission to Mars. The Human Research Program Path to Risk Reduction presented at the December 2018 HEO NAC meeting (see Figure 23) highlights that many areas will remain at medium to high risk through the late-2020s. Below, we discuss the state of research for some of the highest risk areas for human health and timelines to reducing or mitigating these risks.



Source: Scimemi (2018).

Figure 23. NASA Human Research Program Integrated Path to Risk Reduction

1. Radiation

NASA currently follows National Council of Radiation Protection and Measurement Standards. These standards set limits on cumulative lifetime radiation risk to astronauts from radiation. The standards are set for doses that do not exceed a three percent increase in the lifetime risk of developing a fatal cancer.

Two types of radiation risk pose significant problems for humans during the proposed 1,100-day Mars orbital mission: constant exposure to galactic cosmic rays (GCR) and potential solar flares. At high levels, radiation can cause acute symptoms, those that appear within minutes, hours, days, or weeks of exposure. At low levels, radiation may not cause immediate symptoms, but can increase long-term risks of developing cancer and other diseases. On a long-duration mission to Mars and back with an extended stay in Mars orbit, risks of cancer, central nervous system effects, circulatory system effects, and cataracts would likely increase due to increased time of exposure. High uncertainty is associated with estimating the physical and cognitive effects of radiation exposure and the increase in cancer risks associated with long-term, deep space travel. Risk of death directly associated with increased radiation and the risk of death due to indirect radiation effects on cognitive function, the cardiovascular system, immune function, or other systems is likely greater than associated with current missions in LEO. However, more data are needed to accurately classify and assess those risks.

Projecting cancer risks associated with the planned mission to Mars orbit is extremely difficult and highly uncertain due to the limited amount of data available. Most models, however, place the lifetime radiation risk from even a short trip well outside current NASA guidelines (Cucinotta et al. 2013). A major limitation to data collection is the nature of GCR. Unlike radiation sources found on earth, GCR contains a combination of high energy transfer radiation—including high-energy protons, alpha particles, minimal-hazard electrons and positrons, and heavy ions (Sasi et al. 2017). Intermittent solar particle events would add additional radiation. NASA has only one facility capable of simulating GCR for radiobiology (e.g., radiation research on human tissue): the National Space Radiation Laboratory at Brookhaven National Lab (Held et al. 2016).

In addition to the increased risk of cancer, the increased risk of cognitive impairment due to GCR is another area of concern (Parihar et al. 2015b). A high risk of cognitive deficits associated with GCR may not directly increase the risk of death, but could lead to decreased performance, longer response times, delayed decision making, and other potentially adverse behavioral outcomes that would increase the risk of mission failure, including the deaths of astronauts (Parihar et al. 2015a). Heart health is another area of concern related to deep space that could result in short-term negative health impacts, long-term health risks, and increased risk of death (Sasi et al. 2017).

Reducing radiation-related risks associated with a flight to Mars will likely require a combination of prevention and mitigation strategies. To some extent, shielding could limit exposure to galactic cosmic radiation. The proposed design of the DST, with all supplies stored on the outer walls of the habitat to provide additional shielding for the crew living in the central region (Connolly 2017) may reduce radiation exposure, but this has not been quantified in any way. Additionally, lightweight, effective shielding technologies are currently unavailable and are not far enough along in development to be fully evaluated. Smaller, "storm shelters" for use during solar events are more feasible. Mitigation, most likely with pharmaceutical-based treatments, has not progressed to a stage where it could be evaluated, especially against the consequences of GCR.

Timelines for risk mitigation for many of the identified health risks for a mission to Mars were unavailable for this analysis. Some assumptions can be made, however, based on the anticipated pace of research. For example, countermeasures or mitigation strategies that rely on drug development are unlikely to be ready in time for use on a Mars mission departing in the 2030s. According to the Pharmaceutical Research and Manufacturers of America (2015), the process of developing a drug and getting it to market takes at least 10 years from initial discovery to Food and Drug Administration (FDA) approval. If a new drug to mitigate the effect of radiation on human health were discovered today, NASA might be able to access that drug before FDA review (years 9–10) but not before clinical trials, thus shortening the potential time before NASA could provide this drug for use by astronauts. Because there is no reason for researchers outside of those funded by NASA to develop a drug that is specific to GCR effects, the efficacy of this drug would still need to be tested under space-specific conditions, further extending this timeline to the point that determining the efficacy of the drug before the launch of a mission in the 2030s would be impossible. Similarly, DiMasi, Grabowski, and Hansen (2016) estimate the cost of new drug or biologic development to be approximately $2.87 billion, far exceeding the allocated budget for NASA's human research program.

2. Extended Periods in Microgravity

While information on the effects of radiation on astronauts in deep space is lacking, previous space missions on the ISS have been useful for elucidating health risks associated with microgravity. Life in microgravity includes changes that result in health risks related to the cardiovascular system (heart and circulation), immune system, integumentary system (skin), musculoskeletal system, renal system (kidneys), and nervous system (brain, motor functions, and so forth). NASA has developed biological understanding and associated countermeasures and prevention strategies for many of the health issues associated with microgravity, including preventing renal stone formation and exercises to reduce bone and muscle loss. Other issues, such as vision impairment and decline in immune function, are not understood, but NASA has been able to develop mitigation or prevention strategies to deal with the short-term negative effects. However, microgravity may have additional detrimental effects that are currently unknown. These potentially detrimental effects could become significant and even life threatening during or following a 1,100-day mission.

From interviews with NASA officials and internal planning documents STPI reviewed, we found that NASA does not currently have a plan to thoroughly evaluate these longer-term risks before the first Mars mission, other than any observations gained from further one-year missions on the ISS, of which 10 are notionally envisioned (NASA 2018f) and from the one-year (one-third of the Mars mission duration) shakedown cruise for the DST. As NASA currently envisions missions to the Gateway to have a maximum duration of 90 days, longer-term hazards to human health may not be able to be evaluated on these limited duration missions. No missions longer than 1 year are currently planned before the three-year Mars orbital mission.

3. Isolation

The University of Hawaii, with funding from NASA, completed a 365-day isolation experiment in August 2016 to better understand potential issues associated with isolation during future Mars missions (Phys.org. 2016).[46] Additional insights can be gained by understanding isolation associated with time on the ISS, research in Antarctica (Nicolas et al. 2016), the Mars 500 mission (Pagel and Chouker 2016), and other isolation experiments or non-experimental isolation conditions. Insights on group dynamics, human behavior in isolation, and possible behavioral interventions resulting from this research, while valuable, do not accurately simulate the conditions of an extended duration 1,100-day mission in deep space, with no hope of rescue or resupply, communication delays, and only a distant Earth visible in the porthole.

4. Synergistic Effects

Currently, biological data focus on individual risks to human health, such as those described in the previous sections. A 1,100-day trip would combine those risks. For example, psychological stress due to isolation, radiation, and microgravity can have negative impacts on human cardiovascular function. How these risks might combine on a 1,100-day Mars orbital mission cannot be determined using currently available laboratory conditions on Earth or on the ISS. Currently, not enough evidence is available in the ground-based literature to even begin to assess the combined effects of prolonged exposure to microgravity, extreme isolation, and radiation from deep space.

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[46] This study was conducted with a crew of six, rather than a crew of four as in current mission plans. The impact of the extra two crew members on crew mental health is unknown.

5. Individual Variation

Given risks associated with radiation exposure, extended microgravity exposure, isolation, and synergistic combinations among those three stressors, gaining an understanding of the extent of the variability of individual responses to those exposures and the underlying causes of any such variability would help mission planners to identify those astronauts who are best suited to long-duration missions (and those who should not be selected for a 1,100-day Mars trip). Understanding individual variation would require a combination of fundamental research that provides mechanistic understanding and observational data from astronauts. One observational approach is to collect data longitudinally on individual astronauts, and observe how biological parameters underlying health status vary over the course of stays in space. Given the historical profile of missions (mostly men, limited age range), data that have been collected are insufficient to understand potential variations in responses to human health challenges in space by age distribution and by sex—unless it is assumed that the future Mars crew would be younger male astronauts. Moreover, through 2018, most trips to space have been short. As discussed in Section A above, the longest stay in space through 2018 has been 438 days or about 40 percent of the planned mission duration, and only one human has spent this long in space. Few astronauts have been in space for 6 months or longer, limiting the utility of time-series data that have been collected regarding biological parameters of interest. Future human health research, including efforts that involve data collected from astronauts on the ISS and other platforms, offers the potential to use genomic or background health status data as part of the crew selection process to limit mission risk.

6. Other Issues

The impacts of deep space radiation on microbes and pathogens in deep space ECLSS currently under development is unknown, and warrants additional investigation, since the robustness of an ECLSS system is highly pertinent to human health and wellness in deep space. One additional known challenge that may occur prior to the mission to Mars is that of exposure to lunar dust on lunar landing missions. Lunar dust is known to have caused minor lung irritation for Apollo astronauts (Wagner 2006) and has more recently been identified to carry the potential for long-term effects on human lung and neuronal cells (Caston et al 2018).

C. Implications of the Current Human Research Roadmap

Internal NASA planning documents reviewed by STPI identify human health—including radiation exposure—as a primary challenge associated with expanding human presence in the solar system. These documents also noted the possibility that health risks of long-duration spaceflight, such as the planned 1,100-day mission, may exceed limits that have been set for operations in LEO. However, each of these documents provides limited information with respect to the risks under consideration, research plans, or potential mitigation measures, despite being a primary challenge to plans they outline.

