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NASA'S MARS 2020 PROJECT

January 30, 2017

Report No. IG-17-009





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NASA Office of Inspector General
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RESULTS IN BRIEF

NASA's Mars 2020 Project

January 30, 2017

IG-17-009 (A-16-008-00)

WHY WE PERFORMED THIS AUDIT

Since 1964, NASA has spent more than \$21 billion on missions exploring Mars, including four robotic rovers on the Martian surface, five static landers, and numerous satellite missions orbiting the planet. Each mission has contributed to the scientific understanding of Mars and built on discoveries made by prior missions. For example, NASA's most recent rover mission to the planet – the Mars Science Laboratory (MSL), which landed in August 2012 – confirmed that key ingredients needed to support living microbes, such as carbon, nitrogen, oxygen, phosphorus, and sulfur, were present on ancient Mars.

NASA's next robotic rover mission to the Red Planet – known as Mars 2020 – will be equipped with seven science instruments to further scientific understanding of Mars and demonstrate new technologies, including an experiment to produce oxygen from carbon dioxide in the Martian atmosphere that will support the Agency's goal of sending humans to the planet in the 2030s. While the \$2.4 billion Mars 2020 Project will utilize new and modified technology, particularly with respect to its on-board instruments, the Project will also use a significant amount of heritage technology from MSL in an effort to reduce mission costs and risks. The rover will have the capability to travel about 12 miles from the landing site, and the plan is to spend at least 1.25 Mars years (28 Earth months) exploring the surrounding region.

We assessed NASA's management of the Mars 2020 Project relative to achieving technical objectives, meeting milestones, and controlling costs. Our specific objective was to assess how emerging challenges could affect the mission and whether the project plan is based on complete, reliable, and accurate cost, schedule, and risk information. To complete this work, we reviewed key project planning documents, reviewed NASA policies and procedures, and interviewed NASA management, among others.

WHAT WE FOUND

The primary constraint and driver for Mars 2020 development is the Project's planned July 2020 launch date. An optimal 20-day launch window for a trip from Earth to Mars occurs every 26 months. Missing the 2020 launch window would result in significant additional costs related to overhead, stand-by work force, replacement of degraded parts and components, and storage while waiting for the next launch opportunity. Although Mars 2020 Project management has taken appropriate steps to address risks inherent in using heritage technology and several issues identified on the MSL mission, we identified several schedule-related issues that could indicate the Project is overly optimistic, including a condensed development schedule for five of the seven instruments, a shorter development timeframe than MSL, and less detailed Integrated Master Schedule for assigning timelines to all required tasks than MSL.

The largest risk to the Mars 2020 schedule is the Project's Sample and Caching Subsystem (Sampling System), which will collect core samples of Martian rocks and soil and place them on the planet's surface for retrieval by a future robotic or human mission. At Preliminary Design Review (PDR), three of the Sampling System's critical technologies were below technology readiness level (TRL) 6, meaning the prototype had not yet demonstrated the capability to perform all the functions required. Projects are evaluated during PDR to ensure they meet all system requirements with acceptable risk.

and within cost and schedule constraints. The immaturity of the critical technologies related to the Sampling System is concerning because, according to Mars 2020 Project managers, the Sampling System is the rover's most complex new development component with delays likely to eat into the Project's schedule reserve and, in the worst case scenario, could delay launch. As of December 2016, the Project was tracking the risk that the Sampling System may not be ready for integration and testing – the period when a spacecraft is built, undergoes final testing, and is prepared for launch – in May 2019, as planned.

The Mars 2020 Project also does not appear to be on track to meet the 90 percent metric for release of engineering drawings by the February 2017 Critical Design Review (when a project demonstrates its design is sufficiently mature to proceed to full-scale fabrication, assembly, integration, and testing). Engineering drawings communicate to manufacturers the details of a product's design and are considered a good measure of a project's stability. Failure to achieve this metric could affect the Project's ability to ensure design stability, achieve technical objectives, and meet schedule and cost expectations.

In addition to the risks associated with the Sampling System and the engineering drawings, we also identified several other challenges confronting Mars 2020 Project managers, including late delivery of actuators (the components responsible for moving and controlling parts and instruments on the rover); foregoing an engineering model of the Mars Oxygen In-Situ Resource Utilization Experiment (MOXIE) designed to assess the feasibility of producing oxygen on Mars as a cost savings measure; ensuring the rover does not exceed its designed mass limit of 1,050 kilograms; and addressing foreign partner funding issues that may affect their ability to timely deliver components to the Project.

WHAT WE RECOMMENDED

To assist the Mars 2020 rover mission in achieving its technical objectives, meeting Project milestones, and controlling costs, we recommended the Associate Administrator for Science require the Mars 2020 Project Manager to (1) ensure the TRL of critical technologies and the rate of releasable engineering drawings meet established criteria before the Project completes Critical Design Review; (2) develop alternative plans to minimize changes to the overall science mission, Project cost, schedule, and scope if current risks to the actuators, mass growth, MOXIE, and Sampling System are realized; (3) assess the effectiveness of using a less detailed Integrated Master Schedule and make timely adjustments if required; and (4) continue to work with partners facing funding issues.

NASA concurred with our recommendations and described planned actions. We find the actions responsive and will close the recommendations upon verification the Agency has taken the action.

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Acronyms

CDR	Critical Design Review
GAO	Government Accountability Office
HEOMD	Human Exploration and Operations Mission Directorate
IMS	Integrated Master Schedule
INTA	National Institute for Aerospace Technology
JPL	Jet Propulsion Laboratory
KDP	Key Decision Point
kg	Kilograms
MEDA	Mars Environmental Dynamics Analyzer
MEDLI2	Mars Entry, Descent and Landing Instrumentation-2
MOXIE	Mars Oxygen ISRU [In-Situ Resource Utilization] Experiment
NPD	NASA Policy Directive
NPR	NASA Procedural Requirements
PDR	Preliminary Design Review
PIXL	Planetary Instrument for X-ray Lithochemistry
RIMFAX	Radar Imager for Mars' Subsurface Experiment
SHERLOC	Scanning Habitable Environments with Raman & Luminescence for Organics & Chemicals
STMD	Space Technology Mission Directorate
TRL	Technology Readiness Level
UVA	University of Valladolid

INTRODUCTION

Since 1964, NASA has spent more than \$21 billion on missions exploring Mars, including four robotic rovers on the Martian surface, five static landers, and numerous satellite missions orbiting the planet.¹ NASA's next robotic rover mission to the Red Planet – known as Mars 2020 – will both further scientific understanding of Mars and demonstrate new technologies intended to support future robotic missions and the Agency's goal of sending humans to the planet in the 2030s.²

We initiated this audit to evaluate NASA's management of the \$2.4 billion Mars 2020 Project relative to achieving technical objectives, meeting milestones, and controlling costs. Our specific objective was to assess how emerging challenges could affect the mission and whether the Project plan is based on complete, reliable, and accurate cost, schedule, and risk information. See Appendix A for details on our scope and methodology.

Background

NASA has executed 15 successful missions to Mars over the past 50 years, including Mariner 4 and Mariner 9, the first spacecraft to fly-by and orbit the planet, respectively; Viking 1, the first spacecraft to land and successfully operate on the planet; and Mars Pathfinder, the first robotic rover to explore the planet (see Appendix B for details of all the Agency's Mars mission).³ Each mission has contributed to the scientific understanding of Mars and built on discoveries made by prior missions. For example, NASA's most recent surface mission to the planet – the Mars Science Laboratory (MSL), which landed in August 2012 – confirmed that key ingredients such as carbon, nitrogen, oxygen, phosphorus, and sulfur needed to support living microbes were present on ancient Mars.

MSL Self-Portrait



Source: NASA.

Organization of the Mars 2020 Project

NASA's Science Mission Directorate manages the Mars 2020 Project, while the Jet Propulsion Laboratory (JPL) is responsible for performing overall system design and integration and providing two of the seven science instruments the rover will carry. Foreign partner organizations from France, Norway, and Spain,

¹ Figure does not include missions yet to be launched and is expressed in fiscal year 2016 dollars.

² NASA is also working on a static lander known as the Interior Exploration using Seismic Investigations, Geodesy and Heat Transport (InSight) mission, which is scheduled to launch to Mars in May 2018.

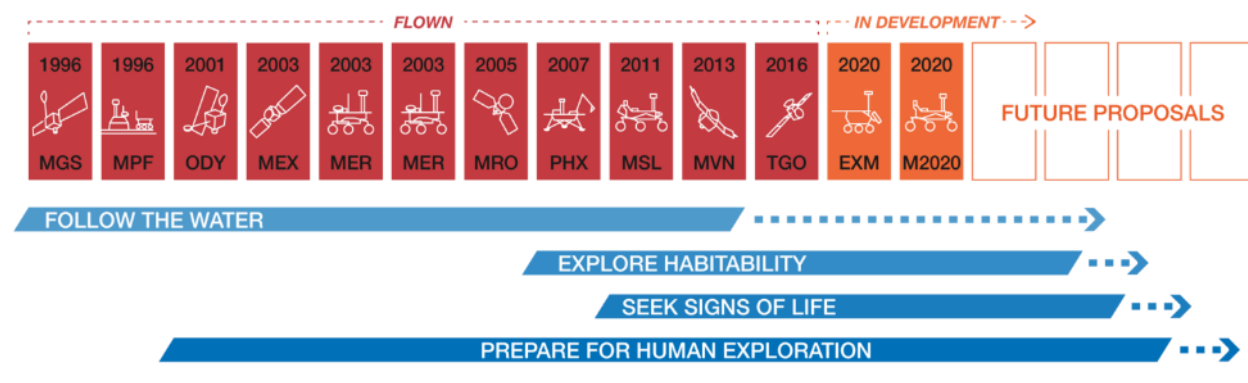
³ Five other Mars missions launched but did not reach their destinations or otherwise failed to perform: Mariner 3 experienced mechanical difficulties, Mariner 8 failed during launch, contact was lost with Mars Observer shortly before it entered Mars orbit, and Climate Orbiter and Polar Lander both were lost upon arrival at the planet.

and domestic partners including universities and other Federal agencies, are also contributing components and instruments to the Project. NASA's Human Exploration and Operations Mission Directorate (HEOMD) and Space Technology Mission Directorate (STMD) are providing funding to support development of several instruments.

