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# NASA'S MANAGEMENT OF THE ORION MULTI-PURPOSE CREW VEHICLE PROGRAM

September 6, 2016

Report No. IG-16-029





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# RESULTS IN BRIEF

## NASA's Management of the Orion Multi-Purpose Crew Vehicle Program

September 6, 2016

IG-16-029 (A-15-003-00)

### WHY WE PERFORMED THIS AUDIT

The Orion Multi-Purpose Crew Vehicle (Orion) will provide NASA with the capability to transport astronauts and cargo beyond low Earth orbit and is essential to achieving the Agency's goal of expanding human presence in the solar system. One leg of a three-part system that includes a heavy-lift rocket known as the Space Launch System (SLS) and a ground and launch support program known as Ground Systems Development and Operations (GSDO), the Orion vehicle has four major components: a crew module, a service module, a spacecraft adapter that connects the vehicle to the rocket, and a launch abort system. NASA began developing the vehicle now known as Orion in 2006 as part of the Agency's Constellation Program and had spent about \$3.7 billion on the effort when the Program was cancelled in 2010. Since then, NASA has spent about \$1 billion annually, or about 6 percent of its overall budget, on the Orion Program. According to current estimates, the Agency will have devoted approximately \$17 billion to the Program by the time Orion makes its first crewed flight in April 2023.

NASA has planned four missions for Orion: Exploration Flight Test-1, an uncrewed mission completed in December 2014 on a Delta IV rocket; Exploration Mission-1 (EM-1), a 22- to 25-day uncrewed mission scheduled for September 2018 that will be the first launch of the combined SLS-Orion system; Ascent Abort Test 2 scheduled for December 2019 when NASA plans to launch a mock-up of Orion to test its launch abort and other systems; and Exploration Mission-2 (EM-2), the first crewed flight for the combined system with a promised launch no later than April 2023. That said, the Orion Program has been working toward an August 2021 launch date for EM-2 in an effort to launch earlier and reduce costs.

In this audit, we assessed the status of the Orion Program, including whether NASA could improve management of the 63 technical, schedule, and cost risks identified by the Program ranging from Orion's flat funding profile to reuse of flight hardware. We also reviewed a sample of 18 risks, 9 of which Program officials identified as the most critical as of February 2015 and an additional 9 that fell into the Program's highest risk category. These risks were characterized as having a greater than 90 percent probability of occurring or, if they did, the potential to cause catastrophic loss of life, loss of vehicle, loss of mission, or cost \$500 million or more.

### WHAT WE FOUND

The Orion Program has met several key development milestones on the path to its first crewed mission, including a successful test flight in December 2014. However, much work remains, including evaluating options related to the delayed delivery of the European Service Module; continuing mitigation of seven critical risks while operating with a less-than-optimal budget profile for a developmental project; addressing a potential shortfall of \$382 million in reserves managed by its prime contractor; and successfully launching and recovering EM-1 after its uncrewed test flight scheduled for September 2018. At the same time, Program officials are working toward an optimistic internal launch date of August 2021 for EM-2 – 20 months earlier than the Agency's external commitment date of April 2023. While we understand the desire to meet a more aggressive schedule, this approach has led the Program to defer addressing some technical tasks to later in the development cycle, which in turn could negatively affect cost, schedule, and safety.

With respect to Orion's major outstanding risks, the Program has made progress in developing the launch abort system, crew module, and service module elements of the Orion vehicle, while mitigating 10 of the 18 sampled risks. However, as of July 2016 NASA was still working to further mitigate seven of the risks we reviewed, including changes to the Program's Test Plan and reuse of hardware on the vehicle that must be resolved prior to the launch of both EM-1 and EM-2.

Over its life, the Orion Program has experienced funding instability, both in terms of overall budget amounts and the erratic timing of receipt of those funds. In past reports, we noted that the most effective budget profile for large and complex space system development programs like Orion is steady funding in the early stages and increased funding during the middle stages of development. In contrast, the Orion Program's budget profile through at least 2018 was nearly flat and Program officials acknowledged that this funding trajectory increased the risk that costly design changes may be needed in later stages of development when NASA integrates Orion with the SLS and GSDO. In addition, Orion officials noted that the timing of appropriations affected their ability to perform work as planned, with the Program receiving its funding between 4 and 8 months after the start of fiscal years 2012 – 2016.

We also found prime contractor Lockheed Martin is expending its management reserves at a higher rate than both the Program and the company expected and that, if continued, would deplete its reserve account almost a year before the planned launch of EM-1. Moreover, we found NASA is not monitoring the impact of this possibility on the Orion Program. Although Program officials acknowledged the current depletion rate is high, they believe it unlikely Lockheed will continue to draw at that rate and, if the reserve is depleted before the EM-2 launch, Lockheed could cover the costs or NASA could draw on other Agency funds. In our judgment, Orion Program managers would be better informed by formally addressing Lockheed's management reserve as a Program cost risk.

Finally, the Program is working toward an internal planned launch date significantly earlier than the Agency's external commitment date or estimates by an independent review board. We are concerned that such an optimistic approach, given the Program's flat budget profile, increases the risk that Orion officials will defer certain tasks, which ultimately could delay the Program's schedule and increase costs.

## WHAT WE RECOMMENDED

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To improve the likelihood Orion will be safely operated and developed on cost and schedule, we made four recommendations to NASA including reevaluating the internal launch readiness dates for EM-1 and EM-2 and designating and managing depletion of Lockheed Martin's reserve as a Program cost risk. The Agency concurred with our recommendations and proposed corrective actions. We find the actions responsive and therefore the recommendations are resolved and will be closed upon verification of the corrective actions.

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# Acronyms

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ASAP	Aerospace Safety Advisory Panel
EFT	Exploration Flight Test
EM	Exploration Mission
ESA	European Space Agency
ESD	Exploration Systems Development
ETA	Environmental Test Article
FCM	Flight Control Module
FY	Fiscal Year
GAO	Government Accountability Office
GSDO	Ground Systems Development and Operations
IMS	Integrated Master Schedule
ISS	International Space Station
JCL	Joint Cost and Schedule Confidence Level
OIG	Office of Inspector General
SLS	Space Launch System
SRB	Standing Review Board
UFE	Unallocated Future Expense

# INTRODUCTION

The Orion Multi-Purpose Crew Vehicle (Orion) will provide NASA with the capability to transport astronauts and cargo beyond low Earth orbit and is essential to achieving the Agency's goal of expanding human presence in the solar system.<sup>1</sup> NASA spends about \$1 billion annually, or about 6 percent of its budget, on the Orion Program. According to current estimates, the Agency will have devoted approximately \$17 billion to the Program by the time Orion makes its first crewed flight in April 2023.

Orion is one leg of a three-part system that includes a heavy-lift rocket known as the Space Launch System (SLS) and a ground and launch support program known as Ground Systems Development and Operations (GSDO). The Orion vehicle has four major components: a crew module; a service module; a spacecraft adapter, which connects the vehicle to the launch system; and a launch abort system. Orion is being assembled and tested at NASA's Kennedy Space Center (Kennedy), Michoud Assembly Facility (Michoud), and Plum Brook Station (Plum Brook). NASA has planned four missions for the Orion Program through 2023, the first of which – Exploration Flight Test-1 (EFT-1) – was completed in December 2014. The Agency launched this uncrewed mission from Cape Canaveral Air Force Station in Florida (Cape Canaveral) on a United Launch Alliance Delta IV rocket and successfully completed a 4.5-hour, two-orbit trip around Earth. For EFT-1, NASA utilized the command and control software United Launch Alliance uses for the Delta rocket ground operations rather than the software GSDO is designing for control of SLS and Orion ground operations.

The second mission – Exploration Mission-1 (EM-1) – is scheduled for September 2018 and will be the first launch of the combined SLS-Orion system. NASA plans to use GSDO software when it launches this 22- to 25-day uncrewed mission from Kennedy. The mission will test system readiness for future crewed operations.

For the third mission – Ascent Abort Test 2 scheduled for December 2019 – NASA will launch a mock-up of an Orion vehicle from Cape Canaveral to test the launch abort system, avionics, and communications systems.

The fourth mission – Exploration Mission-2 (EM-2) – will be the first crewed flight for the combined system. The Agency has committed to a launch readiness date for EM-2 of April 2023. However, the Orion Program has been managing toward an earlier launch date of August 2021 for planning and scheduling purposes.

We initiated this audit to assess the status of the Orion Program. Our specific objective was to determine whether the Program could improve its management of 63 technical, schedule, and cost risks it was tracking. As part of the audit, we reviewed a sample of 18 risks composed of the 9 risks Program officials identified as the most critical as of February 2015 and an additional 9 that fell into the

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<sup>1</sup> Low Earth orbit is defined as the area between 99 and 1,200 miles above the Earth.

Program’s highest risk category as of September 2015, meaning they have a greater than 90 percent probability of occurring or the potential to cause catastrophic loss of life, loss of vehicle, loss of mission, or a cost impact of \$500 million or more. See Appendix A for details of the audit’s scope and methodology.

## Background

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NASA began developing the vehicle now known as Orion in 2006 as part of the Agency’s Constellation Program and had spent about \$3.7 billion on the effort when the Program was cancelled in 2010.<sup>2</sup> Below we discuss the history and current status of the Orion Program.

### Development under the Constellation Program

NASA initiated the Constellation Program in 2005 with the goal of developing a crew vehicle, two launch vehicles, and other systems to support crewed missions to the International Space Station (ISS), the Moon, and eventually Mars. In August 2009, the Government Accountability Office (GAO) reported the Constellation Program was experiencing cost increases and significant technical and design challenges.<sup>3</sup>

In June 2009, NASA chartered the Review of U.S. Human Spaceflight Plans Committee (the Augustine Committee) in response to a White House request to assess the Agency’s space exploration efforts, including the Constellation Program. In October 2009, the Committee reported that without a \$3 billion funding increase the Program would be unable to deliver the heavy lift vehicle and other systems needed to land on or explore the Moon until the late 2020s at the earliest.<sup>4</sup> Based on the Committee’s findings, President Obama did not include funding for the Program in his fiscal year (FY) 2011 budget request. At that point, prime contractor Lockheed Martin Corporation (Lockheed) had spent \$2.4 billion (34.4 percent) of the \$6.9 billion estimated cost to complete the design and development of the crew vehicle (see Table 1).

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<sup>2</sup> NASA established the Constellation Program in response to the NASA Authorization Act of 2005, which called for development of a crew exploration vehicle, crew launch vehicle, heavy-lift launch vehicle, and return to the Moon as a stepping-stone to future exploration of Mars and other destinations. NASA Authorization Act of 2005, Pub. L. No. 109-155, December 30, 2005.

<sup>3</sup> GAO, “NASA: Constellation Program Cost and Schedule will Remain Uncertain until a Sound Business Case is Established” (GAO-09-844, August 26, 2009).

<sup>4</sup> Review of U.S. Human Spaceflight Plans Committee, “Seeking a Human Spaceflight Program Worthy of a Great Nation,” October 2009.

**Table 1: Orion Vehicle Prime Contract Costs as of January 2010 Cancellation**

Description	Cumulative Costs (millions)	Estimated Cost at Completion (millions)	Percent Complete
Spacecraft Development	\$ 1,639	\$ 4,361	37.6
Program/Project Management	346	866	40.0
Vehicle Integration	225	507	44.4
Safety, Reliability, and Quality Assurance	58	193	30.1
Test and Verification	99	402	24.6
Undistributed Budget	-	556	-
<b>Total</b>	<b>\$ 2,367</b>	<b>\$ 6,885</b>	<b>34.4</b>

Source: NASA Office of Inspector General (OIG) analysis of Lockheed’s January 2010 Cost Performance Report.

## The Orion Program

The NASA Authorization Act of 2010 requires the Agency to use, to the extent practicable, contracts, workforce, and capabilities associated with the Constellation Program to continue development of a multi-purpose crew vehicle.<sup>5</sup> Consistent with this direction, in May 2011 the NASA Administrator selected the Constellation crew exploration vehicle as the reference design for the Orion vehicle. The 2010 Act provides that the new vehicle should:

- serve as NASA’s primary crew vehicle for missions beyond low Earth orbit;
- conduct regular in-space operations, such as rendezvous, docking, and extra-vehicular activities;
- have the capacity for efficient and timely evolution, including insertion of new technologies; and
- provide an alternative means of delivery of crew and cargo to ISS in the event commercial or partner-supplied vehicles are unable to do so.

NASA has aligned its Orion development efforts to meet the first three of these goals. However, the Agency does not plan to use Orion as an alternative means of transporting crew and cargo to the ISS both for cost and logistical reasons – namely, the vehicle will be operational for only a short time before the ISS Program is scheduled to end in 2024 and will cost far more to operate than both the Russian Soyuz the Agency currently uses for astronaut transport and the commercial vehicles it hopes to begin using no later than 2018.<sup>6</sup> In addition, in a 2013 audit we reported that equipping Orion with the necessary hardware and software to service the ISS would cost an estimated \$300 million.<sup>7</sup>

<sup>5</sup> NASA Authorization Act of 2010, Pub. L. No. 111–267, October 11, 2010.

<sup>6</sup> In September 2014, NASA awarded \$6.8 billion in contracts to Space Exploration Technologies Corporation and The Boeing Company for crewed flights to the ISS.

<sup>7</sup> NASA OIG, “Status of NASA’s Development of the Multi-Purpose Crew Vehicle” (IG-13-022, August 15, 2013).

## Program Organization

Organizationally, the Program is part of NASA's Exploration Systems Development (ESD) office, a Headquarters organization that reports to the Associate Administrator for Human Exploration and Operations. The Orion Program Office is located at Johnson Space Center (Johnson). Lockheed serves as prime contractor for the vehicle, with the European Space Agency (ESA) providing a service module (the European Service Module) for both EM-1 and EM-2. Approximately 3,000 people in 45 states work on the Orion Program, including civil servants, contractors, subcontractors, and suppliers. See Appendix B for details of the Program's organization.

A variety of boards and panels play a role in the management and oversight of the Orion Program. For example, the Multi-Purpose Crew Vehicle Program Control Board establishes the Program's requirements, plan, and cost and schedule baseline; the Vehicle Integration Control Board manages the detailed configuration and technical baseline and oversees the integration processes; and the Service Module Control Board approves any changes associated with the European Service Module.<sup>8</sup> In addition, the Standing Review Board (SRB) and the Aerospace Safety Advisory Panel (ASAP) provide independent review and counsel to the Agency. The SRB is composed of independent experts from both within and outside NASA who assess the Program's technical and programmatic approach, risk posture, and progress against its baseline at various stages in its life cycle. The ASAP is an independent senior advisory committee that evaluates and advises the Agency on ways to improve its safety performance.<sup>9</sup>

## Program Funding

The Orion Program has planned a budget of \$22.1 billion through FY 2030 to be spent in three overlapping phases (see Figure 1).<sup>10</sup> The first phase, "Design, Development, Test, and Evaluation," is budgeted at \$10.8 billion, runs from FY 2012 to FY 2022, and includes reserve funds known as Unallocated Future Expenses (UFE).<sup>11</sup> The second phase, "Production and Operations," is budgeted at \$7.8 billion and runs from FY 2018 to FY 2030. The third phase, "Capability Enhancements," is budgeted at \$3.5 billion and runs from FY 2022 to FY 2030.<sup>12</sup>

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<sup>8</sup> A cost and schedule baseline allows program officials to compare the baseline to actual performance and determine if performance is within acceptable limits.

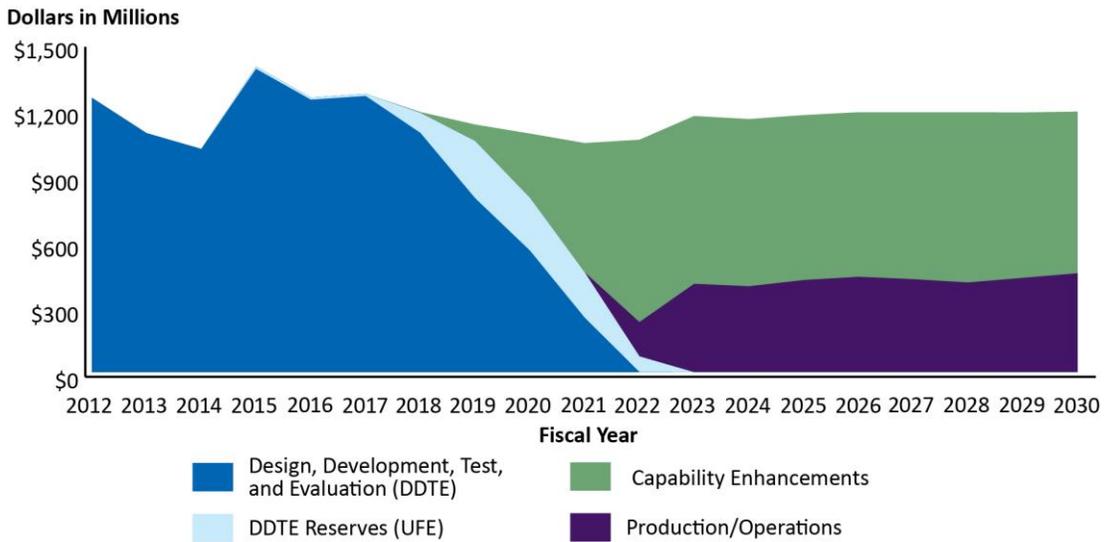
<sup>9</sup> ASAP reports are available at <http://oior.hq.nasa.gov/asap/> (accessed August 30, 2016).

<sup>10</sup> Budget figures are from the Orion Program's FY 2017 budget documents.

<sup>11</sup> UFE are costs a program expects to incur that cannot yet be allocated to a specific sub-element of the program plan.

