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NASA's Plans for Human Exploration Beyond Low Earth Orbit

April 13, 2017

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Office of Inspector General

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NASA Office of Inspector General
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RESULTS IN BRIEF

NASA's Plans for Human Exploration Beyond Low Earth Orbit

April 13, 2017 IG-17-017 (A-16-015-00)

WHY WE PERFORMED THIS AUDIT

Human exploration of Mars has been a long-term goal of NASA and the Nation for the past 5 decades. In 2015, the Agency announced its Journey to Mars framework for deep space exploration with manned missions to Mars beginning in the 2030s. In addition to the technical and health-related challenges of deep space missions, such a multi-decadal venture will be very expensive, with NASA's budget projections for human exploration to Mars exceeding $210 billion by 2033.

A vital part of achieving its long-term human exploration goals is the successful development of NASA's new spaceflight system – the heavy-lift Space Launch System (SLS) rocket, the Orion Multi-Purpose Crew Vehicle (Orion) capsule, and the ground processing and launch facilities (Ground Systems Development and Operations or GSDO) needed to launch the rocket and capsule for cislunar and deep space exploration. NASA has invested more than $15 billion in these three programs since 2012, and its near-term goals include a first uncrewed flight of the integrated SLS/Orion systems – Exploration Mission-1 (EM-1) – no later than November 2018 followed by a crewed flight – Exploration Mission-2 (EM-2) – as early as 2021.[1] However, NASA's plans beyond these two missions are less clear, with several options in early development, including robotic and crewed missions to an asteroid in the early to mid-2020s to test technologies and capabilities that would be needed for a mission to Mars. Moreover, these scenarios were developed during the previous administration, and the Agency's new leadership is seeking to modify those plans with the President's fiscal year 2018 budget request proposing cancellation of the Asteroid Redirect Mission and the Agency issuing a document in March 2017 that modifies and fleshes out some of its plans.

In light of the enormous costs and challenges and the critical decisions that must be made in the next several years, we examined NASA's plans for human exploration beyond low Earth orbit in the near-term, mid-term, and long-term. Specifically, we assessed the Agency's (1) plans for and progress towards its first flights of the integrated SLS/Orion systems in the next 2 to 5 years, (2) challenges in executing a sustainable and affordable plan to send a crewed mission to Mars in the 2030s or 2040s, and (3) strategies to help reduce the costs of its human exploration efforts. To complete this work, we analyzed cost data, interviewed Agency officials, conducted on-site inspections, and reviewed planning documents, feasibility studies, and other relevant program documentation.

WHAT WE FOUND

NASA's initial exploration missions on its Journey to Mars – EM-1 and EM-2 – face multiple cost and technical challenges that likely will affect their planned launch dates. Moreover, although the Agency's combined investment for development of the SLS, Orion, and GSDO programs will reach approximately $23 billion by the end of fiscal year 2018, the programs' average monetary reserves for the years leading up to EM-1 are much lower than the 10 to 30 percent recommended by Marshall Space Flight Center guidance. Low monetary reserves limit the programs' flexibility to cover increased costs or delays resulting from unexpected design complexity, incomplete requirements, or technology uncertainties. Moreover, software development and verification efforts for all three programs are behind schedule to

[1] In February 2017, the Acting NASA Administrator instructed the head of NASA's Human Exploration and Operations Mission Directorate to study the feasibility – from a cost, safety, and technical standpoint – of adding crew to the EM-1 mission.

meet a November 2018 EM-1 launch. Finally, NASA does not have a life-cycle cost estimate or integrated schedule for EM-2, which makes it difficult for Agency officials and external stakeholders to understand the full costs of EM-2 or gauge the validity of launch date assumptions.

Beyond EM-2, NASA's plans for achieving a crewed Mars surface mission in the late 2030s or early 2040s remain understandably high level, serving as more of a strategic framework than a detailed operational plan. For example, the Agency's current Journey to Mars strategy does not identify key system requirements other than SLS, Orion, and GSDO, or offer target mission dates for a crewed orbit of Mars or landings on the planet's surface or nearby moon. If the Agency is to reach its goal of sending humans to the vicinity of Mars in the 2030s, significant development work on key systems such as a deep space habitat, in-space transportation, and Mars landing and ascent vehicles must be undertaken in the 2020s, and the Agency will need to make these and many other decisions in the next 5 years or so for that to happen. In addition, to position itself to make wise investment decisions, NASA will need to begin developing more detailed cost estimates for its Mars exploration program after EM-2. More concrete estimates will also be necessary as Agency officials work with Congress and other stakeholders to ensure the commitment exists to fund a mission of this magnitude over the next several decades. In addition, NASA's decision whether to continue spending $3 to $4 billion annually to maintain the International Space Station after 2024 will affect its funding profile for human exploration efforts in the 2020s, and therefore has implications for the Agency's Mars plans.

NASA acknowledges that to successfully execute the Journey to Mars, cost saving measures and cost sharing must be part of its strategy. Consequently, the Agency has explored reusing systems and subsystems, developing new acquisition strategies, and exploiting technology innovations to help reduce the high cost of deep space exploration. In addition, sharing costs with foreign space agencies and the private sector could help NASA reduce its overall costs, and NASA is partnering with industry to conduct multiple trade studies on the systems needed for the Journey to Mars and providing technical and mission support to Space Exploration Technologies Corporation (SpaceX) related to the company's planned uncrewed Mars mission. Moreover, the recently enacted NASA Transition Authorization Act of 2017 cites expanding permanent human presence beyond low Earth orbit together with international, academic, and industry partners as the country's long-term goal for human space exploration efforts.

What We Recommended

To increase the fidelity, accountability, and transparency of NASA's human exploration goals beyond low Earth orbit, we recommended the Associate Administrator for Human Exploration and Operations (1) complete an integrated master schedule for the SLS, Orion, and GSDO programs for the EM-2 mission; (2) establish more rigorous cost and schedule estimates for the SLS and associated GSDO infrastructure for EM-2; (3) establish objectives, need-by dates for key systems, and phase transition mission dates to flesh out its Journey to Mars framework; and (4) include cost as a factor in NASA's Journey to Mars feasibility studies when assessing various potential missions and systems. To improve cost savings efforts, we recommended the Associate Administrator for Human Exploration and Operations (5) design a strategy for collaborating with international space agencies in their cislunar space exploration efforts with a focus on advancing key systems and capabilities needed for Mars exploration, and (6) incorporate into analyses of space flight system architectures the potential for utilization of private launch vehicles for transportation of payloads.

We provided a draft of this report to NASA management who concurred or partially concurred with our recommendations and described planned corrective actions. We consider the proposed actions responsive to all but recommendation 2, and therefore will close those recommendations upon verification and completion of the actions. For the remaining open recommendation, we will continue to work with the Agency to resolve our concerns regarding establishing more rigorous cost and schedule estimates for the SLS and associated GSDO infrastructure for EM-2.

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Acronyms

AES	Advanced Exploration Systems
CDR	Critical Design Review
EM-1	Exploration Mission-1
EM-2	Exploration Mission-2
ESA	European Space Agency
ESD	Exploration Systems Development
EUS	Exploration Upper Stage
FAR	Federal Acquisition Regulation
FY	Fiscal Year
GAO	Government Accountability Office
GSDO	Ground Systems Development and Operations
HEOMD	Human Exploration and Operations Mission Directorate
ISS	International Space Station
JPL	Jet Propulsion Laboratory
MPR	Marshall Procedural Requirements
NextSTEP	Next Space Technologies for Exploration Partnerships
NPR	NASA Procedural Requirements
OCFO	Office of the Chief Financial Officer
OIG	Office of Inspector General
PDR	Preliminary Design Review
SDR	System Definition Review
SLS	Space Launch System
STMD	Space Technology Mission Directorate
VAB	Vehicle Assembly Building

INTRODUCTION

Human exploration of Mars has been a long-term goal of NASA and the Nation for the past 5 decades. Even before the United States landed a man on the Moon in 1969, NASA began developing the plans and technologies needed to send astronauts to the red planet. However, a change in national priorities in the 1970s shifted the Agency's focus from Mars to building and operating the Space Shuttle and later the International Space Station (ISS or Station) in low Earth orbit – a location humans have not ventured beyond since Apollo 17's final Moon mission in 1972. Since the late 1990s, NASA and its foreign space agency partners have used the ISS to help develop commercial space flight capabilities, test new technologies, and conduct research aimed at mitigating the health risks associated with deep space travel.

NASA is once again pursuing human exploration beyond low Earth orbit, and in 2015 the Agency announced its Journey to Mars – a framework for deep space exploration that culminates in crewed flights to Mars. In addition to the technical and health-related challenges of deep space missions, such a multi-decadal venture will be very expensive. Indeed, NASA's budget assumptions for human exploration to Mars will exceed $210 billion by 2033.[1]

In its early years, the U.S. space program enjoyed substantial support from the President and Congress, with NASA's annual budget increasing from $500 million in 1960 to $5.2 billion just 5 years later. However, after the 1960s, NASA's budget as a percentage of the overall Federal budget has significantly declined. Peaking in 1966 during the Apollo Program at 4.4 percent, by 2016 NASA was receiving only 0.5 percent of overall Federal spending. Similarly, when adjusted for inflation, the Agency's annual funding has been on a nearly consistent downward trend for more than 20 years. Adding to the funding challenge is the uncertainty of operating under an appropriations process where annual budgets are rarely enacted on time and continuing resolutions routinely fund programs at previous-year levels.

Since retirement of the Space Shuttle Program in 2011, NASA has worked with private companies to develop commercial space flight capabilities to deliver cargo and crew to the ISS, focusing the bulk of its human exploration funds on maintaining the ISS and developing a heavy-lift rocket – the Space Launch System (SLS); a crew capsule – the Orion Multi-Purpose Crew Vehicle (Orion); and the related ground processing and launch facilities – Ground Systems Development and Operations (GSDO) – required to launch the new rocket and capsule for cislunar and deep space exploration.[2] With an investment in these three programs of more than $15 billion since 2012, NASA has completed Critical Design Reviews (CDR) for each and is manufacturing both test and flight articles for the initial SLS and Orion and equipment for GSDO.[3] The Agency's near-term goals include a first flight of the integrated SLS/Orion

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[1] Because NASA considers the ISS an important part of the Journey to Mars, the costs of the ISS Program are included in this figure.

[2] Space Exploration Technologies Corporation (SpaceX) and Orbital ATK have been carrying supplies to and from the Station since 2012 and 2013, respectively. NASA has contracts with SpaceX and The Boeing Company to begin ferrying crew between 2018 and 2019. Cislunar space is the area between Earth and the Moon or the Moon's orbit.

[3] A CDR demonstrates that a program or project design is sufficiently mature to proceed to full-scale fabrication, assembly, integration, and testing and is considered a key step in the development process because it often reveals shortcomings that must be addressed before the spacecraft design is finalized and manufacturing begins.

systems – Exploration Mission-1 (EM-1) – no later than November 2018 and a first crewed flight – Exploration Mission-2 (EM-2) – as early as 2021.[4] However, as both the NASA Office of Inspector General (OIG) and the Government Accountability Office (GAO) have cautioned in previous reports, NASA faces significant challenges to meeting these launch dates.[5]

NASA's plans beyond the near-term EM-1 and EM-2 launches are less clear. Agency officials have discussed sending astronauts to retrieve material from an asteroid in 2026 to test several exploration capabilities needed for a Mars mission (the Asteroid Redirect Mission), flying a 1-year "shakedown cruise" in the late 2020s, and traveling to and orbiting Mars and/or its moon Phobos by 2033.[6] However, these scenarios were developed during the Obama administration and the Agency's new leadership is examining modifications to those plans. In addition, influential members of the congressional committees that oversee and fund NASA have advocated for refocusing human exploration on lunar activities, including establishing a surface base on the Moon, rather than following the Journey to Mars plan, parts of which have generated limited support from foreign space agencies. Specifically, some U.S. lawmakers have proposed cancelling the Asteroid Redirect Mission to focus on missions targeting lunar orbit and surface objectives, and the President's fiscal year (FY) 2018 budget request also proposes cancelling the Mission.[7]

In light of the enormous costs and challenges and the critical decisions that will need to be made in the next several years, we examined NASA's plans for human exploration beyond low Earth orbit in the near-term, mid-term, and long-term. Specifically, we assessed the Agency's (1) plans for and progress towards its first flights of the integrated SLS/Orion systems in the next 2 to 5 years, (2) challenges in executing a sustainable and affordable plan to send a crewed mission to Mars in the 2030s or 2040s, and (3) strategies to help reduce the costs of its human exploration efforts. We hope this report provides policy makers with a better sense of the significant technical, financial, and political challenges that will need to be addressed to successfully execute human exploration of Mars. See Appendix A for details of our scope and methodology.

Background

Both the NASA Authorization Act of 2010 and the NASA Transition Authorization Act of 2017 set Mars exploration as the long-term objective for human space exploration.[8] The 2010 law set broad objectives and directed NASA to use an incremental development approach for each particular mission and to build launch vehicles with specific capabilities using hardware from the Space Shuttle and Constellation

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[4] In February 2017, the Acting NASA Administrator announced he had instructed the head of NASA's Human Exploration and Operations Mission Directorate to study the possibility – from a cost, safety, and technical standpoint – of adding crew to the EM-1 mission. EM-2 does not have an official integrated launch schedule. Although all three programs are working towards an August 2021 launch date, NASA's commitment date to Congress for Orion's launch is 2023. We discuss the EM-2 launch date later in this report.

[5] For a full list of relevant NASA OIG and GAO reports, see Appendix A.

[6] For the shakedown cruise, the crew would remain in space for a year to test systems and detect and correct any performance problems before the extended Mars journey.

[7] The NASA Transition Authorization Act of 2017, Pub. L. No. 115-10 (2017), raises concerns about whether the cost of the Asteroid Redirect Robotic Mission is worth the expected technological and scientific benefits and directs NASA to examine alternative missions to test the capabilities needed for human exploration of Mars and report to Congress in 180 days.

[8] NASA Authorization Act of 2010, Pub. L. No. 111-267 (2010) and Pub. L. No. 115-10.

programs.[9] The NASA Transition Authorization Act of 2017 further defined these goals by requiring the Agency to develop a human exploration roadmap to expand human presence beyond low Earth orbit to or near the surface of Mars by the 2030s. Due December 2017 and biennially thereafter, this roadmap should identify critical decisions that must be made before 2020, interim destinations, and opportunities for international, academic, and industry partnerships. Consistent with this legislative direction, NASA's strategic plan describes its long-term goal as sending humans to Mars by developing and demonstrating technologies and capabilities over the next 2 decades.

NASA's Plan for the Journey to Mars

NASA's Journey to Mars sets forth general principles for human exploration and describes three stages of activities, key systems, and capabilities. NASA officials have characterized the document as a "framework" for moving forward rather than a "system architecture." In NASA parlance, a system architecture identifies discrete missions and destinations and the space systems needed to meet the requirements of those missions. For example, ground systems, rockets, spacesuits, and habitation modules would be part of the system architecture for the Journey to Mars. See Appendix B for a history of past NASA frameworks and planning efforts related to the exploration of Mars.[10]

NASA has identified the following eight principles for a sustainable, affordable Mars crewed space program:[11]

1. *Fiscal Realism*. Implementable in the near-term with the buying power of current budgets and in the longer term with budgets commensurate with economic growth.
2. *Scientific Exploration*. Exploration enables science and science enables exploration; leveraging scientific expertise for human exploration of the solar system.
3. *Technology Pull and Push*. Application of highly developed technologies for near-term missions, while focusing sustained investments on technologies and capabilities to address the challenges of future missions.
4. *Gradual Build Up of Capability*. 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.
5. *Economic Opportunity*. Opportunities for U.S. commercial business to further enhance their experience and business base.
6. *Architecture Openness and Resilience*. Resilient architecture featuring multi-use, evolvable space infrastructure and minimizing unique developments, with each mission leaving something behind to support subsequent missions.

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9 In July 2011, after 30 years and 135 crewed missions to low Earth orbit, the Space Shuttle Program completed its final flight. Designed to both replace the Space Shuttle and provide a deep space cargo and crew capability, the lunar-centric Constellation Program was cancelled in 2010, well before its first mission.

10 In March 2017, the Agency presented to the NASA Advisory Council a briefing titled "Progress in Defining the Deep Space Gateway and Transport Plan," which modified and fleshed out some of the plans laid out in the Journey to Mars framework.

11 "NASA's Journey to Mars: Pioneering Next Steps in Space Exploration," October 2015, and HEOMD, "Strategic Principles for Sustainable Exploration," 2017. The Agency added the eighth principle after publication of its Journey to Mars plan.

7. *Global Collaboration and Leadership*. Substantial new international and commercial partnerships that leverage current ISS partnerships and build new cooperative ventures for exploration.
8. *Continuity of Human Space Flight*. Uninterrupted expansion of human presence into the solar system by establishing a regular cadence of crewed missions to cislunar space during ISS lifetime.

Consistent with these principles, NASA outlined three general stages for the Journey to Mars: Earth Reliant, Proving Ground, and Earth Independent. Common to each stage is an incremental approach, proving the required capabilities and building the systems needed to complete each stage of the mission. The Earth Reliant stage focuses on research and testing on the ISS to enable deep space, long-duration crewed missions. As part of this stage, NASA facilitated development of commercial space flight capabilities with U.S. commercial launch companies for transporting cargo and crew to the Station. The Proving Ground stage will test and validate complex operations and components in cislunar space. The Earth Independent stage will demonstrate critical systems in Mars orbit and on its moons and surface to enable human missions to the planet.

NASA has further refined these stages into four measurable parts with Phases 1 and 2 occurring during the Proving Ground stage and Phases 3 and 4 in the Earth Independent stage.[12] Each phase will culminate in a significant exploration activity or transition mission to demarcate completion of one phase and the beginning of the next.

Phase 1 begins with EM-1 and EM-2, the first two flights of the integrated SLS/Orion systems. For EM-1, planned for launch no later than November 2018, an SLS rocket capable of delivering 70 metric tons to low Earth orbit will launch an uncrewed Orion capsule on a 25- to 26-day journey orbiting the Moon. EM-2 will be the combined system’s first crewed flight and will include a human-rated Orion capsule and an upgraded SLS rocket – Block 1B – with a new upper stage.[13] As noted previously, although there is no integrated launch schedule for EM-2, the SLS, Orion, and GSDO programs are all working toward a 2021 launch date. Also during Phase 1, NASA plans to conduct both crewed and uncrewed missions to an asteroid – the Asteroid Redirect Robotic Mission in 2021 and the Asteroid Redirect Crewed Mission in 2026 – during which the Agency would use robotic means to retrieve and return a large boulder from an asteroid to cislunar space from which astronauts would later gather samples. Finally, Phase 1 also includes demonstrations of solar electric propulsion technologies and development of a cislunar habitat.

In Phase 2, NASA plans to field the in-space propulsion systems it will use to reach Mars and perform a year-long crewed shakedown cruise of the deep space transportation system beyond cislunar orbit. This Phase also includes a second major upgrade of the SLS – Block 2 – that will give it sufficient capability to lift the systems and supplies needed for deep space travel.

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12 NASA uses the term Phase 0 to describe its current activities in low Earth orbit – specifically, the testing of deep space subsystems on the ISS and the transportation of cargo and crew by U.S. companies.

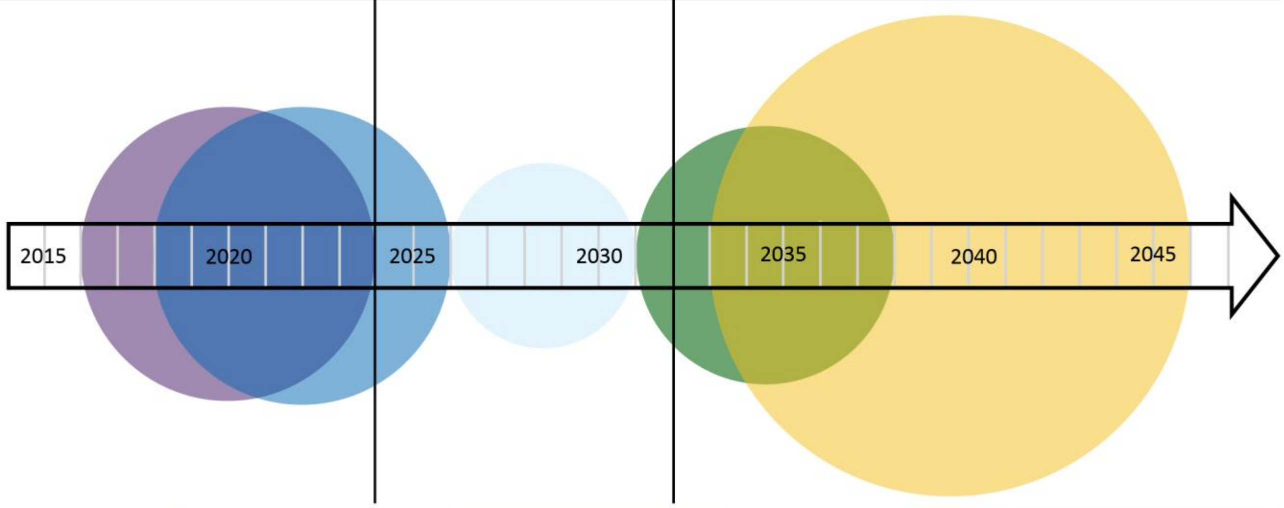
13 As noted previously, in February 2017 the Acting NASA Administrator announced he had directed Agency staff to “initiate a study to assess the feasibility of adding crew to Exploration Mission-1.”

The Earth Independent stage starts with Phase 3 in the early 2030s. During this stage, NASA plans to conduct a crewed orbit of Mars, test descent and ascent vehicles, and visit the Martian moon Phobos. Phase 4 is divided into two parts, both occurring during the 2030s and 2040s. The first part – Phase 4a – will focus on robotic and preparatory missions, while the second part – Phase 4b – will be the initial crewed landing on Mars with a surface habitat and rover.

As of March 2017, NASA had approved the basic objectives for Phases 1 and 2; however, specific activities in the other phases have not been officially approved. Figure 1 illustrates these phases.

Figure 1: Summary of NASA's Plan for the Journey to Mars

	Earth Reliant (low Earth orbit)	Proving Ground (cislunar space)	Earth Independent (Mars orbit/surface)
Mission Duration	6 to 12 months	1 to 12 months	2 to 3 years
Return to Earth	hours	days	months/years
Time Period	2016 to 2024	mid-2020s to early 2030s	early 2030s to mid-2040s



Phase 0	Phase 1	Phase 2	Phase 3	Phase 4
• ISS testing • Commercial crew • Commercial cargo	• EM-1 • EM-2 • Asteroid Redirect Robotic Mission	• Cislunar exploration missions and development of deep space systems	• Mars orbit • Exploration of Mars' moons • Transport system between high and low Mars orbits	• Mars surface • Phase 4a: robotic and preparatory (non-human) missions • Phase 4b: crewed Mars landing (human missions)
Phase Transition Mission undefined	**Phase Transition Mission** Asteroid Redirect Crewed Mission	**Phase Transition Mission** 1-year crewed shakedown cruise	**Phase Transition Mission** undefined	**Phase Transition Mission** undefined

Source: NASA OIG analysis of Agency planning documents for the Journey to Mars.

Notes: See Appendix C for NASA's representation of Phases 0 through 4 of the Journey to Mars. For a full listing of the exploration objectives by Phase, see Appendix D.

Key Systems Required for a Crewed Mars Mission

Sending humans to Mars requires development of a variety of systems, including a heavy-lift launch vehicle, human-rated spacecraft for high-velocity reentry to Earth, in-space propulsion, habitats for long-duration transits, Mars landing and ascent capabilities, and a surface habitat.[14] Each of these systems is required at different phases during the Journey to Mars plan, a sequencing that will inform funding requirements, "need-by" dates, and development priorities. Of these systems, only SLS, Orion, and GSDO are under development, with all others remaining concepts. Appendix E combines Journey to Mars phases with the proposed SLS launch cadences to describe notional Human Exploration and Operations Mission Directorate (HEOMD) mission planning through the 2040s.

Space Launch System

NASA plans to use the SLS to transport cargo and crew into space for missions in cislunar and Mars orbits. The SLS is a two-stage launch vehicle that uses liquid propellant and a pair of five-segment solid propellant boosters. The vehicle concept leverages technologies from the Space Shuttle and Constellation programs. The SLS will use a newly developed core stage that incorporates four RS-25 engines derived from the Space Shuttle Program and dual five-segment solid boosters derived from the Constellation Program. For its uncrewed 2018 mission, the SLS's Upper Stage will use an Interim Cryogenic Propulsion Stage, which is a modified second stage of a Delta IV rocket that uses a single RL-10 engine. NASA originally planned to use this upper stage configuration on its first two SLS missions, but in December 2015 Congress appropriated $85 million toward preliminary design of a new and more powerful second stage – Exploration Upper Stage (EUS) – that will use four RL-10 engines for the crewed EM-2 flight.