Discussion of research plans has instead been confined to the human research roadmap, in which NASA has identified more than 1,000 activities related to mitigating the risk of long-term spaceflight (NASA 2018d; NASA 2018g). For some individual biological systems (e.g., renal stones, spaceflight associated neural-ocular syndrome), the causes and effects of spaceflight-related damage have been identified. With that biological understanding, the activities needed to mitigate health risks and to fill remaining gaps in knowledge can be developed. In other cases, however, (e.g., radiation-related cardiac and other tissue degeneration), the fundamental biological understanding of the sources of health risk are not yet known. Without that knowledge, it is difficult to conduct research to mitigate potential life-threatening issues due to lack of evidence.

While acknowledging these gaps, the publicly available version of the human research roadmap does not describe a set of fundamental research efforts intended to explore the biological underpinnings of these sources of risk. For example, the human research roadmap identifies cardiac rhythm problems as high risk with mitigation required for future deep space and planetary missions. Currently, the document describes the research plan for this subject under the mitigation strategy section, stating, "Space normal must first be defined for this risk; hence data mining tasks are ongoing. Once space normal is defined, the data will be presented to the Human System Risk Board and it will be decided if countermeasures need to be developed" (NASA 2018j). This sort of plan does not provide enough information to determine the timeline or strategy for determining either the baseline or potential countermeasures. This general approach, which lacks consideration of human variation and the interaction of human physiological systems, does not allow for a full and informed evaluation of the risks and process for ensuring human survival on an extended human mission to Mars.

Further, the human research roadmap describes activities intended to understand and mitigate risks associated with individual biological systems. But it does not include a section that explores potential interaction effects or synergies associated with multiple risks (e.g., microgravity, radiation, isolation, and stress) that may affect astronauts simultaneously or the importance of individual variation in the impacts and outcomes of these risks. Given that human beings are more than the collection of individual biological systems, and individuals may respond uniquely, a research plan that considers interaction effects and studies astronauts' health holistically, with an understanding of the role of variation in human biological responses would be useful to identify and mitigate health risks of long-term spaceflight. Such a plan was not available for review.

Within NASA planning documents that STPI reviewed, in the context of the ISS, the discussion of crew health-related research and mitigation focuses on exercise, while the discussion of radiation safety mitigation focuses on research associated with background radiation. The discussion of crew health and medical countermeasures in the context of the initial mission to Mars orbit focuses on in-flight first aid and exercise. Discussion of decisions that must be made mentions human health risks and considers health risks and NASA's risk tolerance to require input from many stakeholders; however, in these documents, NASA has not specified its current thinking with respect to risk tolerance.

In 2014, the National Institute of Medicine (part of the National Academies of Sciences, Engineering, and Medicine—now known as the National Academy of Medicine) convened a panel to consider the ethics associated with the riskiness of human exploration missions. The panel made recommendations as to how NASA should proceed when making decisions regarding spaceflights that may exceed NASA's human health risk standards—or where the uncertainty with respect to potential mission risk was considerable. The panel recommended a process for making ethical decisions in potentially high-risk situations, one that described explicitly the potential societal value of the mission as compared with the potential risks to astronaut health, and one that provided for a process that was "evidence-based, transparent, and solicit[ed] independent advice" (Institute of Medicine 2014).

Given the number of critical decisions that would need to be made with respect to health risk in designing, testing, and eventually operating the Gateway and DST throughout the timeline of a human mission to Mars (without specifying NASA's current approach to the risks of human spaceflight and gaining broad support for that rationale), the possibility exists that shifts in risk tolerance in the future may introduce uncertainties in NASA's ability to complete the mission using the proposed architecture. The rationale for the difference in the presentation of risk across internal planning documents is unclear. These documents, as written, do not provide full confidence that NASA is focusing on the highest risk human health elements of long-duration spaceflight in its approaches to risk mitigation.

D. Key Findings

While no astronauts have died from health-related causes during human spaceflight through 2018, uncertainties remain with respect to threats to human health on an extended orbital mission, as the extensibility of current research to deep space spaceflight is unknown. Although NASA's current and notional plans for ground-based research, launches to the ISS, Gateway operations, lunar landings, and the DST shakedown cruise will provide opportunities to conduct research to reduce these uncertainties, limited plans for long-duration research in deep space may prevent sufficient understanding of synergistic effects of isolation, radiation, and microgravity on human subjects and possible mitigation strategies prior to the orbital mission to Mars. NASA's current Human Research Program Integrated Research Plan to study human health risks associated with long-duration deep space spaceflight lacks sufficient detail in both evidence and strategy to justify the predicted timeline to develop risk mitigation strategies.

7. Summary and Conclusions

Responding to Section 435 of the NASA Transition Authorization Act of 2017 and NASA's request to evaluate its plans for human spaceflights, in the preceding chapters STPI assessed the human health, technology, schedule, cost, and budget risks associated with a 1,100-day Mars orbital human spaceflight mission to Mars and its precursor missions. This chapter presents our overall findings and conclusions.

The plans presented in this report draw on NASA's *The National Space Exploration Campaign Report*, which establishes a spaceflight program for future human exploration of the Moon and, later, Mars. Additionally, the plans are based on public NASA presentations and documents, internal NASA planning documents, and conversations with NASA personnel. Our overall approach was to assess technology, schedule, and cost risks associated with NASA's current and notional plans to evaluate the feasibility of a Mars human spaceflight mission by 2033. Although the adverse effects associated with each type of risk (e.g., schedule delay, cost overrun) vary by risk category, we generated relative, overall risk rankings (low, medium, or high) based on qualitative assessments of the components of risk: severity of event, likelihood, and consequences. Using this approach, we examine the technology pathway, schedule, and the cost and budget envelope for a 19-year exploration campaign that would require the development and assembly of a cislunar space station in the mid-2020s, five lunar landings in the late 2020s and early 2030s, followed by a crewed mission to Mars orbit later in the 2030s. This chapter summarizes the analyses and conclusions from the preceding six chapters.

A. Assessment

1. Technology Assessment

Accomplishing a human orbital mission to Mars requires the development of four key systems: the SLS and supporting ground systems; Orion; the Gateway; and the DST. These systems are at very different stages of design and technological readiness.

Due to long development programs and ongoing testing, SLS and Orion present low technology risks to a Mars orbital mission in the 2030s. Our assessment identifies a need for 12 SLS launches and 11 Orion launches to support an orbital mission to Mars, including 1 cargo SLS to launch the DST, and 6 SLS and Orion launches to support lunar activities from 2027–2032. SLS Block 2 Advanced Boosters, which would debut on EM-8, present a low-to-medium technology risk, depending on the design that is ultimately selected.

Ground system upgrades and refurbishment are nearly complete, and future upgrades do not involve technology innovation, thus ground systems present low technology risk.

Currently, NASA notionally plans to launch crew on the first flight of SLS Block 1B (EM-3) and the schedule presented in this report would launch crew on the debut of SLS Block 2 (EM-8). Although conducting extensive ground testing can reduce the overall risk to astronauts, the notional schedule implicitly accepts a higher level of technology risk than would be the case if new systems were flight tested with uncrewed launches.

The Gateway presents medium technology risk since its current conceptual design largely builds on ISS-heritage technologies. Certain technologies (e.g., xenon refueling and autonomous environmental monitoring) present a medium risk since they have not been previously demonstrated at the scale required by the Gateway. If additional modules are added or mission requirements expand, the Gateway may face higher technology risk. Increasing the complexity and size of the Gateway could require larger power, propulsion, and life support systems, which would add to technology risk. Integrating and testing Gateway elements, whether at its current scale or larger, face medium technology risk.

The DST will require several medium and high-risk technologies. Plans for the DST remain conceptual; many design elements are not yet defined in internal NASA planning documents and NASA currently does not plan to begin design of the system until 2024. In contrast to the Gateway, several new technologies would need to be developed for the DST, especially technologies that need to function without substantial maintenance for the 3 years of the mission. Notably, an ECLSS that meets the performance and reliability requirements of the DST is currently at a low TRL, although NASA plans to test an ECLSS with high oxygen reclamation rates on the ISS starting in 2022. Scaling systems from the Gateway (e.g., 500 kW solar electric propulsion system and reusable in-space engines) presents a medium technology risk. Technologies to transfer cryogenic propellants and prevent unacceptable boil-off losses over long periods of time have not yet been demonstrated at the scales needed for the DST and present a high risk. Integrating each system into a single bus would likely be high risk because a small change to one system could require a series of changes to the rest of the spacecraft due to the scale and interdependent nature of DST systems.

Notional plans for a human orbital mission to Mars rely on several other medium- and high-risk technologies to reach completion. Although spacewalks on the Gateway and DST would be kept to a minimum, deep space spacesuits will be necessary for external repairs. The next generation of spacesuits presents a medium technology risk that must be addressed soon if the spacesuits are to be ready by the launch of the Gateway. Many technologies associated with a Mars surface mission are also high risk, including entry, descent, and landing technologies, a MAV, surface habitation, exploration systems, and in-situ resource utilization.