<sup>12</sup> The Design, Development, Test, and Evaluation phase of a flight vehicle program typically culminates with development and production of the first vehicle. For the Orion Program, this phase involves the development of two vehicles and will culminate with development and production of the vehicle that will be used for EM-2. The Production and Operations phase covers vehicles produced for subsequent missions and the Capability Enhancements phase, which includes a relatively small amount of reserve funds, makes modifications to those vehicles.

**Figure 1: Orion Program Budget Profile**

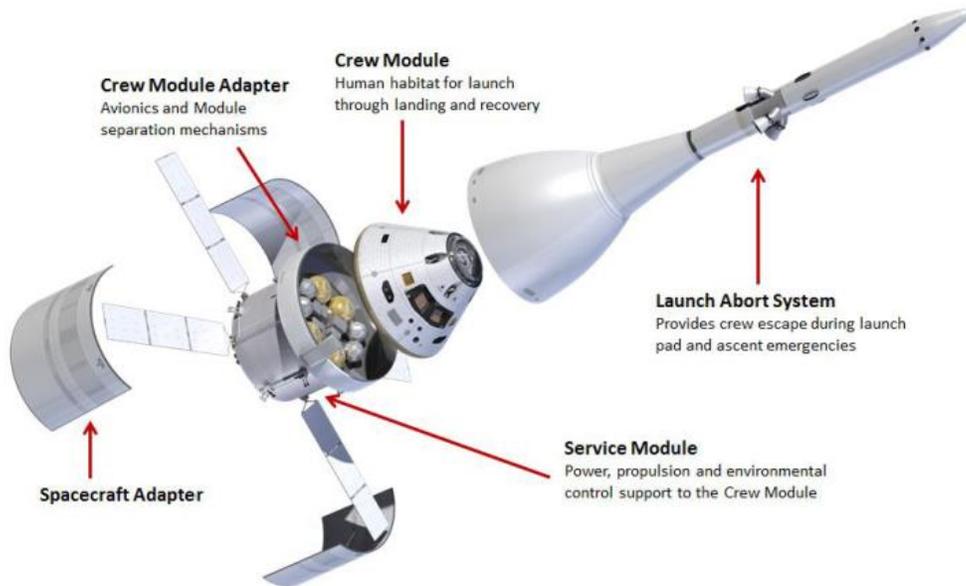


Source: OIG analysis of Orion Program budget documents and the President’s FY 2017 budget request.

## Vehicle Design Elements

Orion includes four functional elements – crew module, service module, spacecraft adapter for connecting the vehicle to the SLS or other launch vehicles, and the launch abort system. See Figure 2.

**Figure 2: Orion Vehicle Design**



Source: NASA

### ***Crew Module***

The crew module provides a habitable environment capable of supporting up to four crew members and functions as the spacecraft’s command, control, communications, and navigation center. The module is a cone-like structure that includes a top section, known as the tunnel; a flat bulkhead that lies beneath the tunnel; cone panels; a large round section at the bottom of the structure known as the barrel; and the bottom or aft bulkhead. Covering the module’s cone-like structure is an exterior shell known as the thermal protection system that uses a combination of thermal barriers, specially manufactured tiles, and a heat shield to protect the module from both the coldness of space and the extreme heat of re-entry into Earth’s atmosphere. The crew module has 11 parachutes to be used for landing when the module returns to Earth.

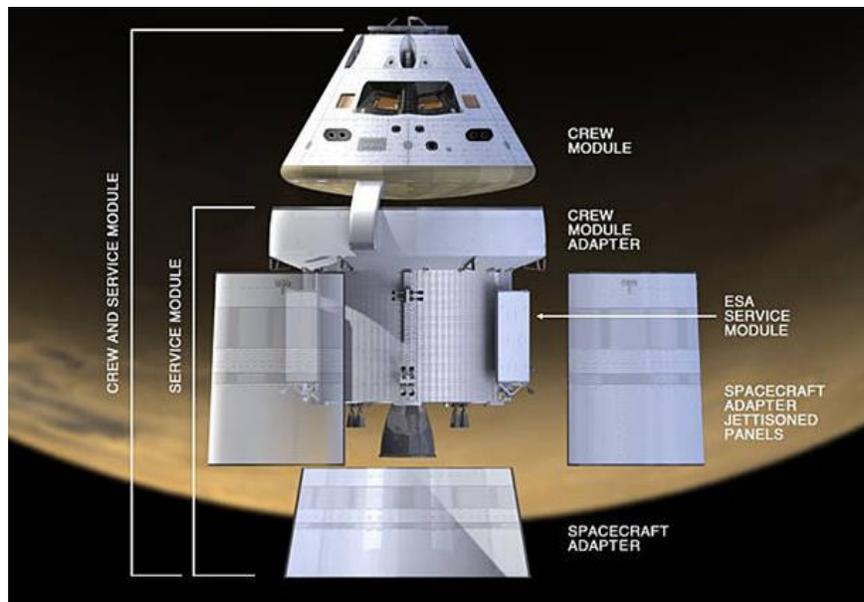
### ***Service Module***

The service module is located directly below the crew module and remains connected to the crew module until just before the capsule returns to Earth. The purpose of the service module is to generate electrical power and reject excess heat during in-space flight and provide propulsion for maneuvering the spacecraft in space and storage for consumables like water and oxygen. NASA and ESA are jointly developing the service module, with ESA furnishing the components – collectively known as the European Service Module – that provide propulsion, life support, consumables storage, heat control, and power to the crew module.

### ***Spacecraft Adapter***

The spacecraft adapter is located beneath the service module and connects Orion to the SLS or other launch vehicle. The adapter carries commands and data between Orion and the launch vehicle and includes panels that protect sensitive components during the early ascent phase of flight and jettison when no longer needed. Figure 3 depicts the crew module, service module, and spacecraft adapter.

**Figure 3: Orion Crew and Service Module Structures**



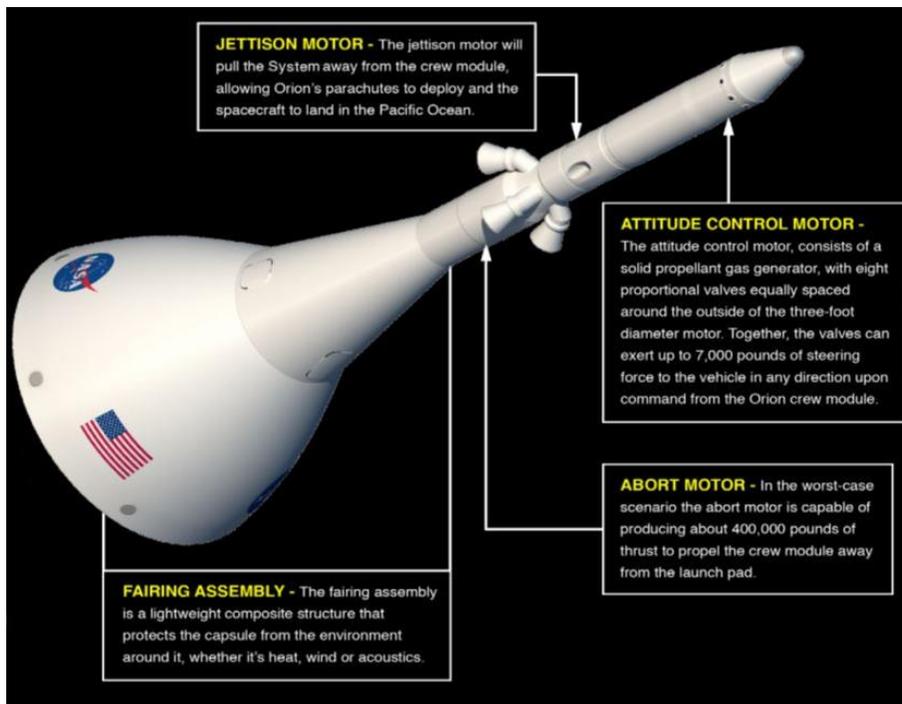
Source: NASA

## Launch Abort System

The launch abort system, which sits atop the crew module, is designed to protect the crew in the event of an emergency during launch by pulling the spacecraft away from the SLS rocket. The abort system provides an emergency escape capability from launch to about 220 seconds (approximately 300,000 feet) in flight. Weighing approximately 16,000 pounds, the launch abort system can activate within milliseconds to disengage the crew module from the rocket and facilitate a safe landing. Ground command personnel arm the system during pre-launch operations after the crew has boarded the vehicle.

The launch abort system has three solid propellant motors: the jettison motor, the abort motor, and the attitude control motor (see Figure 4). The jettison motor is used to discard the launch abort system once the vehicle is safely in flight. The abort motor is a reverse-flow motor that provides thrust to pull the crew module away from the launch vehicle in the event of an emergency. In an abort, the attitude control motor steers the abort system and crew module away from the launch vehicle and once clear, orients the capsule for deployment of parachutes for landing. In addition to the three motors, the launch abort system has a fairing assembly composed of a lightweight composite to protect the capsule.

**Figure 4: Launch Abort System**



Source: NASA

## Vehicle Assembly, Testing, and Integration

Assembly involves a sequence of steps that build vehicle elements from their constituent parts and components, which are then integrated into the overall vehicle. Testing occurs at each step in the assembly sequence and has two objectives: (1) to validate design and (2) determine the acceptability of

workmanship. Testing is conducted according to protocols in the Program’s Testing, Verification, and Validation Plan (Test Plan).

Integration of the Orion vehicle with SLS and GSDO is critical to NASA achieving its human exploration goals. In March 2015, we reported NASA needed to improve coordination efforts to resolve integration issues among the Orion, SLS, and GSDO Programs.<sup>13</sup> We noted that NASA had used a single program structure to manage similar efforts like Apollo and the Space Shuttle and that coordinating and integrating development of the three individual Programs to meet a common milestone date presents a unique challenge. To decrease the risk the GSDO Program would experience cost increases or schedule delays as a result of integration issues, we recommended the Associate Administrator for Human Exploration and Operations reevaluate allowing GSDO to complete Critical Design Review before the Orion and SLS Programs.<sup>14</sup>

## **Missions and Mission Planning**

As noted previously, NASA has planned four missions for the Orion Program through 2023. Following is additional detail about those missions and NASA’s plans for Orion post-2023.

### ***Exploration Flight Test-1 (EFT-1)***

In December 2014, NASA launched an Orion prototype on a Delta IV launch vehicle for a 4.5-hour, two-orbit flight test. On this mission, the Agency tested the heat shield and flight software architectures, parachutes, and landing system of the crew module; the separation mechanisms of the service module; and the jettison motor of the launch abort system. The flight also allowed NASA to observe mission operations and ground support during launch, flight, and recovery.

Following EFT-1, the Program made changes to the vehicle’s heat shield. According to Program officials, although the heat shield met performance expectations during the flight, some weakness and cracking were identified during the manufacturing process. Consequently, the Program changed the shield from a honeycomb to a molded-block architecture. Program officials believe this change will strengthen the shield and make its production easier and more efficient. (See Appendix C for more details on this effort.)

Program officials also said they have altered the design of Orion’s pressure vessel from the one used for EFT-1.<sup>15</sup> For example, they reduced the number of cone panels on the vessel from 12 to 3, the number of welds on the exterior shell from 18 to 7, and the number of shear pins and tension holes on the heat shield-crew module interface from 104 to 20. Program officials also expanded the use of friction-stir

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<sup>13</sup> NASA OIG, “NASA’s Launch Support and Infrastructure Modernization: Assessment of the Ground System Needed to Launch SLS and Orion” (IG-15-012, March 18, 2015).

<sup>14</sup> Critical Design Review is a formal decision point that determines whether the project design is sufficiently mature to proceed to integration; specifically, (1) the project design is sufficiently mature to proceed to full scale fabrication, assembly, integration, and (2) testing and technical aspects are on track to meet performance requirements within cost and schedule constraints.

<sup>15</sup> The pressure vessel is the sealed compartment that provides life support for astronauts.

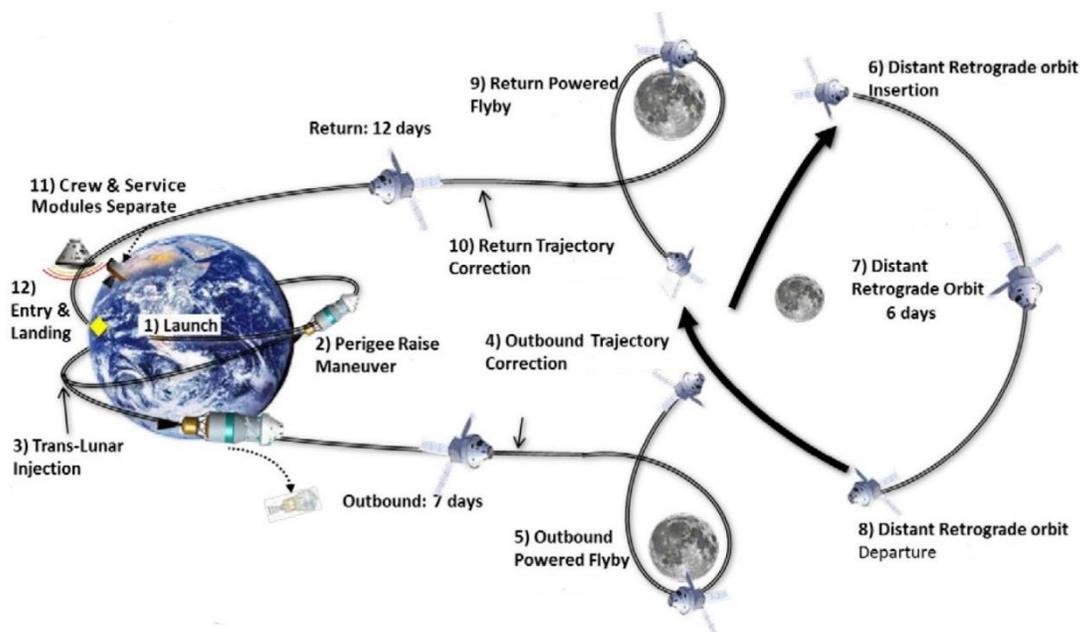
welding, a process that uses a rotating tool to heat and mechanically join two metal surfaces.<sup>16</sup> As a result of these changes, the number of main weld-points on Orion will be reduced from 33 to 7 and the spacecraft will be 700 pounds lighter.

### ***Exploration Mission-1 (EM-1)***

EM-1 will be the first launch of the combined SLS-Orion system. This 22- to 25-day, uncrewed mission will launch from Kennedy using GSDO-designed software and test system readiness for future crewed operations. EM-1 is expected to demonstrate the SLS's heavy lift capability, as well as autonomous operation of the Orion vehicle in the lunar environment (a 6-day orbit of the Moon is planned) and deployment of CubeSats in deep space.<sup>17</sup> During the mission, Orion test activities will include separating the crew module from the launch abort system and insertion into and exit from a Distant Retrograde Orbit.<sup>18</sup> EM-1 will also demonstrate the flight readiness of the heat shield molded-block architecture and other new technologies by executing a high-speed re-entry of the vehicle into Earth's atmosphere.

NASA plans to launch EM-1 in September 2018. The mission profile is illustrated in Figure 5.

**Figure 5: EM-1 Mission Profile**



Source: NASA

<sup>16</sup> In friction-stir welding, the rotating welding tool generates heat between the tool and two metal surfaces that creates a soft region in the metal near the tool. The welding tool then mechanically intermixes the two softened pieces of metal at the proposed joint and joins them together using mechanical pressure, providing superior weld strength compared to other techniques.

<sup>17</sup> A CubeSat is miniaturized satellite composed of multiples of 10×10×11.35 centimeter cubic units. On EM-1, SLS will launch 13 CubeSats weighing about 30 pounds each, which will deploy after Orion has separated from the launch vehicle.

<sup>18</sup> A lunar Distant Retrograde Orbit is a highly stable orbit around the Moon that takes advantage of the mass and gravity effects of the Moon, Earth, and Sun. EM-1 will perform a Distant Retrograde Orbit approximately 37,800 nautical miles above the lunar surface, while EM-2 will perform a High Lunar Orbit at about 5,400 nautical miles.

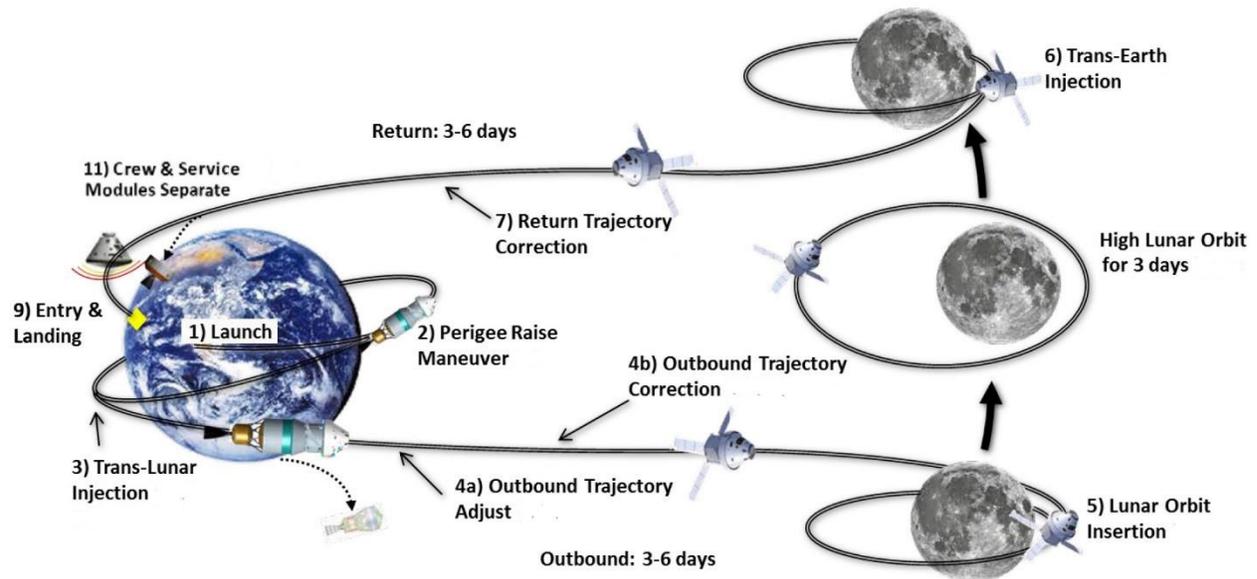
## Ascent Abort Test 2

Ascent Abort Test 2, the last flight test of the launch abort system before a crewed mission, will launch an Orion mock-up to test the functioning of the system's avionics, communications, and reaction control. Planned for December 2019, the test will demonstrate an emergency abort under the highest aerodynamic loads the system could experience in flight. For example, the test will allow aerodynamic forces to build as the booster accelerates through the atmosphere and reaches a maximum speed up to the speed of sound.<sup>19</sup> The launch abort system will then engage to pull the crew module away from the test booster.