Contribution to NASA's Mars Exploration Program Science Goals

NASA's Mars Exploration Program, the organization responsible for managing the Agency's robotic Mars exploration efforts, has four long-term science goals: (1) determine whether life ever existed on Mars, (2) characterize the climate of Mars, (3) characterize the geology of Mars, and (4) prepare for human exploration of Mars. To accomplish these goals, the Program has designed missions to support four science strategies: (1) follow the water, (2) explore habitability, (3) seek signs of life, and (4) prepare for human exploration. Figure 1 depicts these strategies chronologically with some of NASA's completed, on-going, and planned Mars missions.

Figure 1: Mars Exploration Program Science Strategies



Source: NASA.

Notes: The Agency's Mars missions of the past 20 years, listed in chronological order – Mars Global Surveyor (MGS), Mars Pathfinder (MPF), Mars Odyssey (ODY), Mars Express (MEX – partner-led), Mars Exploration Rover (MER), Mars Reconnaissance Orbiter (MRO), Phoenix Mars Lander (PHX), Mars Science Laboratory (MSL), Mars Atmosphere and Volatile Evolution Mission (MVN), Trace Gas Orbiter (TGO – partner-led), ExoMars (EXM – partner-led), and Mars 2020 (M2020).

Mars 2020 has four science and programmatic objectives that link directly to the Mars Exploration Program science strategies:

- *Geologic exploration.* Characterize the geology of the landing site.
- *In situ astrobology and habitability.* Identify ancient environments capable of supporting microbial life, and seek signs of possible past microbial life in those habitable environments, particularly in specific rocks known to preserve signs of life over time.
- *Caching samples.* Collect and store rock and soil samples on the Martian surface for future retrieval.
- *Preparing for humans.* Characterize the surface environment and test techniques to produce oxygen from the Martian atmosphere.

To accomplish these objectives, the Mars 2020 rover will be equipped with seven science instruments as well as measurement sensors on its backshell and heatshield.⁴ As mentioned, JPL is providing two of the seven instruments while Arizona State University, the Massachusetts Institute of Technology, the Norwegian Defence Research Establishment, Spain's National Institute for Aerospace Technology, and the U.S. Department of Energy's Los Alamos National Laboratory are providing the other five. In addition, France's Institute for Research in Astrophysics and Planetology and Spain's University of Valladolid are providing components for one of the instruments.⁵ Table 1 provides descriptions of the seven instruments.

Table 1: Mars 2020 Science Instruments

Instrument	Responsible Organization	Description
Mastcam-Z	Arizona State University	Mast-mounted advanced camera system with panoramic and stereoscopic imaging and zoom capability.
Mars Environmental Dynamics Analyzer (MEDA)	National Institute of Aerospace Technology	Sensors that will provide measurements of temperature, wind speed and direction, pressure, relative humidity, and dust size and shape.
Mars Oxygen ISRU [In-Situ Resource Utilization] Experiment (MOXIE)	Massachusetts Institute of Technology	Exploration technology investigation that will produce oxygen from Martian atmospheric carbon dioxide.
Planetary Instrument for X-ray Lithochemistry (PIXL)	JPL	X-ray fluorescence spectrometer containing an imager with high resolution to determine the fine scale elemental composition of Martian surface materials.
Radar Imager for Mars Subsurface Experiment (RIMFAX)	Norwegian Defence Research Establishment	Ground-penetrating radar that will provide centimeter-scale resolution of the geologic structure of the planet's subsurface.
Scanning Habitable Environments with Raman & Luminescence for Organics & Chemicals (SHERLOC)	JPL	Spectrometer that will provide fine-scale imaging and use an ultraviolet laser to determine mineralogy and detect organic compounds.
SuperCam	Los Alamos National Laboratory	Instrument that will provide imaging, chemical composition analysis, and mineralogy. Includes components provided by France's Institute for Research in Astrophysics and Planetology and Spain's University of Valladolid.

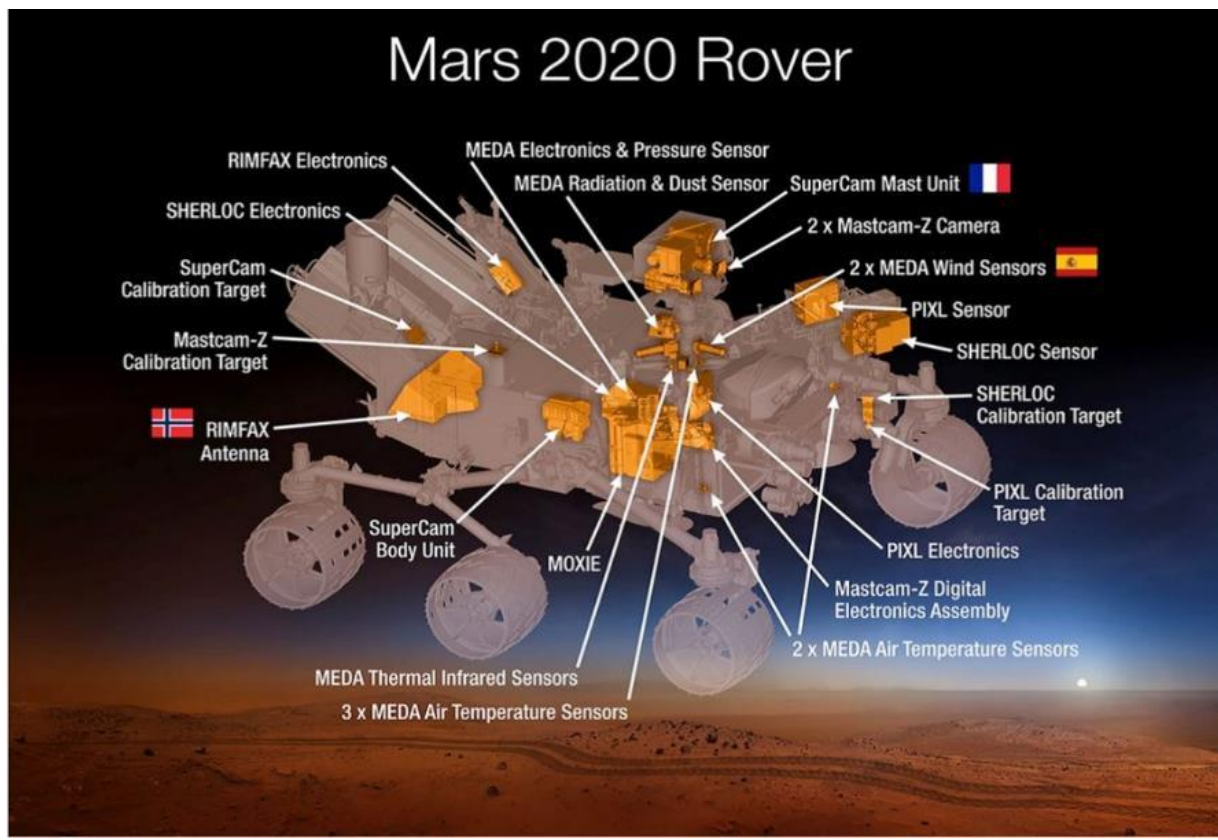
Source: NASA.

⁴ The backshell and heatshield make up the aeroshell in which the rover and its landing system are enclosed during transit between Earth and Mars.

⁵ France's Institute for Research in Astrophysics and Planetology is participating through the Centre National d'Etudes Spatiales, which is the partner on the Implementing Arrangement for the French contribution to SuperCam.

Figure 2 shows how the instruments will be placed on the rover's chassis.

Figure 2: Payload Instruments and Key Components

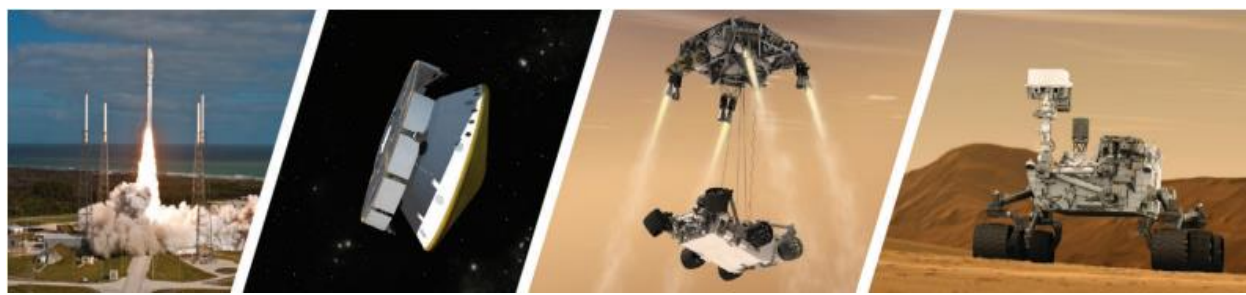


Source: NASA.

Mars 2020 Architecture

Although the mission is designed to support a rover 150 kilograms (kg) heavier (about 330 pounds) than the MSL rover, the Mars 2020 rover is based predominantly on its predecessor's architecture. Moreover, the Mars 2020 rover will launch, enter the Martian atmosphere, and descend and land on the planet using essentially the same technology as MSL (see Figure 3). In an effort to reduce mission costs and risks, the Project is also using spare parts NASA procured for MSL.

Figure 3: Launch, Entry, Descent, and Landing



Source: NASA.