As shown in Figure 2, NASA plans to incrementally increase SLS performance capabilities through a series of upgrades to its boosters and second stage. The Block 1 configuration will be able to lift 70 metric tons to low Earth orbit and is intended for use only on EM-1. The Block 1B configuration, which the Agency plans to use on EM-2, will utilize the EUS to increase upmass capability to 105 metric tons and have the ability to transport additional payloads, known as co-manifested payloads, in the adapter underneath Orion. The Block 2 upgrade, scheduled to be completed by 2028, will replace the solid rocket boosters with advanced boosters that provide a capability to lift 130 metric tons to low Earth orbit and 41 metric tons to Mars. A more detailed description of the SLS Program is found in Appendix F.

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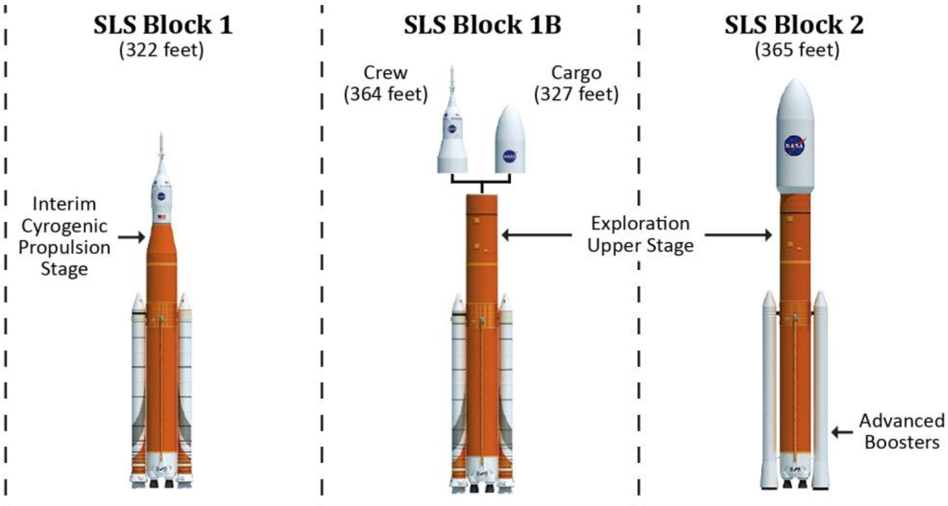
[14] According to NASA Procedural Requirements (NPR) 8705.2B, "Human-Rating Requirements for Space Systems," May 6, 2008, human-rating is the certification granted to crewed space systems prior to the first crewed flight to ensure the system can safely carry astronauts by accommodating human needs, effectively utilizing human capabilities, controlling hazards with sufficient certainty to be considered safe for human operations, and providing the capability to safely recover from emergency situations.

Figure 2: SLS Versions for Journey to Mars Architecture



	SLS Block 1	SLS Block 1B	SLS Block 2
Scheduled completion date	2018	2021 to 2023	no earlier than 2028
Vehicles needed	1	approximately 7	unknown
Upgrades	n/a	Exploration Upper Stage	Advanced Boosters
Cargo payload fairing size (width by height)	n/a	8.4 meters by 27.4 meters	10 meters by 27.4 meters
Co-manifested payload for crew version	n/a	6 to 10 metric tons	10+ metric tons
Upmass to low Earth orbit	70 metric tons	105 metric tons	130 metric tons
Upmass to cislunar orbit	24 metric tons	40 metric tons	52 metric tons
Upmass to Mars	20 metric tons	33 metric tons	41 metric tons

Source: NASA OIG analysis of Agency information.

Orion Multi-Purpose Crew Vehicle

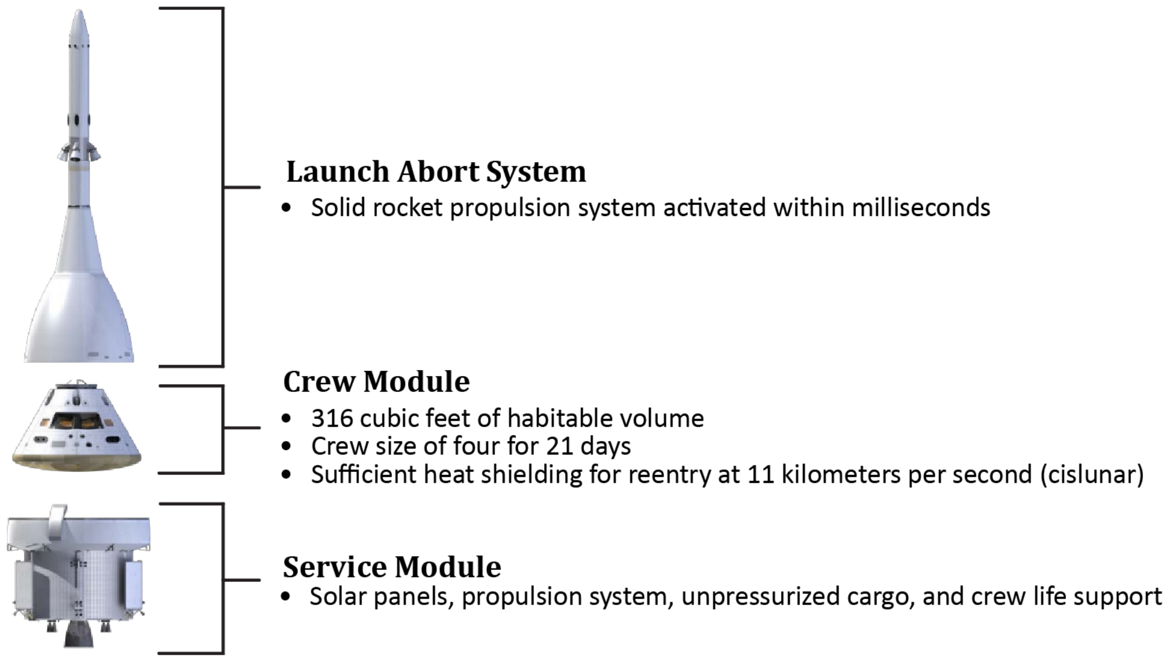
Initiated as part of the Constellation Program for missions to the Moon, Orion is a spacecraft designed for human exploration beyond low Earth orbit and composed of the Launch Abort System; crew module; and service module, which the European Space Agency is supplying for the EM-1 and EM-2 missions.[15] The Launch Abort System sits atop the crew capsule and includes a fairing that covers the crew module during launch. The Launch Abort System can ignite a solid rocket to safely propel the crew module away from the SLS during an emergency either prior to or for several minutes after launch. The current version of the crew module can accommodate up to four astronauts for 21 days in its 316 cubic feet of habitable space – similar in size to a small minivan and thus not suitable on its own for Mars missions, which may last several years in duration. On the underside of the crew module, a heat shield will protect the crew during reentry to Earth.[16] The service module will provide the crew module power using solar panels, life support supplies and in-space propulsion. NASA plans to use the Orion spacecraft

[15] The European Space Agency is building the service module for the first two SLS missions in order to satisfy its share of operating costs for the ISS.

[16] A crew module reentering Earth's atmosphere from a Mars mission is estimated to reach velocities between 11–15 kilometers per second. In comparison, low Earth orbit reentries occur at roughly 7–8 kilometers per second.

as the basic building block for crewed deep space missions in combination with habitation modules or in-space propulsion additions to extend the length of stay or broaden access to Mars or other deep space locations. Figure 3 identifies the key components of the Orion spacecraft. A more detailed description of the Orion Program is found in Appendix F.

Figure 3: Key Components of the Integrated Orion at Launch



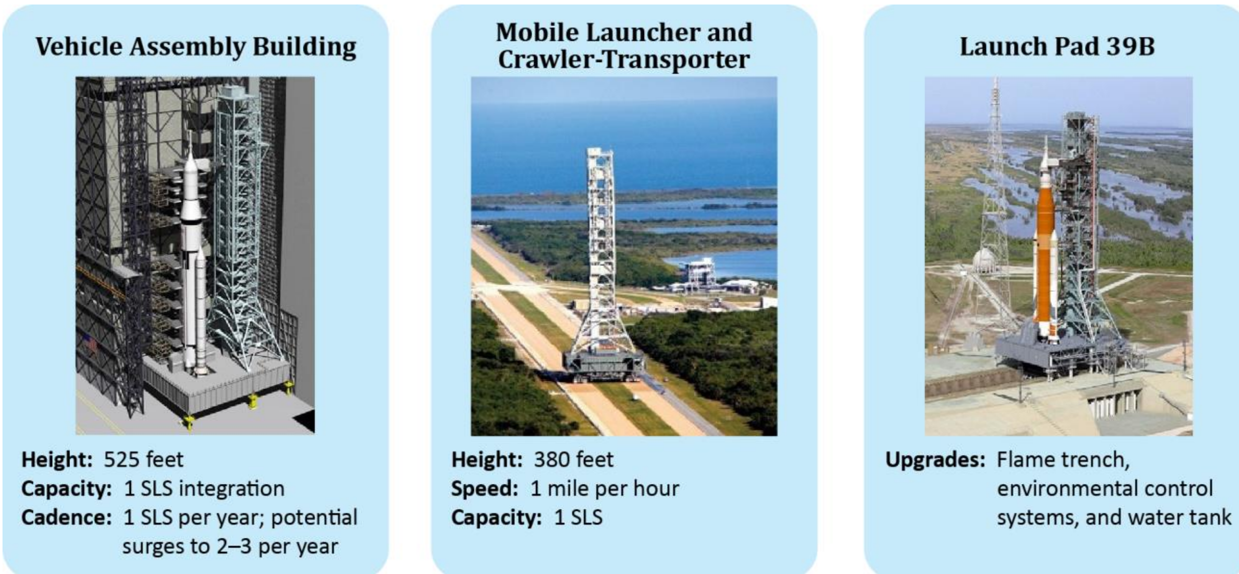
Source: NASA OIG presentation of Agency information.

Ground Systems Development and Operations

All SLS launches will utilize Kennedy Space Center's (Kennedy) processing and launch facilities, which are managed by the GSDO Program. As of March 2017, the GSDO Program was in the process of completing modifications to Kennedy's Vehicle Assembly Building (VAB), Mobile Launcher, Crawler-Transporter, and Launch Pad 39B in preparation for the first integrated SLS/Orion launch in 2018. After the SLS core stage is tested at Stennis Space Center the rocket's two stages, two boosters, and payload will be assembled inside the 525-foot-tall VAB. NASA is also developing computer hardware and software for the Space Command and Control System to control ground launch infrastructure, record launch data, and monitor the vehicle throughout integration and launch.

During the integration process, the SLS will be assembled on the Mobile Launcher, which will provide structural and logistics support up to and during launch. The Mobile Launcher with the attached SLS will then be transported from the VAB to Launch Pad 39B at roughly 1 mile per hour using the Crawler-Transporter. Unlike the Space Shuttle Program, which used two launch pads, Kennedy's ground operations are only capable of integrating, moving, and launching one SLS at a time. However, officials estimate that with significant increases in workforce and resources Kennedy's infrastructure would be capable of up to three launches per year using one Mobile Launcher. Figure 4 shows the key components of the Kennedy vehicle integration and launch infrastructure. A more detailed description of the GSDO Program is also found in Appendix F.

Figure 4: Key Components of Exploration Ground Systems for the Journey to Mars



Source: NASA OIG presentation of Agency information.

Additional Systems Required for the Journey to Mars

NASA's planning and feasibility studies have identified additional systems beyond SLS, Orion, and GSDO that would be required to execute the Journey to Mars. With the exception of the systems associated with the Asteroid Redirect Robotic Mission, for which NASA has approved a baseline mission design, budget, and schedule, these systems are still being conceptualized and have yet to enter official project planning. Table 1 summarizes the key systems and categorizes them by which phase of NASA's plan they are required and need-by dates. See Appendix F for further information on these systems.

Table 1: Additional Systems Required for the Journey to Mars

Additional Key Systems	Description	Need-by Date[a]
Phase 1 (cislunar orbit; early 2020s)		
Asteroid Redirect Robotic Vehicle	The robotic vehicle will demonstrate solar electric propulsion and other systems to land on an asteroid and capture and return a boulder to cislunar orbit.	No earlier than 2021
Asteroid Redirect Crewed Systems	Mission unique systems to support crewed Orion docking with robotic vehicle in cislunar orbit to collect and return asteroid samples to Earth.	No earlier than 2026
Cislunar Habitation Module	The habitat will demonstrate deep space living capabilities through short duration stays in cislunar space.	Early 2020s
Phase 2 (cislunar orbit; mid-2020s)		
In-Space Transportation Architecture	Propulsion systems and demonstrations for transporting human and cargo to and from Mars orbit.	Architecture selection by early 2020s
Long-Duration Deep Space Transit Habitat	Space habitat for humans traveling between Earth and Mars.	Late 2020s
Phase 3 (Mars orbit; late 2020s through early 2030s)		
Mars Orbital Transport Vehicle (Mars Taxi)	Transportation system between long-duration habitat and the Mars' moons or low Mars orbit (may or may not be needed).	Early 2030s
Phase 4 (Mars surface; mid-2030s through late 2030s)		
Mars Lander and Ascent Vehicle	Cargo and crew surface landing systems and ascent propulsion system to reach orbit from the Mars surface.	Early 2030s
Mars Surface Habitat	Surface habitat system for a crew of four with power, rover, and on-site oxygen production.	Mid-2030s

Source: NASA OIG analysis of Agency information.

Note: Additional information for each system can be found in Appendix F.

[a] A need-by date is when NASA needs the system ready for launch or operation.

Developing Capabilities for Needed Systems

To further refine and develop the system architectures required for the Journey to Mars, NASA created the Evolvable Mars Campaign team in 2013.[17] The team identified key systems needed for a flexible approach, conducted feasibility analyses, and developed a set of assumptions and requirements for any Journey to Mars architecture. NASA also formed crosscutting system maturation teams for 15 capability areas, such as in-space propulsion and life support systems, to identify performance gaps. HEOMD is now combining the system maturation teams' analyses to coordinate investment decisions to meet human exploration goals.

[17] This was not NASA's first attempt to develop a system architecture for Mars. Beginning in the 1990s, NASA published a series of studies on potential Mars mission profiles and system architectures. Prior to its current efforts, NASA's most recent Mars architecture was published in 2009. NASA, "Human Exploration of Mars, Design Reference Architecture 5.0" (NASA-SP-2009-566, July 2009).

To spur development of technologies required for future missions, NASA created HEOMD's Advanced Exploration Systems (AES) Division in 2011 and the Space Technology Mission Directorate (STMD) in 2013. The AES Division develops prototypes, demonstrates key capabilities, and validates operational concepts for human exploration missions. Examples of current AES activities include a ground-based demonstration of advanced solar electric propulsion, ground-based prototypes for the cislunar habitat required for Phase 1, and prototypes for advanced spacesuits. Of STMD's nine programs, the Technology Demonstration Missions Program, which tests prototype systems in mission-like environments, and the Game Changing Development Program, which focuses on taking technology from proof of concept testing to component testing in a relevant environment, received more than 50 percent of STMD's $680 million budget in FY 2016. These programs, along with their supporting projects, focus on both science and human exploration technologies, including in-space satellite servicing, solar electric propulsion, nuclear power, robotics for human missions, and propulsive descent systems.

In 2015, STMD and AES divided up technology development activities required for deep space exploration. For example, STMD is focusing on in-space propulsion and landing technologies while AES is examining crew health, habitats, and ascent propulsion technologies. Table 2 summarizes capability areas, the responsible technology program, capabilities identified, status of analysis, and funding status through Phases 1 and 2.

Table 2: Summary of Capabilities Required for the Journey to Mars

Capability or System	Responsible Program	Phase 1 and 2 Current and Projected Funding Status
Communication and Navigation	STMD	Partially funded (optical communication)
Radiation Safety and Crew Health	AES/Human Research Program	Partially funded (radiation forecasting and short-term cislunar stays)
Environmental Control and Life Support	AES	Partially funded (long-duration)
Entry, Descent, and Landing	STMD	Needed in Phase 4; partially funded (human-scale landings)
Exploration Extravehicular Activities (spacewalks)	ISS	Early advanced spacesuit work was conducted in AES; currently not funded (long-duration)
Human/Robotic and Autonomous Operations	AES/ARM/STMD	Partially funded (crew-tended; Earth supervised)
Native Resource Production and Utilization	AES/STMD	Sufficiently funded (exploratory testing planned on robotic Mars and moon missions)
Power and Energy Storage (including Mars surface)	AES/STMD	Partially funded (space solar power and surface power options)
In-Space Propulsion	AES/ARM/STMD	Partially funded
Ascent from Planetary Surfaces	AES	Needed in Phase 3 and 4; not funded (Mars Ascent Vehicle)
Habitation and Mobility	AES	Partially funded (initial short and long-duration)
SLS and Orion Upgrades	ESD	Sufficiently funded (initial capability)
Commercial Cargo and Crew	CCP/ISS	Partially funded

Source: Summary of NASA analysis conducted for STMD briefings.

Note: Asteroid Redirect Mission (ARM), Commercial Crew Program (CCP), and Exploration Systems Development (ESD).

Managing the Integration of NASA's Space Flight Systems

Unlike the Space Shuttle and Constellation programs, which the Agency organized under a single program manager and for which it used a contractor to support integration efforts, NASA established SLS, Orion, and GSDO as three separate programs and created a separate office within HEOMD – Exploration Systems Development (ESD) – to handle integration efforts. Because ESD is not considered a NASA program, it is not required to follow NASA program management policies that call for development of a life-cycle cost estimate, program plan, or schedule.[18] Instead, each program has its own separate performance, cost, and schedule requirements and assists the integration effort by designating staff to serve as systems integrators. Although ESD has a relatively small assigned staff with no prime contractor, it leverages the expertise of approximately 400 personnel across all ESD programs to execute its integration efforts. ESD is responsible for

- managing integrated hazards, cross-program interfaces, integrated risks, top-level integrated schedules, and integrated budgets;
- assuring interfaces across the SLS, Orion, and GSDO programs are properly defined, implemented, and resolved for the best overall system solution;
- ensuring cross-program integration issues are worked in a timely manner and supported by the SLS, Orion, and GSDO programs; and
- leading integrated system trade studies as needed to address technical/programmatic issues.

According to NASA officials, structuring the three programs and ESD in this manner eliminated the cost of setting up a traditional program management office and hiring a support contractor to execute integration. It also allowed each program to proceed along its own developmental timeline.

Cost of Human Exploration Beyond Low Earth Orbit

NASA has already made a substantial investment in developing space flight systems needed for human exploration beyond low Earth orbit. Since FY 2012, the Agency has spent more than $15.6 billion on the SLS, Orion, and GSDO programs and ESD integration activities for EM-1 and EM-2. In addition, NASA spent $5.7 billion between FYs 2006 and 2011 on Orion development as part of the Constellation Program, $1.8 billion in 2011 to fund the transition from Constellation to SLS and GSDO, and $2.8 billion on technology development related to human and robotic space flight between FYs 2012 and 2016, making the Agency's total investment approximately $26 billion as of October 2016.[19]

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[18] According to NPR 7120.5E, "NASA Space Flight Program and Project Management Requirements," August 14, 2012, a life-cycle cost estimate is the total of the direct, indirect, recurring, nonrecurring, and other related expenses both incurred and estimated to be incurred in the design, development, verification, production, launch/deployment, prime mission operation, maintenance, support, and disposal of a program or project, including closeout but not extended operations. The life-cycle cost estimate of a program or project can also be viewed as the total cost of ownership over the program or project's planned life cycle from Formulation through Implementation.

[19] As discussed previously, the AES and STMD groups fund technology activities to develop key system capabilities for the Journey to Mars. For the past 5 years, AES has spent a total of $745 million developing human exploration technologies and capabilities. Likewise, STMD has spent $2 billion over the past 5 years developing broader technologies such as solar electric propulsion that will support a crewed Mars mission.

In addition to development of the SLS, Orion, and GSDO systems, NASA initiated the Asteroid Redirect Robotic Mission as an early proving ground mission to demonstrate solar electrical propulsion capabilities and other systems integral to the Journey to Mars. Although NASA has expended less than $23 million on this Mission since inception, significantly increased funding will be required in the coming years as development efforts mature. Table 3 shows the expenditures for each of these activities from FYs 2012 through 2016.

Table 3: NASA Costs of Systems that Support the Journey to Mars

Mars Systems	FY 2012[a]	FY 2013	FY 2014	FY 2015	FY 2016	Total
SLS	$792,745,524	$1,608,228,490	$1,832,891,618	$1,773,662,418	$1,872,278,727	**$7,879,806,777**
Orion	1,268,539,812	1,117,974,667	1,047,343,380	1,334,495,681	1,354,484,002	**6,122,837,542**
GSDO[b]	174,700,735	294,771,515	349,472,259	376,754,352	388,064,280	**1,583,763,141**
AES	119,052,977	150,316,635	152,829,738	157,804,144	165,356,375	**745,359,869**
ARRM[c]	0	0	0	3,030,841	19,687,856	**22,718,697**
STMD[d]	373,900,000	420,300,000	370,400,000	378,300,000	448,158,000	**1,991,058,000**
Total	**$2,728,939,048**	**$3,591,591,307**	**$3,752,936,995**	**$4,024,047,436**	**$4,248,029,240**	**$18,345,544,026**

Source: NASA OIG analysis of Agency cost and obligation data.

Note: Cost data provided by NASA program analysts, which the NASA OIG verified through NASA's accounting system. This table shows expended costs, which represents actual work performed. Construction of facilities funds and expired funds from FYs 2012 through 2016 are not included.

[a] We determined that prior to FY 2012, the SLS, Orion, and GSDO programs received appropriations from Congress; however, according to NASA officials, the programs were not formally established for accounting purposes until 2012.

[b] GSDO costs do not include any of the costs for the 21st Century Launch Complex. The 21st Century Launch Complex Initiative was established by Congress in FY 2011 to modernize the Florida launch and range complex at Kennedy, Cape Canaveral Air Force Station, and Virgina's Wallops Flight Facility infrastructure to enable NASA's launch facilities to support multiple users. However, a portion of these funds will benefit SLS and Orion, including refurbishment of the Multi-Payload Processing Facility to support Orion processing and modernization of the Cape Canaveral Air Force Station range. Funding for this initiative concludes at the end of FY 2017.

[c] For budgeting purposes, the Asteroid Redirect Robotic Mission's (ARRM) funding is included within the AES budget.

[d] STMD costs only include the Space Technology Research and Development Program, which includes Technology Demonstration Missions and Game Changing Development projects. These projects generally have more advanced technology development and larger annual budgets. Within these projects, STMD conducts technology research aimed at benefiting future science and human exploration missions.

Status of Journey to Mars Cost and Schedule Estimates

NASA policy requires space programs to create life-cycle cost and schedule estimates as a management tool and to provide transparency to Congress and other stakeholders. These estimates are formally approved in a Management Agreement and an Agency Baseline Commitment created at Key Decision Point C – the point at which a program or project receives management approval to proceed into final design and production. NASA completed these commitments and agreements for the SLS and GSDO programs in 2014 and for Orion in 2015.

A Management Agreement is a formal internal agreement between an Associate Administrator and a program manager about the cost and schedule necessary to meet a specific commitment. An Agency Baseline Commitment is a formal external commitment between the Agency and Congress for a program's launch readiness date and life-cycle cost estimates. NASA is required by law to notify Congress if a program's development costs are likely to exceed 15 percent of the total estimate or be delayed 6 months beyond the Agency Baseline Commitment agreement.[20] Further, if development budget increases exceed 30 percent, NASA may not spend any additional money beyond 18 months after notifying Congress unless the program is subsequently authorized by law and the Agency provides a new baseline commitment. NASA uses the internal Management Agreement and external Agency Baseline Commitment to measure the performance of its programs. For multi-decade programs like human exploration of Mars, NASA policy allows programs to limit the scope of life-cycle estimates to short-term measurable activities.

SLS and GSDO have approved life-cycle cost and schedule estimates through EM-1, but not for EM-2. In contrast, Orion's life-cycle cost and schedule estimates are established through EM-2.[21] Although all three programs are working toward launch dates in 2021, NASA has not set a unified integrated schedule for EM-2.

Agency officials have indicated the Journey to Mars is supportable using HEOMD's current budget profile with yearly increases for inflation (estimated at 2.4 percent annually) and economic growth (2.45 percent annually). Based on the Agency's assumptions under these growth scenarios, HEOMD's budget would increase from $9 billion in 2016 to $32 billion in 2046.[22] Even though NASA officials stated this level of funding could support the Journey to Mars, they have not included a cost analysis in their architecture or feasibility studies, noting that cost analyses for a 30-year program are of limited value because of likely changes in policy, funding, or technologies. Moreover, over the last 25 years, NASA's budget has increased on average of only 1.6 percent per year.