2. Estimating Schedule

Four complicated elements—SLS, Orion, Gateway, and the DST—would need to be developed and completed to launch a human mission to orbit Mars. These technology developments would be taking place while NASA also designs and launches lunar landers and eventually human astronauts to the Moon's surface. *We find that a Mars 2033 orbital mission cannot be scheduled under NASA's current and notional plans. Our analysis suggests that a Mars orbital mission could not be feasibly carried out until the 2037 orbital window or later.*

Our schedule rests upon two critical assumptions. First, that NASA will choose the architecture of a human Mars orbital mission and begin systems development in 2024 (as indicated in the *Campaign Report*), which drives the development cycle of DST and timeframes for other human spaceflight activities (e.g., lunar landings) in the report. Second, that there is one human mission to the Gateway annually, either to work aboard the Gateway, operate the DST, or to transfer to the lunar surface (as noted by NASA personnel in discussions), which requires NASA to make trade-offs between focusing on lunar landings and preparing the DST for the mission to Mars. Under these assumptions, NASA would begin Phase-A development of the DST in 2024, with final design occurring in 2028 and delivery for integration with SLS in the second half of 2032 for launch and in-space checkout in 2033. In 2034, the DST would depart on a one-year shakedown mission to validate all systems in deep space before returning to the Gateway. Another mission would be launched in the first half of 2036 to refurbish and refuel at the Gateway in preparation for a low-energy transit to Mars in 2037 or later.

For some architectural elements and technologies, current and notional schedules require parallel development efforts. For example, the lunar surface campaign's technology development efforts would have to occur in parallel with development and launch of the Gateway, while the effort to launch astronauts to the lunar surface would occur in parallel with construction of the DST. These parallel development efforts and associated costs and available budgets provide a source of schedule risk.

3. Estimating Cost

Drawing on NASA documents, interviews with NASA, industry studies, and costs of analogous programs, *STPI estimates that the total costs for the development and operation of the core architectural elements (SLS, Orion, the Gateway, and the DST) from FY 2019 to expected launch of the Mars orbital mission in FY 2037 is likely to be at least $83 billion in FY 2017 dollars. Including the cost incurred from 2038 to 2040 during the orbital mission, the total estimated cost from FY 2019 onward of a human mission to Mars orbit* *is $87 billion in FY 2017 dollars.*[47] *The cost of just the orbital mission to Mars beyond the development of SLS, Orion, and the assembly of the Gateway is $45 billion in FY 2017 dollars.*

Although a human mission to the surface of Mars would not take place until at least 4 years after the first orbital mission to Mars is launched, NASA would need to begin development of the required systems many years in advance. We estimate the development costs for the systems needed for a human landing on the surface of Mars to require an additional $25 billion in FY 2017 dollars. Other human exploration-related costs, including continued support for the ISS, post-ISS flights to another station in LEO, and the costs of the lunar exploration missions would add another $50.9 billion in FY 2017 dollars to the overall cost of the 19-year exploration effort. The aggregate cost of the exploration effort from FY 2019 to FY 2037 is estimated to be $184 billion in FY 2017 dollars.

The elements of a human mission to Mars vary greatly in terms of readiness, greatly affecting the risk of cost overruns in a given program. Orion has already gone through one test launch; the development phases for SLS Block 1 and Orion are almost concluded. Although we believe that there is still risk of additional cost overruns to the SLS and Orion programs in the near term, risk for ongoing cost overruns for these programs over the 19-year period is not high, especially during the period when SLS is being launched on a regular basis.

In contrast to SLS and Orion, NASA has yet to finalize the design of the Gateway. To reduce technology and cost risk, NASA has committed to constructing the Gateway by employing existing technologies. This decision mitigates some cost risk, but risks increase if mission requirements grow for the Gateway, and lead to the addition of more complex systems. Collaborating with international partners also adds to cost risk, as NASA will need to collaborate closely with these partners and integrate their contributions into the overall mission.

The DST and the systems needed for a Mars surface mission are only at the conceptual phase, and would employ many new technologies to be used in a new environment. In addition, the energy needed to transport mass from Earth orbit to Mars greatly constrains the mass and, therefore, the design of these elements. Lastly, the cost required to address, mitigate, and retire risks to human health is uncertain and was not estimated in this report, and could be much higher than current NASA budgets for human health research. These uncertainties introduce high risks of cost escalation.

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[47] As discussed in Chapter 4, this value includes all R&D and operations costs up to and including the first Mars orbit mission. STPI estimated individual system costs for the Gateway, lunar landing systems, and Mars orbital and surface systems and then added a 30% reserve to account for potential contingencies. We did not include possible cost overruns in this figure.

4. Mapping Costs to Budget

NASA was appropriated $20.7 billion for FY 2018 ($20.4 billion in FY 2017 dollars), of which approximately half was devoted to human spaceflight. If NASA continues to receive this amount annually—accounting for inflation—between FY 2019 and FY 2037, it would have a cumulative $192.7 billion in FY 2017 dollars or approximately $10 billion in FY 2017 dollars per year at its disposal for human spaceflight. If NASA were to receive annual budget increases commensurate with annual real GDP growth of an anticipated 1.9 percent, available funds for human spaceflight over the 19-year period could be $233.8 billion in FY 2017 dollars, assuming that the share of the NASA budget devoted to human space exploration remains constant.

Comparing these budgets and our estimates of the costs of systems needed for Mars and lunar exploration with prospective NASA budgets for human space exploration, *we find the aggregate budget under our flat budget scenario ($193 billion FY 2017 dollars) is greater than the aggregate costs for human spaceflight ($184 billion FY 2017 dollars).* If the human space exploration budget increases at the rate of real GDP growth, giving a cumulative budget of $234 billion FY 2017 dollars, there may be sufficient funding for enhanced exploration (e.g., more Moon landings, funding for the development of other technologies such as nuclear thermal propulsion) or to mitigate the impact of cost overruns. Alternatively, if NASA returns to a more budget-constrained environment such as was envisioned in the 2014 National Academies' Pathways to Exploration report, funding would likely be insufficient to complete all of the exploration activities in our schedule.

While cumulative resources are likely to be sufficient to cover cumulative costs of a human mission to Mars, if the costs of systems are spread over time based on their development cycles, we find that the estimated costs of human space exploration peak at $11.5–$11.8 billion in FY 2017 dollars in FY 2035 and FY 2036, with costs running above $10 billion per year in FY 2017 dollars in FY 2023 and FY 2030–2031 and reaching approximately $10 billion per year in FY 2017 dollars in FY 2021, FY 2022, FY 2025, FY 2026, and FY 2028. *Under flat budgets, a 2037 start date for a mission to Mars is feasible; however, cost peaks will require activities, such as lunar landings, to be rescheduled to ensure that annual appropriations match development costs, which could have implications for the Mars orbital mission launch date. Under a budget that matches real growth, budgets always exceed expected costs by $1–6 billion FY 2017 dollars annually, allowing for additional exploration programs, especially after the peak cost years of the DST in the early 2030s.*

We compared our cost estimates associated with a human mission to Mars and the Administration's budget request for FY 2019 to FY 2023. *We find that the current NASA budget sufficiently funds short-term technology development activities for lunar exploration and for the development of the Gateway, though shortfalls may occur late in* *the budget period as NASA's purchasing power declines over time and Gateway costs approach their peak.*

5. Human Health Risks

Discussions with NASA and a review of internal NASA planning documents and academic literature reveals that the understanding of human health risks associated with an extended human orbital mission to Mars is limited. While no astronauts have died from health-related causes during human spaceflight through 2018, uncertainties remain with respect to threats to human health on an orbital mission to Mars that may not be fully understood given NASA's current and notional plans for ground-based research, ISS missions, Gateway and lunar surface operations, and the DST shakedown cruise. NASA's current Human Research Program Integrated Research Plan to study human health risks associated with long-duration deep space spaceflight lacks sufficient detail in both evidence and strategy to justify the predicted timeline to develop risk mitigation strategies. Further, the document does not present a detailed plan to prioritize NASA's approach to filling in gaps in knowledge, especially on the combined effects of radiation, low-or-micro-gravity, and isolation on astronauts. While clear and detailed in some areas, the current research plan is necessarily vague in others. This vagueness, however, decreases the likelihood that by the 2030s the understanding of human health risks and strategies to mitigate them will be sufficient to meet current standards of risk to astronauts or to ensure crew survival on an extended mission.

Because of the nature of the human health risks and knowledge gaps, developing a clear timeline and specific research plan to adequately address these gaps and create mitigation strategies is difficult and nearly impossible to evaluate at this stage. The primary focus for planned research appears to be on currently known risks as opposed to understanding significant theoretical and unknown risks and holistic human health. Even if NASA could give greater priority to addressing human health risks when planning missions, this focus does not negate the real risks of astronauts dying from health-related factors[48] on an extended orbital mission to Mars, and may require addition risk mitigation efforts prior to the orbital mission.