That said, Mars 2020 will utilize a significant amount of new and modified technology, particularly with respect to its on-board instruments. For example, Mars 2020 includes a Sample and Caching Subsystem (Sampling System) that will collect core samples of Martian rocks and soil and “cache” them on the planet’s surface for retrieval by a future robotic or human mission. Caching samples for future retrieval means that subsequent missions will not need to carry sample selection or acquisition equipment, thereby reducing the complexity of those missions. In Table 2, we list Mars 2020 instruments and components and indicate whether they are heritage, new, or modified technology.

Table 2: Technology Type by Instrument and Component

Instrument/ Component	Heritage	New	Modified	Description
Entry, Descent, and Landing System				
Aeroshell	X			Components are predominately heritage. The Mars Entry, Descent and Landing Instrumentation-2 (MEDLI2) will collect data during the mission’s entry through the planet’s atmosphere to enable improved designs of future Mars entry systems and has been modified to accommodate additional sensors.
Cruise Stage	X			Components are predominately heritage. The Cruise Stage Reaction Control System has been modified.
Descent Stage	X			All components are heritage.
Science Instruments				
Mastcam-Z			X	Major modifications on Mastcam-Z include a new zoom lens assembly that provides 3:1 zoom capability.
MEDA			X	See Table 1
MOXIE		X		See Table 1
PIXL		X		See Table 1
RIMFAX		X		See Table 1
SHERLOC		X		See Table 1
SuperCam			X	SuperCam has substantial heritage from MSL with the addition of two new instrument modes – the Raman spectrograph and the infrared spectrograph – that provide information regarding the molecular makeup of a target for improved mineralogy, chemistry, organic detection, and color images.
Rover Chassis	X			Components are predominately heritage. The Terrain-Relative Navigation system is a new addition to improve hazard avoidance. A few heritage hardware components were modified to accommodate the heavier rover.
Sampling System		X		The Sampling System uses a new coring drill, robotic arm assembly, and adaptive caching system. A modified MSL-like arm will carry out functions with similar requirements to MSL.

Source: NASA Office of Inspector General (OIG) analysis of Project data.

Project Life-Cycle Cost, Schedule, and Status

NASA divides the life cycle of its space flight projects into two major phases – Formulation and Implementation – that are further divided into Phases A through F.⁶ Formulation consists of Phases A and B, and Implementation is Phases C through F. This structure allows managers to assess the progress of their projects at Key Decision Points (KDP) throughout the process.⁷ During Phases A (Concept and Technology Development) and B (Preliminary Design and Technology Completion), projects develop and define requirements, cost and schedule projections, acquisition strategy, and project design, and complete development of mission-critical or enabling technology.

Towards the end of Formulation, a Preliminary Design Review (PDR) is conducted by project personnel and an independent Standing Review Board.⁸ The objectives of the PDR are to (1) evaluate the completeness and consistency of the planning, technical, cost, and schedule baselines developed during Formulation; (2) assess compliance of the preliminary design with applicable requirements; and (3) determine if the project is sufficiently mature to begin Phase C. Thereafter, almost all changes to the baseline are expected to represent successive refinements rather than fundamental changes.

Following PDR and to receive management approval to proceed to Implementation, the project must pass through KDP-C where a final assessment of the preliminary design and a determination of whether the project is sufficiently mature to proceed is made. As part of the KDP-C review process, cost and schedule baselines are established against which the project is thereafter measured.

During Phase C of Implementation, the project prepares its final design, fabricates test units that resemble the actual hardware, and tests those components. A second design review, the Critical Design Review (CDR), occurs in the latter half of Phase C. The purpose of the CDR is to demonstrate the design is sufficiently mature to proceed to full-scale fabrication, assembly, integration, and testing, and that the technical effort is on track to meet performance requirements within identified cost and schedule constraints. After the CDR, a System Integration Review takes place during which the readiness of the project to start flight system assembly, test, and launch operations is assessed. Depending on the results of that review, the project may be approved to continue into Phase D, which includes system assembly, integration, test, and launch activities. Phase E consists of operations and sustainment, and Phase F is project closeout.

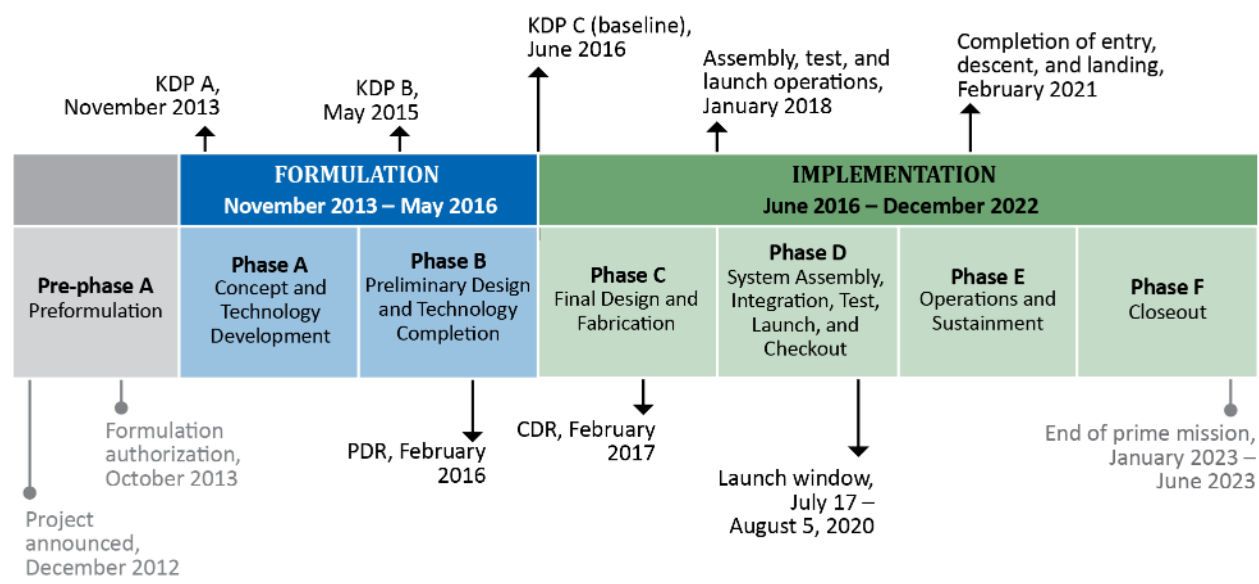
⁶ NASA Procedural Requirements (NPR) 7120.5E, “NASA Space Flight Program and Project Management Requirements w/Changes 1-14,” August 14, 2012. NASA defines Formulation as the period in which project personnel identify how the project supports the Agency’s strategic goals; assess feasibility, technology, concepts, and risk; build teams; develop operations concepts and acquisition strategies; establish high-level requirements and success criteria; prepare plans, budgets, and schedules; and establish control systems to ensure performance to those plans and alignment with current Agency strategies. Implementation is the period in which personnel execute approved plans for the development and operation of the project and use control systems to ensure performance to those plans and continued alignment with the Agency’s strategic goals.

⁷ A KDP is defined as the point in time when the Decision Authority – the responsible official who provides approval – makes a decision on the readiness of the project to progress to the next life-cycle phase. KDPs serve as checkpoints or gates through which projects must pass.

⁸ The Standing Review Board is an independent advisory board chartered to assess programs and projects at specific points in their life cycle and to provide the program or project, the Decision Authority, and other senior management with a credible, objective assessment of how the program or project is doing relative to Agency criteria and expectations.

Mars 2020 entered Formulation in November 2013. PDR was held in February 2016, and in June of that year, NASA's Associate Administrator approved the Project to proceed into Implementation and established an Agency Baseline Commitment life-cycle cost of \$2.44 billion.⁹ CDR is scheduled for February 2017.¹⁰ See Figure 4 for a graphical depiction of the major mission milestones.

Figure 4: Mars 2020 Mission Timeline



Source: NASA.

Mars 2020 is scheduled to launch in July 2020 from Cape Canaveral Air Force Station in Florida on an Atlas V launch vehicle and land on Mars in February 2021 at a site to be determined. The rover will have the capability to travel up to 20 kilometers (about 12 miles) from the landing site, and the plan is to spend at least 1.25 Mars years (28 Earth months) exploring the surrounding region.

Cost Estimates from Project Announcement to Key Decision Point-C

In December 2012, NASA announced a new rover mission for launch in 2020 with a preliminary cost range estimated between \$1.3 billion and \$1.7 billion.¹¹ This estimate was roughly based on a July 2012 Mars Program Planning Group study of a project concept known as Mars Rover-C. The Mars Rover-C concept eventually became the Mars 2020 Project and the cost estimate was further refined.

⁹ The Agency Baseline Commitment establishes an integrated set of project requirements, cost, schedule, and technical content, and forms the basis for NASA's commitment to Congress and the Office of Management and Budget for the Project's life-cycle cost and schedule.

¹⁰ CDR was originally scheduled for December 2016.

¹¹ The estimate was for Phases A through D in fiscal year 2015 dollars.

In the summer of 2013, the first formal cost estimate for Mars 2020 of \$1.81 billion was provided by the Project during the Mission Concept Review.¹² This estimate included costs for Phases A through D and the launch vehicle. At KDP-A in November 2013, Project managers provided a life-cycle cost estimate with a range of \$2.14 billion to \$2.35 billion. The Project life-cycle cost estimate remained in this range through KDP-B. As previously noted, the Agency Baseline Commitment established at KDP-C was \$2.44 billion. This figure includes the contributions from HEOMD and STMD. See Table 3 for additional information about the Project's cost history.

Table 3: Project Estimate from Mission Concept Review to Agency Baseline Commitment (Real Year Dollars in Millions)

	Mission Concept Review	KDP-A	KDP-C
JPL obligations and bypass obligations ^a	\$1,053	\$1,053	\$1,183 ^g
Multi-Mission Radioisotope Thermoelectric Generator	66	66	70
Launch vehicle and Unallocated future expenses-Project ^b	671	671	576
Other NASA costs ^c	22	22	19
Phase E costs and Unallocated future expenses-Headquarters ^d		\$329–543	456
Pre-phase A costs			23
HEOMD/STMD payload accommodations costs ^e			21
HEOMD/STMD payloads ^f			93
Total	\$1,811	\$2,140–2,354	\$2,442

Source: NASA OIG analysis of Project documentation with nominal differences in dollar amounts presented due to rounding.