Several organizations outside HEOMD have examined the potential costs of human exploration of Mars using varied architectures and assumptions. In 2014, the National Research Council used NASA's design reference architecture from 2009 and estimated a Mars mission could cost between $300 and $600 billion depending on the specific mission scenarios.[23] The Council found the continuation of flat budgets for human exploration was insufficient for NASA to execute any pathway to Mars and recommended the Agency seek out international partnerships to help cover costs. More recently, NASA's Jet Propulsion Laboratory (JPL) conducted a feasibility study using current technologies and a limited number of systems to model a crewed landing on the Martian moon Phobos in 2033, a 1-month Mars surface stay in 2037, and 1-year surface stays in 2041 and 2046.[24] The study determined a human

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[20] 51 U.S.C. § 30104, "Baselines and Cost Controls" (2010).

[21] In September 2015, NASA established an Orion Program Agency Baseline Commitment launch readiness date for EM-2 of April 2023. However, the Orion Program is managing to the 2021 date specified in the Management Agreement.

[22] While NASA cited these factors as assumptions for future funding levels, the Agency did not provide detailed calculations. Therefore, we conducted our own analysis based on HEOMD's annual budget of roughly $9 billion in FY 2016. For FYs 2016 through 2022, we used HEOMD's current budget assumptions. For FYs 2023 through 2046, we applied an inflation rate of approximately 2.4 percent annually. Economic growth is the percentage increase in the market value of goods and services (known as the Gross Domestic Product) over time. The U.S. Department of Commerce maintains a record of the Gross Domestic Product annually since 1930. Based on this data, we determined the average economic growth over the last 25 years at 2.45 percent annually, which was applied in our estimates for FYs 2023 through 2046.

[23] National Research Council, "Pathways to Exploration: Rationales and Approaches for a U.S. Program of Human Space Exploration," 2014.

[24] NASA, "Human Journey to Mars: Thoughts on an Executable Program," 2015, updated 2016.

Mars exploration program could be feasible over this time period with NASA's current budget adjusted for inflation. According to the study, to meet this budget profile NASA would need to adopt a simplified approach that limits the number and types of systems used and increases investments for key systems like deep space habitats and in-space transportation during the 2020s.[25] In 2016, NASA's Office of the Chief Financial Officer (OCFO) conducted a high-level cost and schedule feasibility study using two austere Mars architecture studies with assumptions that differ from HEOMD's current Journey to Mars plan.[26] This analysis highlighted the potential impact on future human exploration programs of continued funding of ISS operations beyond the current commitment of 2024.[27]

[25] For the JPL study, the habitat and in-space transportation systems are critical for traveling to deep space and Mars. Generally, the development of a new system can take up to 10 years. If NASA initiates development on these systems early, then other critical systems can be developed such as descent and ascent vehicles and surface habitats.

[26] NASA, "Human Mars Exploration Architecture Analysis," 2015. In contrast to the current Journey to Mars framework, this study utilized previous academic and NASA studies to create an initial concept review of a lower-risk and budget-constrained Mars architecture that does not rely on high-risk, high-cost technology development like nuclear thermal propulsion or Mars surface resource production.

[27] NASA expects to spend between $3 and $4 billion annually on ISS operations and sustainment through 2024 – money that could be redirected toward other NASA programs, including human space flight beyond low Earth orbit, were the ISS retired on its current schedule.

CHALLENGES WITH NASA'S NEAR-TERM MISSIONS ILLUSTRATE DIFFICULTY OF DEEP SPACE EXPLORATION

NASA's first exploration missions – EM-1 and EM-2 – face multiple technical challenges that will likely delay their launch. Moreover, although the Agency's combined investment for development of its deep space missions' three main systems (SLS, Orion, and GSDO) will reach approximately $23 billion by the end of FY 2018, the programs' average monetary reserves leading up to EM-1 are much lower than the 10 to 30 percent recommended in guidance issued by Marshall Space Flight Center (Marshall).[28] Low reserves limit the programs' flexibility to cover any increased costs or delays resulting from unexpected design complexity, incomplete requirements, or technology uncertainties. In addition, software development and verification efforts for all three programs are behind schedule to meet EM-1 requirements, and NASA did not develop a life-cycle cost estimate or integrated schedule for EM-2, which makes it more difficult for Agency officials and external stakeholders to understand the mission's full cost and gauge the validity of launch date assumptions. Finally, NASA officials cite challenges related to operating in an environment in which annual budgets are rarely enacted on time and the Agency routinely functions under continuing resolutions that fund programs at previous-year levels for large portions of the fiscal year, hindering managers' ability to make informed and timely decisions about funding allocations.

Three Separate Programs with Similar Challenges

The SLS, Orion, and GSDO programs are attempting to overcome various technical challenges as they work toward EM-1 and EM-2 launches. In addition, NASA faces coordination challenges in ensuring adequate time for testing and integration of the combined systems, as well as concerns as to whether funding reserves for the individual programs will be adequate to meet anticipated launch schedules.

[28] The costs are for development of the systems and do not include integration and support costs. NASA Special Publication-2014-3705, "NASA Space Flight Program and Project Management Handbook," September 2014, refers to program reserves as Unallocated Future Expenses and states that any reductions to these projected expenses will reduce the ability of the project to achieve its cost and schedule targets. Marshall Procedural Requirements (MPR) 7120.1, "MSFC Engineering and Program/Project Management Requirements," October 20, 2016, provides guidance on standard cost and schedule margins for launch vehicle programs and projects.

Space Launch System Program

EM-1 Challenges

The SLS Program has faced several technical challenges leading up to the EM-1 launch that have eaten into its schedule margin. As a result, the time period for conducting "green-run" testing for the rocket's core stage and for correcting any deficiencies prior to shipment to Kennedy for integration with Orion has been compressed. During the green-run test the core stage with its four RS-25 engines will be mounted on a test stand and fired to simulate an actual launch. The test is designed to check the combined system's compatibility and functionality and will be the only time the engines are test fired as an integrated group.[29] Stennis Space Center (Stennis) is responsible for conducting individual RS-25 engine tests, as well as the integrated core stage green-run test.

Stennis B-2 Test Stand during Construction as of October 2016

Source: NASA.

The green-run test is scheduled to begin in October 2017, and Stennis officials said they have sufficient time to complete it; however, correcting any significant deficiencies found during testing would impact the SLS Program's overall schedule. Even though the SLS Program initially built in a schedule margin of 11 months to allow time to address any unexpected technical issues or other factors, early delays caused in part by repairs on the welding tower at NASA's Michoud Assembly Facility reduced this margin to almost zero. However, according to an SLS Program replan completed in August 2016, the shipment date for the core stage from Stennis to Kennedy has shifted from January or February of 2018 to March or April of 2018. Although this added 30 days of schedule margin for the SLS Program to deliver the core stage, it decreased the time GSDO will have to integrate the various components and process the rocket system for flight. Moreover, despite this adjustment, two issues with the core stage being built at Michoud may further delay delivery to Stennis and Kennedy: SLS Program officials are still evaluating an anomaly found in the welding on a test article and damage from a February 2017 tornado is expected to cause at least a 2-month delay.

While the SLS Program has made progress in resolving technical issues and maturing the rocket's design, the upcoming integration and test phase is historically when problems are discovered. With only 30 days of schedule reserves available, the SLS Program may be hard pressed to meet a November 2018 launch date. According to Marshall guidance, the SLS Program should have a minimum of 60 days of reserve between now and the launch – 30 days each for 2017 and 2018.[30]

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[29] In the rocket industry, engines are routinely tested multiple times before launch. However, because these engines were previously tested and/or flown under the Space Shuttle Program, NASA considers them to be a low risk for failure and therefore requires less testing. In addition, the Agency is performing tests on other RS-25 engines as well.

[30] MPR 7120.1.

EM-2 Technical Challenges

As NASA works towards the EM-2 flight, it will need to make a major change in the SLS configuration by utilizing the EUS as the new upper stage. For EM-1 the SLS's upper stage will be the Interim Cryogenic Propulsion Stage, a liquid oxygen/liquid hydrogen-based system with a single RL-10 engine, which will be capable of transporting 70 metric tons. In contrast, the EUS uses four RL-10 engines and will be capable of transporting 35 more metric tons than the Interim Cryogenic Propulsion Stage.

Program Funding and Monetary Reserves

The NASA Authorization Act of 2010 required the NASA Administrator to provide a detailed report to Congress regarding the SLS and Orion programs. In NASA's 2011 report, the Agency estimated the costs of developing the SLS through EM-1 at $9.5 billion.[31] Although NASA's current development costs for EM-1 of $9.7 billion closely match both the 2011 estimate and its 2014 Agency Baseline Commitment, the SLS Program has minimal monetary reserves to address any technical challenges that may arise for either the EM-1 or EM-2 missions. Thus, NASA may exceed the commitment to spend $9.7 billion if the launch schedule slips beyond 2018. According to guidance developed at Marshall, the standard monetary reserve for a program such as the SLS should be between 10 and 30 percent during development.[32] The SLS Program did not carry any program reserves in FY 2015 and only $25 million in FY 2016 – approximately 1 percent of its development budget. Moving forward, the SLS Program plans to carry only minimal reserves through 2030, which in our view is unlikely to be sufficient to allow NASA to address any issues that may arise during development and testing. See Appendix G for the life-cycle costs compared to expected appropriations.

Orion Program

EM-1 Challenges

NASA considers Orion to be one of the biggest challenges to meeting the EM-1 flight date of no later than November 2018. As we reported in September 2016, the Orion service module has undergone design changes and as a result will be delivered to NASA at least 5 months, but possibly up to 10 months, later than planned.[33] Because the new Orion service module differs from the module flown during the first Orion test flight in December 2014, assembly, integration, and processing of the new module may delay the transfer of Orion to the GSDO Program for integration with the SLS. NASA is also making changes to address Orion systems for which a single failure could be catastrophic. For example, if any of the valves in the propellant storage tank were to develop a leak, all of the fuel would eventually leak out of the system. In addition, NASA considers the Orion heat shield, which developed cracks and showed reduced material strength after the first test flight, to be one of the highest technical risks for the Orion Program. Following the test flight, NASA made design changes to the shield to address these issues.

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[31] NASA, "Final Report regarding NASA's Space Launch System and Multi-Purpose Crew Vehicle, Pursuant to Section 309 of the NASA Authorization Act of 2010 (P.L. 111-267)," December 22, 2011. The report described the progress made to date on the SLS and Orion Programs and outlined the work remaining and included cost estimates for the SLS, Orion, and supporting ground systems for the first uncrewed test flight to be achieved by December 2017.

[32] MPR 7120.1.

[33] NASA OIG, "NASA's Management of the Orion Multi-Purpose Crew Vehicle Program" (IG-16-029, September 6, 2016).

EM-2 Challenges

One of the key challenges NASA faces is ensuring the Orion capsule's Environmental Control and Life Support System properly functions. NASA is testing portions of this critical life support system on the ISS and in facilities on Earth, and will fly some parts of the system on EM-1. Accordingly, the first flight test of the complete Environmental Control and Life Support System will be during EM-2 with crew aboard. The Aerospace Safety Advisory Panel, an advisory committee that reports to NASA and Congress on safety issues, expressed concern in its 2015 and 2016 annual reports about the lack of flight testing before EM-2, arguing there is a strong case for the mission to remain in low Earth orbit until NASA has gained more confidence the life support systems are performing properly.[34] In response, NASA selected a mission that allowed for its first 24 hours in an elliptical high Earth orbit to check the Environmental Control and Life Support System and other systems.

Program Funding and Monetary Reserves

Based upon NASA's current life-cycle cost estimates, officials expect to have sufficient funding for both EM-1 and EM-2 as long as Congress funds the Orion Program at expected levels and there are no delays in schedule or changes in requirements. See Appendix G for the life-cycle costs compared to expected appropriations. Although Orion Program costs will likely exceed the Agency's 2011 estimate of $5.7 billion by $2.7 billion, for a total expected cost of $8.4 billion through the 2018, according to NASA officials, much of this cost includes preparation for EM-2 and subsequent missions which were not included in the original estimate. In addition, Orion's current projected appropriations through EM-2 is $12.3 billion, approximately $1 billion more than Orion's Agency Baseline Commitment of $11.3 billion. According to NASA officials, this increase is mostly attributable to costs for post EM-2 missions.

Like SLS, the Orion Program has less than 1 percent in monetary reserves leading up to EM-1, much less than the recommended 10 to 30 percent.[35] In addition, in our September 2016 Orion report we found the Orion Program's prime contractor, Lockheed Martin, was expending its management reserve funds at a higher rate than both the Program and the company expected. We concluded Lockheed Martin would deplete its reserves by November 2017 – approximately 12 months prior to the planned launch of EM-1 – if it continued to draw from the reserve at a rate similar to the rate it was drawing between July 2014 and February 2016. However, Orion Program officials believe it is unlikely Lockheed will continue to draw at the higher rate and that current reserves will be sufficient. Moreover, NASA expects to increase Orion's reserves for EM-2 to a more appropriate level beginning in 2019 and 2020.

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[34] Aerospace Safety Advisory Panel, "Annual Report for 2015," January 13, 2016, and "Annual Report for 2016," January 11, 2017. The Aerospace Safety Advisory Panel was established in 1968 as an independent senior advisory committee that evaluates and advises the Agency on ways to improve its safety performance.

[35] MPR 7120.1.

Ground Systems Development and Operations Program

EM-1 Challenges

NASA has identified modifications to the VAB and mobile launcher needed to support the SLS as high risks to the GSDO Program. Delays in addressing these issues have left GSDO with only 1 month of schedule margin to deal with any further issues that arise.

Kennedy Space Center Vehicle Assembly Building

Source: NASA.

GAO also reported that required modifications for the VAB include removing about 150 miles of Apollo era cabling, improving the elevators, upgrading cranes, and incorporating fire safety improvements. The most significant project is installation of 10 new platforms that will allow access to the integrated SLS/Orion systems during final assembly.[36] Complications with platform design and installation have exhausted the project's schedule margin; however, the platform installation task was completed in February 2017 and no additional delays are anticipated.

In addition, changes to SLS and Orion requirements caused GSDO to make modifications to the mobile launcher, leaving no flexibility in the schedule. GSDO's original requirement included design and installation of ten umbilical arms attached to the launcher to link the SLS rocket to electrical power, fuel, and data connections. However, according to a July 2016 GAO report, ground support equipment and umbilical design changes resulted in GSDO using nearly 22 percent of its schedule margin.[37] For example, because of contractor performance problems, NASA descoped a fabrication contract, which caused a 5-month delay in delivery of the umbilicals. NASA officials told us that testing of the umbilical system was a high concern for the GSDO Program because the umbilicals need to be attached to the mobile launcher before integrated testing at Launch Pad 39B can be completed. Nevertheless, NASA officials told us they are on schedule to deliver the mobile launcher to the VAB by July 2017, with GSDO hardware integration and testing scheduled to be completed by February 2018 – approximately 1 month before the expected arrival of the SLS core stage.

EM-2 Challenges

After EM-1 is completed, GSDO will need to make additional modifications to Kennedy's launch infrastructure to prepare for EM-2. The height and weight of the SLS will increase with the addition of the EUS, so changes to the VAB and mobile launcher will be necessary. In addition, a new tank will need to be fabricated and installed at Launch Pad 39B to provide the additional fuel the EUS requires.

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[36] GAO, "NASA Human Space Exploration: Opportunity Nears to Reassess Launch Vehicle and Ground Systems Cost and Schedule" (GAO-16-612, July 27, 2016).

[37] GAO-16-612.

Program Funding and Monetary Reserves

The GSDO Program will likely exceed NASA's 2011 estimate of $2.4 billion for EM-1 by $400 million, for a total expected cost of $2.8 billion.[38] Nevertheless, based on NASA's current life-cycle cost estimate, and assuming the GSDO Program receives its expected appropriations, it will have sufficient funding for EM-1. However, the Program has identified a budget shortfall associated with the EUS upgrades leading up to EM-2. The Program is also carrying monetary reserves of only 3 percent of its FY 2016 budget. See Appendix G for the life-cycle costs compared to expected appropriations.

Space Flight System Software is Behind Schedule and May Affect the EM-1 Launch Date

We are concerned NASA will not be able to resolve all necessary ESD software validation and verification efforts in time to meet a November 2018 launch date for EM-1. Final software verification has been delayed approximately 1 year due to late development of operational requirements for the SLS, Orion, and GSDO programs. Specifically, NASA officials told us that late subsystem CDRs – including for the avionics and the Orion's service module, which were completed in the spring and summer of 2016, respectively – have resulted in a compressed time schedule to test and resolve software issues prior to EM-1. As a result, the Agency anticipates only 3 months between Orion's final software verification and the flight readiness date of September 2018 when fully operational and tested software is required.[39] The planned and adjusted software verification completion dates and the cause for the delays are identified in Table 4.

Table 4: Summary of the Software Verification Schedule Adjustments

Software Development Effort	Planned Date for Software Verification Complete	Current Date for Software Verification Complete	Cause of Delay
SLS	January 2018	June 2018	• Purposely deferred start of comprehensive testing to December 2017 in order to allow incremental software releases to go forward and to allow requirements and testing equipment to mature.
Orion	March 2017	June 2018	• Requirements still maturing, especially those that depend on avionics hardware. • Limited flight computer processing power required adjustments in software to conform to the hardware limitations.
GSDO	September 2017	May 2018	• Delays in requirements-related information from the SLS and Orion programs, and the additional time needed to work on software modifications to conform to the new mobile launcher umbilicals.

Source: NASA OIG analysis of Agency information.

[38] NASA, "Final Report Regarding NASA's Space Launch System and Multi-Purpose Crew Vehicle, Pursuant to Section 309 of the NASA Authorization Act of 2010 (P.L. 111-267)," December 22, 2011. At the time of the 2011 report, GSDO was referred to as the 21st Century Ground Support Program.

[39] In comparison, NASA generally had 9 months to test Space Shuttle flight software.

NASA's Integration Plans for EM-2 are Incomplete

NASA does not have an integrated schedule for EM-2. In addition, because the Agency limited its program commitment for the SLS and GSDO programs to development costs through EM-1 and excluded integration activities from its commitments for all three programs, the Agency's associated life-cycle costs do not capture the full cost of the SLS, Orion, and GSDO programs. Without this information, it is more difficult for Agency officials and external stakeholders to understand the full costs of EM-2 or gauge the validity of NASA's launch date assumptions.

NASA Only Recently Began Developing an Integrated Schedule for EM-2

The main focus of ESD's efforts has been EM-1 and the Agency only began developing an integrated schedule for the EM-2 mission in 2016. ESD plans to finalize an initial baseline draft for the EM-2 integrated schedule in summer 2017.

After completion of the SLS CDR in 2015, Congress directed NASA to use the upgraded SLS Block 1B for EM-2 instead of again using EM-1's second stage design. This forced the SLS and GSDO programs to make significant design changes related to the EUS and adapter that connects the SLS's second stage to the Orion. As a result, GSDO is scheduled to complete a supplemental design review (Delta CDR) in May 2018 and a similar SLS review a year later in May 2019. However, because GSDO's design is dependent on stable requirements and mature designs from the SLS and Orion programs, completing GSDO's supplemental review a year before the SLS review increases the risk the GSDO Program will conduct work on facilities that may not meet SLS requirements – an outcome that could require costly redesign. We raised similar concerns about the alignment of the SLS, Orion, and GSDO program design reviews in a 2015 OIG report when we noted the original CDR for GSDO was scheduled several months before the SLS CDR.[40] As a result, NASA changed the dates to have the SLS CDR precede the GSDO review by several months in 2015. With regard to current circumstances, NASA officials explained that the completion of the EUS's early design review at a high level of technical maturity, and its interface with the SLS core stage design, can help mitigate the risks for EUS upgrades.

Agency Commitments Do Not Capture All Space Launch System, Orion, and Ground Systems Development and Operations Program Costs

According to NASA policy, programs are required to develop life-cycle cost and schedule estimates that culminate in an internal Management Agreement and an external Agency Baseline Commitment that set the total cost and completion date for a program.[41] Both internal and external program commitments are approved by an Associate Administrator, reviewed by an independent Standing Review Board, and monitored by NASA's OCFO. For the SLS and GSDO programs, NASA limited the scope of its

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[40] NASA OIG, "NASA's Launch Support and Infrastructure Modernization: Assessment of the Ground Systems Needed to Launch SLS and Orion" (IG-15-012, March 18, 2015).

[41] These requirements are further defined through the NASA Space Flight Program and Project Management Handbook.

commitments to development costs through EM-1 – a scope that does not include ESD integration activities or any Block 1B development costs for EM-2 or later missions. For the Orion Program, the internal and external agreements include costs through the EM-2 mission but not ESD integration activity costs.

These scope limitations and a summary of the various external and internal program management agreements related to the SLS, Orion, and GSDO programs are depicted in Table 5. As the table shows, for the SLS Program, the internal Management Agreement reflects a cost of $9.3 billion and a launch readiness date of September 2018 for EM-1 and NASA's Agency Baseline Commitment reflects a cost not to exceed $9.7 billion and a launch readiness date of November 2018. There are no EM-2 commitments for SLS or GSDO, nor has the Agency prepared life-cycle cost estimates.

Table 5: External and Internal Program Management Estimates For Cost and Schedule

		EM-1		EM-2		Beyond EM-2	
Program Agreements		Estimated Life Cycle Costs	Launch Readiness Date	Estimated Life Cycle Costs	Launch Readiness Date	Estimated Life Cycle Costs	Launch Readiness Date
SLS	Internal[a]	$9.3 billion	September 2018	Outside the scope of Agency Baseline Commitment[b]			
	External	$9.7 billion	November 2018				
Orion	Internal	No separate metrics; part of EM-2 program agreement		$10.8 billion	August 2021	Outside the scope of Agency Baseline Commitment[b]	
	External			$11.3 billion	April 2023		
GSDO	Internal[a]	$2.7 billion	September 2018	Outside the scope of Agency Baseline Commitment[b]			
	External	$2.8 billion	November 2018				

Source: NASA OIG summary of Key Decision Point C memorandums and the August 24, 2016, update to Management Agreements.

[a] For SLS and GSDO, the estimated life cycle costs and launch readiness dates reflect updated internal agreements. Originally, SLS had an estimated cost of $8.4 billion and a launch readiness date of December 2017 and GSDO was working toward an estimated cost of $2.6 billion and a launch readiness date of June 2018.

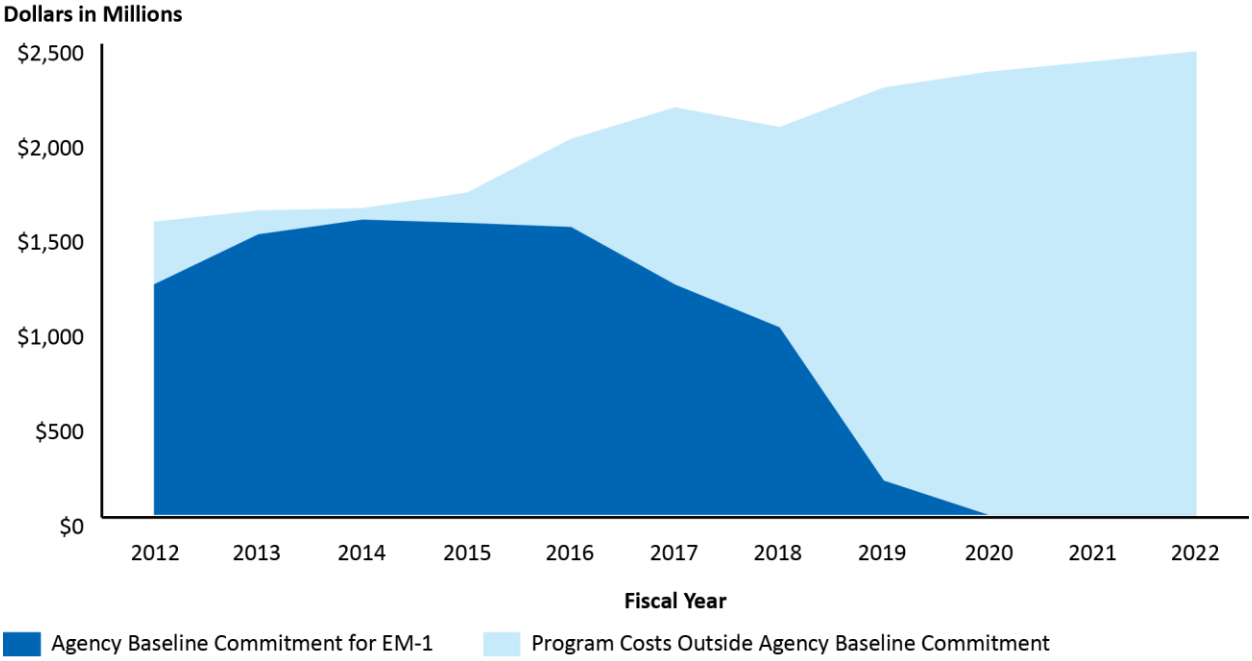
[b] Activities that are outside program management scope are not part of a program's internal Management Agreement with NASA officials or the external Agency Baseline Commitment to Congress and outside stakeholders. Cost spent on those activities are not included in the estimated life-cycle costs or measured against the launch readiness dates.