B. Feasibility of a Mission to Mars Before 2037

No technology or budget scenario with the current configuration of the Gateway accommodates an orbital mission for Mars departing in 2033. Even under a real growth budget scenario that ends support of the ISS in FY 2025 and forgoes all lunar landings, NASA would face multiple years of budget shortfalls during the concurrent assembly of

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[48] As distinct from catastrophic technology failure resulting in death, which has been NASA's primary priority.

the Gateway and development of the DST. In order to launch an orbital mission to Mars in 2033, Phase A development for the DST would need to begin at the start of FY 2020 (October 1, 2019), a milestone which would likely be missed. Further, several critical technologies, including thermal management systems, propulsion systems, and ECLSS, are unlikely to be mature by their need-by date for a 2033 mission. Shrinking the DST's formulation and implementation timeline by violating NASA's standard operating procedures for system development would exacerbate budget shortfalls under this scenario throughout the mid-2020s and lead to very high technology, schedule, and cost overrun risk.

A 2035 launch date for the Mars orbit mission would require substantial real increases in NASA's budget, force NASA to reduce the scope of lunar missions, and pose significant technology, schedule, and cost risks. Under flat budgets, NASA would likely need to delay the first lunar landing until after the DST departs in 2035, which would likely delay Mars surface system development and conflict with current and notional plans.

Under either budget scenario, a 2035 launch date would hold high schedule risk due to increased demand for fabrication and testing facilities, and pressure on NASA management during concurrent development and construction of the Gateway and DST. It would also hold high technology risks as some critical technologies for the DST—such as an advanced ECLSS system and propulsion and thermal management technologies—may not be sufficiently mature by the need-by date for DST development. Prolonged delays in any one of many technology development programs would delay the development of the DST, pushing the mission to the next orbital window in 2037.

A 2035 mission would also reduce NASA's ability to mitigate risks to human health, as NASA would be unable to conduct significant human health research in deep space before finalizing the DST's design, and have less time to learn from the operations of the Gateway before starting DST missions. Although budgets may be sufficient under a real growth budget scenario, a 2035 mission to Mars would be high risk from technology and schedule perspectives under NASA's current and notional plans.

C. Implications of Additional Missions for Budget and Schedule

In this section, we consider the budgetary and schedule implications of varying parameters related to the timing of the ISS phaseout and the cadence of Gateway and lunar operations. These variations from our notional schedule represent potential options for NASA to consider.

1. Implications of Changing the Timing of ISS Phaseout

Currently, the Trump Administration plans to end direct support of the ISS by FY 2025. However, NASA personnel have told STPI that NASA requires a space station in

LEO through at least 2028 to meet mission needs for extended human health research and technology development that would be unmet by the capabilities offered on the Gateway, and that NASA plans to support a platform in LEO through at least this time. Previous STPI research suggests that an alternative to the ISS will not be available during this time without large subsidies provided by NASA (Crane et al. 2017). As such, large cost savings would likely not manifest if NASA ended support of the ISS in 2025.

STPI's analysis suggests that NASA would have sufficient budget to continue to support the ISS until 2028 while pursuing the lunar and Mars orbit plans outlined in this report. According to our cost and budget analysis, NASA has approximately $1 billion per year in budgetary flexibility during the 2025–2028 period under a real growth budget scenario though not in the flat budget one. Continuing to support the ISS beyond 2028, however, would have substantial budgetary implications. The 2030–2031 period represents the peak of STPI's estimated costs of NASA's human exploration program. Continuing to expend $3 billion FY 2017 dollars per year for ISS support and Commercial Transportation, rather than the assumed $1 billion FY 2017 dollars post-ISS expenditure for astronaut habitation and transportation in LEO, would complicate paying for the final lunar missions and the construction of the DST.

2. Implications of Increasing Gateway Use

The cost of using the Gateway is driven by the costs of the SLS and Orion required to transport a crew, which represent 96 percent of the $1.62 billion FY 2017 dollars additional cost of an additional flight. STPI's budget calculations suggest that there might be sufficient funding for one or at most two additional launches to the Gateway in the 2026–2027 period, were additional launchers and Orion capsules available.

STPI also estimates that the cost of resupplying a crew once transported to the Gateway for a full one-year mission would be less than $500 million FY 2017 dollars for supplies sent on commercial flights. This figure is half of our estimate of $1 billion FY 2017 dollars for astronaut transport costs to LEO that would be required post-ISS. This implies that NASA could potentially consider using the Gateway as a post-ISS outpost where long-term health research could be conducted and training for a future Mars mission might occur without necessarily incurring considerable additional costs—although there may be technological challenges or habitation volume limitations that may restrict continuous operations of the Gateway by a single crew.

3. Implications of the Moon Exploration Missions

Including the cost of development and operation of SLS, Orion, the Gateway, and the lunar landing missions, this report estimates the total projected cost of meeting Administration goals to return to the Moon by the end of the 2020s to be about $62 billion.

The base case in this report assumes five landings on the Moon. It is possible, however, that NASA may stay on the Moon beyond the assumptions in the report.

We estimate the cost of an additional lunar exploration mission with a secondary cargo lander and human rover as $3 billion FY 2017 dollars, of which 50 percent is the cost of astronaut transportation using SLS and Orion. The period in which lunar exploration occurs (2028–2032) is the peak-cost period for the construction of the DST. During that time, under a flat budget scenario, there is no budgetary slack for additional lunar missions. However, in 2033 and 2034, funds could be sufficient for one additional lunar exploration mission under the flat budget scenario.

The 2014 National Academies of Sciences' Pathways to Exploration Report assumed a cadence of two lunar missions per year in their campaign rather than the annual missions that STPI's schedule has assumed. Given that in our schedule lunar missions occur in parallel with the peak costs of constructing the DST, increasing the cadence to match the Academies' assumptions would require both transportation and logistics costs to decline substantially. Given that the additional cost of a lunar mission is $2–3 billion FY 2017 dollars depending upon the nature of the mission and the cost of the required supplies and equipment, the costs of crew transportation, supplies, equipment and commercial flights would need to be halved for NASA to be able to support a two-flights-per-year cadence in the flat budget scenario unless construction of the DST were delayed. Additionally, accommodating SLS and Orion production and launch beyond the two per year for lunar missions will require significant infrastructure investment, which has not been estimated.

The schedule presented in this report assumes only five total lunar missions through 2032 and then focuses solely on the missions to Mars orbit and the Martian surface. This assumption, although required to develop and evaluate a possible series of exploration activities leading to a mission to Mars orbit based on NASA's current and notional plans, may be insufficient, especially if future leaders do not want a repeat of the Apollo program, which attempted seven Moon landings before halting human lunar exploration altogether. In the years following 2032, the budget we developed for this report allocated $1 billion FY 2017 dollars a year to support U.S. private (or possibly international) lunar exploration, which could, for example, be used for development purposes or provide a set of lunar landing modules annually. However, this level of investment would likely result in a decrease in the amount of lunar activities for at least the next several years. Creating a sustainable lunar presence for NASA after the missions presented in this report would likely require development of enhanced surface systems, such as permanent lunar habitation systems. Under flat budgets, a trade-off would likely need to be made between lunar surface activities in the late-2030s and Mars surface activities in the early-2040s.

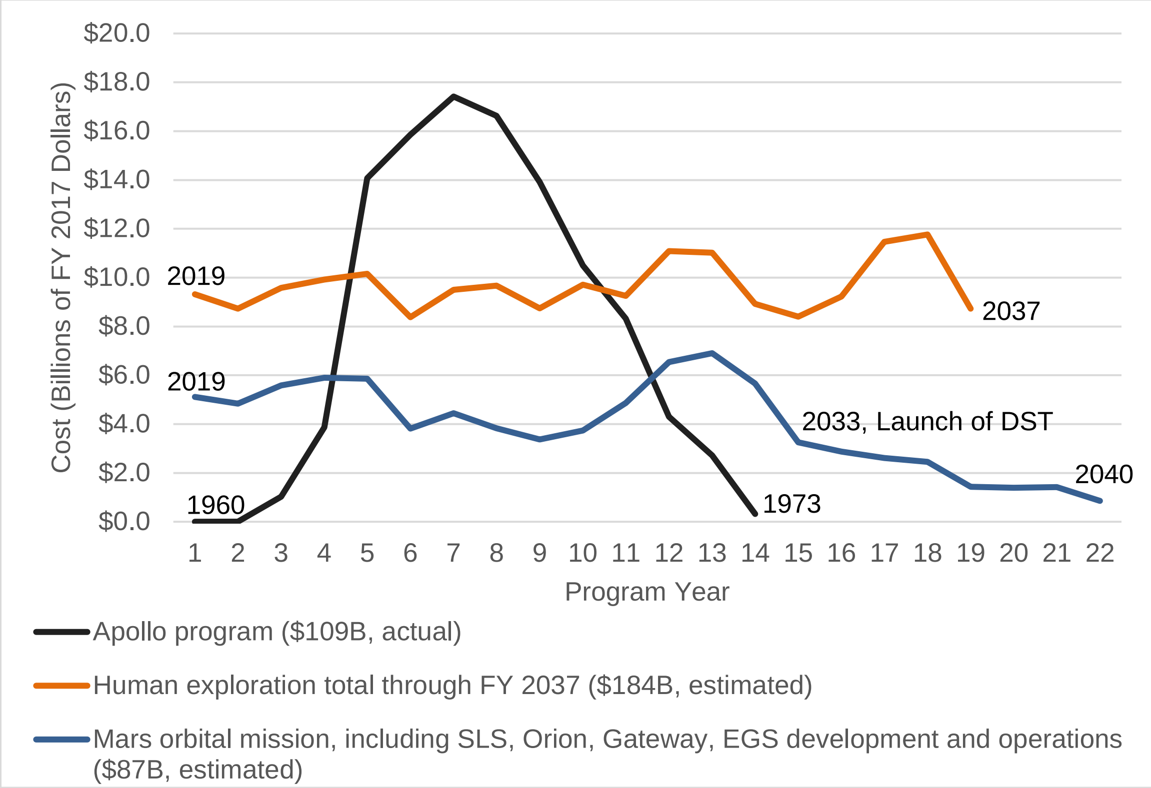
D. Alignment between NASA's Plans for a Human Mission to Mars and its Exploration Strategy Principles

In order to maintain a space exploration campaign over the next two decades through a number of Congresses and Presidential administrations, NASA's plans for human exploration missions will need to be compelling and sustainable. NASA's Human Exploration and Operations Mission Directorate has established eight principles to guide NASA's exploration strategy in such a manner (NASA 2017e). Below we compare the plans for a human mission to Mars with these principles. We find that the mission aligns well with these principles assuming the orbital mission to Mars takes place in 2037 or later, but does not align well with several of them if the mission were to be scheduled earlier.