## Exploration Mission-2 (EM-2)

EM-2 will be the first crewed mission for Orion. NASA is planning a 10- to 14-day flight, including 3 days in high lunar orbit with a crew of two to four astronauts. The mission will demonstrate the functioning of Orion's environmental control and life support systems as well as such activities as crew exercise, waste management, and operating in pressurized spacesuits. Other planned activities include separation events, such as jettisoning of the service module fairings; maneuvers, such as a trans-lunar injection burn; and demonstrations of the capsule's parachute system and the crew module uprighting system, consisting of airbags in the nose of the capsule designed to inflate after splashdown to flip the capsule upright should it come to rest upside down.<sup>20</sup> The mission profile is illustrated in Figure 6.

**Figure 6: EM-2 Mission Profile**



Source: NASA

In September 2015, NASA established an Agency Baseline Commitment launch readiness date for EM-2 of April 2023 and a life-cycle cost of \$11.3 billion. The baseline commitment date is the no-later-than

<sup>19</sup> The speed of sound at standard sea level conditions (corresponding to a temperature of 15 degrees Celsius) is 761.2 miles per hour, 661.5 knots, or 1116 feet/seconds in the Earth's atmosphere.

<sup>20</sup> A trans-lunar injection burn is a propulsion maneuver that puts the Orion vehicle on a trajectory to the Moon.

launch date promised to Congress and other external stakeholders. However, NASA has allowed the Orion Program to continue to manage to an earlier launch date of August 2021 specified in the Management Agreement, which was in place prior to establishment of the baseline commitment date.<sup>21</sup>

### ***Deep-Space Exploration Missions after 2023***

For Orion missions after 2023, NASA has adopted an incremental development approach. According to the Program Plan, the approach is cost-driven and will provide a core vehicle the Agency can upgrade to provide additional capabilities for missions beyond cis-lunar space.<sup>22</sup> Each incremental upgrade will build on flight experience to ensure the vehicle's design is based on viable technology and capabilities.

Consistent with this incremental approach, NASA has not committed to specific missions after 2023 and therefore has not developed detailed plans, requirements, or costs for such missions. According to NASA officials, the Agency will instead focus on building capabilities through defined roadmaps that identify technology development paths and capability requirements for deep space exploration missions. Officials explained the Agency will fund basic research, pursue development of the technologies that appear most viable, and build capabilities based on available funding. Missions will be selected based on the progress and maturity of the developed technology.

In 2014, the National Research Council recommended NASA commit to an exploration pathway beyond low Earth orbit, including a series of defined missions.<sup>23</sup> The report suggested that after selecting the pathway, NASA should identify the steps on the pathway, engage partners in research and technology development, and create a risk mitigation plan to sustain the selected pathway when unforeseen technical or budgetary problems arise. NASA rejected the Council's recommendation and decided to continue the incremental approach. By using the incremental approach, Agency officials believe the Orion Program can make progress on key design aspects while using early test results to "buy down" risks associated with later, more evolved vehicle designs.

In October 2015, we reported the Agency's risk mitigation schedule for physiological and psychological risks related to human exploration of deep space was optimistic and that NASA would not develop countermeasures for many deep space risks until the 2030s, at the earliest.<sup>24</sup> We noted a major factor limiting more timely development of countermeasures is uncertainty about the mass, volume, and weight requirements of deep space vehicles and habitats. Moreover, even as NASA gains knowledge about its vehicles and habitats and the effects of radiation and other space conditions on the human body, the Agency may be unable to develop countermeasures that will lower the risk to deep space travelers to acceptable levels. We recommended NASA ensure the path to risk reduction accurately reflects the status of research and realistic timeframes for countermeasure development to better understand which risks will be mitigated and which will need to be accepted for the first human mission to Mars.

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<sup>21</sup> The Agency Baseline Commitment is a formal commitment between the Agency and Congress for EM-2's launch readiness date and life-cycle cost estimates. The Management Agreement is a formal agreement between the Associate Administrator and the Program Manager for the cost and schedule necessary to achieve launch readiness of EM-2.

<sup>22</sup> "Orion Multi-Purpose Crew Vehicle (MPCV) Program Plan," MPCV 72008, Revision B, April 24, 2014. Cis-lunar space refers to the area within the Moon's orbit or a sphere formed by rotating that orbit.

<sup>23</sup> National Research Council, "Pathways to Exploration: Rationales and Approaches for a U.S. Program of Human Space Exploration," 2014.

<sup>24</sup> NASA OIG, "NASA'S Efforts to Manage Health and Human Performance Risks for Space Exploration" (IG-16-003, October 29, 2015).

## Continuous Risk Management

A risk is an issue or event that could prevent a program or project from meeting its technical, schedule, cost, or safety objectives. At NASA, risks are managed through a process known as “continuous risk management” that seeks to facilitate proactive, risk-informed decisions and involves the identification, analysis, planning, tracking, and controlling of risks until they are mitigated, closed, or accepted. It is a dynamic process in that as project personnel work to mitigate or close risks, new development or programmatic issues are identified and added as risks.

**Identify.** Identification is a process of transforming uncertainties about an event or task into distinct risks that can be described, measured, and acted upon. A risk statement is prepared to describe the risk context, condition, consequence, and general time-interval. The context section provides the what, how, when, where, and why of the risk statement. The condition is a single phrase that briefly describes the key circumstances and situations causing concern, doubt, or anxiety. The consequence is a phrase that describes the negative outcome(s) that may occur due to the condition. The identified risk is then submitted as a candidate and either accepted or closed by the program.<sup>25</sup>

**Analyze.** Analysis includes assessing the likelihood and consequences of each risk, determining the timeframe needed to mitigate each risk, grouping or classifying each risk, and prioritizing identified risks. Likelihood assessments use specific criteria to score risks from 1 (very low likelihood of happening) to 5 (nearly certain to happen). Likelihood scoring criteria are described in Table 2.

**Table 2: Risk Likelihood Scoring Criteria**

	Likelihood Description for Cost/Schedule/Performance Consequences	Likelihood Descriptions for Safety Consequences
5 Very High	Nearly certain to happen ( $P > 90\%$ )	Very likely to happen. Controls are insufficient. ( $P > 1/200$ )
4 High	Likely to happen ( $60\% < P < 90\%$ )	Likely to happen. Controls have significant limitations or uncertainties. ( $1/1,000 < P \leq 1/200$ )
3 Moderate	May happen ( $40\% < P < 60\%$ )	Not likely to happen. Controls have significant limitations or uncertainties. ( $1/10,000 < P \leq 1/1,000$ )
2 Low	Likely not to happen ( $10\% < P < 40\%$ )	Not expected to happen. Controls have minor limitations or uncertainties. ( $1/100,000 < P \leq 1/10,000$ )
1 Very Low	Nearly certain not to happen ( $P < 10\%$ )	Extremely remote possibility that it will happen. Strong controls in place. ( $P < 1/100,000$ )

Source: The Orion Multi-Purpose Crew Vehicle (MPCV) Program Integrated Risk Management Plan, Revision B, June 24, 2014.

Note: P—Probability

<sup>25</sup> When a risk is accepted, program officials decide not to mitigate the risk further and to accept any unmitigated risk. A risk is accepted through a formal process that includes procedures to approve and document the acceptance rationale.

Consequence assessments consider the type of consequence – safety, performance, cost, or schedule – and use criteria to assign a score ranging from 1 to 5. A consequence score of 1 generally involves minor damage or negligible impact, whereas a consequence score of 5 involves loss of life or vehicle (safety), loss of mission (performance), added costs of \$500 million or more (costs), or schedule delay of more than 6 months (schedule). Risk consequence scoring criteria are described in Table 3.

**Table 3: Risk Consequence Scoring Criteria**

Consequence		1	2	3	4	5
Safety	Personnel	Minor injury not requiring first-aid treatment, minor crew discomfort	Moderate injury requiring first-aid treatment, moderate crew discomfort	Severe injury, occupational illness requiring medical treatment	Critical injury or occupational illness requiring definitive/ specialty hospital/ medical treatment, resulting in loss of mission	Catastrophic loss of life or permanently disabling injury
	Facilities, Equipment, or Other Assets	Minor damage to non-essential flight/ground assets	Damage to non-essential flight/ground assets	Damage to significant flight/ground assets	Loss of mission, condition that requires safe-haven or major damage to essential flight/ground assets	Loss of vehicle prior to completing its mission, or loss of essential flight/ground assets
	Environment	Negligible OSHA/EPA violation – non-reportable	Minor reportable OSHA/EPA violation	Moderate OSHA/EPA violation which requires immediate remediation	Major OSHA/EPA violation causing temporary stoppage	Serious or repeat OSHA/EPA violations resulting in action terminating the program
Performance	Requirements	Negligible impact to requirements/design margins	Minor impact to requirements/design margins	Moderate impact to requirements/design margins	Major impact to requirements/design margins	Requirements not achievable
	Operations	Negligible impact to mission operations	Minor impact to mission operations – workarounds available	Moderate impact to operations – workarounds available	Failure to achieve major mission objectives	Total loss of mission or abort
	Supportability	Temporary usage loss or LOCM of non-flight critical asset	Permanent usage loss or LOCM of non-flight critical hardware	Temporary usage loss or LOCM of major element(s) of flight vehicle or ground facility	Permanent usage loss or LOCM of major element(s) of flight vehicle or ground facility	Inability to support further flight operation
Recovery Cost		≤\$0.5 M	>\$0.5 M but ≤ \$5 M	>\$5 M but ≤ \$50 M	>\$50 M but ≤ \$500 M	>\$500 M
Schedule		<1 week	1 week to <1 Month	1 to <3 Months	3 to ≤6 Months	>6 Months

Source: The Orion Multi-Purpose Crew Vehicle (MPCV) Program Integrated Risk Management Plan, Revision B, June 24, 2014.

Note: OSHA—Occupational Safety and Health Administration; EPA—Environmental Protection Agency; LOCM—Loss of Capability to Maintain; M—Million

Risk prioritization is a process of ranking risks and is used to allocate resources for mitigation and develop mitigation strategies. The highest priority risks are classified as “Top Program Risks” and actively managed and frequently reviewed by senior Program officials. Other risks are managed by lower level officials such as Control Account Managers and Integrated Product Teams.

**Plan.** The purpose of planning is to select an appropriate risk owner who will be responsible for the risk and to apply one of four handling strategies – research, accept, watch, or mitigate. A research strategy seeks more information to determine the most effective way to reduce the risk’s likelihood or consequence. An accept strategy applies when the risk’s consequences are tolerable or the risk cannot be reasonably mitigated in a cost-effective manner. When a risk is accepted, the risk owner must document a complete acceptance rationale in the risk database. A watch strategy applies when the program chooses not to accept the risk or commit resources and requires a metric to indicate a change in conditions or scoring. Some mitigation plans may require a fallback plan in case the primary mitigation does not achieve risk reduction. A recovery plan may be established for a risk that has a high confidence of becoming a problem or that has a high consequence. The recovery plan is invoked should the risk actually occur and allows the program to plan for future problems proactively.

**Track.** Risk tracking is a fundamental step in controlling risks. Data, including measures of actual versus planned progress, qualitative descriptions, and quantitative measures, is collected, compiled, and reported so that management can decide whether to update risk mitigation actions, adopt an alternative mitigation approach or handling strategy, analyze other risks, or initiate new risks. For example, management may track quantitative measures of the residual probability that a risk will occur and assess those measures periodically to decide whether to continue mitigation, change the mitigation approach, accept, or close the risk.

**Control.** During the control step, management evaluates risk mitigation tracking reports for progress (actual versus planned) and verifies that appropriate tasks and handling plans are in place. If actual progress differs significantly from planned progress, the risk owner should escalate the risk to the next higher review level. Typical decisions made during the step are: continue as planned; re-plan (develop a new or updated mitigation plan); change the primary plan to the fallback plan; accept the risk; or close. The appropriate management level must concur with the closure rationale before a risk is closed. If residual risk has a score greater than 3, the risk should not be closed but undergo further mitigation or be accepted. Any risk with a score of 3 or lower is assumed to be sufficiently mitigated and may be closed without expending additional resources. Decisions are captured in a program’s risk database.

**Communicate.** Communication and documentation occur in all process steps and ensure risks are properly understood, all consequences are considered, and all options for action are identified and prioritized accurately. Risks are documented in the database appropriate to the risk priority. For example, Top Program Risks are documented in the Active Risk Manager database while lower-level risks can be documented in a database at the organizational level responsible for the risk. Each risk database has the ability to produce summary and detailed reports, which facilitate communication between program stakeholders and managers to enable risk-informed decisions.

## Sampled Risks

For this audit, we reviewed a sample of 18 risks, including 9 risks Program officials identified as the most critical as of February 2015 and an additional 9 that fell into the Program’s highest risk category as of September 2015, meaning they have a greater than 90 percent probability of occurring or the potential to cause catastrophic loss of life, loss of vehicle, loss of mission, or a cost impact of \$500 million or more. Table 4 lists the risks we reviewed (bolded risks were identified as Top Program Risks by Program officials).

**Table 4: Sampled Risks**

Program Identified Risk	Description
<b>Budget Threats to EM-1</b>	<b>Given a flat funding profile of about \$1 billion per year, the Program’s incremental development approach could lead to cost increases and schedule delays.</b>
EM-1 Reusability Effectiveness	The Program plans to reuse avionics systems from EM-1 for EM-2 as part of its cost savings strategy, which carries risks that components could be unusable due to damage or failure or if the EM-1 vehicle cannot be recovered intact.
<b>EM-2 Landed Mass</b>	<b>The Orion crew vehicle cannot exceed weight limits established for each phase of the mission, including lift-off, trans-lunar insertion, and landing. The Orion Program has been tracking a risk that vehicle weight at landing of EM-2 will exceed its limit.</b>
Environmental Test Article Avionics Availability	Environmental testing at Plum Brook, which includes vibration, separation pyroshock, and lightning, requires abort avionics to be functional during and after testing. However, since the Program plans to reuse all EM-1 abort avionics on EM-2, they will be removed from the environmental test article – the EM-1 crew module – and unavailable for testing.
<b>European Service Module</b>	<b>The means by which ESA will provide the service module for EM-2 has not yet been determined and negotiating a second barter agreement and obtaining funding could both delay the mission and increase Program costs.</b>
Fluid Control Assembly Delivery	The fluid control assembly, which adjusts the temperature within Orion and is necessary for the European Service Module to function, is undergoing development and testing by an ESA subcontractor and could be delivered late to the ESA prime contractor.
<b>Flight Control Module Processor Resources for EM-1</b>	<b>As the size of the Orion system increases with EM-1 and EM-2, it is possible that the flight control module will not be able to handle all processing required without significant flight software optimization and some hardware modification.</b>
Flight Software Verification	There is a possibility that schedule and resource estimates could be too low as compared to the actual effort required.
Hardware Reuse for EM-1, EM-2, and Ascent Abort 2 Missions	The Program expects to reuse hardware from prior missions as a fundamental cost savings strategy; however, failure during a mission or test could delay the schedule while Program officials determine the cause of the failure, correct the issue, and procure additional hardware if required.
<b>Heat Shield Architecture</b>	<b>The EFT-1 heat shield material displayed lower-than-expected strength properties during flight and the heat shield itself experienced cracking at the seams during final cure necessitating a change in design that will not be flight tested until EM-1.</b>
Incomplete Parachute Extraction Loads	Parachute load data used in models was outdated and may not reflect actual abort loads possibly exceeding structural design limits, which could require a hardware redesign and put cost and schedule at risk.
Launch Abort Vehicle Transonic Abort Black Zone	Orion is at risk of tumbling immediately after an abort initiated in the transonic flight regime, and if tumbling occurs the vehicle would almost certainly break up leading to possible loss of vehicle and crew.
Loss of Crew from Disorientation during Manual Chute Deploy	If the primary avionics systems fail to deploy the parachutes during descent and the crew is disoriented and cannot manually deploy the final main parachutes, the vehicle and crew would be lost on impact.

Program Identified Risk	Description
<b>Mode 1 Vibroacoustic Environments</b>	<b>During launch aborts, the abort motor produces high levels of random vibrations that will be transmitted to the heat shield and crew module potentially causing hardware components to fail.</b>
Network Switch Radiation Compliance	The possibility exists that network switch performance would be significantly affected in the radiation environment of space and could result in the loss of the ability to record certain types of data.
<b>Orion Vehicle Test and Verification Plan</b>	<b>The Program moved from dedicated to distributed qualification testing as a cost reduction measure, testing individual components and subsystems distributed across multiple vehicles and multiple points instead of testing fully integrated components or test articles.</b>
<b>Pad and Low Altitude Abort Performance</b>	<b>Launch pad and low altitude aborts are a risk because the crew module was not designed to land in water less than 10 feet in depth or on solid ground and doing so could result in significant structural damage and loss of crew.</b>
<b>Parachute Pendulum Swing</b>	<b>In certain test circumstances, Orion was subjected to a pendulum-like swinging motion that could not be overcome by the recovery control system. As a result, the vehicle could enter the water at higher velocities and steeper impact angles, which could result in loss of crew or vehicle.</b>

Source: OIG analysis of Program information.