NASA plans to spend more than $17 billion through FY 2022 on activities that are outside the official cost estimates in the Agency Baseline Commitments.[42] Although the Agency plans to monitor this spending through its annual budget process, that process does not set total life-cycle costs, identify estimated costs on a per-mission basis, or create launch date deadlines.

With respect to SLS, from FYs 2012 through 2016 the Program spent more than $1 billion on activities within its budget authority but outside the scope of the current Agency Baseline Commitment for the EM-1 launch. In FY 2016 alone, the SLS Program spent roughly $460 million beyond program commitments for the ESD integration efforts, the development and fabrication of an SLS core stage and the new upper stage for EM-2, production restart of the RS-25 engine, and other activities. A comparison of total program spending and Agency Baseline Commitment spending is shown in Figure 5.

[42] Using NASA's budget assumptions for FY 2017 through FY 2022, more than 65 percent of SLS, Orion, and GSDO program funding will be spent outside life-cycle costs set by Agency Baseline Commitments.

Figure 5: SLS Spending Outside the Scope of the Agency Baseline Commitment



Source: NASA OIG analysis of Agency cost updates through FY 2016 and budget assumptions through FY 2022.

Note: From FYs 2020 through 2022, roughly $1 billion of the SLS budget assumptions are designated to fund yet-to-be-determined Journey to Mars activities. HEOMD officials said they plan to keep SLS launch vehicle development and integration costs close to $2 billion a year through FY 2022.

NASA officials said they have no plans to revise the current Agency Baseline Commitments for the SLS Program to include these additional activities, nor do they intend to create official program commitments for each SLS mission or launch activity beyond EM-1.[43] According to these officials, this approach reflects the difficulty of estimating a full life-cycle cost for a long-term human exploration program that is likely to last for multiple decades.[44] NASA officials also stressed that ongoing budget uncertainties and the addition of the EUS to EM-2 mission requirements have impacted HEOMD's ability to create consistent cost and schedule estimates.

Although we agree it is impractical to project life-cycle costs through the 2030s and 2040s, NASA's goal is to launch EM-2 as early as 2021 – less than 5 years from now – and the Agency is spending a significant amount of money on this mission with no Agency commitment or life-cycle cost estimate for the SLS or GSDO programs. Without this basic program information, it is difficult for both Agency officials and external stakeholders to gain a full understanding of the true costs of EM-2 or to judge the validity of the Agency's launch date assumptions.[45]

[43] NASA plans to conduct CDRs for each new element, such as the EUS upgrade for the SLS Block 1B, but these reviews will not include development of an official agency commitment.

[44] At the initiation of a project or program, NASA policy allows extended operations, such as any potential continuation of a satellite operation beyond the expected mission timeframe, to be excluded from life-cycle cost estimates. Past human exploration programs, like the Space Shuttle and ISS programs, are examples of long-duration programs that have extended operations beyond an initial mission.

[45] As GAO noted in a 2014 report, NASA's lack of understanding of actual costs contributed to delays in and later cancellation of the Constellation Program. GAO, "NASA: Actions Needed to Improve Transparency and Assess Long-Term Affordability of Human Exploration Programs" (GAO-14-385, May 2014).

Feasibility Study of Crewed Flight on EM-1

In February 2017, the acting NASA Administrator directed HEOMD to study the feasibility of adding crew to the EM-1 launch. A week later, the Associate Administrator for HEOMD published a memorandum that established the study group and outlined its scope to include reviews of technical feasibility, additional work required, risks, benefits, resources needed, and associated schedule impacts. According to the memorandum, the ground rules and assumptions for the study are as follows:

- The study should not impact any current planning or work for EM-1 and EM-2.
- The target launch date is mid-2019.
- An EM-1 crew of at least two.
- EM-1 would adopt the current EM-2 mission profile of 8 days.
- The use of the current EM-1 upper stage (Interim Cryogenic Propulsion Stage) will be compared to accelerating the EUS for EM-1.

As of early April 2017, the study was ongoing. To achieve a crewed EM-1 flight, in our judgment NASA must address not only the additional risks associated with human travel but also a host of existing risks to planned missions. For example, as noted earlier in this report, NASA is working to mitigate risks relating to the Orion's environmental control system and to the EUS for the current EM-2 flight profile scheduled to launch no earlier than 2021 and more likely in 2023. Even if NASA does not use the EUS on an accelerated EM-1 crewed flight, the Interim Cryogenic Propulsion Stage will need to be certified to carry astronauts, and significantly the integrated SLS/Orion system, Orion's heat shield, and ESD software will not undergo a test flight before astronauts are placed on board.

Nominees for NASA Administrator or Deputy Administrator had not been announced as of early April 2017, and it remains unclear who at NASA or in the Administration will review the results of the study and decide whether to move forward under a new plan or stick to the Agency's previously announced schedule of an uncrewed Orion/SLS mission in 2018 followed by the first crewed flight of the space system sometime between 2021 and 2023. As part of the decision making process, several NASA-related groups – perhaps most prominently the Aerospace Safety Advisory Panel – will likely offer their perspectives to the decision makers once the feasibility study is completed.

NASA Challenged to Develop Realistic Cost and Schedule Estimates for Mars Missions Beyond EM-2

Understandably, NASA's plans beyond EM-2 for achieving a crewed Mars surface mission in the late 2030s or early 2040s remain high level, serving as more of a strategic framework than a detailed operational plan. For example, the Agency's current Journey to Mars framework lacks objectives for Phases 3 and 4; does not identify key system requirements other than SLS, Orion, and GSDO; and does not suggest target mission dates for crewed orbits of Mars or planet surface landings. If the Agency is to reach its goal of sending humans to the vicinity of Mars in the 2030s, significant development work on key systems must be accomplished in the 2020s, and the Agency will need to make these and many other decisions in the next 5 years or so for that to happen. In addition, to position itself to make wise investments in such key systems as a deep space habitat, in-space transportation, and Mars landing and ascent vehicles, NASA will need to begin developing more detailed cost estimates for its Mars exploration program after EM-2. More concrete cost estimates will also be necessary as Agency officials work with Congress and other stakeholders to ensure the commitment exists to fund a mission of this magnitude over the next several decades. Finally, NASA's decision whether to continue spending $3 to $4 billion annually to maintain the ISS after 2024 will affect its funding profile for human exploration efforts in the 2020s, and therefore has implications for the Agency's Mars plans.

NASA Has Established Requirements Only Through EM-2

NASA has adopted a framework for the Journey to Mars that contains four phases, with Phase 1 and Phase 2 occurring in cislunar orbit to test and validate key systems, Phase 3 in Mars orbit for descent and ascent vehicle testing, and Phase 4 landing humans on the surface of Mars. While NASA has recently added some detail to this framework, the Agency has not yet set forth the requirements it will need to make the plan a reality.

In September 2016, HEOMD set high-level objectives and identified the transition missions for Phases 1 and 2. For Phase 1, NASA plans to conduct cislunar demonstrations of such key systems as the integrated SLS Block 1B and Orion system with a crewed asteroid retrieval mission scheduled no earlier than 2026. Objectives for Phase 2 include validation of the integrated SLS/Orion systems with habitation and in-space transportation systems in cislunar space. A year-long crewed shakedown cruise to test long-duration activities in deep space environments will serve as the mission to end this Phase. While NASA has provided additional detail on the operational aspects of Phases 1 and 2, it has not yet developed detailed estimates for the cost of undertaking these activities. Table 6 includes the status of NASA's Journey to Mars plan. See Appendix D for a full summary of Phase 0, Phase 1, and Phase 2 objectives, and Appendix H for ESD Requirements.

Table 6: Summary of Agency's Human Exploration Planning

	Phase 0 (Current Activities)	Phase 1 (Present to Mid-2020s)	Phase 2 (Mid-2020s to Early 2030s)	Phase 3 (Early 2030s to Late 2030s)	Phase 4 (Mid-2030s to Mid-2040s)
Phase objectives[a]	17 identified	17 identified	28 identified	Undefined	Undefined
Mission-specific requirements[b]	ISS and Commercial Cargo and Crew	EM-1 and EM-2	Undefined	Undefined	Undefined
Phase Transition mission	Undefined	Asteroid Redirect Crewed Mission	1-year crewed shakedown cruise	Undefined	Undefined
Phase goal	Demonstrate exploration and commercial capabilities on ISS	Crew in cislunar orbit	Crew on long-duration mission	Crew in Mars orbit	Crew on Mars surface

Source: NASA OIG analysis of Agency documents. NASA, "Human Exploration and Operations Objectives," HEOMD-001, September 7, 2016.

[a] Phase objectives are specific capabilities or milestones needed to complete the phase and provide guidance to program managers to develop hardware capabilities and architecture studies.
[b] Mission specific requirements or flight test objectives are specific to each mission and meant to test and validate hardware or capabilities during the mission.

As shown in Table 6, detailed mission requirements, including the system architecture beyond EM-2, have not been set. Although HEOMD is optimistically targeting 2023 for an EM-3 launch, officials say they do not plan to finalize requirements for EM-3 through EM-6 until roughly 2020. In our judgment, this leaves insufficient time to prepare for early 2020 to mid-2020 missions. In addition, most of the details regarding Phase 3 and 4 objectives and phase transition activities have not been determined nor has NASA officially set a target date to orbit Mars or land on the planet's surface. NASA officials explained it is too early in the planning process to set firm requirements or mission dates because of the inherent difficulty of planning detailed requirements for a program that could last 30 years or more while also maintaining the flexibility needed to react to future technological advances and policy changes.

While we agree that finalizing requirements for the Journey to Mars through 2046 is impractical at this point in time, we believe that adding more detail to the plan would help NASA focus funding priorities for the systems the Agency will need to develop to accomplish its goals.[46] This could include establishing the mission requirements and system architecture for the early 2020s, setting need-by dates for key systems, and committing to more specific dates for the 1-year shakedown cruise in Phase 2, orbiting Mars in Phase 3, and landing on the Mars surface in Phase 4.

[46] The Aerospace Safety Advisory Panel's 2016 Annual Report also raised this point and emphasized the necessity of providing a "more focused evaluation of mission architectures in order to have confidence that the required technologies will be sufficiently funded and ready when needed for future human exploration missions."

Cost Estimates for Missions Beyond EM-2

Not surprisingly, given the lack of detailed requirements, NASA has not developed a cost estimate for either the individual systems or the overall cost of its Journey to Mars. Indeed, full life-cycle cost estimates are not required by NASA policy at this stage in the process. However, as with fleshing out requirements, we believe developing rough cost estimates during the early phases of this multi-decade human exploration program would help NASA leaders make more informed decisions regarding the systems the Agency can afford to build and when it should start building them. Moreover, such estimates would help inform other decision makers and stakeholders in the Administration, Congress, and research and business communities of the magnitude of the sustained investment required to make human exploration of Mars a reality by the late 2030s or early 2040s.[47]

Jet Propulsion Laboratory Feasibility Study Shows Funding Deficit in the 2020s

Although NASA has not developed cost estimates for its Journey to Mars framework, in 2015, JPL examined the potential costs of the Agency's long-term human exploration efforts to develop an affordable plan that would enable Mars missions beginning in the 2030s. The JPL study assumed a minimal architecture that relied on key systems already under development, such as SLS and Orion, and avoided complex new technologies.[48] The study set targets of a crewed landing on the Martian moon Phobos in 2033, a 1-month Mars surface stay in 2037, and 1-year surface stays in 2041 and 2046. JPL estimated that a crewed exploration program following this approach would cost at least $430 billion between FY 2016 through FY 2046, with annual HEOMD budgets increasing from roughly $9 billion in 2016 to $19 billion in 2046.

As mentioned earlier, NASA officials stated the Journey to Mars plan would be supportable assuming HEOMD's budget increases each year by 2.4 percent to account for inflation and by another 2.45 percent to account for economic growth, or by an overall rate of 4.85 percent annually. Using these assumptions, NASA would have at least $545 billion available for its exploration programs (including the ISS) from 2016 through 2046, with annual HEOMD budgets increasing from $9 billion in 2016 to $32 billion in 2046. However, we find these funding assumptions overly optimistic given that NASA's budget has increased on average only 1.6 percent annually over the past 25 years. Therefore, funding projections using only inflationary increases of 2.4 percent annually may be more realistic given NASA's funding history. In that case, HEOMD's annual budget would increase over the same period from $9 billion in 2016 to $18 billion in 2046, or a total of roughly $410 billion during the period.

Comparison of HEOMD budget assumptions to the JPL cost analysis shows that while the two architectures are somewhat different, a level of sustained funding that meets HEOMD's budget assumptions for increases based on inflation and economic growth may be sufficient to support NASA's Journey to Mars plan but not on the timeline proposed.[49] In particular, the JPL analysis illustrates the

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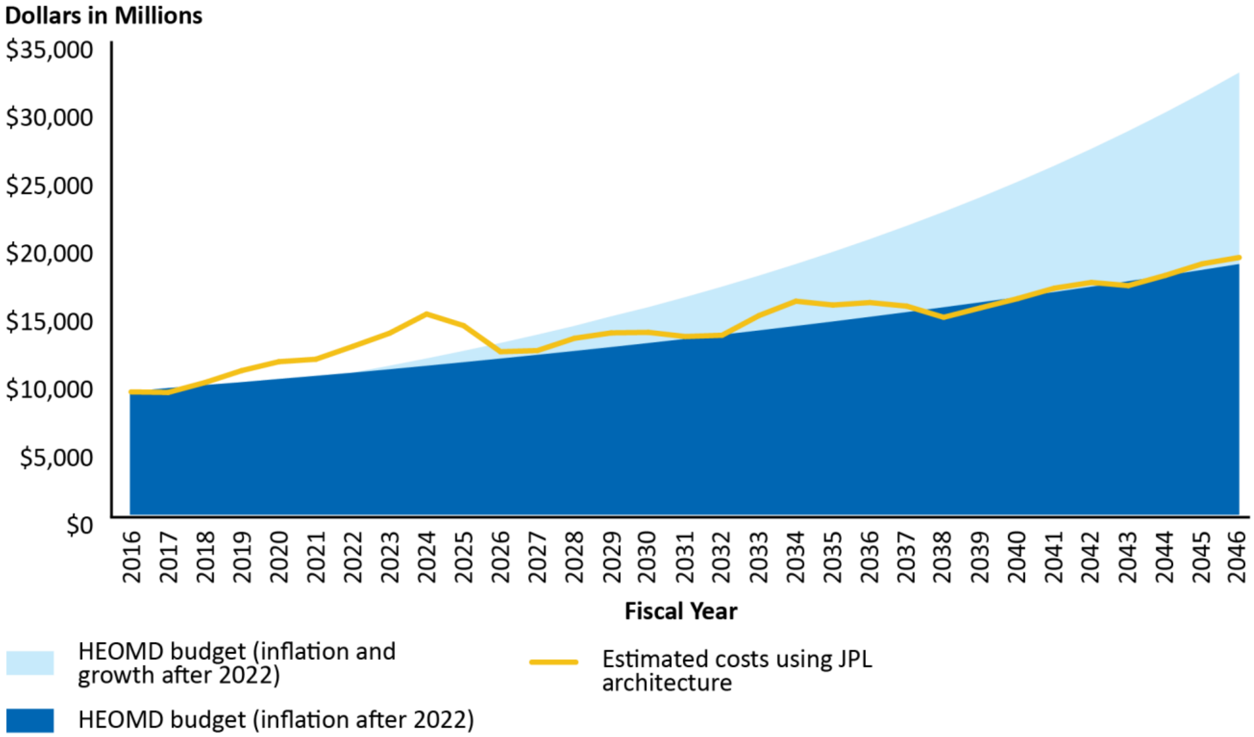
[47] The NASA Transition Authorization Act of 2017 requires that an independent organization study the technical feasibility of a Mars space flight mission in 2033 using annual costs estimates. The report is due 4 months after the law's passage and NASA's findings and recommendations are due to Congress 2 months thereafter.

[48] The study's architecture did not include immature technologies like Mars surface nuclear fission or producing oxygen or methane on the planet's surface.

[49] Using the JPL architecture cost assumptions, a HEOMD budget that only increases for inflation may not be sufficient without significant funding increases to eliminate shortfalls during the 2020s and mid-2030s.

HEOMD funding assumptions may not be sufficient to fund the development of key systems, such as the in-space habitat and in-space transportation systems in the mid-2020s. As noted previously, these systems must be developed in the 2020s to send humans to space in the late 2030s or early 2040s. Figure 6 shows the JPL cost estimates and milestones compared to HEOMD budget assumptions through 2046 assuming steady increases for inflation and inflation plus economic growth.

Figure 6: HEOMD Budget Assumptions Compared to JPL Architecture Cost Estimates



Source: NASA OIG analysis of JPL feasibility study data.

The JPL study built upon cost analysis conducted by The Aerospace Corporation (Aerospace) for the National Research Council's 2014 Pathways to Human Exploration report.[50] At our request, Aerospace reviewed JPL's analysis and verified the study's general findings. Aerospace updated the cost estimates (including expected ISS costs) and determined an overall cost of $450 billion similar to JPL study. In addition, the Aerospace cost analysis also concurred with JPL's observation that development of key systems in the early 2020s is critical to landing on Mars by the late 2030s or early 2040s.

The JPL cost analysis, which assumed a minimal architecture for NASA's Mars exploration missions, does not incorporate all HEOMD assumptions – for example, producing oxygen on the Mars surface or developing a liquid oxygen and methane propulsion system for Mars ascent and descent. Table 7 summarizes several of the fundamental differences in assumptions between the JPL study and NASA's Journey to Mars framework.

[50] The Aerospace Corporation is a nonprofit organization that operates a federally funded research and development center.

Table 7: Comparison of JPL Architecture to HEOMD Journey to Mars Planning

Architecture Assumptions	JPL Feasibility Study	HEOMD's Journey to Mars Planning
Reliance on new technologies	Relied on key systems already in development to reduce costs and schedule delays, such as hypergolic chemical propulsion to transport crewed missions to Mars orbit, and to and from the Mars surface.	Utilized undeveloped new systems, such as 1. fission power for habitation on Mars surface, 2. oxygen production on the Mars surface, and 3. liquid oxygen and methane for Mars ascent propulsion.
Scope of system capabilities for initial missions	Architecture limited to system capabilities needed only for initial missions.	Expanded focus on long-term capabilities, such as liquid oxygen and methane propulsion; oxygen production on Mars.
Development investments in the 2020s	Cost estimates were conducted on each system needed in order to achieve the designated Mars missions and showed a significant investment was needed for the development of these systems in the 2020s.	Assumed supportable with flat budgets with incremental increases based on inflation and economic growth.
Extension of ISS funding beyond 2024	Assumed a reduction of ISS funding after 2024.	No analysis related to key system costs or impact of ISS funding beyond 2024.

Source: NASA OIG analysis of JPL study and HEOMD's Journey to Mars planning and Evolvable Mars Campaign studies.

Funding Development in 2020s of Critical Systems Needed to Support Mars Mission Tied to Decision Whether to Fund ISS After 2024

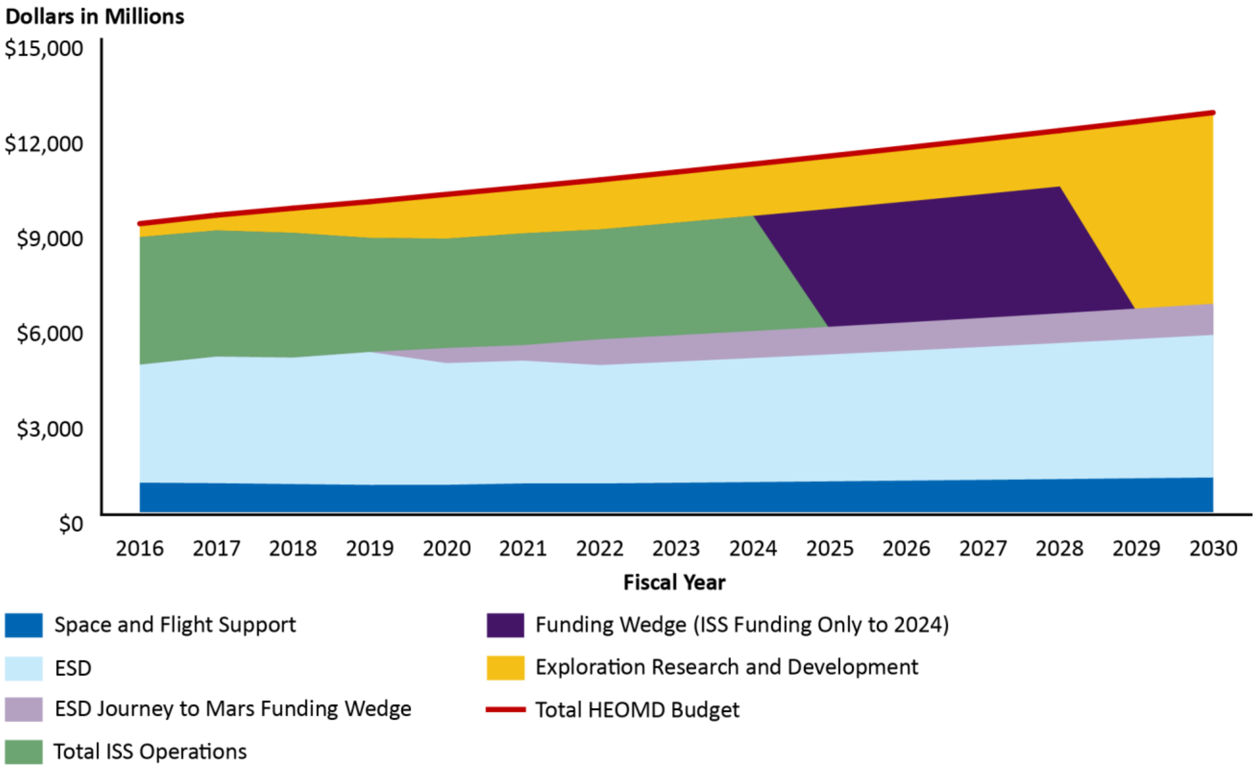
The JPL analysis shows a funding deficit of roughly $16 billion between FY 2018 through FY 2026, a time period in which development of critical systems will be necessary to meet Mars mission requirements in the 2030s. NASA officials confirmed the importance of key system development in the 2020s, citing the expected selection of a cislunar habitat design in 2018 and an in-space transportation system in 2020 as proactive steps to buy-down future development risks.

NASA's decision on the future of the ISS will affect HEOMD's funding profile in the 2020s. NASA is currently committed to supporting the Station through 2024 at funding levels of $3 to $4 billion annually, but the Agency is also studying the feasibility of extending Station operations to 2028.[51] Assuming HEOMD's funding remains constant, a continuation of ISS funding through 2028 will require either increased funding in the 2020s for Phase 1 and 2 key systems or will require the Agency to push out the timeline for its Mars exploration plans. As shown in Figure 7, retirement or reduction in funding for the ISS after 2024 might create a funding "bump" or wedge of roughly $16 billion – money that could be redirected towards developing key systems needed for the Journey to Mars. Additionally, ESD plans to allocate roughly $9 billion of its budget from FYs 2020 through 2030 towards Journey to Mars activities and this ESD funding, combined with retirement of the ISS in 2024, could translate into a funding wedge of approximately $25 billion in the 2020s. Without this wedge or an otherwise significant funding increase from Congress, development of key systems could be delayed to 2029 or

[51] NASA could utilize the extension to conduct additional human exploration research on a variety of issues, including life support systems, spacesuits, and astronaut health.

later – a scenario that likely would delay a crewed mission to Mars. For example, a high-level feasibility study by NASA's OCFO showed a 4-year extension of the ISS to 2028 could push out the Journey to Mars schedule by at least 3 years.[52]

Figure 7: Journey to Mars Funding Wedges Available Assuming Constant HEOMD Budget and ISS Funding Through FY 2024



Source: NASA OIG analysis of JPL feasibility study data.