Principle 1: Fiscal Realism

NASA has set the goal of making a human mission to Mars implementable in the near term under current budgets and in the longer term with budgets commensurate with economic growth. We find that between FY 2019 and FY 2037, the cumulative cost of a human mission to Mars, including a lunar exploration campaign, may fit within cumulative budgeted funds and that, in general, annual budgets meet or exceed annualized costs of human exploration missions. The cost of that campaign, however, could not be compressed into a 15-year budget timeframe to FY 2033. Concurrent development of both the Gateway and DST to meet a 2033 mission to Mars could lead to large budget shortfalls throughout the 2020s, even without the development of lunar surface systems. While the cumulative cost of a human mission to Mars could fit within cumulative budgeted funds between FY 2019 and FY 2035, during several years in the late 2020s, projected annual costs would exceed expected budgets, even under a real growth budget scenario.

In comparison to the Apollo program, the series of missions presented in this report represent a more sustainable program from a budget perspective. Figure 24 overlays the total annualized costs of human exploration and the total annualized cost of the orbital mission to Mars and its precursor mission on top of the Apollo program's annualized cost curve. Between 1960 and 1965, NASA's total budget increased 760 percent (calculated from Ertel and Morse, 1969; Morse and Bays, 1973; Brooks and Ertel, 1973; Ertel and Newkirk, 1978). Notably, over the program's 14-year span, the program represented 47 percent of NASA's budget, which is similar to the assumption used in this report that human exploration would compose 50 percent of NASA's budget. However, the Apollo program peaked at 70 percent of NASA's budget in 1967 and had 7 years where it composed more than 50 percent of NASA's budget. This dramatic and rapid budget increase was unsustainable over the long-term. Decisions made during the Nixon Administration changed NASA's funding model to a flatter budget, which has proved sustainable over the following decades. If the United States were to decide that a human mission to Mars orbit before 2037 is a national imperative, NASA's funding model would require a funding profile more akin to that of Apollo. This goal, however, would likely reduce the sustainably of the human spaceflight program in the long run.



Source: Ertel and Morse, 1969; Morse and Bays, 1973; Brooks and Ertel, 1973; Ertel and Newkirk, 1978.

Figure 24: Overlaying the Profile of the Apollo Program with that of the Proposed Mars and Human Spaceflight Activities through 2037

Principle 2: Scientific Exploration

NASA states that exploration enables science and science enables exploration. NASA's current plans and programs for robotic missions to the Moon and Mars appear to support exploration well. However, the extent of the benefits to scientific research from NASA's human exploration plans is unclear. The Campaign Report provides limited insight into the scientific findings expected from human lunar and Martian orbital missions. Both the Gateway and DST can play a role as deep space science laboratories. They will have the capability to observe the lunar and Martian surface, respectively, and can also be used to conduct science in deep space. Due to the short time astronauts will stay on the Gateway, however, the duration of human-tended experiments on the platform will be limited. Internal NASA planning documents reviewed by STPI do not adequately justify why many of the scientific activities that may be conducted on the Gateway could not be performed using solely robotic means. The DST does offer some unique possibilities for scientific exploration of Mars, including real-time telerobotic operation of airborne platforms, as well as deep-space human health research. However, the three-year duration of a mission to Mars orbit and inability to resupply during missions may limit the number and type of scientific experiments that could be conducted on the DST during transit or while in orbit.

Principle 3: Technology Pull and Push

Using high TRL technologies for near-term missions, while focusing sustained investments on technologies and capabilities to address challenges of future missions is another NASA goal for human space exploration. Fundamental technologies for the DST—especially those associated with propellant systems and the habitat and its required closed-loop ECLSS technologies—require technologies that are not currently at high TRL. NASA is currently investing in technologies to address DST-related challenges and has plans to advance the technologies through testing on the ISS and Gateway. Scheduling the departure of a mission to Mars for 2033 or 2035 would decrease the alignment with this principle, as the partial overlap between the technology development effort and the decision time frame for the DST design and construction poses technology and schedule risk.

Principle 4: Gradual Buildup of Opportunity

Another NASA goal is near-term mission opportunities with a defined cadence of compelling and integrated human and robotic missions providing for an incremental buildup of capabilities for more complex missions over time. Currently planned, near-term missions have a defined cadence. The Gateway demonstrates deep space operating concepts; lunar landings in the late 2020s and early 2030s demonstrate surface landing and ascent capabilities; and the Mars mission demonstrates the feasibility of humans reaching Mars. The transition from Gateway to DST, however, is considerably more challenging in terms of distance from Earth and mission time. There is a considerable jump from Gateway (~1–2 month sojourns in deep space) to the DST checkout and shakedown missions (6 months and then 1 year in deep space). The leap from the DST checkout mission to the Mars orbital mission is even larger (1 year to 3 years in deep space) with respect to mission time and distance.

Principle 5: Economic Opportunity

NASA is seeking opportunities for U.S. commercial business to further enhance the U.S. space industry through the program for human space exploration. U.S. businesses will gain experience in the development of the Gateway and DST habitats, launch, and in-space propulsion systems. NASA documents, such as the Campaign Report, specifically encourage commercial development in LEO as well as commercial resupply missions to the Gateway and the use of the Gateway as a base for commercial missions to the lunar surface, providing opportunities for the extension of the ISS commercial cargo model to cislunar space.

Principle 6: Architecture Openness and Resilience

Internal planning documents call for a resilient architecture featuring multi-use, evolvable space infrastructure, minimizing unique major developments, with each mission leaving something behind to support subsequent missions. The SLS/Orion/Gateway/DST architectural elements are designed to be configurable for many missions, reusable to the extent feasible, and evolvable as technologies improve.

The current approach to the Gateway, however, does not appear to be optimized to support the Mars mission, although, as explained below, it is aligned to a broader set of space objectives. The mission design for a human mission to Mars uses the Gateway as an in-space dockyard for checkout and refurbishment of the DST. From internal planning documents and conversations with NASA personnel, the justifications for why those operations could not be conducted in high Earth orbit by docking Orion and logistics vehicles directly with the DST are unclear. The trips to the Moon add transportation time and delta-V costs to the operations of the DST. If maintenance is routine and the DST ECLSS can be used to provide life support and living quarters for astronauts during refurbishment then direct docking to the DST could be sufficient. The Gateway, however, provides the possibility of long-term habitation for astronauts in the case of complex repairs that require working with the DST ECLSS off-line for an extended period. In short, the Gateway is used only as an insurance policy in the context of Mars missions.

According to experts we spoke to, the Gateway serves other functions. During our discussions, six other distinct (but not necessarily unique) rationales for the Gateway emerged:[49]

- **As a technology testbed for the Mars mission.** The Gateway would test certain technologies needed for the DST, such as Hall thrusters and solar arrays. In addition, the Gateway could test an ECLSS system and radiation hardened electronics in a higher radiation environment than the ISS, which may be necessary to fully understand ECLSS and electronics operations in deep space. Even if the ECLSS system on the Gateway is not as advanced as the one needed for the DST, these data would be useful.
- **As a deep space human habitat laboratory.** The Gateway would host astronauts in deep space for the longest period in spaceflight history until the launch of the DST, providing unique opportunities for research on human health. Although data gathered from 90-day-duration missions may not be fully

[49] As discussed in Subsection 1.B.3, an evaluation of the Gateway was outside the scope of this study.

extensible to a three-year mission to Mars, as discussed in Chapter 6, the environment of the Gateway could allow for novel human health research that cannot be conducted in LEO or on Earth.

- **As a platform to build experience with operations for deep space human missions.** NASA has not operated a human mission in deep space since the Apollo era. The Gateway should help build institutional knowledge for future long-duration deep space missions to the Moon and to Mars.
- **As a deep space science laboratory.** The Gateway could have the capability to observe the lunar surface or deep space from several orbits and conduct science in unique areas of deep space, including telerobotics on the lunar surface.
- **As a transfer station for travel to and from the lunar surface.** Astronauts traveling to the lunar surface via Orion would need to transfer to a lunar descent and ascent vehicle. The Gateway is designed to be used as a transfer port between the two vehicles and a docking station for the descent vehicle between surface missions. The capabilities offered by the Gateway could be extended to private and international lunar surface missions.
- **As an off-ramp for the human exploration program if the journey to Mars is postponed.** The Gateway can be expanded into a more substantial space station with additional modules. If unexpected problems arise in completing a human mission to Mars (e.g., human health concerns for long-duration deep space spaceflight), the Gateway could help sustain the human spaceflight program. Many companies have said they have plans for lunar activities that rely on NASA-sponsored lunar infrastructure. Accordingly, the Gateway may also help spur private cislunar activities.