# ORION MUST OVERCOME TECHNICAL, FUNDING, AND SCHEDULE RISKS TO ACCOMPLISH UPCOMING MISSIONS

The Orion Program has met several key development milestones on the path to its first crewed mission, including a successful test flight in December 2014. However, much work remains, including evaluating options related to the delayed delivery of the European Service Module; continuing mitigation for seven critical risks while operating with a less than optimal budget profile for a developmental project; dealing with a potential shortfall of \$382 million in reserves managed by Lockheed; and successfully launching and recovering EM-1. Furthermore, Program officials continue to work toward an optimistic internal launch date of August 2021 for EM-2, which has a substantially lower confidence level and is 20 months earlier than the Agency's external commitment date of April 2023. While we understand the desire to work toward a more aggressive schedule, this approach has led the Program to defer addressing some technical tasks to later in the development cycle, which in turn could negatively affect cost, schedule, and safety.

## Orion Program Has Made Progress

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The Orion Program has met a number of key milestones since the December 2014 test flight. For example, in September 2015 the Agency Program Management Council found the Program's preliminary vehicle design met requirements, its cost and schedule were adequate to accomplish the mission with acceptable risk, and the Program was sufficiently mature to begin final design and fabrication. Based on those findings, in September 2015 NASA committed the Program to a cost baseline of \$11.3 billion and an April 2023 launch schedule for EM-2.<sup>26</sup> In October 2015, the Program's Critical Design Review validated that Orion's design was sufficiently mature to continue with full-scale fabrication, assembly, integration, and testing.

In addition, the Program has made progress in developing the launch abort system, crew module, and service module elements. For example, the structural test article and abort motor qualification tests have been completed. In addition, welding has been completed for the EM-1 pressure vessel and the pressure vessel's primary structural assembly has been prepared for pressure testing. Finally, the structural test article for the European Service Module was delivered on-time and is undergoing acoustic and vibration testing.<sup>27</sup>

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<sup>26</sup> Successful conclusion of the Preliminary Design Review culminates at Key Decision Point C – a presentation to and decision by the Decision Authority, in this case the Agency Associate Administrator who chairs the Agency Program Management Council, to continue or terminate the Program. The Agency commitment to proceed with Orion development was documented in the Key Decision Point C Decision Memorandum of September 15, 2015.

<sup>27</sup> The structural test article is a replica of the European Service Module that lacks the full functionality of the actual Module.

The Program also followed its risk management process by assessing and scoring the likelihood and consequence of each risk, classifying top Program risks, developing and reporting to management tracking data, and periodically evaluating progress to decide whether to change, continue, or close risks. The Program had mitigated 10 of the 18 risks we sampled, by closing them, lowering their likelihood or consequence score below 5, or projecting they will be moved from mitigation to tracking status in 2016.<sup>28</sup> For example, the Program identified the change from a monolithic honeycomb to a molded-block architecture heat shield as a Top Program Risk and worked to mitigate it by conducting trade studies of alternative architectures and performing load and shock tests of the new architecture. Although the heat shield remains a significant risk, from January 2014 to April 2015 the Program reduced the likelihood of occurrence from high to low and the consequence from very high to high. In another example, in January 2015 Program officials reduced the consequence and likelihood of budget threats to EM-1 to a risk score of 4 following a favorable FY 2015 appropriation from Congress. However, as we discuss below financial risk may increase in future years given the volatility of the annual appropriations process. See Appendix C for a description and status of the mitigated risks.

## **Delay in Delivery of Fluid Control Assembly May Impact EM-1**

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The fluid control assembly is a thermal control system that adjusts the temperature inside Orion and is necessary for the European Service Module to function. The Program identified the assembly as a risk because as of November 2015 it was undergoing development and testing by an ESA subcontractor and would not be ready for delivery to ESA's prime contractor, Airbus Defence and Space, by November 2016 as originally planned.<sup>29</sup> Late delivery could mean delays integrating the assembly with the service module for EM-1, which in turn could affect the launch schedule.

Although the subcontractor's internal schedule indicated an expected delivery of January 2017, Orion Program officials said delivery in late February or early March, after the planned delivery of the service module to Kennedy, is more likely.<sup>30</sup> In October 2015, Program officials were considering whether to delay shipment of the service module so the control assemblies could be integrated before it ships or follow the shipment schedule and integrate the assemblies at Kennedy. In June 2016, ESA confirmed that it would deliver the service module at least 3 months late, a delay that could affect the critical path for transferring Orion to the GSDO Program to support integration with SLS in preparation for launch.<sup>31</sup> As of July 2016, Orion and GSDO Program officials were coordinating schedules and identifying options to maintain the planned launch date for EM-1.

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<sup>28</sup> When a risk is in tracking status, the Program periodically assesses quantitative measures of the residual probability that it will occur to decide whether to continue mitigation, change the mitigation approach, accept, or close the risk.

<sup>29</sup> ESA subcontractors include Airbus, TASI Group, and United Technology Corporation Aerospace System.

<sup>30</sup> According to Program officials, the ESA subcontractor is contractually required to deliver the fluid control assemblies for EM-1 by April 2017.

<sup>31</sup> Critical path is the sequence of tasks that determines the longest duration of time needed to complete the project. It is important to identify the critical path and the resources needed to complete the critical tasks along the path if the project is to be completed on time and within its resources.

## Risks the Program Continues to Mitigate

We found the Program is still working to mitigate 7 of the 18 risks we sampled. Each of these risks has a likelihood or consequence score of 5 and their successful mitigation is essential to developing a safe vehicle for human space flight. Two of the risks (Test Plan and Hardware Reuse) must be resolved to launch both EM-1 and EM-2, while the remaining five, which relate to the vehicle’s electronics, crew life support, vehicle landing, and abort systems, are critical to EM-2. Table 5 summarizes the likelihood rating, consequence rating, and the expected mitigation date or current mitigation status for the seven risks through July 2016. We discuss the risks and the Agency’s mitigation efforts in more detail below.

**Table 5: Risks that Require Additional Mitigation**

Risk	Likelihood	Consequence	Expected Mitigation Date
Orion Vehicle Test and Verification Plan	4	5	Reassessment planned for August 2016
Hardware Reuse for EM-1, EM-2, and Ascent Abort 2 Missions	5	2	Continuous evaluation based on specific hardware through late 2019
EM-1 Reusability Effectiveness	1	5	In tracking status and final closure expected in March 2018
Pad and Low Altitude Abort Performance	2	5	Reassessment planned for August 2016
Parachute Pendulum Swing	3	5	March 2018
Incomplete Parachute Extraction Loads	3	5	July 2016
Launch Abort Vehicle Transonic Abort Black Zone	1	5	December 2018

Source: OIG analysis of Program information.

### Orion Vehicle Test and Verification Plan

During integration and testing, the Program assembles the vehicle and conducts acceptance and qualification tests based on criteria laid out in the Program Test Plan.<sup>32</sup> In 2012, the Program identified the Test Plan as a risk after the Program began moving from dedicated to distributed qualification testing in 2010 as a cost reduction measure. Under a dedicated testing scheme, the Program would have tested a fully integrated component or test article similar to the actual mission component. In contrast, with a distributed qualification approach, the Program tests individual components, subsystems, and the integrated system on a variety of test assets rather than a singular, fully integrated qualification test article. For example, the Program is testing individual components of the life support system as they are produced and will test some components and subsystems in an integrated test environment on the ISS prior to EM-2.

<sup>32</sup> Acceptance tests verify workmanship and ensure that flight and operations hardware and software are in compliance with performance and design requirements before the vehicle is shipped to the launch site. Qualification tests verify design and ensure that the hardware and software will meet functional and performance requirements in the anticipated operational environment.

Although the move from dedicated to distributed qualification saved money, it also led to 18 concerns about gaps in the test and qualification plan. Of the 18 concerns, 16 had been closed by February 2016. The remaining concerns – abort-critical hardware not included on the environmental test article and the absence of a human-in-the-loop test – will be considered for closure in August 2016 at the earliest.<sup>33</sup> Under the distributed qualification plan, the abort-critical hardware will not be tested as a system before EM-2. To partially mitigate this risk, the firing circuits and tubing integrity of the parachute mortars and crew module uprighting systems will be tested on the environmental test article. The human-in-the-loop risk is that the Program may not identify needed adjustments to the crew area until EM-2. To mitigate that risk, the Orion Program is expediting planning efforts, working on the first draft of the human-in-the-loop verification plan, and identifying gaps in hardware or facility capabilities.

## Hardware Reuse

As a cost saving strategy, the Program plans to reuse hardware from earlier missions on subsequent missions. For example, pressure transponders and propellant regulators from EFT-1 will be reused on EM-1, the EFT-1 crew module will be reused for acoustics testing, and hardware and components from EM-1 will be reused on test articles. This approach carries a risk to the schedule of subsequent missions should hardware planned for reuse fail or sustain damage on an earlier flight.

Program officials have completed several actions to mitigate risks related to this issue. Specifically, they identified the hardware and components that would adversely affect the mission should they not be reusable, evaluated options for replacing those items, and developed a list of mandatory spare hardware. However, the Program has not developed a budget line item or a funding source for this spare hardware. Consequently, to fund spare hardware purchases, the Program would need to tap into UFE, reprioritize work, or redirect available funding from another area.<sup>34</sup>

## EM-1 Reusability Effectiveness

The Program also expects to reuse avionics systems from EM-1 for EM-2.<sup>35</sup> Avionics refers to the spacecraft's electronics systems and includes its communications, navigations, display, and flight control systems. Similar to the issues with hardware reuse, the strategy carries risks that the systems will fail or be damaged during EM-1 and therefore not available for EM-2.

In 2015, the Program accepted the risk of a potential loss of a vehicle and developed a contingency plan if EM-1 components are destroyed or unusable. The Program plans to reassess this risk during FY 2016 by applying lessons learned from EFT-1 to the ongoing work for EM-1 and EM-2 and has identified a staged mitigation approach that would incrementally commit resources toward purchase of a second set of avionics for EM-2. The Program is currently tracking the risk and expects final closure in March 2018.

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<sup>33</sup> Human-in-the-loop refers to tests that include the direct involvement of flight crew – usually dressed in flight suits seated in the crew module – to evaluate human factors such as reach, sight lines, lighting, and emergency procedures.

<sup>34</sup> Using UFE to purchase spare parts would reduce the amount of funds available for financing deferred work or addressing yet unrealized and unknown risks.

<sup>35</sup> Program officials estimated that reuse of avionics components will save 80 – 90 percent of the cost compared to new replacement components.

## Pad and Low-Altitude Abort Performance

Orion Program officials identified pad and low-altitude aborts as a risk because the crew module is not designed to land in less than 10 feet of water or on solid ground, and doing so could result in significant structural damage to the capsule and potential injury to or loss of the crew. Program officials estimate the probability of a pad or low-altitude abort at approximately 1 in 2,500; however, modeling scenarios indicate a higher probability of a bad outcome during winter months due to stronger winds that could push the crew module onto solid ground during a pad abort.

The mitigation plan for this risk is additional modeling of pad aborts, development of shallow water landing options, and identification of hardware and system improvements. As of April 2016, the Program reduced the likelihood of occurrence from a score of 3 to a score of 2 based on an updated analysis that estimated the probability of occurrence at 1 in 20,000. Although Program officials expect to further reduce the likelihood score from 2 to 1 by the EM-2 launch, they may not be able to mitigate the consequence score below 4. Program officials stated they plan to reassess their mitigation strategy in August 2016 to determine whether to pursue injury risk analysis for land-based landings and thereby reduce the risk's probability of occurrence or add a wind limit for the day of launch to minimize the risk that higher winds could push the crew module back on shore. This risk is now being managed at the organizational level.

## Parachute Pendulum Swing

Orion uses three main parachutes to slow the crew module to a safe speed for landing.<sup>36</sup> During test drops from high altitudes performed between 2011 and 2014, the parachutes exhibited a potentially

**Deployment Testing of Orion's Main Parachutes**



Source: NASA.

dangerous pendulum-like swinging motion during descent, a characteristic that had not been predicted by computer-based simulations. NASA determined that, once started, the swinging motion could not be reduced by the landing orientation reaction control thrusters, which help maintain proper vehicle orientation upon landing. As a result, the vehicle could enter the water at higher velocities and steeper impact angles than planned, which could result in injury to or loss of crew and damage to the vehicle.

The Program's initial research examined whether loss of one of the parachutes (estimated at a 1 in 180 likelihood) would lead to the pendulum motion and studied several options to mitigate the motion. Potential main parachute canopy modifications were studied using wind tunnel and airdrop testing, which determined that the proposed modifications did not resolve the issue. The Program changed the forward bay structure to increase the angle at which the crew module would hang under the main parachutes, and determined that deploying the parachutes at a lower

<sup>36</sup> Orion's main parachutes are the final 3 of 11 parachutes deployed in a 4-event series used to slow and safely land the vehicle in the ocean. See [https://www.nasa.gov/sites/default/files/atoms/files/orion\\_parachutes.pdf](https://www.nasa.gov/sites/default/files/atoms/files/orion_parachutes.pdf) for details of Orion's parachute deployment sequence (accessed August 30, 2016).

altitude reduced the pendulum effect. The Program also modified software models to study pendulum motion reduction using attitude control thrusters and different landing orientations of the vehicle and found significant improvements in landing performance.

Program officials developed a series of eight test drops over a 3-year period. During the most recent test in August 2015, an aircraft dropped a representative Orion crew capsule from its cargo bay at an altitude of 35,000 feet. The capsule experienced enhanced pendulum motion below 1,000 feet, which NASA attributed to wind shear. However, the Program continued to analyze wind and parachute performance data.

In February 2016, the Program officials determined that no further changes to the parachute system or the vehicle structure were needed and reduced the risk likelihood to a score of 3. However, Program officials reevaluated the Program's loss of crew requirements to determine whether the vehicle could absorb more landing risk.<sup>37</sup> They found the probability of not meeting loss of crew requirements decreased from 89.6 to 83 percent, which was within the acceptable range. Although there is still a risk of loss of crew or vehicle, Program officials decided to accept the residual risk, add residual risk into their assessment models, and rewrite the parachute pendulum swing risk into a risk of not meeting landing probability criteria. The parachute pendulum swing risk was closed as a Top Program Risk, and the Program is tracking the risk of not meeting landing probability criteria at the organizational level. The Program expects final closure in March 2018.

## **Incomplete Parachute Extraction Loads**

In 2010, Orion Program officials determined the parachute load data used in the Program's computer models was outdated and may not reflect actual abort loads.<sup>38</sup> This raised the possibility that abort loads would exceed current plans and require a redesign. Program officials said that a hardware redesign for EM-1 would cost \$500,000 to \$5 million and delay the mission's schedule by more than 6 months.

Program officials developed a mitigation plan that includes modeling parachute loads and assessing the vehicle's primary structures for abort loads. Program officials told us they plan to decide whether a redesign of the vehicle's primary structural configuration is needed for the structural test article and EM-2 vehicle in July 2016 but that the risk will retain a consequence score of 5 because of its potential impact on the Program schedule.

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<sup>37</sup> Loss of crew requirements are established for the Program by ESD. A probability range of 80 percent or less is sufficient; more than 80 to 90 percent is minimal; and more than 90 percent is insufficient.

<sup>38</sup> The "load" or force experienced by a parachute during phases of deployment can be measured in pounds.

## Launch Abort Vehicle Transonic Abort Black Zone

Transonic flight refers to speeds greater than 250 miles per hour but less than the speed of sound, or about 760 miles per hour at sea level. While an aircraft may be traveling at less than the speed of sound, the air surrounding parts of the aircraft may exceed the speed of sound, which can result in severe instability.<sup>39</sup>

Analysis showed a significant risk of Orion and its launch vehicle tumbling out of control if an abort was initiated at transonic flight speeds. If tumbling occurred, the vehicle would almost certainly experience an aerodynamic breakup that would lead to a loss of crew and vehicle. However, analysis showed that a ballast with a maximum weight of 600 pounds shifted the vehicle's center of gravity, made the vehicle more stable, and mitigated the worst of the tumbling. The nose cone was therefore modified so that a ballast could be added if tumbling was anticipated in future vehicle configurations. Additional wind tunnel testing and land-landing analyses have since validated the Program's approach as a risk mitigation strategy, and the Ascent Abort 2 flight test is expected to establish system-level performance near the transonic region during ascent.

## Funding Profile and Timing Not Optimal for Program Development

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In a September 2012 report, we detailed the challenges that unstable funding pose to NASA project managers, both in terms of the amount of funding received and the erratic timing of receipt of funds.<sup>40</sup> Throughout its development, the Orion Program has experienced both types of funding instability.

In an August 2013 report, we noted the most effective budget profile for large and complex space system development programs like Orion is steady funding in the early stages and increased funding during the middle stages of development.<sup>41</sup> GAO guidance shows a bell-shaped curve as the optimal funding profile for research, development, testing, and evaluation because more resources are needed as development progresses and programmatic risks are identified and remediated.<sup>42</sup> In contrast, the Orion Program's budget profile through at least 2018 has been nearly flat with an annual rate between 5 and 10 percent of total design, development, test, and evaluation costs (approximately \$1.1 billion per year). Program officials acknowledged that this funding trajectory was not optimal and increased the risk that costly design changes may be needed in later stages of development when NASA begins to integrate and test Orion with the SLS and GSDO. Figure 7 compares Orion Program funding to funding for Gemini, Apollo, and other development programs.