^a Bypass funds are any funds sent directly from NASA Headquarters to other NASA Centers or Government agencies in support of Mars 2020.

^b Unallocated future expenses held by the Project are the portion of costs that are expected to be incurred, but cannot yet be allocated to a specific work breakdown structure sub-element of a projects plan.

^c A fixed fee that is sent to the California Institute of Technology for all funds received at JPL from NASA.

^d Unallocated future expenses are held at the NASA Headquarters-level to support additional directed scope, or existing scope, if the Project exceeds Project-held reserves, and was provided as a range at KDP-A.

^e Science Mission Directorate funds to accommodate the HEOMD/STMD-funded MEDA, MEDLI2, and MOXIE instruments.

^f MEDA, MEDLI2, and MOXIE instruments, and Terrain Relative Navigation.

^g Includes budget impacts due to additional payload scope from NASA Headquarters Announcement of Opportunity selection, project cost underrun, and a JPL employee retirement benefits funding correction.

¹² At Mission Concept Review, the project demonstrates that the proposed mission, approach, and objectives are feasible and viable; provides a preliminary cost estimate range; and articulates a preliminary plan for life-cycle activities that illustrates a reasonable execution of the mission within estimated programmatic constraints. Costs from this point forward are expressed in real year dollars – the amount spent in the year expended.

Design Stability

According to the Government Accountability Office (GAO), “programs are more likely to succeed in terms of cost, schedule, and performance if agencies collect specific knowledge early, in preparation for critical points in the development process.”¹³ GAO also states that “if design stability is not achieved at the critical design review, but product development continues, costly re-designs to address changes to project requirements and unforeseen challenges can occur.”¹⁴

NASA and GAO have established metrics to assess whether a project’s design is sufficiently stable at specific points in the development cycle to proceed to the next life-cycle phase.¹⁵ Specifically, critical technologies should be matured to a technology readiness level (TRL) of 6 by PDR. Similarly, NASA’s Systems Engineering Handbook provides that approximately 90 percent of engineering drawings should be releasable by CDR and GAO cites this metric as a best practice.¹⁶ An engineering drawing is deemed “releasable” when that portion of the design is finalized and can be turned over to the manufacturing entities.

Critical Technologies and Technology Readiness Levels

Typically, critical technologies are identified as new technologies upon which a project depends to meet the minimal operational performance levels in development, production, or operation. For example, the Solid OXide Electrolyzer, which will be used to convert carbon dioxide into oxygen and is the key component of MOXIE, is a new technology that addresses the program objective of preparing for human exploration of Mars.

NASA categorizes space technologies into TRLs 1 through 9. As shown in Figure 5, at TRL 1 scientific research is in the early stage. In contrast, at TRL 9 the technology has been proven on a successful flight.

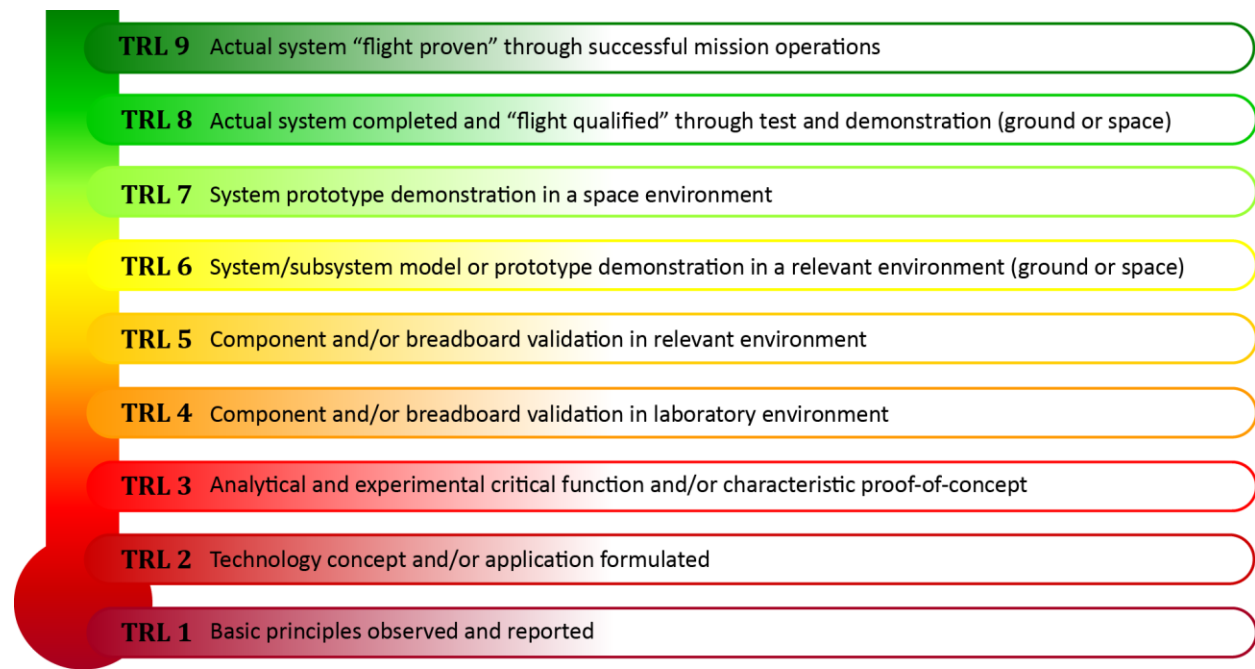
¹³ GAO, “Assessments of Selected Large-Scale Projects” (GAO-15-320SP, March 24, 2015).

¹⁴ GAO, “Assessments of Selected Large-Scale Projects” (GAO-10-227SP, February 1, 2010).

¹⁵ The top five metrics GAO identified (GAO-15-320SP) are: (1) the maturity of technologies to a TRL of 6 by PDR; (2) the percentage of verification and validation plans complete at PDR and CDR; (3) definition of the project’s top level requirements that define mission success criteria and are imposed by NASA, to requirements at the subsystem level by the time of the PDR; (4) the level of funding reserves and schedule margin at various points in the development life cycle; and (5) the percentage of actual mass margin versus planned mass margin over time. See Appendix C for our evaluation of each metric.

¹⁶ NASA, “Systems Engineering Handbook” (SP-2007-6105, December 2007) and GAO-15-320SP.

Figure 5: Technology Readiness Levels



Source: NASA.

NASA and GAO guidelines state that critical technologies should be at least at TRL 6 when a project completes PDR – meaning the technology has been demonstrated in a fully integrated prototype in a relevant environment that simulates the conditions in which it will operate. According to GAO, achieving this level of maturity minimizes risks as the system enters the next stage of development. Accordingly, the TRL of the critical technologies is an important measure of a project’s design stability and one indicator of the likelihood the project will be able to meet cost and schedule goals.

Engineering Drawings

Engineering drawings graphically convey the information required for construction and include details such as dimensions, how a component functions, how it is to be built, the materials to be used, and the processes required to fabricate and test it. Because they are the mechanism by which engineers communicate to manufacturers the details of a product’s design, engineering drawings are also considered a good measure of a project’s stability. As noted earlier, according to NASA’s System Engineering Handbook and GAO, 90 percent of engineering drawings should be releasable by CDR.

MARS 2020 PROCEEDED INTO DEVELOPMENT WITH QUESTIONABLE DESIGN STABILITY AND IS CONFRONTING TECHNICAL, SCHEDULE, AND FOREIGN PARTNER FUNDING ISSUES

Although Mars 2020 Project management has taken appropriate steps during Formulation to address risks inherent in using heritage technology and several issues identified during the MSL mission, five of the Project's seven critical technologies were below TRL 6 at the Project's Preliminary Design Review (PDR). Moreover, the Project does not appear to be on track to meet the 90 percent metric for release of engineering drawings by Critical Design Review (CDR) in February 2017. Failure to achieve these metrics could affect the Project's ability to ensure design stability, achieve technical objectives, and meet cost and schedule expectations. Finally, Mars 2020 Project managers are working on a shorter schedule than the Agency used to develop MSL while confronting technical, schedule, and partner funding issues that may affect the Project's ability to achieve several mission objectives.

Application of Lessons Learned From MSL

Successful organizations develop systems to share information from past successes and failures as part of their knowledge management practices. NASA defines these "lessons learned" as knowledge or understanding gained by experience. This experience may be positive, as in a successful test or mission, or negative, as in a mishap or failure. Sharing lessons learned can reduce risk, improve efficiency, promote validated processes, and improve performance in ongoing and future NASA projects.

Due to several technical challenges, MSL missed its initial launch window in September 2009, delaying the mission by 26 months and raising the mission life-cycle cost estimate by \$834 million. Given that Mars 2020 is reusing many MSL component technologies, it is critical Project management incorporate the lessons learned from the MSL mission in order to avoid a similar costly launch delay.

We found Mars 2020 Project managers used a variety of strategies to incorporate MSL lessons learned into project planning and development, including retaining MSL staff, performing an "inheritance" review, incorporating the results of a lessons learned study into the project plan, and reviewing MSL Problem Failure Reports.¹⁷

¹⁷ An "inheritance" review evaluates the compatibility of the product or design being reused with the mission, science, system, and environmental requirements of the current project to assess potential risks and benefits associated with its use and the need for modification or additional testing and analysis.

One tangible result of this process was a redesign of the rover's wheels to minimize the premature wear and tear MSL experienced 14 months into its mission. The redesigned wheels are twice as thick as MSL's and add 10 kg of mass to the Mars 2020 rover. Similarly, Mars 2020 engineers are considering software changes that could improve the rover's ability to match wheel drive with the terrain.