The design of the Gateway is flexible. This, however, may be a mixed blessing, as space systems without definite mission requirements have historically faced growth in scope, mission, and cost. Internal NASA planning documents contain limited detail with respect to the operations of the Gateway and even fewer details on what it will do between missions related to human missions to the Moon and to Mars when it is to operate autonomously.

Principle 7: Global Collaboration and Leadership

Orion, the Gateway, and potentially the DST provide opportunities for substantial new international and commercial partnerships, leveraging current ISS partnerships and building new cooperative ventures for exploration while maintaining U.S. leadership in the field. International partnerships are envisioned with respect to Orion and the Gateway. International partnerships entail additional costs as well as savings. Commercial partnerships as embodied in the NextSTEP approach are being used to develop the Gateway.

Development of the DST is at an early stage, so it is not clear which aspects of the transport or the overall Mars missions would allow for international collaboration.

Principle 8: Continuity of Human Spaceflight

NASA seeks to establish a regular cadence of crewed missions to cislunar space during the lifetime of the ISS for the uninterrupted expansion of human presence into the solar system. Since the ISS's end-of-life may be in 2024 or later, the extent to which this principle is fulfilled remains unclear. It cannot be fulfilled if the ISS is decommissioned in 2024. By the beginning of 2024, at most two short crewed missions (EM-2 and EM-3) will have flown to cislunar space. Our schedule envisions one crewed mission per year from 2025 through 2036 (with the exception of 2035, when the DST is undergoing its one-year shakedown mission), which may comport with "regular cadence." The 2024, 2025, and 2026 flights will be one-month flights associated with the construction of the Gateway, while the 2027 through 2032 missions involve lunar operations. Missions beginning in 2033 are longer than those associated with the initial operations of the Gateway.

E. Observations on the Campaign Report

The *Campaign Report*, used as the basis of this assessment, provides a call to arms for NASA, potential international partners, and the private sector to expand human presence on the Moon and subsequently send humans to Mars. The report also presents a notional description of potential missions and milestones; describes the integration across NASA of the agency's efforts to focus and achieve its objectives; and outlines a framework and set of decisions to meet mission goals in LEO, cislunar space, the lunar surface, and Mars, and evolve its exploration technology capabilities. An important difference from previous NASA strategy documents is the focus on use of open architectures and the development of interface and operational standards, that will enable industry and international partners to contribute to exploration by bringing new capabilities at their own pace and risk.

The *Campaign Report* delineates a host of critical decisions for lunar and Martian exploration technologies that will be made in or around 2024, many of which depend on the timely development of the Gateway. Given the schedule risks outlined in this report, delays in the Gateway could potentially cause disruption to and require redesign of large elements of the future exploration architecture, such as lunar landers, given the dates of decisions for these systems in the *Campaign Report*. Additionally, the 2024 or later dates for several critical decisions, such as the design of the DST and Mars surface systems, will push many of these difficult decisions into another Administration. However, because of the lack of detail and the optimistic assumptions, the report conveys a positive prospect of launching humans to Mars via the proposed architectures. Since the timeline stops at 2024, the question of the report's role in getting NASA to Mars orbit by 2033 cannot be addressed.

The NASA Transition Authorization Act of 2017 specifically calls for NASA to develop a "Human Exploration Roadmap (U.S. Congress 2017)." The *Campaign Report* is not a "roadmap," and commendably does not call itself that. Instead it refers to itself as a "Campaign Report," which is a much more apt title. A roadmap would be expected to include additional details, such as a time-phased sequence of events, decision points, descriptions of all major architectural items, workflows, technology on-ramps and off-ramps, and budgets. Although the *Campaign Report* provides a high-level strategy for the next 7 years of human spaceflight, it is mainly a plan for a plan, and may not ultimately play a substantive role in efforts to place humans in Mars orbit by 2033. Further specificity of NASA's long-term plans in a public document would help Congress and other public policy officials make informed decisions over the coming decades.

F. Overall Assessment and Recommendations

A 2033 launch date for the Mars orbit mission is infeasible given the requirements imposed by NASA's current and notional plans, the National Space Exploration Campaign Report, and the human health, technology, schedule, cost, and budget risks associated with a mission to Mars orbit and its precursor missions. A 2035 launch date for the Mars orbit mission would require substantial real increases in NASA's budget, force NASA to reduce the scope of lunar missions, and pose significant technology, schedule, and cost risks. Our analysis suggests that 2037 is the earliest NASA could feasibly launch the DST to Mars orbit given current and notional plans and budgets *assuming cost peaks in the 2030s can be smoothed*. Delays to the development or testing of the DST or flat budgets with no reduction in lunar missions could push the Mars orbit mission to 2039.

Figure 24 above compares the cost profile of the Mars mission projected in this report to that of Apollo to show the aggressiveness of the effort required. Shifting the DST's construction and launch date to align with a 2037 Mars orbit mission poses some advantages. For example, it allows NASA to learn from the design and operations of the Gateway as part of the design and construction of the DST. Construction of the DST subsequent to the completion of the Gateway also reduces the likelihood of budget shortfalls throughout the 2020s, as SLS and Orion complete development, as the ISS is used for technology testing, and as the Gateway and lunar exploration systems are constructed and operated.

Although limited lunar landings and the 2037 Mars orbital mission are feasible together under notional budgets, limitations imposed by the budget render unlikely a long-term human presence on the Moon in the 2030s concurrent with a 2037 mission to Mars orbit and subsequent Mars landing mission in the early 2040s. The schedule as described in our analysis does not include NASA missions to the Moon after the DST is launched. NASA is constrained both by the limitations of its core architecture—as only one crewed SLS launch is available per year—and by the cost of additional landings relative to the budget available (assuming that the flat budget of approximately $10 billion per year in FY 2017 dollars is available for human space exploration).

The schedule as described in our analysis also does not include R&D towards the development of technologies that could be used for long-term lunar habitation. Instead R&D funds are devoted to the development of technologies intended for long-term stays on Mars, but in the 2040s. Under flat, or even slightly increasing budgets, given the cost of Gateway construction and lunar landing R&D during the 2020s, and DST development and the lunar landings during the early 2030s, cost and budget considerations preclude funding R&D on lunar habitation technologies to allow for long-term lunar habitation or supporting the establishment of commercial lunar activities as part of the 19-year exploration plan we describe. Adding long-term lunar habitation or support of commercial lunar activity to the notional schedule would likely require rising budgets. Alternatively, a second possibility might arise were new launch capabilities to emerge that were less expensive and allowed for a larger number of launches per year than the SLS/Orion combination upon which NASA's current plans—and this notional analysis—are based.

The risks to human health posed by a 1,100-day human orbital mission to Mars are highly uncertain. NASA documents, human research priorities, and the history of human spaceflight suggest that catastrophic technology failure resulting in death is the most important risk to human health, and as such, reducing this risk has been NASA's primary priority. While true, this focus does not negate the real risks of astronauts dying or suffering significant health degradation from spending 3 years in deep space on an extended orbital mission to Mars. The primary focus for planned research appears to be on currently known risks as opposed to understanding significant theoretical and unknown risks and holistic human health. The lack of information on the effects of 3 years in deep space on human health is a significant concern. This information is needed to design the DST to protect human health.

Understanding human variation and its relevance to human health outcomes will require a great deal more data. However, the limited time and resources currently allocated to collecting that data as well as the large knowledge gaps lead to a decreased likelihood of mitigating risks to human health by the time of the first mission to Mars. Although long-duration missions can take place aboard the ISS, limitations to studying synergistic health impacts relevant to deep space travel are inherent to LEO. Future plans for only one- to three-month missions on the Gateway constrain NASA's ability to reduce the knowledge gaps concerning a three-year Mars mission and its impact on human health. The planned one-year shakedown cruise for the DST takes place too late to incorporate changes in design based on information from the shakedown cruise without greatly increasing schedule and cost risk, and even if fully successful, still leaves a two-year gap between those data and the three-year Mars orbital mission.

In light of these findings, we have three high level recommendations. First, given that there is near-certainty that NASA cannot meet the 2033 goal, and 2037 and beyond is a more realistic timeline, NASA has time to consider a mission with value greater than that obtained from just orbiting Mars and returning. For example, NASA could consider making the first Mars mission a journey to one of the Martian moons, Phobos. This would increase the value of the mission from scientific, exploration, and public interest perspectives without taking on the risk or cost of a surface mission.

Second, regardless of what the specific mission to Mars is, the organizational challenges of managing combined developments and missions to ISS, Gateway, the lunar surface, and Mars are significant and should be addressed. If Congress would like NASA to abide by a specific timeframe in which to reach Mars, a goal not unlike Apollo, there may be value to creating an Associate Administrator position in charge of the Mars missions, with discrete budget authority over the required Mars elements (distinct from Associate Administrator oversight of the Gateway and the ISS).