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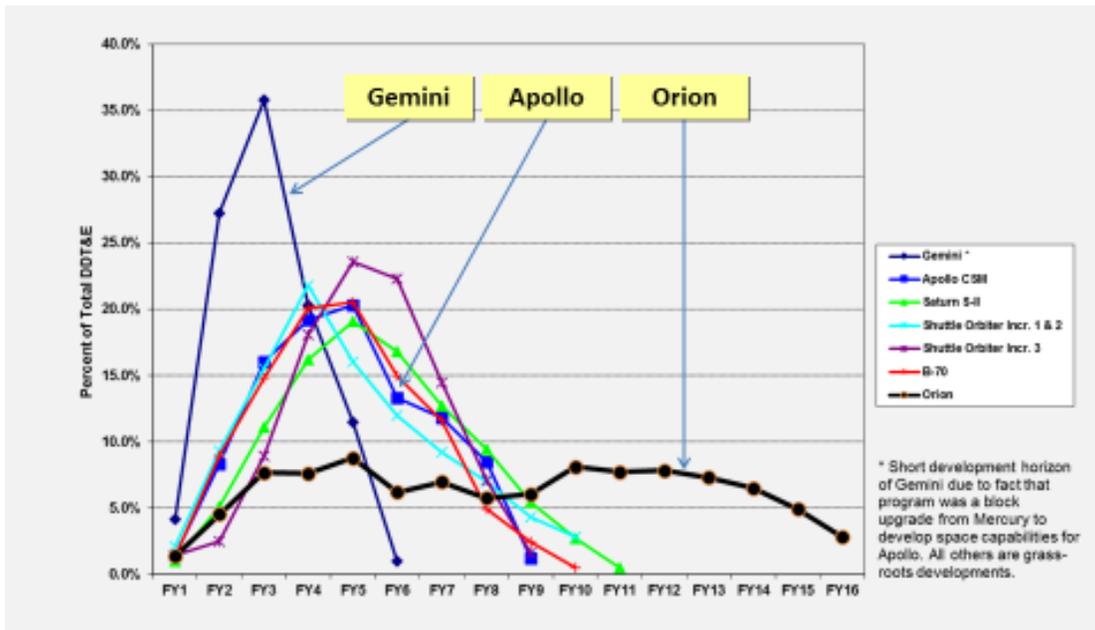
<sup>39</sup> Instability occurs as shock waves move through the air at the speed of sound. When an object such as an aircraft also moves at the speed of sound, these shock waves build in front of the aircraft to form a single, large shock wave. During transonic flight, the plane must pass through this large shock wave, as well as contend with the instability caused by air moving faster than sound over parts of the wing and slower in other parts.

<sup>40</sup> NASA OIG, "NASA's Challenges to Meeting Cost, Schedule, and Performance Goals" (IG-12-021, September 27, 2012).

<sup>41</sup> IG-13-022.

<sup>42</sup> GAO, "GAO Cost Estimating and Assessment Guide" (GAO-09-3SP, March 2009).

**Figure 7: Comparison of Various Program Funding Profiles**



Source: NASA

Note: The Saturn S-II was the second stage of the Saturn V rocket used on 12 Apollo missions. NASA and the Air Force collaborated on the B-70, a research project that sought to develop a nuclear-armed, deep-penetration strategic aircraft capable of reaching Mach 3 speed while flying at 70,000 feet.

Although the Orion Program received more funding than the President requested in FYs 2012 – 2016, the additional funding was not sufficient to alter the basic flatness of the Program’s budget profile. In addition, Orion officials noted that the timing of receipt of appropriations affected their ability to perform work as planned. As shown in Table 6, the Program received its annual appropriation between 4 and 8 months after the start of each of these fiscal years.

**Table 6: Orion Program Budget, FYs 2012 through 2016**

Fiscal Year	President’s Budget Request (billions)	Congressional		Received by Program	
		Authorization (billions)	Enacted Appropriation (billions)	Final Amount (billions)	When Received (months into FY)
2012	\$ 0.92	\$ 1.40	\$ 1.20	\$1.16	February 2012 (5 months)
2013	1.03	1.40	1.20 <sup>a</sup>	1.09	May 2013 (8 months)
2014	1.03	(none)	1.20	1.17	February 2014 (5 months)
2015	1.05	(none)	1.19	1.18	January 2015 (4 months)
2016	1.10	(none)	1.27	1.25	January 2016 (4 months)

Source: OIG analysis of NASA budget documentation.

<sup>a</sup> The FY 2013 appropriation was reduced to \$1.114 billion due to sequestration.

According to Program officials, these funding issues have impacted the Program in three primary ways. First, NASA and contractor staff have spent significant time developing contingency plans to ensure continuity of operations. For example, for the 4 months preceding the December 2015 enactment of the FY 2016 budget NASA and Lockheed managers studied a variety of potential scenarios and developed strategies to minimize detrimental effects in case appropriation levels were unfavorable.

Second, the timing of when funds are released to the Program has required NASA and contractor officials to continually assess upcoming funding and expenses. When necessary to avoid cost overruns, officials have deferred work on development tasks not on the Program's critical path, an action that increases risk. For example, Program officials said that in November and December 2014 Lockheed deferred work on about 50 electronics drawings related to launch abort system communications for 2 to 4 months to temporarily redirect resources to higher priority work on the crew module. Although deferring work on the drawings did not increase launch abort system schedule or cost for that year, it could affect the Program's critical path in the future by, for example, delaying work that cannot start until the drawings are complete.

Third, Program officials stated that in 2015 and 2016 management delayed some purchases and made multiple individual purchases rather than purchasing in bulk. Officials estimated these measures increased costs by 10 to 25 percent. For example, Program officials approved a year-long delay in purchasing a full set of valves for the life support system for EM-2 and delayed purchases related to the heat shield and propulsion thrusters for the mission to keep expenses within funding targets. Although delaying purchases reduced current-year costs, the parts will now be delivered much closer to the time they are needed, leaving less margin should delivery be delayed.

## **NASA Should Monitor Lockheed Management Reserve More Closely**

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We found Orion's prime contractor, Lockheed, is expending its management reserve at a rate that, if continued, would deplete its reserve account almost a year before the planned launch of EM-1, and that NASA is not properly managing the impact of this possibility on the Orion Program.

### **Lockheed Management Reserve**

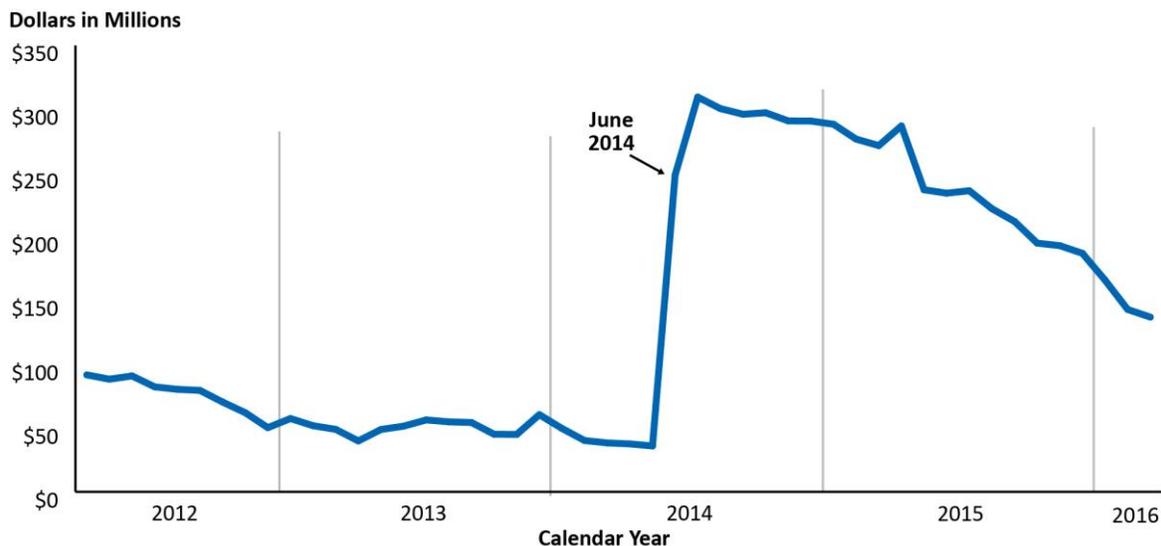
Lockheed allocated a portion of its total contract value to a management reserve account to address growth in authorized work scope, risk mitigation plans, rate changes, and other Program unknowns through development and launch of EM-2. Orion Program managers have given Lockheed autonomy in controlling and allocating this fund. For example, in May 2015, Lockheed allocated \$12 million of the reserve to a subcontractor to mitigate the heat shield architecture risk, requiring the contractor to report reserve transactions and the account balance to NASA in monthly "cost performance reports." As of March 31, 2016, Lockheed's management reserve balance totaled \$137 million.<sup>43</sup>

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<sup>43</sup> This was the most current information available as of May 2016.

Lockheed typically designates funds for reserve when the contract value changes. For example, as shown in Figure 8 the balance remained under \$100 million until June 2014 when it spiked based on a February 2014 contract modification that added \$4.6 billion to the contract value. Additionally, in July 2014 Lockheed discovered an inadvertent budget overstatement of \$64 million in some of the Orion control accounts and moved those funds to the management reserve.

**Figure 8: Lockheed Management Reserves Month-End Balances**

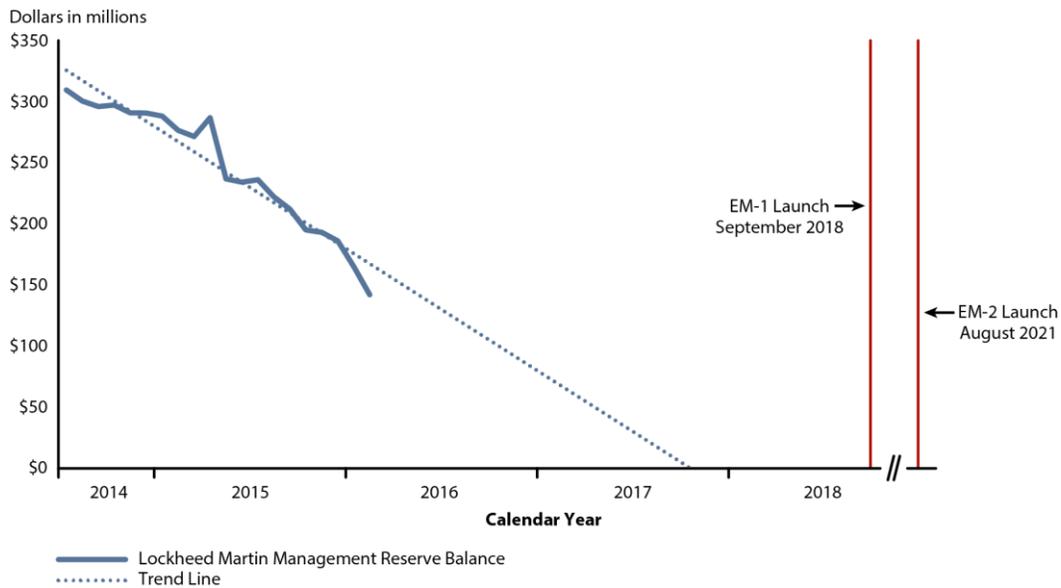


Source: OIG analysis of budget documents.

We analyzed Lockheed’s use of its management reserve account and found the company is expending funds at a higher rate than both the Program and the company expected. Our analysis shows that if Lockheed continues to draw from the reserve at the rate it did between July 2014 and February 2016, the fund will be depleted in November 2017, approximately 10 months prior to the planned launch of EM-1 (see Figure 9). Should that occur, we calculate the company might need an additional \$382 million in reserve to get to EM-2.

Although Orion Program officials acknowledged the current depletion rate is high, they believe it is unlikely Lockheed will continue to draw on the fund at that rate, and accordingly that the reserve will be sufficient. Rather, they anticipate most Program risks will be mitigated before 2018, and that as this occurs Lockheed will have less need to draw on the reserve. Furthermore, Program officials said that if the reserve is depleted before the EM-2 launch, Lockheed could cover the costs from other funds or NASA could draw on its Program-level UFE account.

**Figure 9: Lockheed Management Reserve Balance Trend**



Source: OIG regression analysis of Lockheed data.

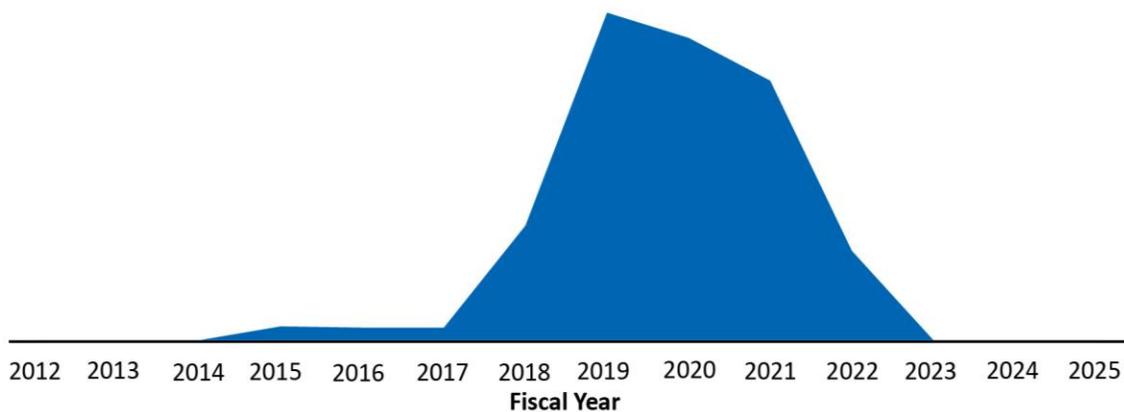
## Orion Program UFE

Separate from Lockheed’s management reserve, the Orion Program maintains a UFE account to address costs expected to be incurred by the Program but which cannot be allocated to a specific work sub-element.<sup>44</sup> As illustrated in Figure 10, the Program has allocated the bulk of its UFE to pay for items in the years after 2018, the end of the Program’s Design, Development, Test, and Evaluation phase. Program officials told us they will manage projected budget shortfalls before 2018 by identifying scope or schedule changes and deciding whether to defer work, select hardware with a lower quality or capability than originally planned, or pursue cost efficiencies. This strategy is intended to create a funded schedule margin at the end of the Design, Development, Test, and Evaluation phase and allow for efficient utilization of available funding earlier in Program development.

<sup>44</sup> NASA policy describes UFE as the portion of estimated cost required to meet a specified confidence level the Program will allocate to specific project work elements as risks are realized. The Orion Program directly manages approximately \$10 million of the UFE per year, while the balance is phased to later years in accordance with Human Exploration and Operations Mission Directorate strategy.

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**Figure 10: Orion Program Budgeted UFE**



Source: OIG analysis of budget data.

We do not believe the Orion Program’s UFE will be sufficient to make-up the potential \$382 million deficit in Lockheed’s management reserve. During the Agency’s annual budgeting process, the Program determines the required amount of UFE from quantitative risk assessments that consider risk probability and uncertainty. The risk assessment from the FY 2017 budgeting cycle showed the Program would need \$770 million of UFE between FY 2015 and 2022 to cover the projected cost impacts of known development, management, and production risks. According to Program officials, the remaining UFE would be needed for “unknown/unknowns” that might occur during that period. The strategy of creating funded schedule margin at the end of the Design, Development, Test, and Evaluation phase is consistent with GAO’s finding that projects often experience development challenges that affect cost and schedule during system assembly, integration, and testing.<sup>45</sup> GAO further reported that projects are most likely to require rebaselining due to cost or schedule changes between the Critical Design Review, which the Orion Program completed in October 2015, and System Integration Review, planned for September 2020.<sup>46</sup> Although the Program has tracked and quantitatively assessed individual risks, its UFE planning process did not fully consider the impact of potential deficits in Lockheed’s management reserve. Further, the UFE the Program set aside for unknown/unknowns was not marked to cover deficits in the contractor’s management reserve and could be several hundred million dollars less than is needed to fund a \$382 million shortfall.

We believe the rapid depletion of Lockheed’s reserve warrants the Program’s attention. During discussions, Program officials explained they manage individual risks that contribute to drawdowns on the reserve, but not the overall balance. Although we understand the need to manage individual risks, managing the depletion of Lockheed’s reserve as an overall cost risk would afford Program officials the opportunity to reduce the risk of future cost and schedule overruns. Moreover, by formally addressing the management reserve as a Program cost risk, managers would be better informed when planning for use of the Orion Program’s UFE.

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<sup>45</sup> GAO, “NASA: Assessments of Major Projects” (GAO-16-309SP, March 30, 2016).

<sup>46</sup> At the System Integration Review, a program is evaluated for its readiness to begin the assembly, integration, and testing phase with acceptable risk and within cost and schedule constraints.

## Optimistic Cost and Schedule Estimates Could Have Negative Consequences

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In September 2012, we reported NASA’s optimistic culture may lead managers to overestimate their ability to overcome the risks inherent in delivering projects within established timeframes and budgets and that this could lead to the development of unrealistic cost and schedule estimates.<sup>47</sup> The Orion Program developed internal cost and schedule estimates for EM-1 and EM-2 that rely on the Program receiving funding at levels above the amounts projected in the President’s budget through FY 2019, while NASA has committed to a cost estimate and launch schedule for EM-2 that conforms to the President’s proposed funding levels. The internal estimates were assessed by the SRB and found to have a low confidence level of being achieved, and by the ASAP which raised concerns about the safety consequences of meeting the earlier launch date.