MSL Wheel Damage



Source: NASA.

Critical Technologies Not at Recommended Maturity Level at PDR

At PDR in February 2016, five of the Project's seven critical technologies, including the seal for the sample caching mechanism, were at or below TRL 5 rather than at the recommended TRL 6 (see Table 4). Although only one level separates the two, there is a significant difference between TRLs 5 and 6. At TRL 5, basic technological components are integrated on a smaller than operational scale so that the system configuration can be tested for functionality similar to the final application. A technology merits TRL 6 only when a project shows that the prototype is capable of performing all the functions required of the operational system.

Table 4: Mars 2020 Critical Technologies

Critical Technology Description (Associated Instrument)	Basis of Criticality	TRL at PDR
Coring Drill Mechanical Percuss (Sampling System)	The drill is required to meet various Level 1 requirements. The drill's light tapping action (percuss) is necessary for drilling all but the weakest rock.	5
Sample Caching Hermetic Seal (Sampling System)	The seal prevents the loss of volatiles from the sample, which can affect science data. It also prevents cross contamination from other samples and from rover contaminants.	4–5
Core Breakoff (Sampling System)	A key function of the drill in obtaining core samples.	5
Terrain Relative Navigation	Accessing new sites will require the Terrain Relative Navigation, which will also assist in avoiding landing hazards.	6
ISRU Solid OXide Electrolysis	Key component of MOXIE, the technology demonstration instrument for the program objective of preparing for human exploration of Mars.	5
PIXL Grounded Cathode X-Ray Source (PIXL)	The grounded cathode (rather than anode) requires much less volume for the supporting electronics. This is important for PIXL to fit on the arm turret.	6
SuperCam Transmission Spectrometer (SuperCam)	A key part of the instrument science that has not been used before.	5–6

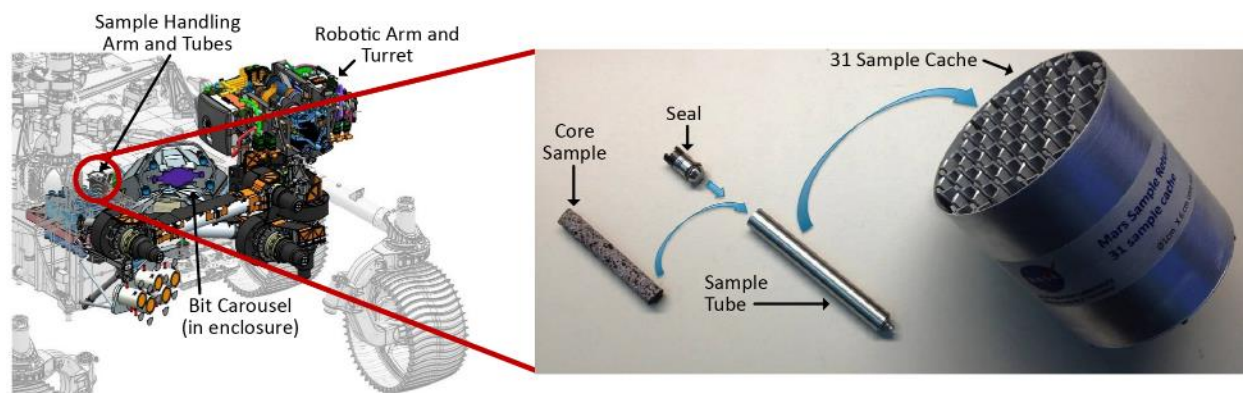
Source: Mars 2020 Project management.

Historically, proceeding into development before critical technologies are matured to TRL 6 has been associated with costly redesigns later in development. Project managers stated they recognized and addressed this risk as part of their presentation to the Decision Authority at KDP-C, and the Project's risk mitigation and technology development plan was accepted and approved. Although the Project was still showing five technologies below TRL 6 in May 2016, improvements were made in the maturity of Sampling System technologies and by December Project personnel were showing all seven technologies as having reached TRL 6.¹⁸ Despite this progress, given the low TRL scores at PDR, it is imperative the technologies be validated as part of the CDR in February 2017 to ensure each is sufficiently mature before the Project proceeds to the next phase of development.

Sampling System

Three of the five critical technologies that had not reached TRL 6 by PDR are related to the Sampling System. As shown in Figure 6, a coring drill located at the front end of the rover will use specially designed drill bits to acquire samples of soil or rock and deposit them in a tube. A robotic arm then pulls the tube from the drill, after which an assessment station performs a visual and volume inspection before the tube is sealed and stored on the planet's surface for retrieval by a future mission.

Figure 6: Sampling and Caching Subsystem Hardware



Source: NASA.

Note: Caching hardware depicted was a preliminary design that in December 2016 project personnel said was replaced with an alternative design.

The immaturity of critical technologies related to the Sampling System is concerning for three reasons. First, managers told us the Sampling System is the most complex new development component of the Project. Accordingly, solutions to address associated risks are likely to be complicated and time consuming. Second, other risks being tracked by the Project related to the Sampling System include potential delays in development of the actuators, additional restrictions on assembly and tests due to new or modified planetary protection and contamination control requirements, and a redesign of

¹⁸ Given the timing of our audit fieldwork, we were unable to verify the change in status.

hardware necessitated by limitations in performance or increases in mass or volume of the new actuators.¹⁹ Third, because the Sampling System is on the Project's critical path, delays are likely to eat into the Project's schedule reserve and, in the worst case scenario, could delay launch.²⁰

As of December 2016, the Project was tracking the risk that the Sampling System may not be ready for integration and testing in May 2019, as planned. Referred to at NASA as the Assembly, Test, and Launch Operations phase of a project, this is when a spacecraft is built, undergoes final testing, and is prepared for launch. During this phase, instruments will be shipped to a cleanroom and mated with the rover and spacecraft before the entire structure is put through rigorous environmental, electronics, software, and systems testing. Late deliveries at the Assembly, Test, and Launch Operations phase could mean some tests are performed with surrogate rather than flight hardware or some tests may need to be repeated or not performed at all. Although we are unable to determine the extent to which immature critical technologies contribute to this risk, ultimately the Sampling System is a mission critical component and Mars 2020 may not launch without it.

Releasable Engineering Drawings are Significantly Below Recommended Levels

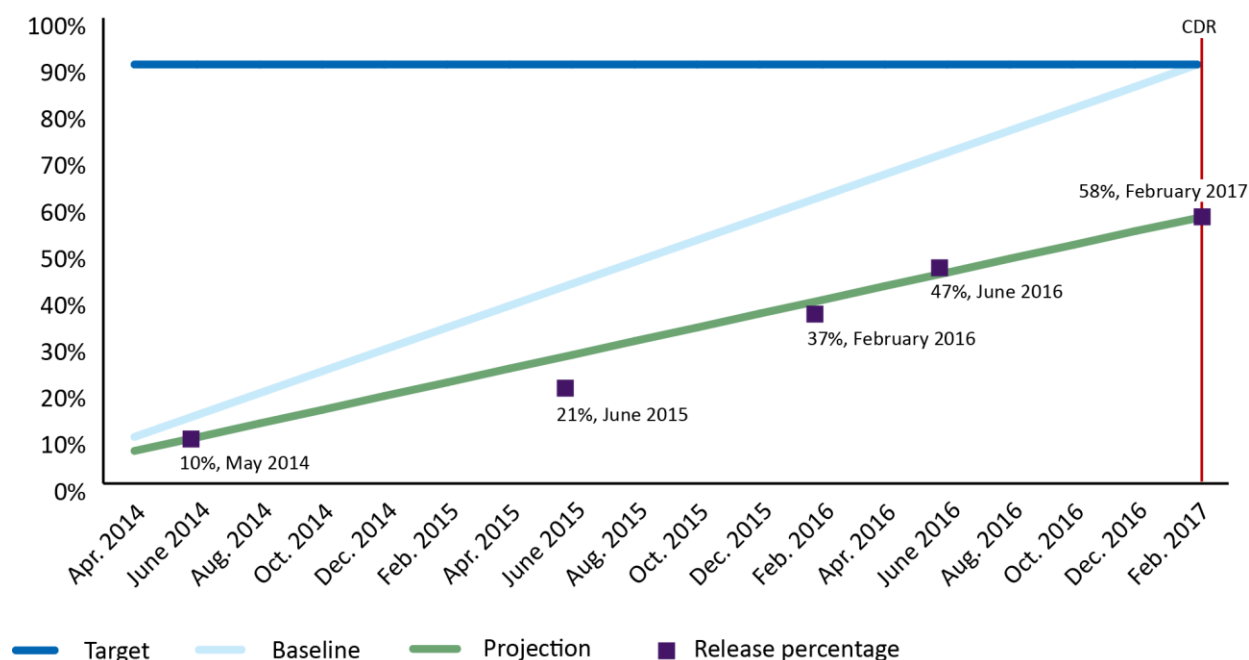
There are approximately 9,000 engineering drawings associated with Mars 2020. As discussed earlier, these drawings are the mechanism by which engineers communicate to manufacturers the details of a component's design. As of June 2016, 4,200 of the Project's drawings, or about 47 percent, were releasable – significantly under the 90 percent threshold both NASA and GAO guidelines recommend by CDR.²¹ Although CDR is not scheduled to begin until February 2017, based on the rate of progress the Project made between June 2015 and June 2016 we are concerned about its ability to meet the 90 percent target. As shown in Figure 7, if Project personnel continue releasing drawings at the same rate as they did during this period, only 58 percent of drawings would be releasable by CDR.

¹⁹ NPR 8020.12D, "Planetary Protection Provisions for Robotic Extraterrestrial Missions," April 20, 2011. This policy addresses (1) the control of terrestrial microbial contamination associated with robotic space vehicles intended to land, orbit, flyby, or otherwise encounter extraterrestrial solar system bodies, and (2) the control of contamination of the Earth and the Moon by extraterrestrial material collected and returned by robotic missions. Section 5.3.2.2 of the policy contains biological cleanliness requirements, but they are not adequate to establish a systems-level approach to meeting Project Level 1 requirements identified as necessary by NASA. Therefore, the Project is developing its hardware and operational scheme to meet the Level 1 requirements for contamination.