Lastly, from the point of view of human health risks, given the knowledge gaps, NASA may benefit from developing a unified research plan intended to prioritize its approach to fill in gaps in knowledge, especially on the combined effects of radiation, microgravity, and isolation that may be encountered on a human mission to Mars and precursor missions. We recommend giving human health research a first-order priority in mission planning for the ISS, Gateway and Moon between now and 2037, creating a systematic research plan that addresses synergistic risks of long-duration missions outside of LEO, and emphasizing human research on topics that focus on overall crew health and survival during missions. Given that the uncertainties associated with the human health risks of a Mars orbital mission may not be fully known or mitigated at the time the decision to build a DST is made, NASA should follow the ethical principles laid out in the Academies' report, and discuss publicly and transparently the risk-benefit trade-off associated with NASA's decision to pursue a Mars orbital mission. Clarifying NASA's approach to integrating human health and risk issues into vehicle and mission design may be an important contributor to gaining consensus from stakeholders with respect to the human research approaches NASA is undertaking.

The 20-year plan for human exploration based on NASA's current and notional plans presented in this report represents one of the largest exploration endeavors humanity has ever undertaken. Throughout the 10 Congresses and several Administrations this plan covers, changes are likely to occur to meet the evolving needs of the U.S. Government, U.S. industry, and international partners, requiring NASA's plans to be flexible. During the preparation of this report, we noted the flexibility inherent in NASA's current and notional plans, as NASA has been able to adjust its plans to focus on returning to the Moon to conform to Administration direction. Notably, the designs for the Gateway did not dramatically change whether it was the staging ground for missions to the lunar surface or to Mars. Much of NASA's flexibility comes from the types of missions that compose NASA's longer-term visions for exploration. In particular, current and notional missions for the lunar surface and Mars focus on visiting locations, not staying; although lunar landers and the DST are required to reach a destination, they are not sufficient for establishing long-duration habitation of the Moon or Mars.

Over the coming years, as these initial missions are completed, and plans shift from visiting to staying, organizational inertia, mission creep, and extant infrastructure will reduce NASA's flexibility. For example, by constructing the Gateway, NASA is making a commitment to maintain a presence in cislunar space through at least the lifetime of the Gateway as other NASA systems, such as lunar landers and the DST, will be designed to use a platform like the Gateway. Additionally, the Gateway's role as a dockyard for NASA systems could expand to include private and international lunar surface missions, which may increase system requirements (e.g., adding a propellant depot). Decisions that entrench systems as key components to an overall architecture—such as the ISS—create inertia in the system that may divert plans away from other goals. This is especially true of systems that create locations to stay, as these become permanent destinations—and sometimes the sole destination—because of organizational inertia. However, it is this very organizational inertia that can create sustainable programs that can weather shifting priorities. As future Congresses and Administrations debate the destinations for human spaceflight and the scope of activities to be conducted once there, decision-makers must balance the tension between creating sustainable programs for continuous human habitation in space and the drive to keep setting and meeting explicit horizon goals.

Appendix A. Legislation

NASA Transition Authorization Act of 2017, Section 435. MARS 2033 REPORT.

a) In General.

Not later than 120 days after the date of enactment of this Act, the Administrator shall contract with an independent, non-governmental systems engineering and technical assistance organization to study a Mars human space flight mission to be launched in 2033.

b) Contents.

The study shall include-

   a. a technical development, test, fielding, and operations plan using the Space Launch System, Orion, and other systems to successfully launch such a Mars human space flight mission by 2033;
   b. an annual budget profile, including cost estimates, for the technical development, test, fielding, and operations plan to carry out a Mars human space flight mission by 2033; and
   c. a comparison of the annual budget profile to the 5 year budget profile contained in the President's budget request for Fiscal Year (FY) 2017 under 31 U.S.C. §1105.

c) Report.

Not later than 180 days after the date of enactment of this Act, the Administrator shall submit to the appropriate committees of Congress a report on the study, including findings and recommendations regarding the Mars 2033 human space flight mission described in subsection (a).

d) Assessment.

Not later than 60 days after the date the report is submitted under subsection (c), the Administrator shall submit to the appropriate committees of Congress an assessment by the NASA Advisory Council of whether the proposal for a Mars human space flight mission to be launched in 2033 is in the strategic interests of the United States in space exploration.

Appendix B.
Interviews

2017

August 28	Kickoff Meeting with NASA National Space Exploration Campaign Report Team
September 5	Meeting with James Free (Vice President of Aerospace Systems Group at Peerless Technologies, former Associate Administrator of NASA Human Exploration and Operations Mission Directorate)
September 11	Mike Griffin (former Administrator of NASA)
September 12	Dava Newman (former Deputy Administrator of NASA)
September 14	Joe Cassady (Executive Director for Space in Aerojet Rocketdyne Washington Operations)
September 15	Ann Zulkosky, Tony Antonelli, Rob Chambers, Timothy Cichan, Michael Hawes, and Steve Jolly (Lockheed Martin)
September 19	Frank Slazer (Vice President of Space Systems at Aerospace Industries Association)
September 22	Kris Leinhardt (Attending Physician and Assistant Professor at George Washington University)
October 5	Steve Cook (Vice President of Dynetics)
October 6	NASA National Space Exploration Campaign Report Team
October 10	Mike Elsperman (Director of Boeing's Space Science and Advanced Space Utilization Division)
October 12	John Connolly (Team Lead, NASA Mars Study Capability Team)
October 19	Robyn Gatens (Deputy Director, ISS Division and System Capability Leader for ECLSS at NASA)
October 20	James Reuter (STMD Deputy Associate Administrator)
October 25	Bruce Hather and Victor Schneider (NASA Office of the Chief Health and Medical Officer)

2018

October 11	Patrick Besha and Chris Flaherty (NASA Office of the Administrator and Office of Legislative and Intergovernmental Affairs)
November 19	Patrick Besha, Jason Crusan, Jonathan Krezel, Kathleen Gallagher Boggs, Craig Kundrot, Stephen C. Davison, Nicole B. Herrmann, Prasun Desai, Richard Irving, Stacey Brooks, Douglas A. Craig (NASA)

Appendix C.
Cost Performance of NASA Programs

Deep Space Projects	Percent Change	Year Initially Budgeted
Galileo	227	1978
Ulysses	-14	1979
Magellan	43	1984
Mars Observer	67	1985
Cassini	-4	1990
Advanced Composition Explorer	-20	1994
Mars Global Surveyor	-7	1994
Mars Pathfinder	0	1994
Near Earth Asteroid Rendezvous Mission	-23	1994
Deep Space-1	29	1996
Lunar Prospector	0	1996
Mars Climate Orbiter	3	1996
Microwave Anisotropy Probe	7	1996
Genesis Spacecraft	20	1998
Mars Odyssey	37	1998
Triana Spacecraft	29	1998
Comet Nucleus Tour	40	2000
Mars Exploration Rover	26	2000
Dawn	-2	2007
Herschel	8	2007
Kepler	25	2007
Lunar Reconnaissance Orbiter	12	2008
Mars Science Laboratory	84	2008
Gravity Recovery and Interior Laboratory	-7	2009
Juno	-4	2009
James Webb Space Telescope	140	2009
Lunar Atmosphere and Dust Environment Explorer	14	2011
Mars Atmosphere and Volatile Evolution	-14	2011
InSight	24	2014
OSIRIS-REX	-10	2013

Deep Space Projects	Percent Change	Year Initially Budgeted
Mean Project Overrun (of projects that had cost overruns)	46% ± 57%	

Human-Oriented Projects	Percent Change	Year Initially Budgeted
Orbital Maneuvering Vehicle	107	1986
Space Shuttle Endeavour	-14	1987
Space Station	86	1987
Multifunction Electronics Display Subsystem	4	1992
Mean Project Overrun (of projects that had cost overruns)	66% ± 54%	

Observing/Satellite Projects	Percent Change	Year Initially Budgeted
Hubble Space Telescope	255	1977
Land Remote Sensing Satellite-D	93	1977
Gamma Ray Observatory	203	1981
Cosmic Background Explorer	64	1982
Upper Atmosphere Research Satellite	7	1982
Advanced Communications Technology Satellite	41	1983
Extreme Ultraviolet Explorer	-20	1984
Geospatial Operational Environmental Satellite I-M	124	1984
Tethered Satellite System	274	1984
NASA Scatterometer	100	1985
Fourier Transform Spectrometer	43	1986
Second Tracking and Data Relay Satellite Ground Terminal	56	1986
Tracking and Data Relay Satellite-7	38	1986
Topography Experiment	25	1987
Global Geospatial Science Program	37	1988
Fast Auroral Snapshot Explorer	32	1989
Wide Field Infrared Explorer	52	1989
Advanced X-Ray Astrophysics Facility	15	1990
X-Ray Timing Explorer	78	1990
Earth Observing System, Terra Satellite	14	1991
Tropical Rainfall Measuring Mission	12	1991