## Internal Cost and Schedule Estimates the Program is Working Toward are Optimistic

In recent years, NASA has required progressively more sophisticated cost estimating techniques for all projects, including a Joint Cost and Schedule Confidence Level (JCL) analysis that produces probabilistic estimates of the impact of risk and uncertainty on planned cost and schedule.<sup>48</sup> Since 2009, NASA has required JCL be developed for the baseline life-cycle cost and schedule estimates established at Key Decision Point C, which is about midway through a project’s development cycle.<sup>49</sup> The Agency requires programs to develop budgets consistent with a 70 percent joint cost and schedule confidence level of being achieved.<sup>50</sup>

In September 2015, the NASA Associate Administrator approved a decision memorandum establishing the Agency’s commitment regarding the cost and schedule for achieving launch readiness for EM-2. As part of that decision, the Management Agreement established estimated life-cycle costs through the EM-2 mission at \$10.8 billion and a launch date of August 2021. In its July 2015 assessment, the SRB for the Orion Program determined this launch date had a JCL of only 40 percent. To meet the NASA-required 70 percent JCL, the SRB estimated life-cycle costs at \$11.6 billion and a launch date of October 2023 for EM-2. The Associate Administrator established the Agency Baseline Commitment at \$11.3 billion and an EM-2 launch date of April 2023.

As shown in Table 7, the life-cycle cost estimate and launch readiness date for EM-2 that the Program is working toward are \$500 million – \$800 million less and 14 – 20 months earlier than the estimates developed by the SRB and committed to by the Agency.

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<sup>47</sup> IG-12-021.

<sup>48</sup> NASA Policy Directive 1000.5, “Policy for NASA Acquisition,” January 15, 2009.

<sup>49</sup> Per the Key Decision Point C Decision Memorandum, the life-cycle cost estimate covers the scope of Orion Design, Development, Test, and Evaluation from the start of formulation through EM-2 launch readiness.

<sup>50</sup> A 70 percent confidence level indicates the project’s likelihood of being completed within the established cost estimate and schedule. See NASA OIG, “Audit of NASA’s Joint Cost and Schedule Confidence Level Process” (IG-15-024, September 29, 2015) for more details on NASA’s JCL process and requirements.

**Table 7: Comparison of Cost and Schedule Estimates for EM-2 Launch Readiness**

Description	Program’s Cost Estimate and Planned Launch Date	Agency’s Cost and Schedule Estimates	Standing Review Board’s Cost and Schedule Estimates
Program Life-cycle Cost	\$10.8 billion	\$11.3 billion	\$11.6 billion
EM-2 Launch Readiness	August 2021	April 2023	October 2023
Joint Cost and Schedule Confidence Level	40 percent	70 percent	70 percent
Funding Assumptions	Funding levels consistently higher than President’s Budget Request	Funding levels in President’s Budget Request	Funding levels in President’s Budget Request and adjustments for lower risk mitigation

Source: OIG analysis of Program documentation.

Program officials acknowledged that working toward the August 2021 date for an EM-2 launch may affect the Program’s risk position but noted that doing so also provides for the possibility of achieving human exploration capability beyond low Earth orbit sooner and at a lower cost. According to these officials, working toward the aggressive schedule has enabled the Program to overcome development challenges within funding constraints and pointed to the recent on-schedule delivery of the EM-1 crew module structure as an example.

## Negative Consequences of Working toward Earlier Launch Readiness Date

In our September 2012 report, we explained that unrealistic cost and schedule estimates can require project managers to defer tasks to later project years, which can delay schedule and increase costs.<sup>51</sup> The Orion Program’s SRB, in its July 2015 report, assessed the Program as having no or low probability of meeting either the September 2018 EM-1 launch date or the August 2021 EM-2 launch date. In fact, the Program already made changes in its testing approach beginning in 2010, by moving from a dedicated to distributed testing approach in order to save production time and costs through 2021. In addition, when possible the Program relocated tests to Kennedy where vehicle assembly will occur. For example, the crew and service modules will undergo element-level vibroacoustic testing separately at Kennedy rather than as an integrated unit at Plum Brook with integrated crew and service module testing on structural test articles at Lockheed’s facility in Denver, Colorado. According to Program officials, these changes were made to reduce schedule risk for EM-1, address conflicts in the use of test facilities, and enable acceptance testing for subsequent missions to be performed at Kennedy.

Given the low likelihood of achieving an August 2021 launch date for EM-2 and the Program’s flat budget profile, we believe that working to a schedule built around this date increases the risk the Program may reduce or defer tasks. Indeed, the SRB concluded that if the Program was to receive a funding profile consistent with the Agency Baseline Commitment, the Program would have to postpone

<sup>51</sup> IG-12-021.

68 tasks to a later date, including moving the Ascent Abort 2 test to a date only 4 months before launch of EM-2. Other testing changes include using a mock-up crew module as the Ascent Abort 2 test article and dropping plans for flight testing the integrated life support systems prior to EM-2. The Program instituted these changes to meet the aggressive 2021 launch date for EM-2. Although these changes will reduce cost and schedule pressure, the Ascent Abort 2 mission is the only opportunity to flight test the launch abort system and its interactions with other vehicle systems.

In addition, the Program has begun deferring tasks to complete certain priorities within funding limits and has reported several tasks being moved from FY 2016 to FY 2017. Program officials stated deferring those tasks allowed the Program to make progress on current year priorities within funding limits and acknowledged that doing so created additional cost and schedule risk in future years. Officials explained that, as cost pressure escalates during the year, Orion Program managers work with Lockheed to identify activities, purchases, or other planned expenditures that can be delayed with minimum impact to the overall Program. While most of the delays will increase Program cost or schedule risk in future years, management of current year priorities is central to the aggressive management posture used by the Orion Program to stay within its funding profile.

Some of the tasks the Program deferred in early 2016 affect both the crew and service modules. For the crew module, the Program will defer the hardware build for EM-2's landing recovery system; delay procurements of valves for propulsion components, life support systems engineering, and integration work for EM-2; and the heat shield test article build. For the service module, the Program will defer manufacturing the test article spacecraft adapter jettison, spacecraft adapter, and crew module adapter; mechanism qualification and acceptance testing; and service module solar cell procurements for EM-2.<sup>52</sup> Program officials also acknowledged that delivery of the European Service Module for EM-1 is likely to be delayed by at least 5 months, with the potential for a delay of 10 months or longer. Also, because the EM-1 service module is not comparable to the EFT-1 service module, the Program reported that assembly, integration, and processing of the EM-1 module may affect the overall Program schedule.

Program officials provided further examples of deferred tasks relating to the launch abort system and software development in order to manage the phasing of funds. For example, completion of EM-1 flight software verification has been deferred at least twice from its estimated completion in March 2017, to June 2017, and then to June 2018 – just 3 months prior to the planned EM-1 launch date and at a cost more than twice as much as originally planned (\$3.8 million compared to \$1.8 million).

As also discussed in our September 2012 report, when tasks are deferred to a later phase, managers may have to sustain a workforce longer than originally planned or add shifts in an attempt to make up for lost time – both of which can lead to increased costs. Given that most of the tasks the Orion Program has deferred were planned for completion between 2010 and 2015, completing them prior to the expected launch dates could stress Program resources and potentially result in significant increases in overall costs. Specifically, deferred tasks will be added to the workload already planned for later phases and resulting costs and resources needed in those years could reduce the Program's UFE. The need to address deferred tasks is in addition to the contingencies discussed previously such as procurement of spare hardware and the potential \$382 million deficit in Lockheed's management reserve.

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<sup>52</sup> The service module solar cell provides power to the service module. It has four solar wings each 7 meters long consisting of three panels that provide power for computers, experiments, and other hardware.

## Increased Risk to Orion and Astronaut Safety

In the ASAP's January 2016 annual safety report, the Panel raised concerns about planned schedules and other measures such as test plan changes that appear to be safety trade-offs in order to maintain the 2021 launch date for EM-2.<sup>53</sup> The Panel noted that NASA had not fully assessed the aggregate increase in risk the Program is accepting to maintain schedule and content for EM-2, and externally committing to a 2023 launch while making decisions based on a 2021 launch date creates a risky situation, because, unless guiding safety principles are established and maintained, safety could be unnecessarily compromised. The ASAP explained that generally program managers diligently work toward a targeted milestone completion date and stated it is vital to send a message to program managers that schedule and mission content are not absolute constraints. Rather, they are elements of the decision-making process, especially in safety matters. The Panel further noted that while the desire to fly crew on Orion as soon as possible is understandable, adjustments to the near-term schedule or mission content that result in far safer systems can be an advantageous trade.

The ASAP highlighted several concerns with the Program's test plan. For example, the Panel was concerned that NASA intended to use a mock-up crew module rather than the actual Orion vehicle as the Ascent Abort 2 test article given that the mission will provide the only opportunity to flight test the abort system to see how it interacts with other Orion systems prior to EM-2.<sup>54</sup> In addition, the Panel was concerned with the new heat shield architecture because current testing techniques cannot inspect all areas of the shield and because flight testing of the shield's redesigned molded block architecture will not occur until EM-1. The Panel was similarly concerned with the lack of a flight test of the life support system prior to EM-2. The ASAP noted that with no flight test before the actual mission, the crew will have only the time they are traveling in low Earth orbit to test the life support system before deciding whether to continue or abort the mission. The ASAP said the plan to forego testing the system prior to EM-2 – when it could take as long as 11 days to return to Earth – increases safety risk without a clearly articulated rationale.<sup>55</sup>

Program officials said they will conduct ground and flight tests of components, subsystems, and integrated systems before EM-2 and do not believe an unmanned flight test of the fully integrated life support system is necessary because system hardware is less complex than earlier life support systems. In a February 2016 presentation to the ASAP, the Program described a test plan that included ground tests of developmental hardware as well as critical components, subsystems, and integrated systems. In addition, the Program will use the ISS for long-duration flight testing of life support hardware such as the carbon dioxide and humidity control system, air monitoring, and the waste management system. Furthermore, the Program will perform ground tests prior to EM-2 to qualify components relative to EM-2 flight requirements such as shock and random vibration.

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<sup>53</sup> ASAP, "Annual Report for 2015," January 13, 2016.

<sup>54</sup> The Program initially planned to reuse the EFT-1 crew module for the Ascent Abort 2 test but later decided to use a mock-up crew module to reduce costs and impact to hardware reuse risk by eliminating the Ascent Abort 2 test article from the hardware reuse risk.

<sup>55</sup> NASA is preparing a formal response to the ASAP report and anticipates issuing the response in 2016.

# Sound Scheduling Practices and Risk Management Procedures Could Help Mitigate Risks

In light of the cost, schedule, and safety risks the Orion Program is managing, we believe the Program would benefit from the Agency establishing an integrated launch date for EM-2 as early as practicable. In addition, Program managers should ensure its procedures for managing risk and schedule align with best practices.

## Integrated Launch Dates

In September 2011, NASA announced the design for SLS and GSDO, which, along with Orion, the Agency decided to develop as separate programs, breaking from the more traditional model of developing integrated systems and projects under a single program umbrella. As of May 2016, NASA had not planned an integrated EM-2 launch date for Orion, SLS, and GSDO. Rather, each Program is working toward its own launch readiness dates within a launch window of September to November 2018 that was formally established and controlled by ESD.<sup>56</sup> Table 8 shows the launch readiness dates for EM-1 and EM-2 by Program as of November 2015.<sup>57</sup>

**Table 8: Launch Readiness Dates by Program**

Program	EM-1 Management Agreement	EM-1 Agency Baseline Commitment	EM-2 Management Agreement	EM-2 Agency Baseline Commitment
Orion	N/A	N/A	August 2021	April 2023
SLS	December 2017	November 2018	N/A	N/A
GSDO	June 2018	November 2018	N/A	N/A

Source: NASA.

The Orion Program has no launch commitment date for EM-1, while the SLS and GSDO Programs have different Management Agreement dates (December 2017 and June 2018, respectively) and the same Agency Baseline Commitment date of November 2018. For EM-2, the Orion Program shows the April 2023 Agency Baseline Commitment launch date, while the SLS and GSDO Programs show no commitment dates. According to the Key Decision Point C Decision Memorandum, NASA will not establish an integrated launch date for EM-2 until after completing EM-1, giving the Agency an opportunity to evaluate the results from that flight before deciding on an integrated launch date.<sup>58</sup>

In our judgment, not having a single, integrated launch date for EM-2 makes efficient planning and scheduling more difficult. In our March 2015 report, we identified the sequencing of the Critical Design Review as an example of where NASA needed to increase coordination efforts to resolve integration issues among the Orion, SLS, and GSDO Programs.<sup>59</sup> We believe the same is true for integrating the

<sup>56</sup> This was the window as of July 2016.

<sup>57</sup> The “Key Decision Point C Decision Memorandum for Orion” states that the commitment was “not an Agency commitment to the integrated EM-2 launch date.” According to the memorandum, “the target launch date for EM-2 will not be determined until after the completion of EM-1.” Decision Memorandums for the SLS and GSDO Programs established Agency Baseline Commitments for EM-1 only and similarly did not commit to a launch date.

<sup>58</sup> According to Program officials, ESD will recommend a specific launch date in late 2016 after concluding formal program review processes.

<sup>59</sup> IG-15-012.

launch date for EM-2. By integrating and planning to a specific launch date for EM-2, NASA could more efficiently plan the use of labor and production capacity as the Programs transition from EM-1 vehicle production, integration of the vehicle and launch system, and mission launch, to development and launch of EM-2.

## Scheduling Practices

An integrated master schedule (IMS) provides a road map for systematic project execution, defining when and how long work will occur and how activities relate to one another, providing a time sequence for the duration of project activities, and an understanding of the dates for major milestones and the activities that drive the project schedule. The success of a program depends in part on having a reliable IMS that enables program officials to decide between possible sequences of activities, determine the flexibility of the schedule based on available resources, and predict the consequences of managerial action or inaction on events to mitigate risk.

We evaluated the Orion Program's November 2015 IMS using GAO's Schedule Assessment Guide that outlines 10 best practices for project scheduling.<sup>60</sup> We found the Program has generally aligned the IMS with nine of the Guide's practices, but could improve in the practice of "Sequencing All Activities." According to the Guide, activities need to be logically sequenced – that is, listed in the order in which they are to be carried out. In particular, the sequence should identify activities that must be completed before other activities can begin (predecessor activities), as well as activities that cannot begin until other activities are completed (successor activities). In our review of the monthly IMS reports, we found 112 missing predecessors and 120 missing successor activities in the IMS, as well as a trend towards reducing the amount of missing predecessors and successors.<sup>61</sup> The SRB also found the sequencing of activities within a flight mission or a major test did not include all logic steps to properly sequence activities between the missions or test activities.

The cause of most of the missing successor links is Lockheed's use of rolling wave planning, pursuant to which the contractor schedules once during the year the work that will be funded the following fiscal year.<sup>62</sup> This causes successor links to not be deleted in a timely manner. Program managers responsible for scheduling stated they are working to reduce the number of missing predecessor and successor activities. Because the IMS undergoes continuous changes, close monitoring of this recurring vulnerability is required.

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<sup>60</sup> GAO, "Schedule Assessment Guide: Best Practices for Project Schedules" (GAO-12-120G, May 2012).

<sup>61</sup> The 232 tasks in question represented about 3 percent of the 7,100 tasks in the November 2015 IMS. In July 2016, Program officials said there were 111 tasks with missing predecessors and successors.

<sup>62</sup> Lockheed uses rolling wave planning, a 1-year planning technique to perform detailed planning for the upcoming fiscal year (October-September). The program's rolling wave planning occurs during the summer and is set within the server database in time for the start of the fiscal year. The contractor then loads resource requirements into the IMS.

## Risk Management Procedures

The Program's risk schedule management plan requires mitigation tasks to be linked or integrated into the IMS.<sup>63</sup> Although the Program is actively managing about 60 risks, the IMS included mitigation tasks for only 5 risks, 4 of which had already been mitigated. In addition, for our sample of 18 risks, only 2 had reference numbers to link them uniquely to the IMS or showed the reference number on the risk statement. Mitigation tasks for all 18 sampled risks had been worked and funded and, according to policy, should have been integrated into the IMS. For unfunded mitigation tasks, the IMS should have included a reminder to integrate the mitigation task the year the task is funded. Consequently, the IMS may not reflect the current progress of mitigation, which could affect the accuracy of milestone dates that depend on the mitigation of the risks.

Program officials stated they are currently updating the IMS to include more Top Program Risks and plan to input all funded Top Program Risks into future versions of the IMS. They added that the Program does not plan to include mitigation tasks for all high-consequence risks because that level of granularity is not required and including the tasks would be labor intensive. Alternatively, the Program relies on a schedule risk analysis of all Program risks that estimates completion dates for mitigation tasks. Program officials said that they annually evaluate the schedule risk analysis and adjust the IMS to reflect mitigation progress as part of the scheduling and budget process.

Although we agree the IMS does not need to include low-level mitigation tasks, we believe it should be adjusted more frequently than annually to reflect the progress of mitigation tasks for Top Program Risks and those risks with likelihood or consequence scores of 4 or 5. Ensuring that the progress of these mitigation tasks is reflected in the IMS allows Program officials to adjust the IMS for mitigation delays or advances that occur during the year and that could impact milestone dates.

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<sup>63</sup> Orion Multi-Purpose Crew Vehicle Program Schedule Management Plan, September, 2015, requires that the mitigation plan be entered into the IMS and reference a unique IMS identifier from either the IMS or a supplemental schedule to the IMS.

# CONCLUSION

Successful development of the Orion vehicle is essential to achieving NASA's goal of expanding human presence beyond low Earth orbit and the Moon. To facilitate Orion's development, the Agency is using a risk management process to proactively address issues that could impede progress. That process has advanced vehicle development through a successful flight test mission, resolution of issues disclosed by the test flight, and reduction of some Program risks.

However, the Program continues to face significant obstacles to developing a flight-ready vehicle that meets safety requirements for human space flight, including mitigating risks for EM-1 and EM-2, managing risks to contractor reserves, and addressing schedule issues. The Program must overcome these obstacles within the context of anticipated flat budgets and future funding uncertainty. At the same time, the Program is working toward an internal planned launch date that is more optimistic than the Agency's external commitment date or independent review board estimates. This funding and scheduling scenario poses cost, schedule, and safety risks to the Program. NASA can reduce cost, schedule, technical, and safety risks by reviewing mission profiles; establishing a realistic, coordinated launch date for EM-2; and implementing a fully integrated risk management process that accounts for all Program risks.