Whether to extend the ISS beyond 2024 is a critical decision for NASA and its Journey to Mars, particularly because of the funding shortfalls projected during the 2020s and the need for development of key systems during that time period. Funding the ISS at $3 to $4 billion annually past 2024 would require significant funding increases beyond projected HEOMD budget levels to keep the Journey to Mars on its current rough timetable of Mars exploration in the late 2030s and early 2040s.[53]

[52] The NASA Transition Authorization Act of 2017 requires NASA to submit a report to Congress by December 1, 2017, describing how the ISS is contributing to the Agency's efforts to further deep space exploration goals and evaluating the feasibility of extending its life through 2028. As part of the report, NASA is directed to examine "the impact on deep space exploration capabilities, including a crewed mission to Mars in the 2030s, if the preferred service life of the ISS is extended beyond 2024 and NASA maintains a flat budget profile."

[53] NASA is exploring commercializing some activities on the ISS to reduce the Agency's funding burden, and in 2016 requested proposals from the private sector regarding how best to utilize ISS capabilities to commercialize low Earth orbit. In response, the Agency received proposals to attach commercial space station modules to the ISS as a means of encouraging private companies to develop space travel and habitation capabilities that could eventually be available to NASA at a lower cost than current ISS activities.

NASA PURSUING OPTIONS TO MAKE THE JOURNEY TO MARS LESS COSTLY

NASA acknowledges that to successfully execute the Journey to Mars, cost saving measures and cost sharing must be part of its strategy. The Agency has explored reusing systems and subsystems, developing new acquisition strategies, and exploiting technology innovations to help reduce the high cost of operating in space. Sharing costs with foreign space agencies and the private sector also could help NASA reduce its overall costs. For example, NASA is partnering with industry to conduct multiple trade studies on the systems needed for the Journey to Mars and providing technical and mission support to Space Exploration Technologies Corporation (SpaceX) related to the company's planned uncrewed Mars mission. Indeed, the Aerospace Safety Advisory Panel's 2016 Annual Report noted that NASA can use international and commercial partnerships to create a more robust exploration architecture, enhance the cislunar space economy, and increase the safety of Mars missions.[54] Moreover, the NASA Transition Authorization Act of 2017 cites expanding permanent human presence beyond low Earth orbit together with international, academic, and industry partners as the country's long-term goal for NASA's human space exploration efforts.

Program Management Strategies to Reduce Costs

According to Agency officials, NASA plans to manage current and future costs of its deep space exploration goals in five ways: (1) using ESD rather than establishing another program and hiring a private contractor as integrator for the SLS, Orion, and GSDO systems; (2) incremental development of capabilities; (3) reusing key systems; (4) exploring the use of competitive fixed-price contracts during production and operations; and (5) leveraging new technologies. Although it is too early to tell if they will be successful, these efforts are credible cost reduction strategies.

Integration Approach

According to NASA officials, a major reason to use ESD as the integrator for the SLS, Orion, and GSDO systems is to reduce overall costs. These officials told us that integration efforts and decision making under ESD are more affordable than they were for the Constellation Program or when the Agency used an integration contractor for the Space Shuttle Program, and believe the resulting savings could amount to hundreds of millions of dollars a year.

Although integration and support costs for the systems used in the Journey to Mars are projected to remain relatively low at $73 million on average through FY 2019, it is too early to tell if NASA's integration approach will ultimately reduce costs.

[54] Aerospace Safety Advisory Panel, "Annual Report for 2016."

Incremental Development

Beginning in 2011 with development of the SLS and Orion programs, NASA made affordability a key component of its deep space ambitions by developing a methodical and incremental developmental approach. As a result, NASA is developing space flight systems only when they are actually needed and only for a specific capability. SLS Program officials cited examples such as the evolving SLS architecture with a basic model using heritage hardware (Space Shuttle RS-25 engines, solid rocket boosters, Delta IV upper stage, etc.) for the first launch that eventually evolves into the final Block 2 for deep space that will lift 130 metric tons to low Earth orbit using advanced rocket boosters and a new upper stage. For the additional systems needed for a crewed mission to Mars, NASA plans to follow a similar approach: the Mars transit habitat and propulsion system are not required for a crewed asteroid mission in 2026, so these capabilities will be scaled back to meet only cislunar mission requirements. In addition, deep space habitats will only be built when they are needed – by the late 2020s to conduct long-duration missions such as the 1-year shakedown cruise.

Reusing Systems

NASA intends to reuse many of the systems it is designing for the Journey to Mars and is using systems left over from prior programs to save money. For example, NASA plans to reuse Orion capsules and certain Orion subsystems such as the avionics package rather than fabricate new systems. The Agency is also using engines left over from the Space Shuttle Program (16 RS-25 engines) and a supply of solid rocket booster structural hardware that should last until EM-8. In addition, NASA hopes to reuse some of the systems from the 1-year shakedown cruise, such as the deep space habitat in the late 2020s, propulsion system, and Orion capsule for future Mars missions.

Acquisition Strategy

NASA is examining its acquisition strategies to identify lower-cost options to develop and purchase space flight systems. Both SLS and Orion program officials told us they are examining ways to reduce production costs over the long run. In July 2016, the Deputy Associate Administrator for ESD briefed the NASA Advisory Council about the results of ESD studies to help reduce production and operations costs to improve the long term sustainability of the Journey to Mars. Specifically, NASA is trying to reduce production costs for the SLS, Orion, and GSDO systems from more than $3.5 billion per year to approximately $2 billion per year.

To achieve this goal, NASA officials told us they are exploring the use of competitive, fixed-price contracts after systems development has ended and production begins. Since NASA owns the plans and designs for the SLS and Orion, production of additional vehicles could be competitively bid to companies other than the current contractors. For example, in September 2016, NASA issued a Request for Information from the commercial sector to reduce production and operations costs for the Orion spacecraft. In November 2016, NASA made a second request to industry to solicit information intended to maximize the long-term efficiency and sustainability of the ESD programs, including the SLS, Orion, and Exploration Ground Systems by minimizing production, operation, and maintenance costs. Lockheed Martin, the current Orion contractor, responded to the ESD request that the transition to production could reduce recurring Orion production costs by 50 percent. Additional efficiencies and cost savings may be realized if NASA buys more systems as it gets closer to both short- and long-duration stays on Mars. Some mission scenarios may require the support of up to 11 launches – all of which will need to be built and launched within a few years.

In addition, NASA has several ongoing cost-sharing ventures and is partnering with commercial companies to develop advanced propulsion systems, habitation systems, and small satellite missions through contracts awarded under its Next Space Technologies for Exploration Partnerships (NextSTEP-1 and -2). NASA expects NextSTEP-1 and -2 awardees to contribute a portion of the funding for development. In previous commercial partnerships using Space Act Agreements, NASA effectively used cost-sharing arrangements with commercial partners to develop the Orbital ATK (Orbital) and SpaceX cargo vehicles that are currently servicing the ISS and the SpaceX and Boeing crew vehicles expected to begin servicing the Station in 2018.[55] Although Orbital and SpaceX received more than $700 million from NASA to help develop their respective cargo transportation systems, each company also contributed more than 50 percent of the total development costs.

Technology Development

NASA is using multiple trade studies to explore new technologies and develop solutions that may reduce the costs of deep space exploration. For example, NASA is examining ways to produce oxygen, water, and fuel on Mars or another nearby celestial body to avoid the costs of transporting these supplies. In addition, the Agency is exploring solar power arrays for advanced electric propulsion for deep space travel, which may reduce the need for cryogenic propulsion systems that require large amounts of fuel. NASA also is examining methane- and nuclear-enhanced propulsion systems in an effort to make deep space missions more efficient.

Partnerships with Other Space Agencies May Provide Opportunities for Collaboration and Cost Savings

International partnerships have the potential to benefit NASA in its Journey to Mars by reducing costs and providing access to partner capabilities. With the ISS as the prime example, NASA has a history of strong international cooperation in its aerospace endeavors. In a May 2016 report, we identified several benefits from international partnerships.[56] First, cost growth for uncrewed and robotic projects in which NASA collaborated with foreign space agencies was lower on average in comparison to both NASA projects with no international collaboration and NASA projects with other Federal agencies. International collaboration also allows NASA to tap into the technical and financial resources of multiple countries to increase the scope of projects beyond the capabilities of individual participants. In addition, as in the case of the ISS, international partnerships may help shield programs and projects from cancellation.

NASA and a core group of four partners – the Canadian Space Agency, European Space Agency (ESA), Japan Aerospace Exploration Agency, and Roscosmos State Corporation for Space Activities – developed and have operated the ISS for 2 decades using a well-defined cost sharing agreement that holds each partner responsible for certain costs, services, and hardware. The United States entered into an international agreement with partner governments in 1998 that outlined the legal framework for the development and operation of the ISS. Although the ISS experienced significant cost growth throughout its development, this cost-sharing framework has proven effective in maintaining Station operations (see Figure 8).

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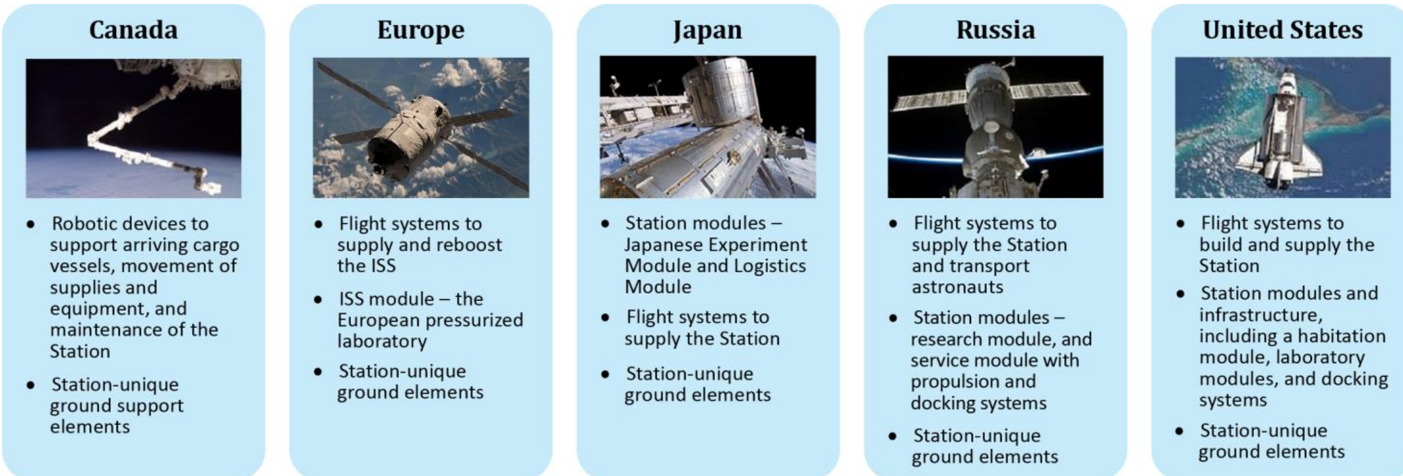
[55] Space Act Agreements are a form of "Other Transaction Authority" provided in the National Aeronautics and Space Act of 1958 (as amended) that allows NASA to establish a set of legally enforceable commitments between the Agency and a partner per NASA Policy Directive 1050.1I, "Authority to Enter Into Space Act Agreements," December 23, 2008.

[56] NASA OIG, "NASA's International Partnerships: Capabilities, Benefits, and Challenges" (IG-16-020, May 5, 2016).

Figure 8: ISS Partner Contributions



Source: NASA OIG analysis of the 1998 ISS Intergovernmental Agreements.

Replicating this framework for NASA's Journey to Mars may be difficult because the Agency's goals may diverge from those of its partners. While NASA is building and testing capabilities to pursue a crewed mission to Mars, many foreign space agencies plan to focus their exploration efforts on the Moon, with the ESA Director General, in March 2016, calling for establishment of a "Moon Village."[57] As NASA progresses from Phase 2 to Phase 3 in its Journey to Mars, operations will shift from cislunar space to Mars and its moons, which may limit the extent to which NASA and its partners collaborate.

Geopolitical events can also impact NASA's ability to partner with foreign space agencies. As a result of the conflict in Ukraine in April 2014, the United States Government suspended NASA's collaboration with Russia with a few exceptions, namely the ISS and space flight operations in support of the Station. In consultation with the State Department, NASA is currently reviewing and approving partnership opportunities with Russia on a case-by-case basis. In addition, since November 2011, annual appropriations guidance has limited NASA's ability to partner with China.

Despite these limitations, several international collaboration efforts are underway for Phase 1 activities in NASA's Journey to Mars. For example, NASA and ESA executed a barter agreement under which ESA will provide the Orion service module for missions EM-1 and EM-2 to cover ESA's portion of ISS operating costs. While there have been delays in development of the service module, NASA is currently in discussion with ESA regarding the possibility of producing service modules for additional Orion missions.

NASA is also engaging in long-term planning with other space agencies in the 15-member International Space Exploration Coordination Group.[58] Moreover, NASA and its ISS partners are discussing potential areas of collaboration after retirement of the ISS, with several areas identified thus far:

- *Near-Rectilinear Orbit*. NASA plans to conduct missions in cislunar space to validate habitation capabilities to support human Mars exploration. At the same time, NASA's partners are examining Lunar orbits that could facilitate orbit and landing missions on the Moon. Officials have identified one type of orbit – near-rectilinear orbit – that would be suitable for both of

[57] ESA, "Moon Village"; www.esa.int/About_Us/Ministerial_Council_2016/Moon_Village (last accessed February 15, 2017).

[58] The International Space Exploration Coordination Group is a voluntary association of 15 space agencies whose goal is to exchange plans in space exploration and encourage collaboration.

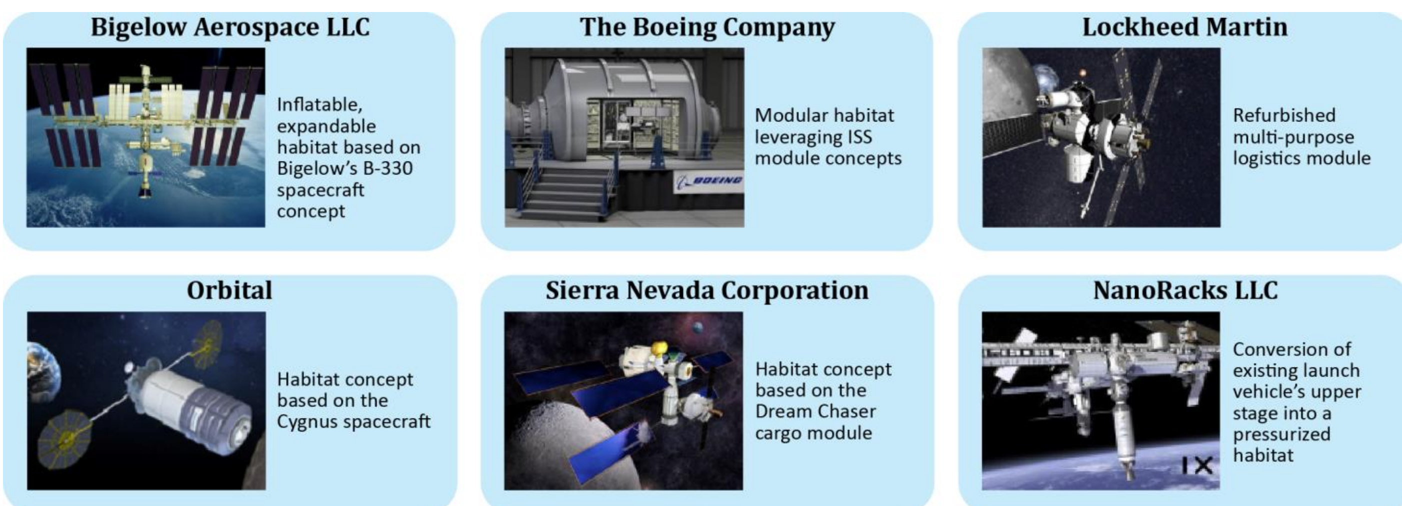
these objectives. Near-rectilinear orbits are favorable for staging Mars systems as they allow for long-term cislunar operations and require relatively little propellant to keep the system in orbit. At the same time, such an orbit could also provide transfer options for landing and ground systems to further the international space community's Moon exploration ambitions.

- *Solar Electric Propulsion*. A key objective of NASA's Phase 1 plans is to test long-duration solar electric propulsion, which has a much higher engine efficiency than chemical propulsion, allowing for cheaper staging of systems in orbit. Members of the international space community are interested in developing this technology to stage systems in orbit to support their Lunar surface missions.
- *Pressurized In-Space Habitat*. NASA plans to test a pressurized in-space habitat in cislunar space to assess technology that will ultimately be used on the Journey to Mars. Similarly, the international space community will need a pressurized in-space habitat for staging in a lunar orbit to support surface missions.

Commercial Partnerships May Help Defray Costs

Development of certain systems needed for the Journey to Mars may lend themselves to public-private partnerships that could translate into cost savings for NASA. For example, AES issued two rounds of Broad Agency Announcements, the first of which asked commercial partners to develop advanced propulsion systems, habitation systems, and small satellite missions.[59] For the second round, NextSTEP-2, NASA awarded fixed-price contracts to six commercial partners who are developing a pressurized deep space habitat concept and producing full-size ground prototypes (see Figure 9).

Figure 9: NextSTEP-2 Habitat Systems Awardees



Source: NASA OIG analysis of NASA information.

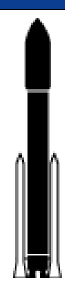
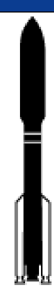
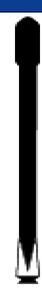
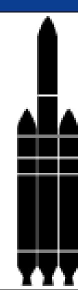
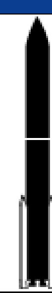
NASA is also partnering with companies through its Commercial Space Capabilities Office. For example, in partnership with SpaceX, NASA will provide deep space communications and telemetry, deep space navigation and trajectory design, and analyses and consultation in support of the company's "Red

[59] Broad Agency Announcements are used to solicit ideas from industry regarding potential public-private partnerships.

Dragon" mission to Mars. This uncrewed mission is designed to test deep space systems for traveling to and landing on the surface of Mars, ultimately paving the way for SpaceX's goal of conducting crewed missions to Mars in the mid-2020s. In exchange, SpaceX will provide NASA with entry, descent, and landing data as well as Mars science data. NASA is expected to spend more than $30 million in support of the mission. Although NASA has agreed to support the first Red Dragon mission, NASA and SpaceX have not entered into any other formal agreements regarding the company's Mars plans. However, in February 2017, NASA issued an announcement seeking potential partnerships with private industry to fly NASA scientific payloads on private missions to Mars to assist the Agency's human and robotic deep space exploration program.

One area in which NASA has successfully leveraged commercial partnerships is utilization of private launch vehicles, which have transported cargo to the ISS since 2012. Although the ISS's Commercial Resupply Services has suffered two launch mishaps, this cargo service has enabled NASA to utilize commercial launch vehicles at relatively low cost to the Agency. Given that costs associated with an SLS launch are expected to exceed $1 billion, private launch vehicles may provide a cost-effective means of transporting certain payloads to low Earth and cislunar orbit as part of the Agency's Journey to Mars. Table 8 shows commercial launch systems both in service and in development that may support NASA's future exploration missions.

Table 8: Select U.S. Launch Vehicle Information Provided by NASA's Launch Services Program

	NASA	Commercial Currently in Service				Commercial Currently in Development		
	SLS Block 2	Atlas V	Falcon 9	Antares 230	Delta IV Heavy	Falcon Heavy	Vulcan ACES	New Glenn 3-Stage
								
Scheduled completion date	No earlier than 2028	Currently in service	Currently in service	Currently in service	Currently in service	2017	2023	Not reported
Cargo payload fairing size (meters)	10	5	5.4	3.9	5.2	5.2	5	
Upmass to low Earth orbit (metric tons)	130	7.4–17.9	11.2–15	4.4	25.5	–	–	
Upmass to cislunar orbit (metric tons)	52	2.1–6.3	1.9–3.5	1.5[a]	10.5	6.1–12.9	14	
Upmass to Mars (metric tons)	41	1.4–4.8	Not applicable	1[a]	8.1	3.9–9.3	10.5	

Source: NASA and NASA Launch Services Program information.

Note: Upmass figures include calculations and assumptions from NASA's Launch Services Program.

[a] Denotes upmass value for Antares 232 variation.

As NASA continues to develop its Mars architecture and identifies ways in which commercial space partners can contribute, the Agency may be able to use funded Space Act Agreements – an authority provided under the Space Act of 1958 – pursuant to which NASA works with domestic partners to undertake activities consistent with its mission.[60] Funded Space Act Agreements are not subject to the Federal Acquisition Regulation (FAR), which allows NASA and its commercial partners considerable latitude in negotiating terms. This increased flexibility can make funded Space Act Agreements more cost-effective than FAR contracts. For example, NASA used funded Space Act Agreements for the Commercial Orbital Transportation Services to stimulate space flight development efforts by three U.S. commercial companies, two of which – Orbital and SpaceX – are now delivering supplies to the ISS under a FAR-based contract. NASA officials estimated that for SpaceX alone, using a funded Space Act Agreement to develop this technology saved the Agency between $1.4 billion and $4 billion in development costs.[61] As NASA continues to stimulate development of the private sector in its Journey to Mars, funded Space Act Agreements may provide a cost-effective option to develop needed technology, including habitat and propulsion systems.

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[60] National Aeronautics and Space Act of 1958 (Space Act), Pub. L. No. 85-568, 72 Stat. 426 (current version at 51 U.S.C. §§ 20101-20164 (2010)).

[61] NASA OIG, "NASA's Use of Space Act Agreements" (IG-14-020, June 5, 2014).

CONCLUSION

NASA faces a host of formidable challenges as it develops plans for human exploration of Mars. The technical challenges are unprecedented and the costs enormous with even austere budget estimates totaling more than $400 billion by the time a second visit to the Martian surface is completed in the 2040s.

We believe NASA has developed a sound framework for its Journey to Mars. To its credit, the Agency has made affordability and sustainability key components of its deep space ambitions, adopting an incremental approach under which space flight systems are developed when needed and planning for reuse of some systems. Moreover, NASA is examining its acquisition strategies to determine whether it can lower costs by using fixed-price contracts once system development has ended and production begins.

That said, we offer several observations about NASA's deep space exploration efforts. First, the Agency's first exploration missions – EM-1 and EM-2 – have little schedule margin and low reserves and are not likely to launch by 2018 or 2021, respectively. In addition, NASA's integration plans for EM-2 are incomplete, making it more difficult for both Agency officials and external stakeholders to gain a full understanding of the costs of that mission or to assess the validity of the Agency's launch date assumptions. Moreover, the Agency is still working to overcome technical challenges in the SLS, Orion, and GSDO programs, and development of many critical systems needed for the Journey to Mars has not begun. Finally, one of the keys to executing NASA's Journey to Mars plan on the timetable the Agency has set will be developing and building needed space systems in the 2020s. However, NASA has not identified the requirements or costs for missions beyond the mid-2020s and its decision regarding ISS operations beyond 2024 may impact the funds available for its deep space exploration efforts.

RECOMMENDATIONS, MANAGEMENT'S RESPONSE, AND OUR EVALUATION

To increase the fidelity, accountability, and transparency of NASA's human exploration goals beyond low Earth orbit, we recommended the Associate Administrator for Human Exploration and Operations

1. complete an integrated master schedule for the SLS, Orion, and GSDO programs for the EM-2 mission;
2. establish more rigorous cost and schedule estimates for the SLS and GSDO programs for the EM-2 mission mapped to available resources and future budget assumptions and independently reviewed by the Office of the Chief Financial Officer;
3. establish objectives, need-by dates for key systems, and phase transition mission dates for the Journey to Mars; and
4. include cost as a factor in NASA's Journey to Mars feasibility studies when assessing various missions and systems.

To improve efforts at cost savings, we recommended the Associate Administrator for Human Exploration and Operations

5. design a strategy for collaborating with international space agencies in their cislunar space exploration efforts with a focus on advancing key systems and capabilities needed for Mars exploration, and
6. incorporate into analyses of space flight system architectures the potential for utilization of private launch vehicles for transportation of payloads.

We provided a draft of this report to NASA management who concurred or partially concurred with our recommendations and described planned corrective actions. We consider the proposed actions responsive for five of the six recommendations and will close them upon verification and completion of those actions.

The Associate Administrator partially concurred with our second recommendation, stating the Agency frequently updates SLS, Orion, and GSDO plans based upon requested and received appropriations and the impacts of continuing resolutions. However, he did not agree to establish more rigorous cost estimates for the SLS and GSDO programs for EM-2. While we understand the challenges posed by the appropriations process and the difficulty of projecting long-range life-cycle costs, the Agency is currently spending significant amounts of money on EM-2 without an official cost estimate for these programs. Moreover, only Orion has undergone the rigor of an Agency Baseline Commitment for EM-2. In our judgment, a detailed EM-2 cost estimate would allow Agency officials and external stakeholders to better understand the mission's progress and the full costs involved. Therefore, this recommendation is unresolved pending further discussion with Agency officials.