Observing/Satellite Projects	Percent Change	Year Initially Budgeted
Earth Observing System, Aura Satellite	0	1993
Tracking and Data Relay Satellite System Replenishment	–11	1994
Far Ultraviolet Spectroscopic Explorer	40	1995
Earth Observing-1	119	1996
Ice Cloud and Land Elevation Satellite	46	1996
Imager for Aurora to Magnetopause Global Exploration	7	1996
Space Infrared Telescope Facility	53	1996
Stardust Spacecraft	–1	1996
High Energy Transient Explorer-II	15.1	1997
Thermosphere, Ionosphere, Mesosphere, Energetics, and Dynamics Space Science Satellite	26	1997
Galaxy Evolution Explorer	112	1998
High-Energy Solar Spectroscopic Imager	61	1998
Cloud-Aerosol Lidar and Infrared Pathfinder Satellite	43	1999
CloudSat Spacecraft	32	1999
Solar Radiation and Climate Experiment	10	1999
Aquarius	17.2	2008
Gamma-ray Large Area Space Telescope	5	2007
Glory	100	2008
National Polar-orbiting Operational Environmental Satellite System (NPOESS) Preparatory Project	30	2007
Orbiting Carbon Observatory	18	2008
Solar Dynamics Observatory	9	2007
Wide-Field Infrared Explorer	2	2008
Radiation Belt Storm Probes	-4	2009
Global Precipitation Measurement	-8	2010
Landsat 8	-1	2010
Magnetospheric Multiscale Mission	2	2009
Tracking and Data Relay Satellite Replenishment	-12	2010
Orbiting Carbon Observatory-2	29	2011
Ice Cloud and Land Elevation Satellite 2	37	2012
Soil Moisture Active Passive	-1	2012
Gravity Recovery and Climate Experiment Follow-On	0	2014
Mean Project Overrun (of projects that had cost overruns)	57% ± 63%	

Appendix D. Calculating the Probability of an Improbable Event: Using Observational Data to Estimate Uncertainty in Human Deep Space Exploration

As described in Chapter 6, space agencies have been successful to date in maintaining the health of astronauts while in space. Although fatalities have occurred as a result of vehicle accidents due to mechanical failures, no deaths have occurred to date from health-related causes during human spaceflight. The absence of observed fatalities to date, however, does not mean that space travel is risk-free. Moreover, the Mars mission analyzed in this report envisions a space travel event that is different from previous experiences. Most observations to date have been of individuals spending 30 or fewer days in space. As shown Chapter 6, Figure 22, as of 2018 there have been nearly 1000 individual flights by astronauts spending less than 1 month in space (or astronaut-missions); 252 astronaut-missions have involved humans spending 1–6 months in space; and 17 astronaut-missions have involved humans spending more than 6 months in space at one time.[50] The Mars mission, however, represents a three-year journey. Moreover, nearly all observations to date have been in LEO, where the Earth's magnetic field screens out much of the radiation to which astronauts would be exposed in a deep space journey (Sihver et al. 2015) and where astronauts could return quickly to Earth in case of emergency.

Researchers have noted that NASA possesses observational data associated with individual astronauts' biological responses to space travel that could be useful in reducing the uncertainties associated with extrapolating current knowledge to predict the risk of deep-space travel, but that privacy considerations complicate non-NASA researchers' ability to access these data and to incorporate them into their research (Chancellor et al 2018). The question, therefore, is whether some information may be gleaned from the observational data even without direct access to astronauts' medical records and exposure histories. For medically adverse events, the literature has developed statistical methods for quantifying risk based on observational data (Hanley and Lippman-Hand 1983; Eypasch et al. 1995) intended to consider the range of uncertainty of the risk that can be associated

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[50] Astronauts who have flown multiple missions would be counted as having flown multiple astronaut-missions.

with a potential adverse effect that has not yet been observed to occur.[51] This approach can be applied to astronaut health.

While there have been no three-year, deep-space missions flown by astronauts, there have been 17 astronaut-missions of 6–15 months as of 2017—albeit in LEO rather than deep space and flown solely by male astronauts—without any observed astronaut fatalities. The "Rule of Three" approach therefore suggests that the 95 percent confidence interval around the risk of a fatality from a 6–15 month mission in LEO flown by a male astronaut would be between 0 and 18 percent.[52] Of course, crews will be on the ISS through at least 2024, and the schedule described in this report envisions trips to the Gateway and to the Moon before the DST is completed and launched. Observational data will be collected from these flights, and, assuming that there continue to be no fatalities, the confidence interval for risk estimates associated with spaceflight to LEO and to cislunar environments will narrow. Even making the strong and potentially unfounded assumptions required to extrapolate these results to estimate the risk of a three-year, deep space spaceflight, however, the "Rule of Three" suggests that 100 successful astronaut-missions would be required to reduce the 95th percentile upper confidence limit to the three percent risk level that the National Council on Radiation Protection and Management has recommended NASA use (NCRP 2014, Cucinotta et al 2018).

Relying solely on observations that no astronaut has yet died from natural causes in space provides limited insight into the health risks that astronauts would face in undertaking the planned 1,100-day Mars mission. As such, NASA should continue to conduct and publish statistically rigorous analyses to estimate the mean probability of astronaut mortality in deep space with quantified uncertainty, using Bayesian as well as frequentist approaches.

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[51] The limited representative abilities of any sample size allows for an effect to have a non-zero risk of occurrence in the greater population even if a sample shows zero outcomes for that effect. The risk can be represented using a binomial probability distribution, where statistical confidence levels are used to represent (based on the number of observations) the degree of uncertainty in estimating the "true" risk of an adverse event. As more observations are collected showing that the adverse event of concern has not yet occurred, our confidence that the risk is close to zero increases, even though it cannot be concluded that there is no risk of that event. If a data set of sample size n shows zero occurrences of an outcome, the risk of that outcome can be estimated using the Rule of Three: one can construct a 95% confidence interval between zero and $3/n$ (see Hanley and Lippman-Hand 1983 for derivation and explanation). The approach is intended to calculate a confidence interval rather than a mean value.

[52] Given an n of 17 astronauts having flown individual missions of 6–15 months, 3/17 = 17.6%

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Abbreviations

AEPS	Advanced Electric Propulsion System
CBO	Congressional Budget Office
CLPS	Commercial Lunar Payload Services
CM	Crew Module
CMA	Crew Module Adapter
DSAC	Deep Space Atomic Clock
DST	Deep Space Transport
ECLSS	Environmental Control and Life Support System
EM	Exploration Mission
ESA	European Space Agency
ESM	European Service Module
EUS	Exploration Upper Stage
EVA	Extravehicular Activity
FDA	Food and Drug Administration
FY	Fiscal Year
GAO	Government Accountability Office
GCR	galactic cosmic ray
GDP	gross domestic product
GFAS	Ground and Flight Application
HEO NAC	Human Exploration and Operations Committee of the NASA Advisory Council
HERMeS	Hall Effect Rocket with Magnetic Shielding
HRP	Human Research Program
IDA	Institute for Defense Analyses
ISS	International Space Station
LAS	Launch Abort System
LCH_4	methane
LEO	low Earth orbit
LOX	liquid oxygen
LVSA	launch vehicle stage adaptor
MAV	Mars Ascent Vehicle
MCLAV	Mars Crew Landing/Ascent Vehicle
MDV	Mars Descent Vehicle
MOXIE	Mars Oxygen In-situ Resource Utilization
MSA	multi-purpose crew vehicle stage adapter
NASA	National Aeronautics and Space Administration
NextSTEP	Next Space Technologies for Exploration Partnerships
NPOESS	National Polar-orbiting Operational Environmental Satellite System

NRHO	near rectilinear halo orbit
OMB	Office of Management and Budget
Orion	Orion Multi-Purpose Crew Vehicle
PPE	Power and Propulsion Element
PBR	President's Budget Request
PMAD	power management and distribution
R&D	research and development
RFI	request for information
ROSA	Roll-Out Solar Array
RRM	Robotic Refueling Mission
SCCS	Spaceport Command and Control System
SEP	Solar Electric Propulsion
SFS	Space and Flight Support
SLS	Space Launch System
SM	Service Module
SRR	System Requirements Review
STMD	Space Technology Mission Directorate
STPI	Science and Technology Policy Institute
TLI	trans-lunar injection
TRL	technology readiness level
U.S.C.	United States Code
USA	Universal Stage Adaptor
VAB	Vehicle Assembly Building

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6. AUTHOR(S)
Linck, Evan
Crane, Keith W.
Zuckerman, Brian L.
Corbin, Benjamin A.
Myers, Roger M.
Williams, Sharon R.
Garcia, Rodolfo
Lal, Bhavya

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IDA Science and Technology Policy Institute
1899 Pennsylvania Avenue, NW, Suite 520
Washington, DC 20006-3602

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National Aeronautics and Space Administration
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14. ABSTRACT
The NASA Transition Authorization Act of 2017 mandated that NASA ask an independent organization to study a Mars human spaceflight mission to be launched in 2033, including an evaluation of technologies, schedules, estimated costs, and budget profiles for the mission to Mars and its precursor missions. NASA requested STPI conduct this analysis and base the study's schedule for human spaceflight on NASA's current and notional plans leading to a mission to Mars orbit. STPI found that a 2033 departure date for a Mars orbital mission is infeasible under all budget scenarios and technology development and testing schedules. We found that 2035 may be possible under budgets that match 1.9 percent real growth, but carries high risks of schedule delays due to complex technology development, testing, and fabrication schedules for the Deep Space Transport. 2037 is the earliest the mission could feasibly depart for Mars assuming a small budget increase or smoothing budgets over two time periods in the 2030s, with 2039 being a more realistic timeframe.

15. SUBJECT TERMS
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