# RECOMMENDATIONS, MANAGEMENT'S RESPONSE, AND OUR EVALUATION

To improve the likelihood Orion is developed on cost and schedule and safely operated, we recommended the Associate Administrator for Human Exploration and Operations:

1. Reevaluate whether the Program should continue working toward its internal launch readiness dates for EM-1 and EM-2 or otherwise ensure that doing so does not impose unnecessary cost, schedule, and safety risks to the Program.
2. Require the Orion Program Manager to designate and manage depletion of Lockheed's reserve as a cost risk to the Program.
3. Require the Orion Program Manager to include activities in the IMS that must be completed before other activities can begin (predecessor activities), as well as activities that cannot begin until other activities are completed (successor activities) as described in the GAO Schedule Assessment Guide.
4. Require the Orion Program Manager to develop procedures for adjusting the IMS outside of the annual scheduling and budget process so that it reflects the progress of mitigation tasks for all Top Program Risks and risks that are not Top Program Risks but have likelihood and consequence scores of 4 or 5.

We provided a draft of this report to NASA management who concurred with our recommendations and described corrective actions the Agency has taken or will take to address them. We consider these actions responsive. Therefore, the recommendations are resolved and will be closed upon verification and completion of the proposed actions.

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

Major contributors to this report include Raymond Tolomeo, Science and Aeronautics Research Director; Nora Thompson, Project Manager; Gregory Lokey; Jobenia Parker; James Pearce; Jim Richards; and Robert Rose. Additional support provided by Benjamin Patterson and Patricia Reid.

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](mailto:laurence.b.hawkins@nasa.gov).

A handwritten signature in black ink, appearing to read 'PKMA'.

Paul K. Martin  
Inspector General

# APPENDIX A: SCOPE AND METHODOLOGY

We performed this audit from January 2015 through July 2016 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.

Our overall audit objective was to assess the Orion Program's progress in managing vehicle development risks. Our specific audit objective was to determine whether NASA could improve its management of the Program's technical, schedule, and cost risks. Our review of Orion Program was conducted at Johnson, Kennedy, Langley Research Center (Langley), Michoud, Plum Brook, and NASA Headquarters. We observed on-going Orion efforts at Kennedy, Langley, Michoud, and Plum Brook.

## Scope

To assess the Orion Program's progress in managing technical, schedule, and cost risks, we reviewed a sample of 18 risks. The sample consisted of the nine Top Program Risks as of February 2015. The sample also included all other risks that as of September 2015 had a likelihood score of 5 (probability higher than 90 percent) or consequence score of 5 (potential for catastrophic loss of life, loss of vehicle, loss of mission, or cost impact of \$500 million or more). For each sampled risk, we interviewed Program officials responsible for each risk; reviewed Program documents such as risk management reports, planning documents, and risk management criteria; and reviewed other relevant documents such as independent reviews. When appropriate, we conducted on-site inspections of risk mitigation work.

To assess schedule risk and performance, we evaluated the Program's IMS dated November 2015 against the "GAO Schedule Assessment Guide: Best Practices for Project Schedules" and the schedule evaluation in the Preliminary Design Review dated July 2015. We used a NASA proprietary program, "STAT," to identify gaps between the IMS and the GAO best practices to determine whether the Program took corrective action in response to recommendations in the Preliminary Design Review. We interviewed Program officials, reviewed Program documents, and analyzed independent reports and Program reviews.

To assess the Orion Program's management of cost risks, we analyzed the depletion rate of the prime contractor's management reserve fund and reviewed a sample of management reserve transactions for appropriateness. To analyze the management reserve depletion rate, we obtained all transactions from April 2012 through February 2016 and performed a linear regression analysis of monthly fund balances since the beginning of July 2014. We began our regression analysis with July 2014 data because the management reserve reached its highest level, \$309.5 million, in that month and Program managers expected no additions to the fund after July 2014. To review management reserve transactions for appropriateness, we selected a sample of 24 transactions from the universe of 547 transactions occurring between April 2012 and June 2015. Our sample consisted of 14 high-dollar and 10 randomly selected transactions. We reviewed available supporting documentation and discussed the sampled transactions with Program managers.

To assess Orion Program funding constraints and challenges, we reviewed Program documents and interviewed Program officials. We also reviewed the final Key Decision Point C Decision Memorandum

which set the Management Agreement and Agency Baseline Commitment budgets and launch readiness milestones for the Orion Program life cycle.

To assess the Orion Program's requirements for complying with NASA JCL standards we reviewed NASA's OIG report, "Audit of NASA's Joint Cost and Schedule Confidence Level Process" and the SRB report "Orion Multi-Purpose Crew Vehicle (MPCV) delta Preliminary Design Review (dPDR) Standing Review Board (SRB) Management Briefing to the Agency Program Management Council." The OIG report contained details of the JCL process and Agency requirements. The SRB report provided an assessment of the Program's JCL analyses.

To assess the Program's process for testing and integration, we reviewed the Orion Program Plan, documentation and policies of Cross-Program Integration Teams, and the delta Preliminary Design Review. We also interviewed Headquarters and Orion Program officials.

## Review of Internal Controls

We reviewed and evaluated internal controls related to NASA's risk management of the Orion Program. This included assessing the Program's compliance with internal control requirements of the Agency's risk management policy and the best-practices described in Carnegie Mellon University's "Continuous Risk Management Guidebook," 1996.<sup>64</sup> We concluded that the Program's internal controls, except for those practices discussed in the report, complied with Agency requirements and best-practices and were adequate to manage technical, schedule, and cost risks. The internal control recommendations discussed in the report, if implemented, should correct the weaknesses identified.

## Use of Computer-Processed Data

We relied on computer-processed data such as risk detail reports produced from NASA's Active Risk Management system, NASA IMS schedules produced from Microsoft Project, and prime contractor logs of management reserve transactions and balances produced in Microsoft Excel. Although we did not independently verify the reliability of all this information, we compared it with other available supporting documents to determine data consistency and reasonableness. From these efforts, we believe the information we obtained is sufficiently reliable for this report.

## Prior Coverage

During the last 5 years, the NASA Office of Inspector General issued five reports, and the Government Accountability Office issued four reports of significant relevance to the subject of this report. Unrestricted NASA OIG and GAO reports can be accessed at <https://oig.nasa.gov/audits/reports/FY16/index.html> and <http://www.gao.gov>, respectively.

### *NASA Office of Inspector General*

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

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<sup>64</sup> NASA Procedural Requirements 8000.4A, "Agency Risk Management Procedural Requirements," December 16, 2008.

*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)*

*Status of NASA's Development of the Multi-Purpose Crew Vehicle (IG-13-022, August 15, 2013)*

*NASA's Challenges to Meeting Cost, Schedule, and Performance Goals (IG-12-021, September 27, 2012)*

### ***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 2016)*

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

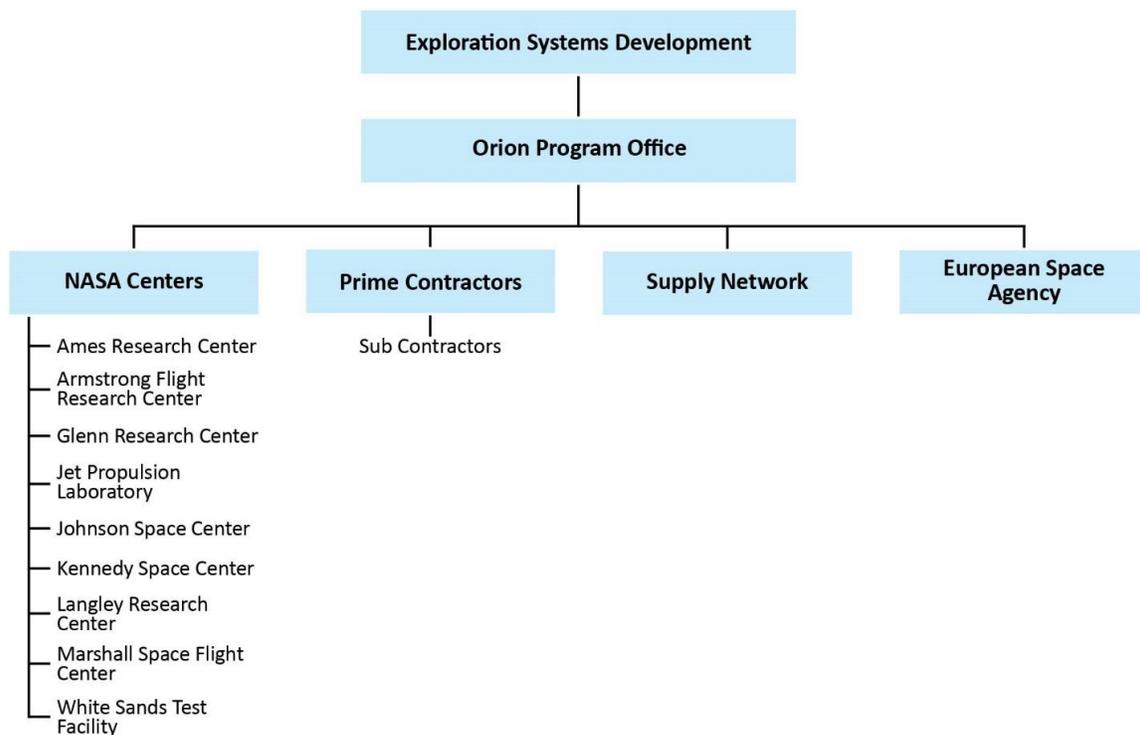
*NASA: Assessments of Selected Large-Scale Projects (GAO-15-320SP, March 2015)*

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

## APPENDIX B: PROGRAM ORGANIZATION

The Orion Program consists of NASA organizations and external entities. NASA organizations include the Exploration Systems Development Division, Orion Program Office, and Agency Centers and Facilities. External entities include the prime contractor, subcontractors, the supply network, and the European Space Agency. These are shown in Figure 11.

**Figure 11: Orion Program Organization**



Source: NASA.

Boards and panels are used to control requirements and to make decisions necessary to stay on plan. They generally include both NASA and contractor personnel and may be led by NASA or the contractor.

### Exploration Systems Development

ESD, located at NASA Headquarters, provides the Program oversight and direction. According to NASA policy, the NASA Associate Administrator is the decision authority for authorizing the Program to advance through milestone reviews. The Associate Administrator for Human Exploration and Operations has delegated Program authority to the ESD Deputy Associate Administrator, including responsibility for the Orion, SLS, and GSDO Programs.

## Orion Program Office

The Orion Program Office, located at Johnson, is responsible for controlling the Program’s technical objectives, schedule, and cost. The Program Office is organized by function, including separate offices for Program planning and control, the launch abort system, crew and service module, avionics and power systems, flight operations, ESA integration, flight test office, and vehicle integration. The Program also has three technical authorities: safety and mission assurance, health and medical, and engineering. Responsibility is delegated to managers of the respective offices. For example, the Launch Abort System Office is led by a manager who independently verifies development of the system and supports integration of the launch abort system into the vehicle. The Vehicle Integration Office is led by a control area manager who is responsible for integrating systems engineering activities across the vehicle’s elements and modules.

## NASA Centers

In addition to officials at NASA Headquarters, about 250 civil servants from nine NASA Centers and Facilities provide products and services to the Program. Civil servants work on tasks such as requirements, testing, and contract oversight. Each civil servant has a support office that reports directly to the Program Manager responsible for providing resources and ensuring execution of the assigned tasks and activities.

## Prime Contractor and Subcontractors

Lockheed is the prime contractor.<sup>65</sup> Major subcontractors are Aerojet Rocketdyne, Inc., Honeywell Aerospace, and United Technologies Aerospace Systems. Contractor personnel work collaboratively with NASA personnel on what are called integrated project teams.

## Supply Chain

About 3,000 people in 45 states make up a supply chain for the approximate 200,000 specialized parts and assemblies that will be needed by the Program. The supply chain begins with loads analysis and proceeds through component engineering, procurement, vendor manufacturing, transportation, and receiving inspection. The Program established a joint NASA and Lockheed “Demand Management Team” to provide oversight and manage the Orion Supply Chain processes.

## European Space Agency

ESA, the European Union’s counterpart to NASA, provides products and services according to requirements laid out in a partnership agreement. Under the agreement, ESA is responsible for building and delivering a fully qualified European Service Module for both EM-1 and EM-2 and assisting in integrating that unit to other parts of the service module.

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<sup>65</sup> The Lockheed-Martin contract is a cost-plus-award fee contract with a period of performance from August 2006 through December 2020 and a total value of \$11.5 billion.

## **Boards, Panels, and Working Groups**

The Program is aided by various boards that differ in the scope of their reviews and authority. Program officials use them to help control requirements, evaluate performance, and make decisions necessary to stay on plan. For example, the SRB conducts key milestone reviews throughout the project and recommends technical, schedule, and programmatic changes as part of their reviews; the Multi-Purpose Crew Vehicle Program Control Board establishes the Program baseline, the approved plan for the Program with approved changes, and resolves baseline issues; and the Service Module Control Board approves changes to the European Service Module documents that define the Module's baseline, product changes, schedules, and risks.

## APPENDIX C: SAMPLED AND MITIGATED RISKS

Program officials made progress in mitigating 10 of the 18 risks we sampled for this review. The Agency has either closed the risk, lowered the likelihood or consequence score below 5, or projected that the risk will be moved from mitigation to tracking status in 2016. Table 9 shows their likelihood scores, consequence scores, and expected mitigation dates as of July 2016. Following the table is a description of Agency actions mitigating or closing the risk.

**Table 9: Risks that Show Mitigation Progress**

Risk	Likelihood	Consequence	Expected Closure Date
European Service Module	3	4	December 2016
Heat Shield Architecture	2	4	February 2017
EM-2 Landed Mass	2	3	July 2016
Flight Control Module Processor Resources for EM-1	2	4	June 2018
Mode 1 Vibroacoustic Environments	2	3	November 2019
Flight Software Verification	0	3	To Be Determined
Environmental Test Article Avionics Availability	2	3	To Be Determined
Budget Threats to EM-1	4	4	January 2017
Network Switch Radiation Compliance	1	3	Mitigated/Closed September 2015
Loss of Crew from Disorientation during Manual Parachute Deploy	0	0	Closed April 2016

Source: OIG analysis of Program information.

### European Service Module

NASA is procuring the service module for EM-1 through a barter agreement with ESA. Although the barter agreement contains an option for ESA to provide the service module for EM-2, no formal agreement has yet been signed between the partners for EM-2.<sup>66</sup> Program officials identified the lack of a barter agreement for the service module for EM-2 as a level 5 risk to that mission.

In March 2016, the Orion Program Manager signed a letter addressed to the European Service Module Program Manager that formalizes NASA's intent for ESA to provide the service module for EM-2, and ESA and NASA are negotiating a formal agreement the Program expects will be finalized in July 2016. Once signed by the parties, the agreement must be ratified at ESA's ministerial conference, the next session of which is scheduled for December 2016. ESA anticipates obtaining most or all of the estimated \$200 million cost of the service module for EM-2 from its governing board.<sup>67</sup>

<sup>66</sup> Under the agreement, ESA provided the service module for EM-1 in exchange for one astronaut flight on the ISS.

<sup>67</sup> Should the board fail to fund the full cost of the module, NASA might have to offset any shortfall. Orion Program officials deem this a low probability and therefore have not reserved funds to cover this contingency.

## Heat Shield Architecture

The heat shield, a critical element of the Orion vehicle, protects the vehicle and crew members from the extreme temperatures experienced during reentry through the Earth's atmosphere. The heat shield material risk was a concern going into EFT-1, as mentioned in our August 2013 report.<sup>68</sup>

Analyses performed during production of the EFT-1 heat shield disclosed two pre-flight issues: the heat shield material displayed lower than expected strength properties, and the heat shield itself experienced cracking at the seams during final cure. The strength issue did not impact the EFT-1 mission as the cracks were plugged and the repair process proved successful. The two issues coupled with the prospect of higher thermal environments on later missions prompted the Program to shift focus from heat shield material to heat shield architecture. EFT-1 used a heat shield with a honeycomb architecture that was attached to an underlying structure. The honeycomb sections were each injected with "Avcoat" material, a specially manufactured material. As a result of post-flight analysis, the Program decided to research use of new molded block architecture. The molded block version directly bonded about 180 Avcoat blocks to the composite skin of the heat shield, with gap-filler material placed into thin spaces between the Avcoat blocks. The Program estimated the recurring cost of the molded block architecture as costing \$6 million to \$8 million less than the previous honeycomb architecture. The molded blocks could be produced in-house throughout the year, which would use production labor more efficiently.

Risk mitigation efforts included trade studies and various tests of the heat shield material and architecture, such as load and shock tests. For example, in February 2014, a failure review board sanctioned a trade study of the heat shield material. In October 2014, the trade study recommended the "molded block" architecture as the preferred heat shield option for parallel development with the honeycomb architecture of EFT-1. In April 2015, based on the trade study and testing, the Program proceeded with the molded block version for EM-1 and EM-2. In September 2015, the Program refocused the heat shield risk mitigation on development and production of the new molded-block architecture, its certification, and impacts on cost and schedule milestones. In March 2016, the Program reduced the consequence score from "high" to "moderate" after fracture analysis margin testing showed positive results. By February 2017, the Program plans to complete static load and cold soak proof tests for acceptance of the heat shield for the EM-1 mission. If the tests are successful, the Program plans to reduce the likelihood rating from "low" to "very low" and close the heat shield risk.

## EM-2 Landed Mass

The Orion crew vehicle cannot exceed weight limits established for each phase of the mission, including lift-off, trans-lunar insertion, and landing. In our August 2013 report, we reported that vehicle weight at lift-off was projected to be 5,444 pounds (7 percent) over the lift-off limit. That risk was eventually mitigated and closed. During our current review, the Orion Program has been tracking a risk that vehicle weight at landing of EM-2 will exceed its limit.