Management's response to our report is reproduced in Appendix I. Their technical comments have been incorporated, as appropriate.

Major contributors to this report include Ridge Bowman, Space Operations Director; Kevin Fagedes, Project Manager; Susan Bachle; David Balajthy; Mike Beims; Cedric Campbell; Frank Martin; and Robert Proudfoot. Sarah McGrath provided editorial and graphic assistance.

If you have questions about this report or wish to comment on the quality or usefulness of this report, contact Laurence Hawkins, Audit Operations and Quality Assurance Director, at 202-358-1543 or laurence.b.hawkins@nasa.gov.

Paul K. Martin
Inspector General

APPENDIX A: SCOPE AND METHODOLOGY

We performed this audit from June 2016 through March 2017 in accordance with generally accepted government auditing standards. Those standards require that we plan and perform the audit to obtain sufficient, appropriate evidence that provides a reasonable basis for our findings and conclusions. We believe that the evidence obtained provides a reasonable basis for our findings and conclusions based on our audit objectives.

Our overall audit objective was to examine NASA's management of its space systems needed to support human exploration of celestial bodies. Our review was conducted at Johnson, Kennedy, Marshall, Michoud Assembly Facility, Stennis, NASA Headquarters, and contractor locations. We observed on-going SLS, Orion, and GSDO efforts at Kennedy, Michoud Assembly Facility, Stennis, and the software testing laboratories at Marshall's Systems Integration Laboratory and Lockheed Martin's Integrated Test Laboratory in Denver, Colorado.

To assess the cost, schedule, and performance of the key systems for EM-1, we reviewed program and OCFO cost and budget documentation and schedules for each of the SLS, Orion, and GSDO programs. Specifically, we analyzed FY 2011 through FY 2016 cost data provided by HEOMD resource management officials and SLS, Orion, and GSDO program officials. We also obtained FY 2011 through FY 2016 cost data from NASA's accounting system to compare with the data obtained from the SLS, Orion, and GSDO programs and interviewed program, planning, and control officials for each Program. We interviewed SLS, Orion, and GSDO program officials to determine past and expected technical challenges and the impact to schedule. We reviewed program documents such as the System Definition Review (SDR), Preliminary Design Review (PDR), and CDR, planning documents, and Federal and NASA criteria. We also reviewed relevant documents, including NASA's Strategic Plans, NASA's Journey to Mars plan, past presidential budget submissions, and NASA authorization and appropriation bills. When appropriate, we conducted on-site inspections of the SLS, Orion, and GSDO programs, including software testing conducted at Marshall and at the Lockheed Martin contractor facility in Denver, Colorado.

To assess the estimated costs to meet human exploration requirements through EM-2, we reviewed program life-cycle review documentation and OCFO and program projected budget documentation the SLS, Orion, and GSDO programs. Specifically, we analyzed the SLS Program, Orion Program, and GSDO Program's life-cycle review documentation for the SDR, PDR, and CDR; President's budget requests from FY 2012 through FY 2016; and Program-specific budget submissions to the OCFO. We also reviewed the cost analyses and technology assumptions conducted by The Aerospace Corporation (Aerospace) in conjunction with JPL. We interviewed HEOMD management; ESD officials; OCFO representatives; SLS, Orion, and GSDO program officials; and JPL and Aerospace officials. We reviewed criteria in the form of the NASA and GAO cost estimating guides and NASA Authorization and Appropriation bills.

To assess NASA's planning efforts beyond EM-2, we reviewed planning documents and feasibility studies. Specifically, we reviewed NASA's Journey to Mars plan, Evolvable Mars Campaign trade studies and requirements, HEOMD objectives, JPL feasibility studies and associated Aerospace Corporation cost analysis, and system architecture documentation. We interviewed officials from the HEOMD; ESD; STMD; AES Division, including the Evolvable Mars Campaign group; JPL; and Aerospace. We also reviewed other relevant documentation, such as past National Research Council studies.

To assess how NASA is pursuing the means to make the Journey to Mars more affordable, we reviewed SLS, Orion, and GSDO program documentation on cost reduction analyses and planning documentation on partnering with other entities. Specifically, we reviewed the SLS and Orion program documentation on reducing production and operation costs and planning documents related to acquisition strategies and system re-use. We interviewed SLS, Orion, and GSDO program officials, along with officials from the Commercial Spaceflight Development Office, Johnson's Exploration Integration and Science Directorate, AES Division, Exploration Mission Planning Office, and the ISS Program. We also reviewed prior OIG work on NASA's international partnerships.

Use of Computer-Processed Data

We used computer-processed data to perform this audit, and that data was used to materially support findings, conclusions, and recommendations. Specifically, we analyzed cost data for the SLS, Orion, and GSDO programs; AES activities; and STMD activities related to human exploration for FYs 2011 through 2016 in the form of Excel spreadsheets. We then verified that data with NASA's accounting system and through independent calculations and input from SLS, Orion, and GSDO program officials. We reviewed cost data for FYs 2016 through 2030 in the form of Excel spreadsheets for life-cycle reviews, and we reviewed SLS, Orion, and GSDO program and OCFO projected budgets. We also reviewed cost analyses conducted by the Aerospace Corporation in conjunction with JPL through FY 2046 based on JPL architecture assumptions. In order to assess the quality and reliability of the data, we verified the information through independent calculations and corroboration with SLS, Orion, and GSDO program documents and the input of various officials these three programs.

Review of Internal Controls

We evaluated the internal controls associated with NASA's management of space systems needed to support human exploration of celestial bodies. The control weaknesses we identified are discussed previously in this report. Our recommendations, if implemented, will correct the identified control weaknesses.

Prior Coverage

During the last 5 years, the NASA OIG and the GAO have issued 16 reports of significant relevance to the subject of this report. Unrestricted reports can be accessed at https://oig.nasa.gov/audits/reports/FY17 and http://www.gao.gov, respectively.

NASA Office of Inspector General

NASA's Management of the Orion Multi-Purpose Crew Vehicle Program (IG-16-029, September 6, 2016)

NASA's Commercial Crew Program: Update on Development and Certification Efforts (IG-16-028, September 1, 2016)

NASA's Response to SpaceX's June 2015 Launch Failure: Impacts of Commercial Resupply of the International Space Station (IG-16-025, June 28, 2016)

NASA's International Partnerships: Capabilities, Benefits, and Challenges (IG-16-020, May 5, 2016)

Audit of the Spaceport Command and Control System (IG-16-015, March 28, 2016)

NASA's Efforts to Manage Its Space Technology Portfolio (IG-16-008, December 15, 2015)

NASA's Efforts to Manage Health and Human Performance Risks for Space Exploration (IG-16-003, October 29, 2015)

Audit of NASA's Joint Cost and Schedule Confidence Level Process (IG-15-024, September 29, 2015)

NASA's Launch Support and Infrastructure Modernization: Assessment of the Ground Systems Needed to Launch SLS and Orion (IG-15-012, March 18, 2015)

NASA's Use of Space Act Agreements (IG-14-020, June 5, 2014)

Commercial Cargo: NASA's Management of Commercial Orbital Transportation Services and ISS Commercial Resupply Contracts (IG-13-016, June 13, 2013)

Government Accountability Office

Orion Multi-Purpose Crew Vehicle: Action Needed to Improve Visibility into Cost, Schedule, and Capacity to Resolve Technical Challenges (GAO-16-620, July 27, 2016)

NASA Human Space Exploration: Opportunity Nears to Reassess Launch Vehicle and Ground Systems Cost and Schedule (GAO-16-612, July 27, 2016)

NASA: Assessments of Major Projects (GAO-16-309SP, March 30, 2016)

NASA: Assessments of Selected Large-Scale Projects (GAO-15-320SP, March 2015)

NASA: Actions Needed to Improve Transparency and Assess Long-Term Affordability of Human Exploration Programs (GAO-14-385, May 2014)

Appendix B: History of Past Mars Frameworks and Planning Efforts

The Journey to Mars plan is the most recent initiative in NASA's long history of creating frameworks and planning efforts for exploring Mars. Within months of the Apollo 11 landing on the Moon in 1969, a Space Task Group report was submitted to President Nixon and found that NASA possessed an organizational competence and technology base necessary to land humans on Mars by roughly 1985. Although NASA provided a detailed proposal, the President and Congress opted for building the Space Shuttle and consequently the focus on a sustained human presence in low Earth orbit began. In the late 1980s, President George H.W. Bush's Space Exploration Initiative developed a Mars mission architecture that was also not implemented. NASA completed its most recent Mars mission architecture in 2009 and the current Journey to Mars framework in 2015.[62] Other proposed plans that include future exploration of Mars include the "Global Exploration Roadmap," which focused on common interests of international partners for future exploration, and a 2014 National Research Council study – "Pathways to Exploration" – that examined the feasibility of a Mars program using NASA's current budget profile and capabilities.[63] These historical planning documents, task forces, and studies illustrate that human exploration of Mars has been a long-term goal for NASA throughout multiple decades and administrations. See Figure 10 for major planning efforts since 1969.

Figure 10: History of Past Frameworks and Planning Efforts

Source: NASA OIG analysis of past Mars plans and architecture studies.

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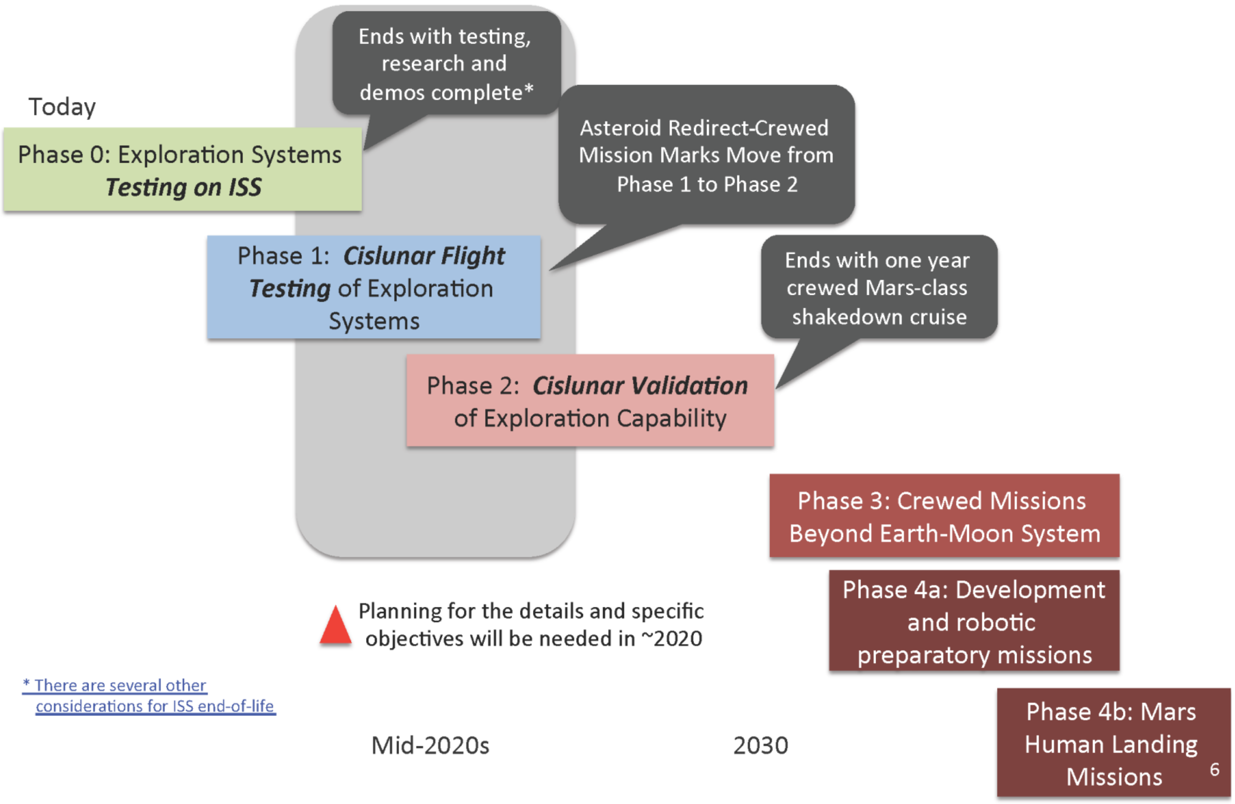
[62] NASA-SP-2009-566.

[63] International Space Exploration Coordination Group, "Global Exploration Roadmap," August 2013, and National Research Council, "Pathways to Exploration: Rationales and Approaches for a U.S. Program of Human Space Exploration," 2014.

APPENDIX C: JOURNEY TO MARS PHASES

NASA has a multi-phase strategy for human space exploration culminating with a human landing on the surface of Mars, as shown in Figure 11.

Figure 11: NASA Presentation of Journey to Mars Phases



Source: NASA.

APPENDIX D: JOURNEY TO MARS PLAN OBJECTIVES

On September 7, 2016, HEOMD approved human exploration objectives for Phase 0 (current), Phase 1, and Phase 2 of the Agency's Journey to Mars plan, as shown in Tables 9, 10, and 11, respectively. These general objectives will identify and prioritize investments in science and technology and determine the phase transition mission architecture.

Table 9: Phase 0 (Current) Objectives: Exploration Systems Testing on ISS and in Low Earth Orbit

Objective Number	Requirement Description	Objective Category
P0-01	Acquire routine round-trip U.S. crew transportation to low Earth orbit.	Transportation
P0-02	Acquire routine U.S. cargo transportation to low Earth orbit.	Transportation
P0-03	Evaluate communications with increased delay.	Working in Space
P0-04	Demonstrate in-space exploration class extravehicular activity technologies.	Working in Space
P0-05	Demonstrate exploration environmental control and life support system and environmental monitoring technologies and validate real-time on-orbit environmental monitoring.	Working in Space
P0-06	Validate in-space fire detection, suppression, and cleanup technologies suitable for exploration missions.	Working in Space
P0-07	Demonstrate radiation monitoring technologies in low Earth orbit and evaluate radiation mitigation capabilities.	Working in Space
P0-08	Demonstrate autonomous operations in low Earth orbit.	Working in Space
P0-09	Demonstrate human and robotic mission operations.	Working in Space
P0-10	Evaluate technologies that may enable operations with reduced logistics capabilities.	Working in Space
P0-11	Demonstrate docking and close-proximity technologies and operations.	Working in Space
P0-12	Enable science community objectives in low Earth orbit.	Working in Space
P0-13	Demonstrate crew acclimation to and from zero gravity.	Staying Healthy
P0-14	Demonstrate medical diagnosis capability and treatment protocols for exploration missions.	Staying Healthy
P0-15	Demonstrate protocols to understand crew task performance and operations planning for human space missions.	Staying Healthy
P0-16	Demonstrate countermeasures to mitigate the hazards of long-duration space flight.	Staying Healthy
P0-17	Demonstrate long-duration viability and stability of food and pharmaceuticals.	Staying Healthy

Source: NASA OIG analysis of NASA HEOMD-001.

Table 10: Phase 1 Objectives: Cislunar Demonstration of Exploration Systems

Objective Number	Requirement Description	Objective Category
P1-01	Demonstrate SLS Block 1 elements in flight and integrated performance with Orion.	Transportation
P1-02	Demonstrate Block 1B trans-lunar injection performance.	Transportation
P1-03	Demonstrate SLS Block 1B co-manifested capability.	Transportation
P1-04	Demonstrate Orion's ability to support crew in deep space.	Transportation
P1-05	Demonstrate Orion's ability in conjunction with additional habitation element(s) to support missions with at least four crew members for a minimum of 30 days.	Transportation
P1-06	Demonstrate operation of long-duration high power solar arrays and solar electric propulsion transportation of in-space propulsion elements.	Transportation
P1-07	Demonstrate ability to stage habitation and other capabilities in deep space for later utilization.	Transportation
P1-08	Demonstrate ability for crewed rendezvous and operation with a previously staged element(s).	Transportation
P1-09	Demonstrate autonomous rendezvous, proximity operations, and docking in deep space.	Transportation
P1-10	Demonstrate ability to dispose of assets from deep space.	Transportation
P1-11	Demonstrate autonomous deep space trajectory design, planning, and navigation.	Transportation
P1-12	Demonstrate deep space crewed operations up to Mars communications latency.	Working in Space
P1-13	Validate ability to conduct extravehicular activities in deep space.	Working in Space
P1-14	Validate integrated radiation risk mitigation ability to provide as low as reasonably acceptable exposure, including monitoring, mitigation, and operational strategies.	Working in Space
P1-15	Demonstrate transition between crewed and uncrewed operations.	Working in Space
P1-16	Demonstrate human/robotic interactions in deep space.	Working in Space
P1-17	Demonstrate stowage strategies within available volume for deep space missions.	Working in Space
P1-18	Demonstrate the collection and return of geologic, biological and/or scientific samples including planetary protection protocols.	Working in Space
P1-19	Evaluate the nature and distribution of volatiles and extraction techniques and decide on their potential use in human exploration architecture.	Working in Space
P1-20	Demonstrate crew operations with a natural space object in a low gravity environment.	Working in Space
P1-21	Enable science community objectives in deep space.	Working in Space
P1-22	Enable commercial and international partnership objectives in deep space.	Working in Space
P1-23	Demonstrate ability to use an uncrewed capability to enable science, technology, and exploration.	Working in Space
P1-24	Demonstrate and evaluate exploration medical capabilities.	Staying Healthy
P1-25	Demonstrate and evaluate human flight operations crew physiological well-being in deep space.	Staying Healthy
P1-26	Demonstrate and evaluate human flight operations crew psychological well-being in deep space.	Staying Healthy
P1-27	Demonstrate and evaluate human health countermeasures.	Staying Healthy
P1-28	Evaluate the effects of deep space on complex organisms, plants, food, pharmaceuticals, and animal models.	Staying Healthy

Source: NASA OIG analysis of NASA HEOMD-001.

Table 11: Phase 2 Objectives: Cislunar Validation of Exploration Systems

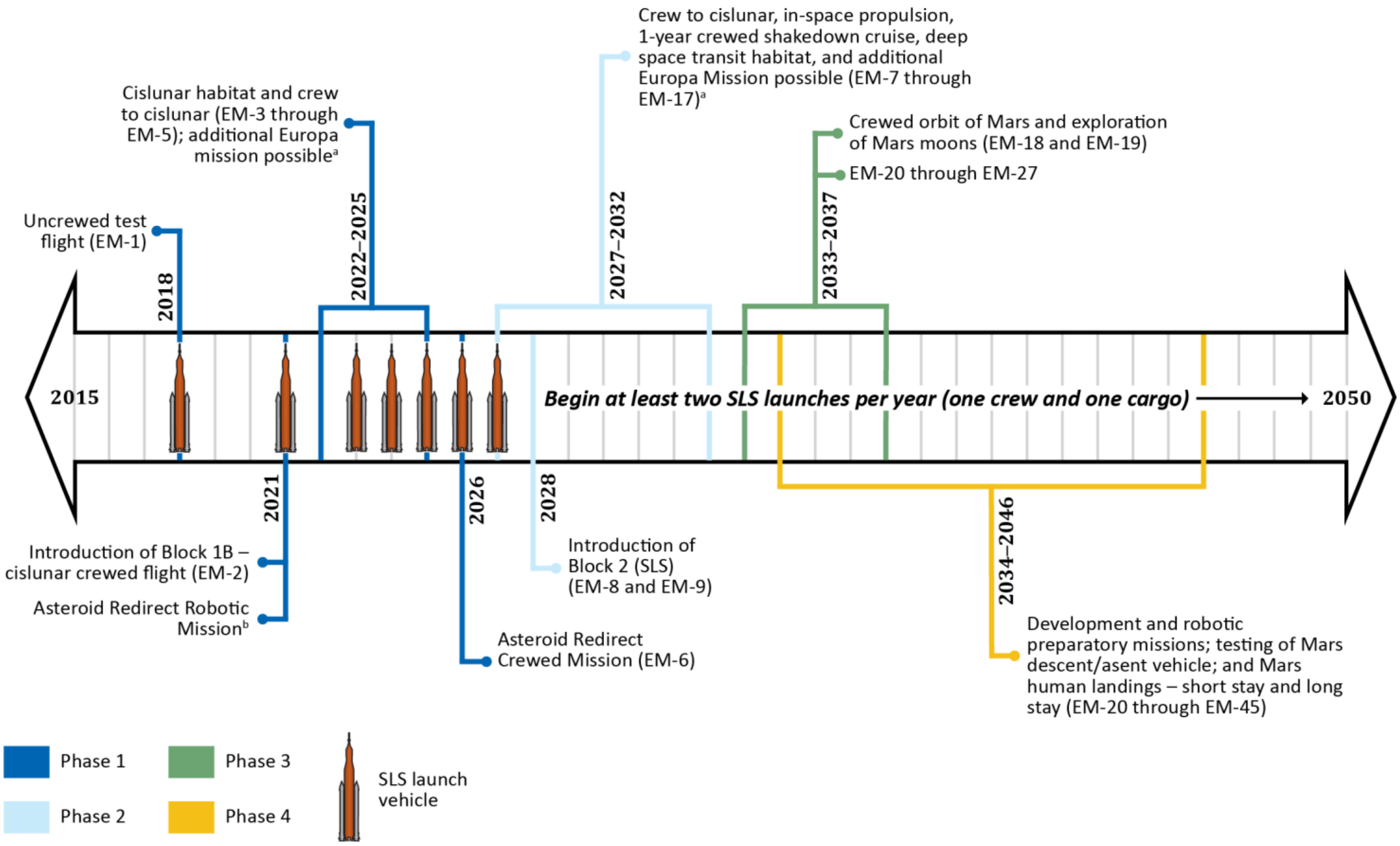
Objective Number	Requirement Description	Objective Category
P2-01	Demonstrate SLS Block 2 trans-lunar injection performance.	Transportation
P2-02	Demonstrate SLS Block 2 co-manifested capability and cargo only capability.	Transportation
P2-03	Validate long-duration, long-distance in-space propulsion capabilities, including refueling and long-term fuel storage.	Transportation
P2-04	Validate high bandwidth and high data rate deep space communication capabilities to support real-time high resolution video.	Working in Space
P2-05	Validate capability and reliability of Environmental Control and Life Support System to support a Mars class mission including dormancy periods.	Working in Space
P2-06	Validate Mars class habitation system transition between crewed and uncrewed operations.	Working in Space
P2-07	Demonstrate use of the habitat capability to conduct remote robotic operation of systems.	Working in Space
P2-08	Validate Mars habitat integrated system performance and reliability in deep space.	Working in Space
P2-09	Demonstrate the ability to conduct extended missions in deep space leading to a Mars class transit duration.	Working in Space
P2-10	Validate maintenance and repair capabilities in deep space with limited or no resupply.	Working in Space
P2-11	Evaluate capabilities to produce and store resources in-situ for ascent propellant and life support consumables in deep space.	Working in Space
P2-12	Enable science community objectives in deep space.	Working in Space
P2-13	Enable commercial and international partnership objectives in deep space.	Working in Space
P2-14	Validate exploration medical capabilities in deep space.	Staying Healthy
P2-15	Validate human flight operations crew physiological well-being on Mars class missions.	Staying Healthy
P2-16	Validate human flight operations crew psychological well-being on Mars class missions.	Staying Healthy
P2-17	Demonstrate Mars flight mass and form factor exercise system capability and reliability.	Staying Healthy

Source: NASA OIG analysis of NASA HEOMD-001.

APPENDIX E: JOURNEY TO MARS MISSION PLANNING

To achieve the goals for the Journey to Mars plan, NASA is scheduling to launch EM-1 in November 2018, working towards an EM-2 launch in 2021, and initiating mission planning through the 2040s. All launch dates beyond EM-2 are notional and based on an assumed launch cadence of one SLS per year with a potential to surge to two or three launchers per year. Using the general objectives of Phases 1 through 4 of the Journey to Mars plan and HEOMD's assumed SLS launch rate, the following mission set can be extrapolated for missions through the 2040s (see Figure 12).

Figure 12: Journey to Mars Mission Planning



Source: NASA OIG analysis of HEOMD mission planning assumptions and Journey to Mars phases.

[a] While not part of the Journey to Mars plans, the one or two proposed Europa missions could impact the SLS mission cadence during the early 2020s.

[b] The ARRM has not selected a launch vehicle as of 2017 but the mission requirements are compatible with the Delta IV Heavy, Falcon Heavy, or SLS launch vehicles.