²⁰ The critical path is the sequence of logically related activities with the longest overall duration through project completion. According to Mars Exploration Program personnel, the Project was holding approximately 7 months schedule reserve as of December 2016.

²¹ Project personnel stated that an updated count of releasable drawings was not available as of November 2016.

Figure 7: Number of Releasable Drawings vs. Baseline



Source: NASA OIG presentation of Project status report data.

According to Project personnel, the large number of heritage technologies that will be used on Mars 2020 means that there will be little or no revisions required to existing engineering drawings used for MSL. However, Project managers conceded they were unlikely to reach the 90 percent standard and believe the Project will get close to releasing 80 percent of the drawings by CDR.²² We did not perform a technical assessment of the Project's engineering drawings to verify Project management's assertion, but as we have noted in a prior OIG report Project managers are often overly optimistic about the advantages of using heritage technology.²³

Other Technical Issues Facing the Project

In addition to the issues discussed previously, we identified several other challenges that pose a risk to the Mars 2020 Project's scope, cost, and schedule. These challenges relate to the rover's actuators, MOXIE, and growth in the mass of the rover.

Actuators

An actuator is a complex component comprised of as many as 500 parts that make up a motor and gearbox responsible for moving or controlling a mechanism or system. The motor is coupled to a gearbox that provides torque and causes the attached object to rotate. Actuators are inherently risky

²² Project personnel explained that drawings are typically finalized closer to CDR to ensure late changes are incorporated and because the tendency is to wait until manufacturers perform readiness reviews prior to making the drawings releasable.

²³ NASA OIG, "NASA's Challenges to Meeting Cost, Schedule, and Performance Goals" (IG-12-021, September 27, 2012).

due to their technical design and must be able to withstand a large number of starts and stops without deterioration. In addition, actuators are exposed to severe environmental conditions in space such as temperature fluctuations, vacuum, radiation, long mission life, and no possibility of maintenance.

Fifteen of the Mars 2020 rover's 35 actuators are very similar to the actuators used on MSL and are being supplied by the same company that supplied some of the MSL actuators.²⁴ Unfortunately, the company was late delivering the MSL actuators, which significantly contributed to MSL missing its original launch date and increasing the mission life-cycle cost estimate by \$834 million. As of October 2016, the company was also late in delivering the first Mars 2020 actuators, and the Project was providing additional oversight and support in an effort to ensure the contractor meets future delivery dates. The first actuator was delayed 3 months from the scheduled delivery date, and at the time of our audit it was not clear whether the company would make the second delivery on time. According to company personnel, they had to hire new engineers to meet their commitments to NASA and other clients and the new personnel were experiencing a learning curve. In addition, company officials indicated they had agreed to a delivery schedule 3 months shorter than their proposal and they provided their vendors' statements of work later than promised. The company was working a 6-day workweek, establishing a supply management team, and breaking up larger work tasks into smaller tasks to better monitor progress. However, although the company has been on a 6-day work schedule since the beginning of 2016, the expected delivery time for the actuators has not improved.

The other 20 new actuators are being provided by two other vendors, one of which worked on MSL actuators and the other on other Mars missions. The new actuators will be used for the drill, robot arms, bit, and caching assembly on the Sampling System. According to Project personnel, these two vendors are on schedule.

Mars Oxygen ISRU Experiment

MOXIE is an instrument designed to assess the feasibility of producing oxygen on Mars. Project managers said if they are able to produce oxygen on the Mars 2020 mission, there is potential to scale up solid oxide electrolysis technology to produce enough oxygen to support human travel to Mars and provide liquid oxygen to fuel return trips to Earth.

As a result of various technical challenges, MOXIE's estimated costs grew by 54 percent from the initial proposed amount of \$29.2 million in August 2014 to \$45 million by March 2015. To save costs, NASA eliminated the engineering model for MOXIE, which would have remained on Earth and allowed the operations engineer to simulate commands prior to executing them on the flight unit on Mars in order to reduce risk, ensure accuracy, and increase efficiency. Foregoing development of the engineering model eliminates NASA's ability to work on problems the flight unit might face while operating on Mars using a duplicate component.

In addition, NASA eliminated the third design iteration of MOXIE's Solid OXide Electrolyzer, the component in which the carbon dioxide molecule is electrochemically split to produce oxygen. Past practice has shown that successive design iterations of an instrument can provide a project with additional opportunities to identify and resolve issues. Project personnel conceded that while the de-scoped third design iteration may not have an impact on performance, it is one less opportunity to make adjustments and other modifications during fabrication.

²⁴ These actuators will operate the high gain antenna, remote sensing mast, and wheel and steering mechanism.

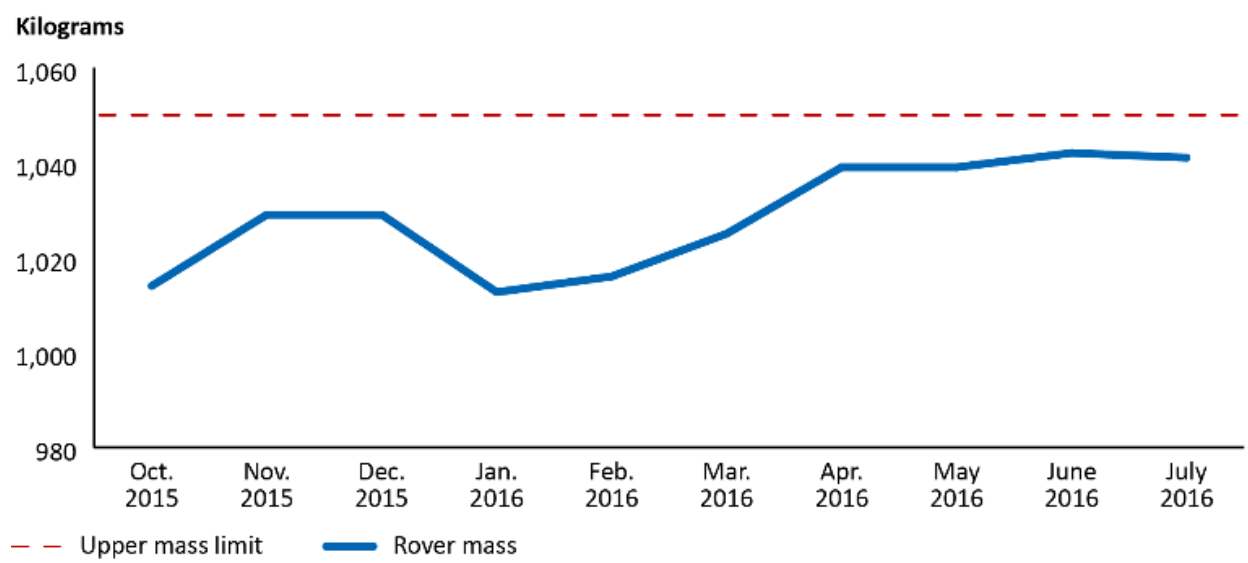
These changes reduced MOXIE's cost to \$42.8 million, or \$13.6 million over initial estimates, which will be funded by HEOMD and STMD. Project managers indicated that as of November 2016 they had sufficient reserve to develop an engineering model and conduct a third design iteration, but do not believe such steps will be necessary.

Rover Mass Growth

Mars 2020 managers have identified rover mass growth as one of the Project's open risks.²⁵ Although they do not foresee further growth, Project managers continue to monitor the mass and volume of the turret for the rover's robotic arm.²⁶ In addition, the rover's capability to access science targets at high terrain angles will be driven by ground pressure, which is also a function of vehicle weight. Accordingly, mass growth in any of the turret's components has the potential to impact the robotic arm design and increase the vehicle's overall mass, which could result in the rover exceeding the designed mass limits of the landing system.

At PDR in February 2016, Project management estimated the rover's mass at launch would be 1,013 kg. By July 2016, the estimate had increased to 1,041 kg, only 9 kg below the rover's designed upper mass limit of 1,050 kg.²⁷ That said, Mars 2020 is faring better than MSL, which had exceeded its rover mass allocation before CDR. Figure 8 depicts how Mars 2020's projected mass has changed over time.

Figure 8: Mars 2020 Rover Mass History



Source: NASA.

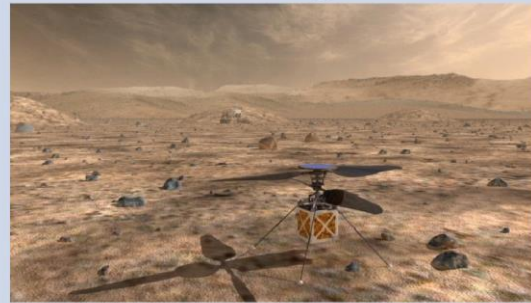
²⁵ Mass is a measurement of how much matter is in an object and is directly related to the object's weight. Mass affects inertia and center of gravity, both of which relate to the amount of thrust needed to move and maneuver an object in space.

²⁶ The turret is a fixture or platform mounted at the end of the robotic arm that houses PIXL, SHERLOC, and the coring drill.

²⁷ The Project's mass estimate includes approximately 100 kg of estimated uncertainty to address unforeseen issues.

Although Project managers do not foresee further mass growth, they are monitoring the mass and volume of the turret. They indicated that, if necessary, they could take additional steps such as removing a proposed helicopter technology demonstration from the mission to keep the mass below 1,050 kg.²⁸

Artist's Rendering of Helicopter Demonstration Technology on Mars



Source: NASA.