Orion Program officials mitigated the weight risk for EM-1 through two actions. First, officials made changes to the vehicle's design and improved the process for managing vehicle weight. Program officials reduced the number of panels and supporting braces in the crew modules skeleton structure and thereby reduced vehicle weight. This weight reduction was part of the Program's effort to reduce total vehicle weight by assessing and tracking the weight of each vehicle part and reviewing vehicle

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<sup>68</sup> IG-13-022.

design changes to look for opportunities for weight reduction. Second, Program officials assessed mission-level requirements, raised the weight limits for EM-1, and increased the weight reserve for EM-1. However, EM-2 increases vehicle weight because the mission adds the weight of the crew and crew supplies. This leaves an insufficient reserve to mitigate risks that increase with weight and to meet weight limits for landing the vehicle (landed mass) during EM-2.

Mitigation actions through January 2016 were completed successfully and as of March 2016, the remaining mitigation action was to assess weight changes caused by mitigation efforts associated with the abort vibroacoustic risk. If mitigation actions are unsuccessful, the Program plans to modify EM-2 to fit within vehicle weight limits. Mission modifications include, for example, reducing crew size, shortening mission duration so that fewer supplies will be carried onboard, or making minor design changes. In October 2015, the EM-2 landed mass risk was downgraded from a “moderate to low” likelihood score of 2, but retained a “moderate” consequence score of 3. In March 2016, Program officials de-escalated the risk from a Top Program Risk to a top sub-organization risk and expect to close the landed mass risk in July 2016.

## **Flight Control Module Processor Resources for EM-1**

As the demand on Orion’s flight control system increases from EFT-1 through EM-1 and EM-2, it is possible that the flight control module (FCM) will not be able to handle all of the processing required for the two missions without significant flight software optimization and minor hardware modification. FCM functions include: (1) guidance, navigation, control, and propulsion; (2) environmental control and life support; and (3) command and telemetry processing. This risk has implications for performance, cost, and schedule. Specifically, performance implications include the possibility that selected functional capabilities of the FCM could be deferred to a future mission, cost implications include the possibility that flight software optimization efforts could exceed several million dollars, and schedule implications include the possibility of impacting critical Program milestones by 3 to 6 months.

This risk was originally opened in September 2013. At that time, the risk was assessed as having a moderate likelihood (likelihood score 3) and a very high consequence (consequence score 5). Program managers are mitigating this risk by focusing on software optimization techniques, as well as making limited hardware modifications. Significant hardware modifications are not considered viable because of cost and schedule constraints. The goal of risk mitigation is to limit aggregate FCM processor utilization to no more than 80 percent during flight. As a result of optimization efforts and improvements in processor utilization rates, in July 2015, the risk was reassessed as having a “low” likelihood of occurring. Program officials lowered the consequence score to “high” and expect that this risk will be de-escalated from a Top Program Risk and that it will transition from active mitigation to “watch” status in October 2016.

## **Mode 1 Vibroacoustic Environments**

During launch aborts, the abort motor will produce high levels of random vibrations (vibroacoustic energy) that will be transmitted to the heat shield and crew module. Vibroacoustic energy carries a risk that hardware components may fail unless they are capable of withstanding the predicted energy levels. These at-risk components require qualification testing and may require modification or redesign. Consequently, this risk may lead to increased costs and schedule delays. Specifically, the cost impact of redesigning components that fail qualification testing is estimated between \$5 million and \$50 million. Schedule delays associated with redesign could be 1 to 3 months.

Mode 1 vibroacoustic environments became a Top Program Risk in 2013. At that time, the risk was assessed as having a “high” likelihood of occurring (likelihood score 4) and the potential for causing total mission loss (consequence score 5). To mitigate the risk, Program officials adopted a plan to identify and assess abort critical hardware components (called mode 1 abort critical components) and then modify or redesign components, as needed, to ensure they are capable of withstanding predicted vibroacoustic energy levels. In January 2015, Program officials reassessed this risk as having both a moderate likelihood of occurring (likelihood score 3) and the potential for a moderate mission impact (consequence score 3). As of April 2016, there were 117 mode 1 abort critical components. Of the 117 critical components, 93 were classified as “low” risk and 24 as “medium” risk. Of the 24 medium risk components, 7 will be flown on EM-1 and the remaining 17 will see first flight on EM-2. Program officials expect that all EM-1 first-use critical components will complete abort level qualification testing by July 2017. At that time, officials expect to reassess the risk as having a very low likelihood of occurring.

## **Exploration Mission Flight Software Verification Risk**

Program officials identified the exploration mission flight software verification a risk because there is a possibility that schedule and resource estimates could be unfavourable as compared to the actual effort of software verification. (Effort includes both verification of new software and "re-verification" of EFT-1 software code.) Resources applied late for verification would cause a greater than 6-month impact to the Program’s critical path. This consequence may be mitigated in part by applying additional resources earlier in the plan. However, in October 2015, the Software Risk Board lowered the schedule consequence score from 5 to 3. The Board based this action on a clarification that schedule consequence should be based on potential impact to mission schedule versus its potential impact to the software development schedule. The Board had based the earlier, higher consequence score on impact to the software development schedule rather than impact to mission schedule.

## **Environmental Test Article Avionics Availability**

Program officials identified environmental test article (ETA) avionics availability as a risk because the Program planned to reuse the majority of crew module avionics from EM-1 on EM-2 and their reuse creates a risk that avionics will be unavailable to support ETA testing at Plum Brook. Avionics refers to the spacecraft’s electronics systems and includes its communications, navigations, display, and flight control systems. The ETA testing requires abort avionics to be functional during and after testing; however, since the Program plans to reuse all EM-1 abort avionics on EM-2, they will not be available for ETA testing. Abort avionics used on the EM-2 mission will not be available in the ETA testing timeframe.

The Program has taken steps to mitigate the risk by deciding not to use EM-1 avionics hardware to support ETA testing. The Program will instead utilize existing qualified avionics hardware to support ETA testing.

## **Budget Threats to EM-1**

Program managers expect their budget to be “flat-lined” at \$1 billion per year through at least 2018. Given a flat funding profile going forward, the Program’s incremental development approach could lead to cost increases and schedule delays. Program officials acknowledged that a flat funding trajectory is not optimal and increases the risk that costly design changes may be needed later in the development

stage as vehicle elements are completed, integrated, and tested with other elements. Officials confirmed that previous budget reductions made it difficult to plan and execute a viable development schedule. For example, NASA delayed development of environmental control and life support systems and some avionics components due to budget reductions.

In August 2012, the Program documented a risk to the EM-1 launch date based on the combination of flat budget projections, buying power erosion, cost growth for EFT-1 and EM-1, fixed costs transferred from NASA Centers to the Program, and reduced savings. The Program took action with Lockheed to reduce fixed costs, and the contractor identified steps to mitigate cost growth in EFT-1, EM-1, and fixed costs.

When the Program initially opened the risk, likelihood and consequence both had scores of 5. In January 2015, the Program reduced both scores to 4. The lower scores were based on multiple favorable appropriations and scope refinements. Program officials monitor cost performance for growth and opportunities to off-set cost growth. Currently, officials are watching this risk.

## **Network Switch Radiation Compliance**

Program officials identified the network switch radiation compliance risk during the preliminary design phase for the vehicle camera/instrumentation architecture. Given that the network switch is new to the Orion vehicle design, Program officials concluded that there was a possibility that switch performance would be significantly affected in radiation environments and could result in the loss of the ability to record certain types of data. Program officials conducted radiation testing to determine the extent of this risk. Upon early results from radiation testing, Program officials determined that an architecture or component change was required. The risk was documented because the likelihood and consequences were high enough that they could affect flight test objectives for EM-1. Various technical solutions also had cost and schedule impacts to Program need dates for EM-1. The components involved in this risk have been replaced with more radiation-tolerant designs, which mitigated the likelihood and consequences of this identified risk at or below scores of 3. This risk was closed in September 2015.

## **Loss of Crew from Disorientation during Manual Chute Deployment**

Although Orion's primary avionics system is designed to deploy the main parachutes automatically without action by the crew, the crew would have to manually deploy the parachutes in the event the avionics system failed. The risk of avionics system failure is low, and based on landing simulation models NASA has determined there is 1 to 10 percent probability the crew would be too disorientated to perform this manual task during landing.

Program officials mitigated the risk associated with manual deployment by adding a hardwired backup timer that would automatically deploy the main parachutes in the event the avionics system failed and the crew was incapacitated. The Program closed the risk in April 2016.

# APPENDIX D: MANAGEMENT'S RESPONSE

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



August 26, 2016

Reply to Attn of:

Human Exploration and Operations Mission Directorate

**TO:** Assistant Inspector General for Audits

**FROM:** Associate Administrator for Human Exploration and Operations  
 Mission Directorate

**SUBJECT:** Agency Response to OIG Draft Report, "NASA's Management of the Orion  
 Multi-Purpose Crew Vehicle Program" (A1500300)

The National Aeronautics and Space Administration (NASA) appreciates the opportunity to review and comment on the Office of the Inspector General (OIG) draft report entitled, "NASA's Management of the Orion Multi-Purpose Crew Vehicle Program" (A-15-003-00), dated July 29, 2016.

NASA has chosen to challenge the Orion program to be more innovative and affordable as it designs, builds, and tests the first deep-space crew vehicle in a generation. NASA strongly believes that Orion is achieving this and endorsed Orion moving from formulation into development after the very successful Exploration Flight Test (EFT)-1 deep-space flight test and Key Decision Point C (KDP-C) review. Orion's flight test provided NASA with an unprecedented set of design, production, and demonstrated flight data, as well as actionable information on supplier performance, cost, delivery schedules, and risks. This highly successful accomplishment provides actual experience that has validated the aggressive management techniques that Orion employed to develop this complex spacecraft.

Adopting a development strategy of this complexity is not without risk, and the OIG focus on the top risks that Orion Program is managing during this audit period is appropriate. It is key that the OIG found the Orion Program risk management process to be effective in defining and mitigating the key risks with robust processes that also determine when residual risk is acceptable to the Agency. This audit witnessed the Orion Program successfully executing mitigation plans for several risks with potentially serious implications. Several of the risks now have reduced likelihood and consequence scores or have been closed as defined risks. The audit team also saw the level of dynamic change in some mitigation plans as steps are performed and more is known that affects the resolution path and subsequent mitigation steps. Orion has shown flexibility and adaptability in its management of risk that contributes to the remarkable progress of the program. This is direct evidence of a healthy risk management process.

As the OIG report states, the “successful development of the Orion vehicle is essential to achieving NASA’s goal of expanding human presence beyond low Earth orbit and the Moon.” The Orion Program continues to make extraordinary progress toward that goal. The excellent schedule performance has been achieved while the Orion development team successfully overcame many difficult development challenges. One recent example, highlighted in the OIG report, is the delivery of a mass-optimized Exploration Mission (EM)-1 Crew Module structure on the original schedule that had been established over 24 months earlier despite encountering major manufacturing challenges.

In the draft report, the OIG makes the following recommendations to the NASA Associate Administrator for Human Exploration and Operations (HEO) intended to improve the likelihood Orion is developed on cost and schedule and safely operated:

**Recommendation 1:** Reevaluate whether the Program should continue working toward its internal launch readiness dates for EM-1 and EM-2 or otherwise ensure that doing so does not impose unnecessary cost, schedule, and safety risks to the Program.

**Management’s Response:** Concur. The HEO Mission Directorate continually evaluates progress of the exploration enterprise under the direction of the Exploration Systems Development (ESD) Division, including the progress of the Orion Program. In particular, NASA evaluates program progress against the actual resource levels appropriated through the budget formulation and execution process. Given the levels that have been actually appropriated for Orion, NASA believes that Orion is on track for the 2021 launch readiness date that is the internal plan. NASA policy is to make external cost and schedule commitments at the less aggressive 70 percent confidence level, which for Orion is its 2023 commitment date assuming the President’s Budget Request. However, it should be clear that this is a cost and schedule confidence level; human spaceflight safety requirements pertain regardless. The Agency embraces the aggressive cost and schedule posture to acquire the exploration assets quickly and affordably within the defined constraints while achieving the standards of rigor and safety necessary to accomplish the ambitious exploration missions in the future.

The Agency strategy of establishing launch “windows” for future flights strives to maintain maximum flexibility in program execution and always prioritizes crew safety highest among the program management objectives. The Agency agrees that synchronization of all elements of the enterprise is desirable and we believe ESD pursues a rigorous process of routine review to assure all critical aspects of program integration are managed actively. But it is important to note that NASA is developing a system that will be used for many decades beyond the initial flights on EM-1 and EM-2. NASA is investing in much more than just EM-1 and EM-2. Although EM-1 and EM-2 are critical near-term milestones, these missions do not reflect the total breadth of systems being developed.

**Estimated Completion Date:** NASA has met the intent of the recommendation and proposes the action be closed. The Agency, through a series of design and programmatic reviews and status updates, remains confident that the cost and schedule risk of the current approach is manageable since any element that achieves launch readiness before another is

able to deploy resources on future flight build activities that would be expended in any event.

**Recommendation 2:** Require the Orion Program Manager to designate and manage depletion of Lockheed's reserve as a cost risk to the Program.

**Management's Response:** Concur. The Agency agrees that judicious and constant monitoring of all authorizations to expend program budget is critical to both the success of the program and in maintaining confidence of stakeholders in the effective management of the program. The Orion Program has visibility into allocations of management reserves within the prime contract, and in many cases is part of the decision process. These reserves fall within the existing contract value and represent flexibility of the prime contractor to authorize previously undefined work within the contract scope without formal contract action or additional funding from the Government. Allocation of the contract management reserves are always subject to existing funding constraints with which the contractor must comply. The primary risk of depleting management reserves, therefore, is that of contract expenditures exceeding contract value which will then require specific approval from the Government to allow additional allocations. The Orion Program has initiated a continuous assessment of contractor management reserves allocation and will report these results to the Program Manager monthly. This action will be defined as a mitigation step in the existing top program risk #11973 "Budget Threats to EM-1 Schedule/Content."

**Estimated Completion Date:** December 2016, upon documentation that the mitigation plan for Top Program Risk #11973 is updated to include the tracking of management reserves.

**Recommendation 3:** Require the Orion Program Manager to include activities in the Integrated Master Schedule (IMS) that must be completed before other activities can begin (predecessor activities), as well as activities that cannot begin until other activities are completed (successor activities) as described in the GAO Schedule Assessment Guide.

**Management's Response:** Concur. NASA agrees that a high quality IMS identifies all predecessor and successor activities in the schedule network that fully represents the Program. In citing this concern first voiced by the Standing Review Board months earlier, the OIG lends further emphasis to the importance of this good practice. In the data first reviewed during this audit, the OIG correctly observes that about three percent of tasks had broken logic (mostly post-delivery operations tasks) which measures in the healthy category using generally accepted NASA assessment criteria. A recent update showing the metric improved further to about 1.5 percent of total IMS tasks demonstrates the program commitment to develop and maintain the best possible management visibility and analysis tools for the Orion Program. ESD and the Orion Program are committed to improving all aspects of performance management practice for the ultimate benefit of the exploration enterprise. Part of the success demonstrated on EFT-1 and EM-1 is a direct result of decoupling precursor activities.

**Estimated Completion Date:** NASA has met the intent of the recommendation and proposes the action be closed. The Orion Program has further reduced the already small number of broken logic links in the program IMS. The IMS is robust and accurate, but as with all processes, Orion will continue to look for opportunities to further improve the system.

**Recommendation 4:** Require the Orion Program Manager to develop procedures for adjusting the IMS outside of the annual scheduling and budget process so that it reflects the progress of mitigation tasks for all Top Program Risks and risks that are not Top Program Risks but have likelihood and consequence scores of 4 or 5.

**Management's Response:** Concur. NASA agrees that visibility into the downstream schedule implications of risk mitigation planning requires good schedule and performance management tools and a vigilance of program management to assure timely execution of the plan. The Orion Program demonstrated the use of locally controlled supplemental schedules for capturing the integration of risk mitigation planning within the established baseline schedule. These schedules include tasks, decision points, and latest target dates for resolution that avoids collateral downstream production or integration impacts. For the highest criticality risks, the Orion Program Manager reviews progress weekly or biweekly with potential to direct adjustments to the mitigation plans as more information is uncovered. When mitigation plans cannot support the baseline schedules, the program utilizes schedule analysis tools to assess the impacts of missing formal schedule milestones. Changes to the IMS based on delayed or unsuccessful risk mitigation (realized risk) can be implemented at any time. The program has found, however, that capturing highly dynamic detailed mitigation plans in the IMS is very labor intensive and cannot respond as quickly as other proven techniques to inform the Orion Program. The Orion Program will endeavor to annotate for visibility in the IMS which "parent" tasks contain significant portions of planned risk mitigation steps that may result in delays in planned completion.

**Estimated Completion Date:** NASA has met the intent of the recommendation and proposes the action be closed. Risk mitigation steps are taken into account in the IMS, and adjustments are made when realized risks cause movement in planned work.

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

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

A handwritten signature in black ink that reads "William H. Gerstenmaier". The signature is written in a cursive style with a large, stylized 'W' and 'G'.

William H. Gerstenmaier

# APPENDIX E: REPORT DISTRIBUTION

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## National Aeronautics and Space Administration

Administrator  
Deputy Administrator  
Associate Administrator  
Chief of Staff  
Associate Administrator for Human Exploration and Operations  
Deputy Associate Administrator for Exploration Systems Development  
Orion Program Manager  
Johnson Space Center Director

## Non-NASA Organizations and Individuals

Office of Management and Budget  
    Chief, Science and Space Branch  
  
Government Accountability Office  
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## Congressional Committees and Subcommittees, Chairman and Ranking Member

Senate Committee on Appropriations  
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    Subcommittee on Space, Science, and Competitiveness  
  
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House Committee on Appropriations  
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