APPENDIX F: KEY SYSTEMS FOR THE JOURNEY TO MARS PLAN

PHASE 1 Key Systems (Early 2020s)

During Phase 1 of the Journey to Mars plan, NASA will develop and test the Block 1B version of the SLS, solar electric propulsion, and a cislunar habitat. For its second launch in 2021, SLS Block 1B will utilize the EUS to increase the SLS's upmass capability to 105 metric tons for low Earth orbit and 40 metric tons for cislunar orbit. On September 7, 2016, NASA set the baseline for the Phase 1 objectives for the Journey to Mars. This baseline will inform and shape the mission objectives for EM-2 through EM-7, including the first habitation module scheduled to launch in the early to mid-2020s. The key requirements for Phase 1 are (1) SLS, (2) Orion, (3) GSDO, (4) Asteroid Redirect Mission, and (5) a cislunar habitation module.

Space Launch System

The SLS will be the next large heavy launch vehicle to transport U.S. cargo and crew to cislunar and Mars orbits.

Space Launch System

NASA Lead	NASA Lead Center	Cost as of FY 2016[a]
ESD SLS Program	Marshall Space Flight Center	$7.9 billion

Launch Schedule	Cumulative Estimated Costs
November 2018 (EM-1)	$12.1 billion[b]
August 2021 (EM-2)	$19.1 billion[b]
1+ Launch/Year (Beyond EM-2)	Undetermined[c]

Proposed System Timeline

TD[d] | Formulation | Implementation

- **2010** Program funded
- **2015** CDR complete
- **2018** Block 1 launch (EM-1)
- **2021** Block 1B launch (EM-2)
- **2023** EM-3 launch; at least one launch per year thereafter

Performance Requirements

Cislunar Missions	Mars Missions	Upmass Goal	Cargo Payload Fairing
Up to two launches per year	Up to three launches per year	130 metric tons to low Earth orbit; 52 metric tons to cislunar orbit	Up to 10 meters wide

[a] Costs as of FY 2016 include costs starting in FY 2012 through the end of FY 2016. If we include the costs appropriated to the SLS Program during the Constellation Program transition year of FY 2011, the total costs through the end of FY 2016 would be $9.4 billion.

[b] Estimated costs are all cumulative program costs from FY 2012 through the launch date, adjusted to the closest fiscal year. For the EM-1 launch date of no later than November 2018, estimated costs are through FY 2018 ending on September 30, 2018. For the EM-2 launch date of August 2021, estimated costs are through FY 2021 ending on September 30, 2021. All costs include both system development and program integration and support. These costs include activities beyond the current missions.

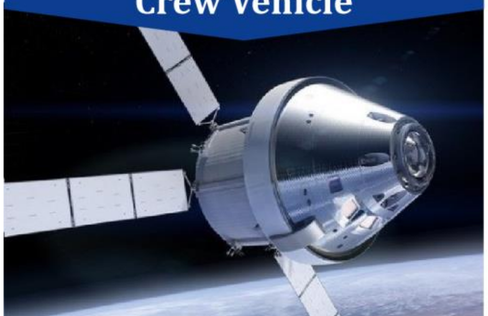
[c] Official cost estimates for the Journey to Mars beyond EM-2 are undetermined for the SLS Program. A JPL human exploration of Mars study conducted in 2015 and updated in 2016 estimated SLS costs to be $131 billion from 2011 through a long-duration surface stay in 2046.

[d] Technology Development (TD).

Orion Multi-Purpose Crew Vehicle

Orion is a human spacecraft for deep space exploration designed for reentry into Earth's atmosphere at high velocities.

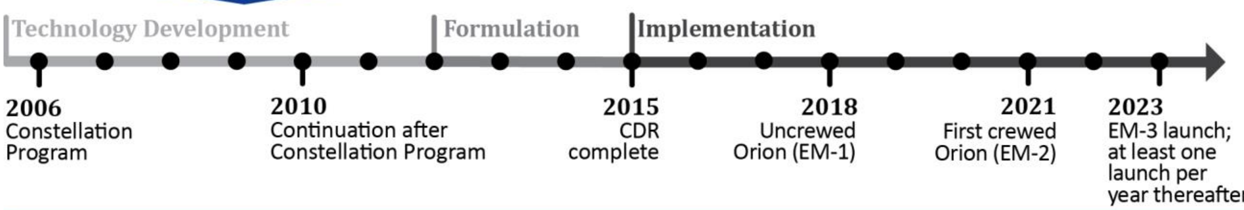
Orion Multi-Purpose Crew Vehicle



NASA Lead	NASA Lead Center	Cost as of FY 2016
ESD Orion Program	Johnson Space Center	$6.1 billion[a]

Launch Schedule	Cumulative Estimated Costs
November 2018 (EM-1)	$8.7 billion[b]
August 2021 (EM-2)	$12.7 billion[b]
1+ launch/year (beyond EM-2)	Undetermined[c]

Proposed System Timeline



Performance Requirements			
Crew Size 4	Habitat Volume 316 cubic feet	Mission Duration Up to 21 days	Earth Reentry Up to cislunar orbit

[a] Costs as of FY 2016 include costs starting in FY 2012 through the end of FY 2016. If we include the costs spent during the Constellation Program starting in FY 2006 and through the transition year of FY 2011, the totals costs through the end of FY 2016 would be $11.8 billion.

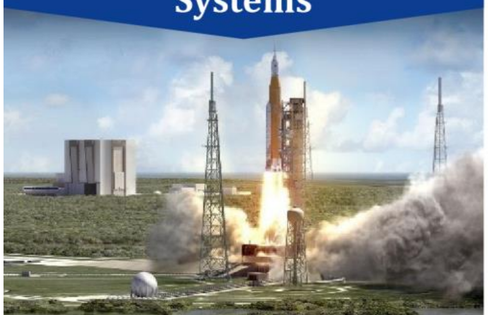
[b] Estimated costs are all cumulative program costs from FY 2012 through the launch date, adjusted to the closest fiscal year. For the EM-1 launch date of no later than November 2018, estimated costs are through FY 2018 ending on September 30, 2018. For the EM-2 launch date of August 2021, estimated costs are through FY 2021 ending on September 30, 2021. All costs include both system development and program integration and support. These costs include activities beyond the current mission.

[c] Official cost estimates for the Journey to Mars beyond EM-2 are undetermined for the Orion Program. A JPL human exploration of Mars study conducted in 2015 and updated in 2016 estimated Orion costs to be $43 billion from 2011 through a long-duration surface stay in 2046.

Ground Support Development and Operations

GSDO is responsible for preparing Kennedy to process and launch the integrated SLS/Orion by developing the necessary ground systems, infrastructure, and operational approaches. GSDO is comprised of the Exploration Ground Systems and the 21st Century Launch Complex.

Exploration Ground Systems



NASA Lead	NASA Lead Center	Cost as of FY 2016[a]
ESD Exploration Ground Systems	Kennedy Space Center	$1.6 billion

Launch Schedule	Cumulative Estimated Costs
November 2018 (EM-1)	$2.6 billion[b]
August 2021 (EM-2)	$4.2 billion[b]
1+ launch/year (beyond EM-2)	Undetermined[c]

Proposed System Timeline

TD[d] | Formulation | Implementation

- **2010** New funding after transition from Constellation Program
- **2015** CDR complete
- **2018** Block 1 launch (EM-1)
- **2021** EM-2 launch; completion of ground system upgrades
- **2023** EM-3 launch; at least one launch per year thereafter

Performance Requirements

Launch Capacity	Key Infrastructure
1 per year, surging to 3 per year	Vehicle Assembly Building, Mobile Launcher, Crawler-Transport, Launch Pad 39B, and the Space Command and Control System

[a] Costs as of FY 2016 include costs starting in FY 2012 through the end of FY 2016. If we include the costs spent during the Constellation Program transition year of FY 2011, the total costs through the end of FY 2016 would be $1.8 billion.

[b] Estimated costs are all cumulative program costs from FY 2012 through the launch date, adjusted to the closest fiscal year. For the EM-1 launch date of no later than November 2018, estimated costs are through FY 2018 ending on September 30, 2018. For the EM-2 launch date of August 2021, estimated costs are through FY 2021 ending on September 30, 2021. All costs include both system development and program integration and support. These costs include activities beyond the current missions.

[c] Official cost estimates for the Journey to Mars beyond EM-2 are undetermined for the GSDO Program. A JPL human exploration of Mars study conducted in 2015 and updated in 2016 included GSDO costs in the SLS costs and not separately.

[d] Technology Development (TD).

Asteroid Redirect Mission

The Asteroid Redirect Mission has two segments – one robotic and one crewed – designed to capture part of an asteroid and eventually return samples to Earth. The ARRM, scheduled to launch in 2021, will demonstrate solar electric propulsion systems before landing on an asteroid, capturing a boulder, and returning it to cislunar orbit. The Asteroid Redirect Crewed Mission planned for 2026 will send a crewed Orion spacecraft with unique mission kits to dock with the robotic vehicle in cislunar orbit to collect samples from the boulder and safely return to Earth.

Asteroid Redirect Mission

NASA Lead	NASA Lead Center	Cost as of FY 2016
HEOMD's Asteroid Redirect Mission	Headquarters, Jet Propulsion Laboratory, and Johnson Space Center	$26.8 million

	Estimated Launch Date	Estimated Project Costs
Asteroid Redirect Robotic Mission	No earlier than 2021	$1.8 billion[a]
Asteroid Redirect Crewed Mission	No earlier than 2026	Undetermined

Proposed Timeline

Technology Development | Formulation | Implementation

- **2013** Start of Solar Electric Propulsion Demonstration Project (STMD), and Request for Information for Asteroid Redirect Mission
- **2017** Preliminary Design Review (ARRM)
- **2021** Launch of Asteroid Redirect Mission
- **2026** Crewed mission to asteroid boulder in cislunar orbit

Performance Requirements

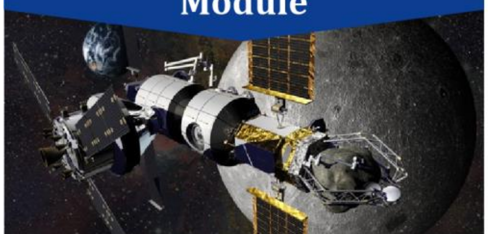
Asteroid Redirect Robotic Mission Project	**High-Powered Solar** 50 kilowatts (STMD)	**Electric Propulsion** 40 kilowatts (STMD)	**Purpose** Validate solar electric propulsion systems; capture asteroid boulder and remove to cislunar orbit by 2026
Asteroid Redirect Crewed Mission Project	**Mission Reference** 26 days with a 2-person crew	**Extra-Vehicular Activities** A minimum of two, 4-hour spacewalks	**Purpose** Dock with robotic vehicle and asteroid; crewed mission in cislunar space to collect samples and return to Earth

[a] Estimated project costs include design, development, testing, and evaluation for the mission and estimated launch vehicle costs and do not include possible mission operations costs.

Cislunar Habitation Module

By the mid-2020s, NASA plans to launch a habitat into cislunar orbit capable of supporting a four-person crew for 60 days to test and validate short-duration and deep space capabilities. In August 2016, NASA selected six U.S. companies to develop ground prototypes of cislunar habitation modules for completion during FY 2018. These companies' efforts were discussed in the main body of this report.

Cislunar Habitation Module



Source: Lockheed Martin.

NASA Lead	NASA Lead Center	Cost as of FY 2016
HEOMD's Advanced Exploration Systems	Johnson Space Center	$26.8 million

Estimated launch date	Early 2020s
Estimated program costs	Undetermined[a]

Proposed System Timeline

Technology Development — Formulation — Implementation

- **2015–2017** Life support hardware on ISS, autonomy and communication demonstrations, NextSTEP Award for cislunar habitation concepts, Bigelow Expandable Augmentation Module on ISS, fire safety demonstration on ISS missions, and NextSTEP award for ground prototypes
- **2018/2019** Development of cislunar habitation module based on NextSTEP awards
- **Early 2020s** Launch of cislunar habitation module during Phase 1 of Journey to Mars

Performance Requirements

Crew	Mission Duration	Selection of Habitat System	Purpose
4	Up to 60 days; more than 1 year dormant	2018	Support crew for short duration stays in cislunar space

[a] Official cost estimates for the Journey to Mars beyond EM-2 are undetermined for the Cislunar Habitat Module. A JPL human exploration of Mars study conducted in 2015 and updated in 2016 estimated Cislunar Habitat Module costs to be $3.5 billion through the completion of a long-duration surface stay.

Phase 2 Key Systems (Mid-2020s)

The introduction of the Block 2 version of the SLS (130 metric ton upmass) by 2028 or later marks the beginning of Phase 2 for the Journey to Mars. During this phase, the Agency will focus on validating in-space propulsion systems and a deep space transit habitat within cislunar space before conducting a year-long crewed mission in deep space.[64] For Block 2 of the SLS, NASA plans to replace the existing five-segment solid booster hardware with a new Advanced Booster design using either liquid or solid propulsion to reach its required 130 metric ton upmass capability to low Earth orbit. While no configuration has been selected, HEOMD officials stated the SLS Core Stage has sufficient structural margin to adapt to the boosters with increased power but design changes may require modifications to the ground systems infrastructure. The key additional requirements for Phase 2 are (1) in-space transportation architecture and (2) long-duration deep space transit habitat.

[64] The target of the 1-year-long crewed mission has not been decided but some architectures keep the mission within cislunar orbit.

In-Space Transportation Architecture

By the early 2020s, NASA plans to select an in-space transportation architecture for both cargo and crew, choosing between a chemical propulsion, solar electric propulsion, and/or hybrid system.[65]

In-Space Transportation Architecture

NASA Lead	NASA Lead Center	Cost as of FY 2016
HEOMD and STMD	Multiple Centers	n/a[a]

Estimated need-by date	Late 2020s
Estimated program costs	Undetermined[b]

Proposed System Timeline

Technology Development | Formulation | Implementation

2013–2015 Solar Electric Propulsion Demonstration Project (STMD), and NextSTEP awards for 100 kilowatt SEP demonstration

2020 Selection of In-Space Architecture

2021 Launch of Solar Electric Demonstration (ARRM)

Late 2020s Demonstration of In-Space Propulsion System

In-Space Transportation Options and Requirements

Solar Electric Propulsion	Solar Electric and Oxygen Methane Propulsion	Solar Electric and Hypergolic Propulsion	Nuclear Thermal Propulsion
50 kilowatt demonstration on ARRM, increasing to 150–300 kilowatts for Mars missions	one 190 kilowatt class solar array; 150 kilowatt propulsion system; oxygen and methane engine	two 200 kilowatt class solar arrays; two 150 kilowatt propulsion systems; hypergolic engine	Nuclear reactor heats propellant to improve engine efficiencies and reduce mass

[a] NASA's future in-space transportation architecture activities are not organized as an official program or project because the selection is not needed until roughly 2020. Currently, STMD and AES are both carrying out technology projects related to in-space transportation, such as STMD's solar electric propulsion or AES's ground testing of a 100 kilowatt electric propulsion system, to better inform the Agency's decision process.

[b] Official cost estimates for the Journey to Mars beyond EM-2 are undetermined for the in-space transportation architecture because technology development is still ongoing and an architecture approach will not be selected until at least 2020. A JPL human exploration of Mars study conducted in 2015 and updated in 2016 adopted as their in-space architecture hypergolic propulsion for crew missions and solar electric propulsion for cargo missions. This architecture, which is substantially different than NASA's current trade studies that use Oxygen and Methane propulsion or a hybrid solar electric propulsion with hypergolic propulsion, was estimated to cost at least $29 billion through the completion of a long-duration surface stay.

[65] Chemical propulsion will allows for faster transit times to Mars with a trade-off of less useable cargo or crew capability. Solar electric propulsion can transport mass slowly with increased payload mass. A hybrid system could use both systems on one vehicle or potentially separate the payloads by using chemical propulsion for crewed missions and solar electric propulsion for uncrewed cargo.

Long-Duration Deep Space Transit Habitat

To build on the cislunar habitat tested during Phase 1, NASA plans to develop and test a deep space transit habitat system capable of supporting a crew of four for 1,100 days for Mars missions.

Long-Duration Deep Space Transit Habitat

NASA Lead	NASA Lead Center	Cost as of FY 2016
HEOMD's Advanced Exploration Systems	Multiple Centers	n/a[a]

Estimated need-by date	Late 2020s
Estimated program costs	Undetermined[b]

Proposed System Timeline

Technology Development | Formulation | Implementation

2016
Cislunar Habitat development activities (NextSTEP and Bigelow Expandable Activity Module) and Deep Space Habitat Trade Studies (Evolvable Mars Campaign)

Late 2020s to Early 2030s
Demonstration of Deep Space Habitat in Phase 2 of the Journey to Mars and Crewed Long Duration Shakedown Cruise

Performance Requirements

Capabilities	Mass Limit	Purpose
4 crew, up to 1,100 days	21 metric tons	Operate and live for long duration Mars transits

[a] NASA does not have an official long-duration deep-space habitat project or program and there are no official costs as of FY 2016.

[b] Official cost estimates for the long-duration deep-space habitat module for the Journey to Mars are undetermined. A JPL study conducted in 2015 and updated in 2016 for the human exploration of Mars estimated the long-duration deep-space habitat prototype and module costs to be roughly $23 billion.

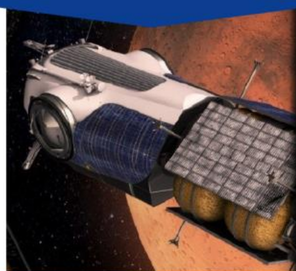
Phase 3 Key System (Late 2020s to Early 2030s)

Phase 3 will combine the validated systems from Phase 2 activities to conduct crewed missions beyond the Moon and within Mars orbit. These long-duration missions over 2 years will demonstrate the in-space propulsion architecture, deep space habitat, and long-term human presence in deep space. While still notional, initial planning documents have targeted Phase 3 missions to the Mars moon Phobos for landing a crew and conducting extravehicular activities on the surface. The possible key additional requirement for Phase 3 is the Mars Taxi concept.

Mars Taxi Concept

NASA plans to develop and test a Mars Taxi vehicle to move up to four crew between high- and low-Mars' orbits. Reusable and refuelable, the Mars Taxi will allow for repeated trips between deep space transportation vehicles traveling in high-Mars orbit to destinations on the Mars moons or surface. The Mars moon habitat will validate crew systems for up to four humans for 500 days and extravehicular activities outside on the moon surface in preparation for Mars surface landing.

Mars Taxi Concept



NASA Lead	NASA Lead Center	Cost as of FY 2016
HEOMD's Advanced Exploration Systems	Multiple centers	n/a[a]

Estimated launch date	Early 2030s
Estimated program costs	Undetermined[b]

Proposed System Timeline

Technology Development | Implementation

2016
Trade studies for Mars Taxi architecture

Early 2030s
Transport crew to and from Mars moons from deep space habitat module

Late 2030s
Transport lander and crew to low-Mars orbit for a long duration surface stay

Early 2040s
Transport lander and crew to low-Mars orbit for a long duration surface stay

Performance Requirements

Capabilities	Mass Limit	Systems	Purpose
4 Crew for up to 2.5 days, roughly every 2 years	14 metric tons	Solar power, refuelable and reuseable	Transport crew and cargo from high-Mars orbit to moons or low-Mars orbit

[a] Some planning architectures do not use the Mars Taxi system so this key system is notional and not needed until the early 2030s. Although there are technology activities ongoing to better understand system trades needed for transportation within Mars orbits, there are no official program or project costs.

[b] Official cost estimates for the Mars Taxi for the Journey to Mars are undetermined. A JPL study conducted in 2015 and updated in 2016 for the human exploration of Mars did not include a Mars Taxi system in its architecture.

Phase 4 Key Systems (Mid-2030s to Late 2030s)

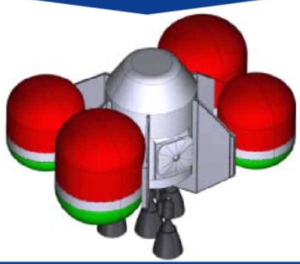
Phase 4 is divided into system development and robotic preparatory missions and human landing on the Mars surface during the late 2030s or early 2040s. The first part of Phase 4 will test and validate the Mars lander, surface habitat and power systems, rovers, and ascent vehicle architecture. The second part of Phase 4 will land humans on the surface of Mars possibly for a short duration followed by second, longer-duration mission with a larger habitat. The key additional requirements for Phase 4 are (1) Mars lander and ascent vehicle and (2) Mars surface habitat.

Mars Lander and Ascent Vehicle

During the first part of Phase 4, the Mars lander will transport 20 to 30 metric ton payloads to the Mars surface at reentry speed up to 4.7 kilometers per second using an inflatable heat shield or parachutes and rocket engines to slow the landing. The Mars rover will provide mobility for up to four crew and 3 tons of cargo within a range of 90 kilometers. The second part of Phase 4 will include the ascent vehicle, which was initially tested and developed during Phase 3. The ascent vehicle will use locally sourced oxygen and methane to launch four crew and a maximum 250 kilogram payload from the Mars surface to orbit. Then the vehicle will dock with the in-space propulsion and deep space habitat in Mars orbit to travel back to Earth orbit where the Orion spacecraft will safely land the crew back on Earth's surface.

Mars Lander and Ascent Vehicle

NASA Lead	NASA Lead Center	Cost as of FY 2016
STMD (landing) AES (ascent)	Multiple centers	n/a[a]



Estimated launch date	Early 2030s
Estimated program costs	Undetermined[b]

Proposed System Timeline

Technology Development — Implementation

2016
Low Density Supersonic Decelerator (STMD), Supersonic Retro Propulsion (STMD/SpaceX), Hypersonic Inflatable Aerodynamics Decelerator (STMD), flight test of Morpheus Lander (AES), and Oxygen and Methane Propulsion (AES)

Early 2030s
Demonstration of landing technology during robotic missions

2030s
Demonstration of propulsion system during Mars moons missions

Late 2030s
Land crew and cargo on Mars surface and return to orbit

Performance Requirements

Entry Capabilities	Mass Limit	Mars Ascent Propulsion	Purpose
Up to 4.7 kilometers per second using propulsion, parachutes, and inflatable shields	40 to 60 metric tons (orbit) 20 to 30 metric tons (surface)	35 metric tons upmass using oxygen and methane from local resource production	Land crew and cargo on Mars surface and return to orbit

[a] The Mars Lander and Ascent Vehicle architecture is not needed until the early 2030s and, although there are technology activities ongoing to better understand system trades, there are no official program or project costs.

[b] Official cost estimates for the Mars Lander and Ascent Vehicle for the Journey to Mars are undetermined. A JPL study conducted in 2015 and updated in 2016 for the human exploration of Mars estimated Mars Lander and Ascent Vehicle costs to be $44 billion through the completion of a long-duration surface stay in 2046.

Mars Surface Habitat

The surface habitation module will house up to four crew for up to 500 days and will require a power system with a 40-kilowatt capability, a minimum of 20 kilowatts of power to convert carbon dioxide to oxygen for life support and propulsion, 15-year lifetime, and dormancy capability of up to 5 years.

Mars Surface Habitat

NASA Lead	NASA Lead Center	Cost as of FY 2016
HEOMD's Advanced Exploration Systems	Multiple centers	n/a[a]

Estimated launch date	Mid-2030s
Estimated program costs	Undetermined[b]

Proposed System Timeline

Technology Development — Implementation

2016
Surface power studies (STMD)

Early 2020s
In-situ demonstration on Mars surface (Mars 2020 Mission)

Late 2030s
Deploy habitat, power, and in-situ systems on Mars surface

Performance Requirements

Crew	Habitat Mass Limit and Surface Power	Surface Rover	Oxygen Production	Purpose
4 crew, up to 500 days	11 metric tons and 40 kilowatts	Up to 4 crew and 3 metric tons, 90 kilometer range (AES) (STMD)	Less than 1 metric ton; 20 kilowatts power (STMD)	Provide power, mobility, resource production, and habitat on Mars surface

[a] The Mars Surface Habitat architecture is not needed until the mid-2030s and, although there are technology activities ongoing to better understand system trades, there are no official program or project costs.

[b] Official cost estimates for the Mars Surface Habitat architecture for the Journey to Mars are undetermined. A JPL study conducted in 2015 and updated in 2016 for the human exploration of Mars estimated Mars Surface Habitat costs to be $48 billion through the completion of a long-duration surface stay in 2046 and did not include advanced surface power or oxygen production as part of its architecture.

APPENDIX G: PROGRAM LIFE-CYCLE AND PROJECTED COSTS FOR SLS, ORION, AND GSDO PROGRAMS

Figures 13, 14, and 15 show the life-cycle and projected costs for each of the three main systems – SLS, Orion, and GSDO – through each program's life-cycle review process. According to NASA guidance, the SDR is the initial review to examine the proposed program architecture and the flow down to the functional elements of the system.[66] The PDR demonstrates that the overall program preliminary design meets all requirements with acceptable risk and within the cost and schedule constraints and establishes the basis for proceeding with detailed design. The CDR demonstrates that the maturity of the program's design is appropriate to support proceeding with full-scale fabrication, assembly, integration, and testing, and that the technical effort is on track to complete the flight and ground system development and mission operations to meet overall performance requirements within the identified cost and schedule constraints. The rocket symbol indicates the anticipated launch schedule for EM-1 during the time each review was conducted. Since the programs based their costs on expected appropriations for that given year, the yellow line on each chart shows the actual and projected appropriations.