Overly Optimistic Scheduling Decisions

The primary constraint and driver for Mars 2020 development is the July 2020 launch date. An optimal launch window from Earth to Mars of approximately 20 days occurs every 26 months.²⁹ Therefore, when a Mars mission misses its launch window, the Project incurs significant additional costs related to overhead, stand-by work force, replacement of degraded parts and components, and storage while waiting for the next launch opportunity. Additionally, launch delays may negatively impact the Agency's reputation, public support, and the scientific community's interest in the mission.

We identified several schedule-related decisions that could indicate the Project is being overly optimistic about the development schedule for Mars 2020, including a condensed schedule for five of the seven instruments, a shorter development schedule than MSL, and a less detailed Integrated Master Schedule (IMS) than MSL.³⁰ In our 2012 assessment of NASA's project management challenges, we noted that the previous success of the Mars Exploration Rover projects drove an unhealthy level of optimism in the development of MSL.³¹ While the impact of these issues on the overall schedule for Mars 2020 cannot be determined due to the short period of time since the Project baseline was established in June 2016, monitoring these issues is essential to managing potential negative effects to the Project's schedule.

²⁸ The proposed helicopter demonstration would weigh approximately 1.4 kg and measure 1.2 meters from the tip of one blade to the other. By providing visual information and help in choosing sites to explore, the helicopter could potentially increase the distance the rover could drive in a Martian day. The helicopter could fly ahead of the rover scouting for points of interest and help rover operators plan optimal driving routes. It could also potentially provide visual information to assist the science team in choosing regions of interest for the rover to explore. NASA approved development and testing of the demonstration technology through fiscal year 2016 after which a decision about whether to proceed was to be made. The helicopter and associated components add a total of 10 kg to the rover's mass.

²⁹ About every 26 months, Mars and Earth reach a position in their respective orbits that offers the best trajectory between the two planets. Timing is critical and the launch needs to be such that spacecraft and Mars converge at exactly the same point in space.

³⁰ An IMS is a logic-driven schedule that identifies and assigns timelines to all tasks required to complete a project.

³¹ IG-12-021.

Reduced Schedule Duration of Instruments

In January 2016, JPL's Cost Estimating and Pricing Group noted that since KDP-B the schedule for development of five of the seven instruments has been condensed.³² Project managers reduced the amount of time allotted to complete development of Mastcam-Z, MEDA, MOXIE, RIMFAX, and SuperCam by at least 4 months and up to 10 months since KDP-B, requiring instruments be completed sooner than originally planned. As a result, MOXIE and RIMFAX in particular have more aggressive development schedules compared to similar instruments. According to Project personnel, the schedule durations were reduced because PDR had been delayed and at the time of analysis personnel had a better technical understanding of the instruments and the steps needed to complete them. As of September 2016, no other instruments have had their schedules shortened significantly, and Project personnel expressed no instrument schedule duration concerns, stating there are no indications any of the instruments will fail to meet their established deadlines.

Shorter Development Schedule than MSL

Mars 2020's development schedule is 9 months shorter than the MSL schedule. MSL development (Phases C and D) took 62 months to complete (September 2006 to November 2011).³³ Conversely, Mars 2020 development duration is 53 months (June 2016 to November 2020). Project personnel indicated they have no concerns with the 53-month schedule. However, as previously discussed the Sampling System poses the largest schedule risk, which Project personnel said they are closely monitoring and will reassess at CDR.

Less Detailed Integrated Master Schedule than MSL

Project management changed their scheduling approach for Mars 2020 based on their experience with MSL. According to Project management, they elected to proceed to development with a less detailed IMS than that used to develop and launch MSL to allow for more scheduling flexibility. Mars 2020's IMS contains approximately 15,000 lines compared to MSL's approximately 40,000 lines.³⁴ Based on the experience of Mars 2020 personnel who also worked on MSL, Project management believes MSL's schedule was too detailed and therefore too stringent and may have affected the Project's ability to deal with challenges effectively.

According to Project personnel, the use of the less-detailed IMS allows for more flexibility regarding the order in which work is completed and makes dealing with challenges easier. For example, the schedule for MSL required tasks be performed in sequential order, and it would take 2 to 3 weeks to update the schedule with any changes. In contrast, the Mars 2020 schedule allows technical managers to decide in which order to perform work and it takes just 6 days to update the schedule. While Project personnel

³² According to Project personnel, the development schedule is measured by the number of work months between the PDR or CDR and instrument delivery.

³³ MSL was unable to complete development in the original 36 months planned and therefore was rebaselined in February 2009, extending development by 26 months and pushing the launch date from September 2009 to November 2011.

³⁴ For comparison, NASA's \$915 million Soil Moisture Active Passive satellite mission, launched in January 2015 on a 3-year mission to measure Earth's soil moisture and freeze/thaw states, had an IMS comprised of approximately 11,000 lines, while the \$8.8 billion James Webb Space Telescope, designed for a 5- to 10-year mission to help understand the origin and destiny of the universe and the creation and evolution of the first stars and galaxies, has an IMS of approximately 50,000 lines.

cite no disadvantages to using a less-detailed IMS, GAO's Schedule Assessment Guide warns that "schedules that are defined at too high a level may disguise risk that is inherent in lower-level activities."³⁵

Additionally, GAO's Schedule Assessment Guide states that at its most detailed level the schedule should clearly reflect the work needing to be accomplished and define the activities necessary to produce and deliver each product. Failing to include all work for all deliverables can hamper Project personnel's understanding of the schedule plan and the Project's progress toward a successful conclusion. Unless all necessary activities are accounted for, Project personnel cannot be certain whether all activities are scheduled in the correct order, resources are properly allocated, the critical path is valid, or a schedule risk analysis will account for all risk.³⁶ It will be months until the Mars 2020 Project progresses far enough into development and has sufficient performance data to assess the effectiveness of Project management's change in approach and whether they may have taken on additional risk if the IMS is not sufficiently detailed.

Foreign Partner Funding and Schedule Issues

Four foreign partners are collaborating with NASA on the Mars 2020 mission. The Norwegian Defence Research Establishment is responsible for RIMFAX, Spain's National Institute for Aerospace Technology (INTA) is responsible for MEDA, and Spain's University of Valladolid (UVA) and France's Institute for Research in Astrophysics and Planetology are responsible for components of SuperCam.

We sent questionnaires to these partners requesting information on the status of their contributions, ability to meet agreed-upon technological and schedule commitments, and expectations for agency funding. Based on those responses, we identified funding issues that may affect timely delivery of the components being supplied by INTA and UVA.

National Institute for Aerospace Technology

According to INTA, financial reorganization has led to delays in some activities, impacting the development of sensors for MEDA that will provide measurements of temperature, wind speed and direction, pressure, relative humidity, and dust size and shape. These sensors will provide daily weather information and data on Mars designed to help prepare for future human exploration, as well as surface science data that could be helpful in characterizing the environment at the landing site. MEDA is led by the INTA Center of Astrobiology, but is being developed by a consortium of partners including U.S., Finnish, Italian, and Spanish institutions. A Memorandum of Understanding between NASA and the Spanish participants was completed in October 2016 defining responsibilities of individual institutions including the Ministry of Economy and Competitiveness funding MEDA scientific activities and the Ministry of Industry, Energy, and Tourism funding industrial activities associated with development of MEDA.³⁷

³⁵ GAO, "Schedule Assessment Guide – Best Practices for Project Schedules" (GAO-16-89G, December 2015).

³⁶ Schedule risk analysis is a technique that connects the risk information of project activities to the baseline schedule to assess the potential impact of uncertainty on the final project duration and cost.

³⁷ The Memorandum of Understanding between NASA; the Ministry of Economy and Competitiveness of Spain; the Ministry of Industry, Energy, and Tourism of Spain; the Center for the Development of Industrial Technology; and the National Institute for Aerospace Technology of Spain outlines the responsibilities of each party regarding MEDA and states each party will bear the costs of its respective obligations.

According to Mars 2020 Project personnel, MEDA's funding issues have led to schedule delays and it is highly likely that the original delivery date of April 2018 for flight hardware will not be met. However, they also indicated that the INTA Principal Investigator for MEDA and the Center of Astrobiology Director are aggressively working to minimize the consequences of the funding uncertainty and to formalize a new funding plan, and that they expect the funding situation to be resolved in the near future.³⁸

Mars 2020 Project managers appear to be adequately monitoring the issue, although it continues to pose significant schedule risks for MEDA. In sequence of increasing severity, a late MEDA delivery could lead to (1) a phased delivery with some deliveries occurring after cruise system testing; (2) special rover integration schedule accommodation, adding risk and cost to the Assembly, Test, and Launch Operations phase; and (3) MEDA not being "integratable" and not making launch. According to Project personnel, the mission can meet all four of its science and program objectives without MEDA and indicated the mission will continue without MEDA if necessary.

University of Valladolid

UVA noted concerns with the availability of testing facilities, test sample failures, and timely funding possibly affecting the development of the calibration target for SuperCam, which consists of a framework (holder) and a set of samples allowing the calibration of different spectroscopic techniques. The samples are the responsibility of an international consortium comprised of Canada, Denmark, France and Spain. UVA representatives indicated a lack of aerospace testing facilities for high-shock tests raised a concern for meeting technological commitments. However, they have included an early test model for risk mitigation, plan to perform some tests in Spain at industry facilities, and other tests at JPL with an UVA engineering team collaborating with JPL staff.

UVA representatives also indicated that meeting schedule commitments depends on several technical and programmatic issues. They noted confidence the holder and samples will meet the schedule for integration and testing and said they are mitigating the risk of possible failure of samples through the use of sample backups. Further, while UVA has enough funds to cover activities through the end of 2016, UVA officials raised concerns regarding whether consistent funding will be available to support the long-term instrument development schedule. UVA said it has requested contributions from the Ministry of Economy and Competitiveness, regional government, and their own institution. Project personnel said they are aware of UVA's funding issues and indicated these problems are similar to MEDA in that they have to work through a complicated group of agencies. Furthermore, the calibration system UVA is providing to SuperCam is a non-load-bearing secondary structure that several other entities could provide if necessary.