When examining the costs over time for SLS, Orion, and GSDO there are several key considerations when interpreting these figures:

1. For SLS, the SDR and PDR focused on the SLS Block 1 vehicle configuration and included the Interim Cryogenic Propulsion Stage. It was intended that the Block 1 SLS vehicle and ICPS would be used for EM-1 and EM-2, and that the Block 1B configuration which includes the EUS would be used on EM-3 and beyond. The SLS CDR focused on the Block 1 configuration. Congress directed that the EUS be incorporated earlier, on EM-2. As such, SLS has thus far held an SDR and PDR for the EUS.
2. For Orion, because much of the early development was completed under the Constellation Program, we have only reflected the updated PDR completed in 2014 and the CDR data compiled from the FY 2017 program budget estimates. In addition, the updated PDR only included costs through EM-2 with a target launch of 2021 and did not show an extended life cycle. However, the CDR data and the actual appropriation and projected budget include costs beyond EM-2.
3. GSDO life cycles are similar for comparison as they each only reflect costs for the first mission and do not include the upgrades that will be necessary for EM-2. However, the actual appropriation and projected budget include costs for EM-2 and subsequent missions.

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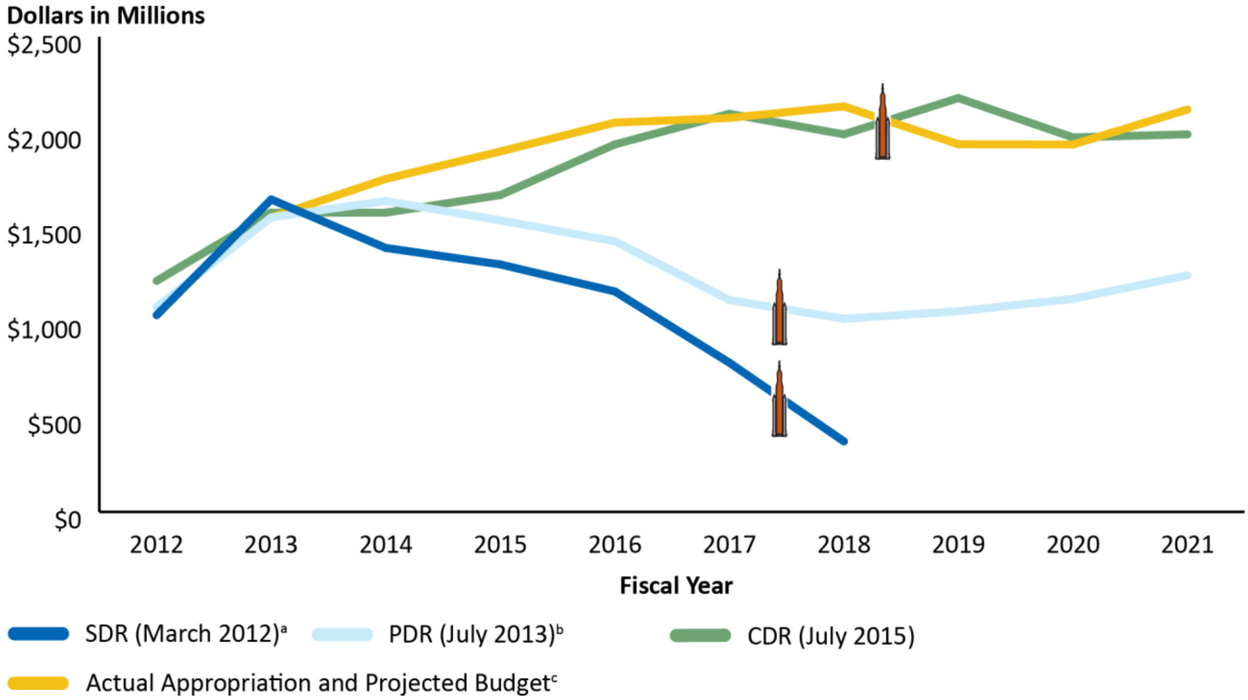
[66] The purposes of the life-cycle reviews are explained in NASA/SP-2007-6105 Rev1, "NASA Systems Engineering Handbook," December 2007.

Figure 13: SLS Life-Cycle and Projected Costs



Source: NASA OIG analysis of NASA approved SDR, PDR, and CDR documentation, along with the actual appropriation and the projected budget from the OCFO.

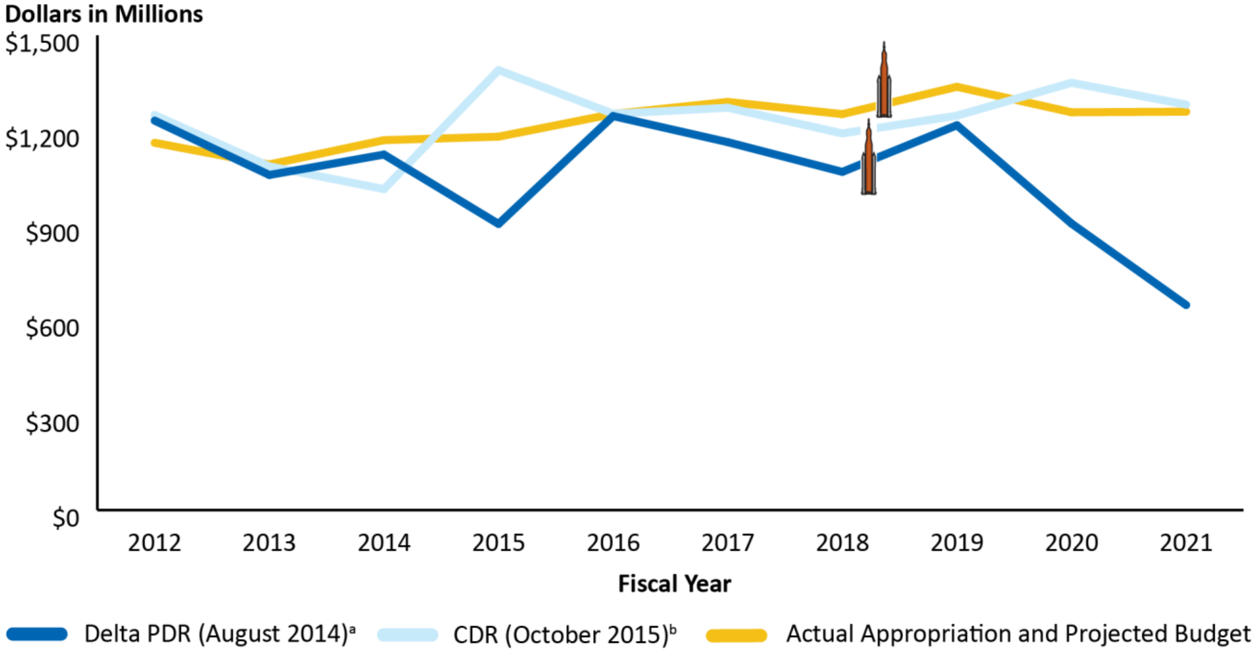
Note: While the SDR only included costs through EM-1, the PDR and CDR included costs through EM-2, and the actual appropriation and projected budget include costs for EM-2 and subsequent missions.

[a] For SDR, we included the program reserve amount in the total, including reserves is consistent with the costs in the PDR and CDR. The SDR did not include data for FYs 2019 through 2021.

[b] For PDR, we included the CDR amounts for FYs 2012 and 2013 since the document did not include data for those years.

[c] For actual appropriations in FY 2012, we subtracted $311.3 million of preformulation costs because the SDR, PDR, and CDR did not include preformulation costs.

Figure 14: Orion Life-Cycle and Projected Costs



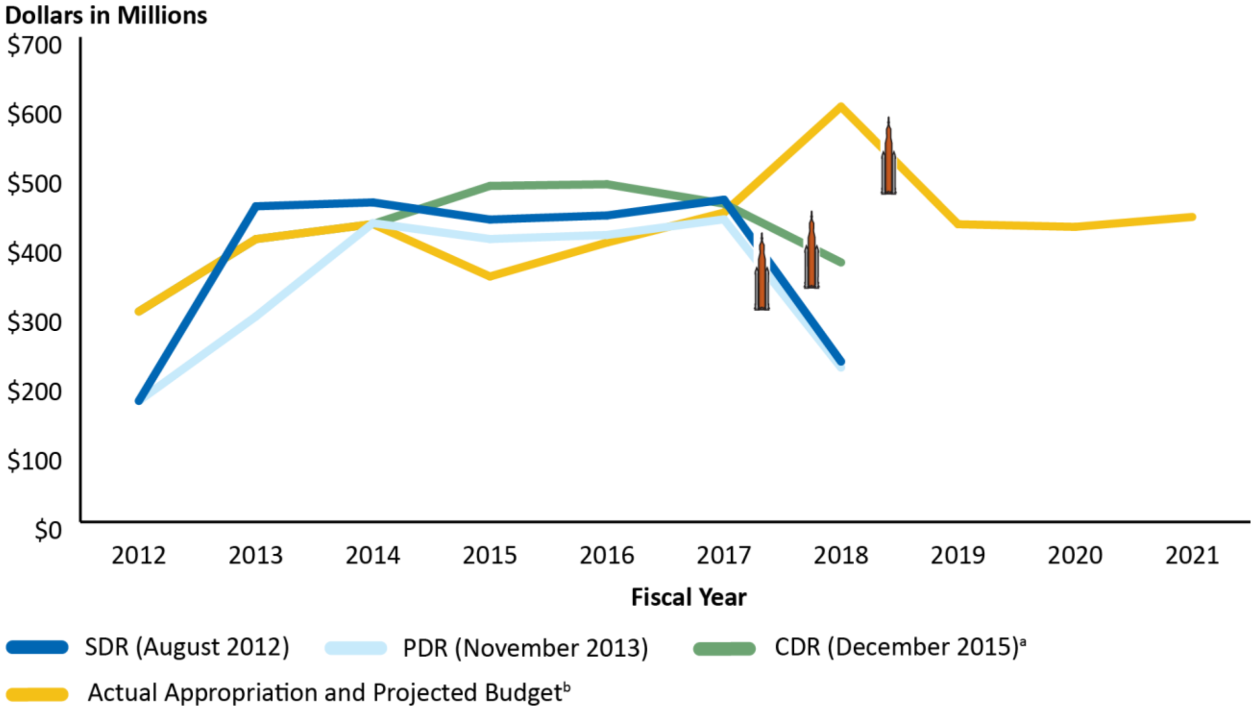
Source: NASA OIG analysis of NASA approved delta PDR and CDR documentation, along with the actual appropriation and the projected budget from the OCFO.

Note: The CDR data and the actual appropriation and projected budget include costs beyond EM-2.

[a] The initial SDR and PDR were completed during the Constellation Program in 2008 and 2010, respectively. The PDR data included in the figure is the delta PDR.

[b] The CDR data was not readily available so we used the Orion's Planning, Programming, Budgeting, and Execution 2017 Program Manager's Recommend Submit to NASA's HEOMD, dated December 2015, which is close to the CDR date of October 2015.

Figure 15: GSDO Life-Cycle and Projected Costs



Source: NASA OIG analysis of NASA approved SDR, PDR, and CDR documentation, along with actual appropriation and projected budget from the OCFO.

Note: The SDR, PDR, and CDR did not include data for FYs 2019 through 2021.

[a] For CDR, we included the actual appropriation for FYs 2012 through 2014 since the document did not include data for those years.

[b] For actual appropriations in FY 2016, we subtracted $8 million of preformulation costs. The actual appropriation and projected budget includes costs for EM-2 and subsequent missions.

APPENDIX H: ESD REQUIREMENTS

Created in 2011 and last updated in 2016, HEOMD established a baseline document of ESD requirements for SLS, Orion, GSDO, and any other future related programs. While not actual program requirements, the ESD requirements form the basis for specific SLS, Orion, and GSDO program requirements. Table 12 is a summary of the 27 ESD requirements:

Table 12: ESD Requirements

Number	Requirement	Description
R-1	Earth Entry Velocity	The Orion spacecraft shall provide a direct Earth entry capability with reentry velocities up to 11.05 kilometers per second. This requirement only allows for reentry directly from cislunar orbit.
R-2	Orion Crew Size	The Orion spacecraft shall support a crew of two, three, or four with a demonstrable evolution path of up to six.
R-3	None	This requirement was retired in 2014 and is no longer used.
R-4	Orion Mission Duration	The Orion spacecraft shall provide a habitable environment of a crew of four for a minimum of 21 days.
R-5	Orion Lift-Off Control Mass	The Orion Spacecraft shall have mass no greater than 35,385 kilograms at lift-off and 26,520 kilograms at a trans-lunar injection based on a four-crew, 21-day loaded configuration.
R-6	Landing Recovery	GSDO must be able to recover the Orion spacecraft crew within 2 hours after landing within a designated area.
R-7	Post-Landing Survival	The Orion spacecraft must allow for crew survival for a minimum of 24 hours with the hatch closed in case of emergencies.
R-8	Cargo Return Mass	The Orion spacecraft must be capable of returning 100 kilograms of pressurized cargo with a crew of four or 250 kilograms with a crew of two or three.
R-9	Orion Service Module	The Orion service module must be configurable as a stand-alone element with the ability to perform autonomous maneuvers on-orbit.
R-10	Human-Rating	All elements of the SLS, Orion, and GSDO programs must be human-rated as defined in NASA Procedural Requirement 8705.2B, “Human-Rating Requirements for Space Systems.”
R-11	SLS Lift Capability	The SLS launch vehicle must be capable of delivering 70 metric tons to low Earth orbit using the Block 1 configuration and 105 metric tons using the Block 1B upgrades with a demonstrable path to 130 metric tons.
R-12	SLS Payload Dimensions	For Block 1B, SLS payloads may have a width of up to 7.5 meters and a volume up to 538 cubic meters. For Block 2, SLS payloads may have a width up to 9.1 meters and a volume up to 1,320 cubic meters. For cargo configurations, the payload fairing dimensions could reach 10 meters wide and 24.4 meters tall.
R-13	Orbit Insertion Accuracy	The SLS launch vehicle must accurately deliver its payload into low Earth orbit within certain allowances.
R-14	Optional ISS Crew Missions	The SLS, Orion, and GSDO programs must be capable of delivering crew to and from the ISS if other vehicles are unable to perform that function.

Number	Requirement	Description
R-15	Launch Rate	The SLS, Orion, and GSDO programs shall support one launch every 2 years with the ability to temporarily surge to three launches per year every 120 days.
R-16	Loss of Crew Risk	The ESD architecture shall limit the loss of crew risk to no greater than one lost life in a certain amount of missions (one lost life: X missions). For launch and ascent, the loss of crew risk must be no greater than 1:1,400 for Orion and 1:550 for SLS. For reentry, landing, and recovery, the loss of crew risk cannot be greater than 1:650.
R-17	None	Open, no requirement set yet.
R-18	None	Open, no requirement set yet.
R-19	None	Open, no requirement set yet.
R-20	Audio and Video Data	The ESD architecture shall provide audio and video data to the ground during missions, including in-cabin and external feeds.
R-21	None	Open, no requirement set yet.
R-22	SLS Secondary Payloads	The SLS launch vehicle shall be capable of transporting small secondary payloads within the adapter connecting Orion to the SLS second stage. The SLS Block 1 will have up to 17 secondary payloads for a total of 238 kilograms. The SLS Block 1B and Block 2 configurations will be capable of carrying secondary payloads up to 300 kilograms.
R-23	Orion Secondary Payloads	The Orion spacecraft shall be capable of transporting up to 382 kilograms on the service module.
R-24	Orion Propellant Tank Loading	The Orion spacecraft shall provide at least 8,602 kilograms of usable propellant.
R-25	SLS Trans-Lunar Injection Capability	The SLS launch vehicle shall deliver the following minimum metric tons of mass for trans-lunar injection capability. For Block 1B, a minimum of 37.3 (crewed) and 41.3 (cargo) metric tons. For Block 2, minimum of 41 (crewed) and 45 (cargo) metric tons.
R-26	Co-manifested Payloads	The SLS launch vehicle shall provide at least 286 cubic meters of useable volume for a co-manifested payload capability within the adapter connecting Orion to the SLS second stage. The width of the payload may taper from 8.4 to 5.5 meters wide and shall not exceed 10 meters tall.
R-27	Orion Control Mass With Docking Capability	The Orion spacecraft shall be capable of docking with a vehicle in space with a control mass no greater than 35,934 kilograms at lift-off and 27,025 kilograms at a trans-lunar injection based on a 4-crew, 21-day configuration.

Source: NASA OIG presentation of ESD Requirements. ESD 10002. September 7, 2016. Revision D.

Note: The SLS, GSDO, and Orion programs have more specific program requirements based on these general ESD Program Requirements.

Appendix I: Management's Comments

National Aeronautics and Space Administration
Headquarters
Washington, DC 20546-0001

APR 12 2017

Reply to Attn of: Human Exploration and Operations Mission Directorate

TO: Assistant Inspector General for Audits

FROM: Associate Administrator for Human Exploration and Operations

SUBJECT: Agency Response to OIG Draft Report "NASA's Plans for Human Exploration beyond Low Earth Orbit" (A-16-015-00)

NASA appreciates the opportunity to review and comment on the Office of Inspector General (OIG) draft report entitled, "NASA's Plans for Human Exploration Beyond Low Earth Orbit" (A-16-015-00).

Overall, the draft is a sound and balanced assessment of NASA's exploration plans to date and of the environment and associated challenges. The draft OIG report offers six recommendations, to which we respond below.

To increase the fidelity, accountability, and transparency of NASA's human exploration goals beyond low Earth orbit, OIG recommends the Associate Administrator for Human Exploration and Operations Mission Directorate (HEOMD):

Recommendation 1: Complete an integrated master schedule for the Space Launch System (SLS), Orion, and Ground Systems Development and Operations (GSDO) programs for the Exploration Mission (EM-2) mission.

Management's Response: Concur. An integrated master schedule exists for EM-1, and a draft version is available for EM-2. These schedules are very dynamic and often change with the critical path shifting between elements. They are regularly presented at NASA agency budget and planning reviews. We agree that a more formal high level process controlled schedule management is needed. Development of an initial, enterprise-level EM-2 schedule is contingent on a number of factors, including Fiscal Year (FY) 2017 appropriations, the FY 2018 President's Budget Request with out-year projections, typical challenges in fabrication and assembly new complex and spaceflight system developments, and assessment of the impacts of damage caused by the tornado that impacted SLS core stage production at the Michoud Assembly Facility in Louisiana on February 7, 2017. Once developed, this enterprise-level EM-2 schedule will evolve as necessary, including results from EM-1.

Estimated Completion Date: November 30, 2017.

Recommendation 2: Establish more rigorous cost and schedule estimates for the SLS and GSDO programs for the EM-2 mission mapped to available resources and future budget assumptions and independently reviewed by the Office of the Chief Financial Officer (OCFO).

Management's Response: Partially concur. NASA frequently updates planning for SLS, GSDO, and Orion to accommodate differences between requested and appropriated funding levels and impacts of Continuing Resolutions. The OCFO reviews these estimates before they are provided to the Office of Management and Budget and the Congress. These plans are also reflected in products such as the integrated enterprise schedules for EM-1 and EM-2 (see Management Response to Recommendation 1) and program-level schedules that are updated as necessary, including when funding levels are appropriated. However, NASA does not concur with developing mission-specific cost estimates beyond those made as part of the Agency Baseline Commitment for GSDO and SLS development for EM-1. It is unclear what decisions would be informed by a cost estimate for a specific flight. NASA uses cost and schedule estimates to manage development of spaceflight systems and constrain operations costs and is doing so for these programs. The enterprise is developing a program and not a series of missions. Further budget uncertainty is more of a concern to cost and schedule estimates. There is a direct linkage between budget availability and cost estimates. The phasing of funds from appropriations is driving the cost estimate variability.

Estimated Completion Date: Ongoing.

Recommendation 3: Establish objectives, need-by dates for key systems, and phase transition mission dates for the Journey to Mars.

Management's Response: Concur. NASA has already baselined an objectives document, *HEOMD-001 Human Exploration and Operations Exploration Objectives*, on September 16, 2016. This initial version baselines objectives for Phases 0, 1 and 2. HEOMD anticipates periodic updates to this document, both to refine objectives for these phases and add objectives for subsequent phases. This document also includes initial phase transition time frames, which will also be updated in future additions. Need dates for key systems and mission cadence and time frames will be captured in the exploration roadmap due to the Congress per the NASA Transition Authorization Act of 2017.

Estimated Completion Date: December 31, 2017.

Recommendation 4: Include cost as a factor in NASA's Journey to Mars feasibility studies when assessing various missions and systems.

Management's Response: Concur. Cost follows closely behind technical feasibility and architecture robustness as a figure of merit in assessing mission and system choices in NASA's evolving exploration architecture. Launch mass and number of launches required often serve also as proxy measures for cost; so also is schedule in the form of orbital transit times. Thus, not all trades where cost is a major factor are denominated in dollars. As some exploration architecture trades are intentionally left open to leave room for new technologies and partnerships, this will be an ongoing activity as some decisions are made when needed to support development timelines and others left open to allow for disruptive or higher performing technologies. This is a continual activity; the next update of NASA's plans will be the exploration roadmap due to the Congress in December 2017.

Estimated Completion Date: December 31, 2017.

To improve efforts at cost savings, OIG recommends the Associate Administrator for HEOMD:

Recommendation 5: Design a strategy for collaborating with international space agencies in their cislunar space exploration efforts with a focus on advancing key systems and capabilities needed for Mars exploration.

Management's Response: Concur. NASA has been in active discussion with current and potential partners in a number of forums. NASA and its International Space Station (ISS) partners are jointly studying cislunar architectures with the aim of informing respective governments' decisions on contributions to cislunar exploration capabilities. The NASA Administrator holds focused meetings with counterpart agency heads on exploration planning, capitalizing on existing venues such as the annual International Astronautical Congress and National Space Symposium meetings. The member space agencies of the International Space Exploration Coordinating Group are preparing a third edition of the Global Exploration Roadmap for release this fall. These efforts are continual, and each prospective partner nation or group of nations has its own processes and time frames for decision making.

Estimated Completion Date: Ongoing.

Recommendation 6: Incorporate into analyses of space flight system architectures the potential for utilization of private launch vehicles for transportation of payloads.

Management's Response: Concur. NASA has already done so in the establishment of the Commercial Resupply Services program for ISS cargo, the Commercial Crew Program for ISS crew transportation, the Collaboration for Commercial Space Capabilities, the Lunar CATALYST and NextSTEP Broad Area Announcement, and other initiatives. Commercial engagement in the human space is one of NASA's Exploration Principles. NASA is counting on commercial participation as one means to achieve sustainable deep space exploration. These efforts are continual and will also be reflected in the exploration roadmap due to the Congress in December 2017.

Estimated Completion Date: Ongoing.

We have reviewed the draft report for information that should not be publicly released. As a result of this review, we have not identified any information that should not be publicly released.

Once again, thank you for the opportunity to review and comment on the subject draft report. If you have any questions or require additional information regarding this response, please contact Michelle Bascoe on (202) 358-1574.

William H. Gerstenmaier

APPENDIX J: REPORT DISTRIBUTION

National Aeronautics and Space Administration

Acting Administrator
Acting Deputy Administrator
Chief of Staff
Associate Administrator for Human Exploration and Operations
    Deputy Associate Administrator for Exploration Systems Development
Associate Administrator for Science
Associate Administrator for Space Technology
Director, Jet Propulsion Laboratory
Director, Johnson Space Center
    Program Manager, Orion Multi-Purpose Crew Vehicle
Director, Kennedy Space Center
    Program Manager, Ground Systems Development and Operations
Director, Marshall Space Flight Center
    Program Manager, Space Launch System

Non-NASA Organizations and Individuals

Office of Management and Budget
    Deputy Associate Director, Energy and Space Programs Division

Government Accountability Office
    Managing Director, Office of Financial Management and Assurance
    Director, Office of Acquisition and Sourcing Management

Congressional Committees and Subcommittees, Chairman and Ranking Member

Senate Committee on Appropriations
    Subcommittee on Commerce, Justice, Science, and Related Agencies

Senate Committee on Commerce, Science, and Transportation
    Subcommittee on Space, Science, and Competitiveness

Senate Committee on Homeland Security and Governmental Affairs

House Committee on Appropriations
    Subcommittee on Commerce, Justice, Science, and Related Agencies

House Committee on Oversight and Government Reform
    Subcommittee on Government Operations

House Committee on Science, Space, and Technology
    Subcommittee on Oversight
    Subcommittee on Space

(Assignment No. A-16-015-00)