Mars 2020 personnel have not identified concerns with the components being provided by the French or Norwegian partners. Additionally, they told us they communicate frequently with these partners, use the same reporting processes, and require the same documentation as they would for NASA contractors or in-house work, including monthly management, design, and implementation reviews.

³⁸ As of November 2016, the MEDA principal investigator reported that funding arrangements have been resolved.

CONCLUSION

NASA's Mars 2020 rover mission entered the Implementation Phase of development in June 2016 and Project managers have expressed confidence the mission has sufficient funding, is on an achievable schedule for launch in July 2020, and can meet its scientific and technical requirements. However, we identified concerns with design stability of some of the rover's hardware and science instruments – specifically, the slow maturation of some critical technologies and slow release of technical drawings – that may affect the Project's ability to meet technical requirements, its optimistic schedule, and other development challenges that may increase the mission's overall risk. Additionally, as of the end of fiscal year 2016 two foreign partners were experiencing funding issues that may impact timely delivery of their instrument components. Mars 2020 Project managers need to address these issues to achieve the mission's technical objectives, meet Project milestones, and control costs.

RECOMMENDATIONS, MANAGEMENT'S RESPONSE, AND OUR EVALUATION

To assist the Mars 2020 rover mission in achieving its technical objectives, meeting Project milestones, and controlling costs, we recommended the Associate Administrator for Science require the Mars 2020 Project Manager to

1. ensure the TRL of critical technologies and the rate of releasable engineering drawings meet established criteria as the Project completes its upcoming CDR;
2. develop alternative plans to minimize changes to the overall science mission, Project cost, schedule, and scope if current risks to the actuators, mass growth, MOXIE, and Sampling System are realized;
3. assess the effectiveness of the less detailed IMS and make timely adjustments if required; and
4. continue to work with international partners facing funding issues, including developing alternate options to mitigate delivery delays and potentially reduce technical capability or non-inclusion of the instruments.

We provided a draft of this report to NASA management who concurred with our recommendations and described planned actions to address them. We consider the proposed actions responsive to our recommendations and will close the recommendations upon verification and completion of the actions.

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

Major contributors to this report include, Raymond Tolomeo, Science and Aeronautics Research Director; Gerardo Saucedo, Project Manager; Sarah Beckwith; and Simon Chan.

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



Paul K. Martin
Inspector General

APPENDIX A: SCOPE AND METHODOLOGY

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

The overall objective was to evaluate NASA's management of the mission relative to achieving technical objectives, meeting milestones, and controlling costs. Our specific objective was to assess whether emerging challenges may prevent NASA from achieving these goals, and whether the baseline plan for project development was constructed from complete, reliable, and accurate cost, schedule, and risk information.

To evaluate NASA management of Mars 2020 goals and objectives, we reviewed key Project planning documents, including the Project and Business Plan. We also reviewed the final KDP-C Decision Memorandum that set the Management Agreement and Agency Baseline Commitment budgets and launch readiness milestones for the Project's life cycle. Additionally, we reviewed NASA Policy Directives (NPD) and NASA Procedural Requirements (NPR) related to flight program and project management practices, including:

- NPD 1000.0B, "NASA Governance and Strategic Management Handbook," November 26, 2014
- NPR 7120.5E "NASA Space Flight Program and Project Management Requirements, w/Changes 1-14," August 14, 2012
- NPR 8020.12D, "Planetary Protection Provisions for Robotic Extraterrestrial Missions," April 20, 2011

To assess the Project's progress in achieving technical objectives, we interviewed Program and Project management personnel and GAO representatives. We also reviewed the Project's risk list and periodic status reports. Additionally, we reviewed and analyzed documentation related to lessons learned from previous Mars missions and documentation and criteria related to design and technology readiness levels.

To assess the Project's progress in meeting milestones, we interviewed Program and Project management personnel, performed a site visit of a key sub-contractor, reviewed and analyzed documentation related to the IMS for the mission, analyzed instrument schedule duration, and reviewed responses to a NASA OIG questionnaire sent to international partners regarding their technological commitments and associated delivery timeframes.

To assess the Project's progress in controlling costs, we interviewed Program and Project management personnel at JPL, and interviewed personnel from the Agency's Independent Program Assessment Office. In addition, we obtained, reviewed, and analyzed cost data prepared for the Agency Program Management Council, relevant GAO reports, Project monthly and quarterly status reports, Joint Cost and Schedule Confidence Level analysis, and cost and schedule support documentation, and the reconciliation of base estimates to supporting cost data.

Use of Computer-Processed Data

We used limited computer-processed data such as risk detail reports produced from JPL's Risk Management system and the Joint Cost and Schedule Confidence Level model that included cost and schedule data. Generally, we concluded the data was valid and reliable for the purposes of the review.

Review of Internal Controls

We reviewed the internal controls associated with Mars 2020 Project management's assessment of technical, schedule, and cost risks that could impact the launch schedule. We found the Program's internal controls appear adequate to manage technical, schedule, and cost risk, and noted areas for improvement as stated in the report.

Prior Coverage

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

NASA Office of Inspector General

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

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

NASA's Management of the Mars Science Laboratory Project (IG-11-019, June 8, 2011)

Government Accountability Office

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

NASA: Assessments of Selected Large-Scale Projects (GAO-15-320SP, March 24, 2015)

APPENDIX B: NASA'S MARS EXPLORATION MISSIONS

Table 5 provides a timeline and description of NASA's missions to Mars since 1964. It also includes the life-cycle cost of each mission in fiscal year 2016 dollars, totaling \$24.4 billion dollars.

Table 5: Mars Exploration Program and Missions

Mission	Mission Timeframe			Mission Description and Significant Discoveries	Life-Cycle Costs (Dollars in Millions)
	Launch	Arrival	End		
Mariner 3 and Mariner 4 ^a	11/28/1964	07/14/1965	12/20/1967	First successful flyby of Mars that captured the first pictures of the planet.	\$1,060
Mariner 6	2/24/1969	7/30/1969	7/31/1969	First completion of dual flyby mission to Mars that analyzed the Martian atmosphere and surface with remote sensors.	1,281
Mariner 7	3/27/1969	8/4/1969	8/5/1969		
Mariner 8 and Mariner 9 ^b	5/30/1971	11/13/1971	10/27/1972	Flyby mission that revealed gigantic volcanoes and a grand canyon across Martian surface and provided the first close-up pictures of two Martian moons.	1,154
Viking 1 (Lander)	8/20/1975	6/19/1976	11/11/1982	The first U.S. mission to land a spacecraft safely on the surface of Mars and return images. The two landers (each mission also had an orbiter) also conducted three biology experiments designed to look for possible signs of life.	6,741
Viking 2 (Lander)	9/9/1975	8/7/1976	4/11/1980		
Mars Observer	9/25/1992	n/a ^c	8/22/1993	The payload of science instruments was designed to study the geology, geophysics, and climate of Mars.	1,755
Mars Global Surveyor	11/7/1996	9/12/1997	11/2/2006	The mission studied the Martian surface, atmosphere, and interior and determined Mars has very repeatable weather patterns.	568
Mars Pathfinder	12/4/1996	7/4/1997	9/27/1997	Spacecraft returned vast amounts of information, including 15 chemical analyses of rocks and soil and extensive data on winds and other weather factors.	456
Mars Climate Orbiter	12/11/1998	9/23/1999	9/23/1999	The Orbiter was designed to function as an interplanetary weather satellite and a communications relay for Mars Polar Lander. Mars Polar Lander was set to land a spacecraft down on Mars' south polar cap and dig with a robotic arm.	486
Mars Polar Lander ^d	1/3/1999	12/3/1999	12/3/1999 ^e		
Phoenix Mars Lander	8/4/2007	5/25/2008	11/2/2008	The Phoenix Lander collected samples of soil and ice for evidence about whether the site was ever hospitable to life. Phoenix also obtained data about the formation, duration, and movement of clouds, fog, and dust plumes.	512

Mission	Mission Timeframe			Mission Description and Significant Discoveries	Life Cycle Costs (Dollars in Millions)
	Launch	Arrival	End		
Mars Exploration Rover (Spirit)	6/10/2003	1/3/2004	3/22/2010	These robotic explorers conducted field geology, made atmospheric observations, and found evidence of intermittently wet and habitable conditions existed.	1,464
Mars Exploration Rover (Opportunity)	7/7/2003	1/24/2004	Ongoing		
Mars Odyssey	4/7/2001	10/24/2001	Ongoing	Spacecraft has collected more than 130,000 images and continues to send information to Earth about Martian geology, climate, and mineralogy.	925
Mars Reconnaissance Orbiter	8/12/2005	3/10/2006	Ongoing	Camera capability helps identify obstacles and a sounder to find subsurface water, both important consideration in selecting sites for future exploration.	1,163
Mars Science Laboratory (Curiosity)	11/26/2011	8/5/2012	Ongoing	Collects Martian soil and rock samples and analyzes them for organic compounds and environmental conditions that could have supported microbial life now or in the past.	3,086
Mars Atmosphere and Volatile Evolution	11/18/2013	9/21/2014	Ongoing	Obtains critical measurements of the Martian atmosphere to help understand climate change over its history.	600
InSight	5/2018	Scheduled for 11/26/2018	Future mission	InSight will place a geophysical lander on Mars to study its deep interior. InSight will delve beneath the surface of Mars to explore the processes of terrestrial planet formation as well as measure the planet's "vital signs."	675
Mars 2020	7/2020	2/2021	Future mission	Mission hopes to identify past environments capable of supporting microbial life, seek signs of possible past microbial life, collect "soil" samples and store them on the Martian surface, and prepare for human exploration.	2,444
Total					\$24,370

Source: NASA OIG analysis of mission information.

^a Mariner 3 launched on November 5, 1964, but failed to reach Mars due to mechanical difficulties.

^b Mariner 8 failed during launch.

^c Contact was lost with Mars Observer shortly before it entered into Mars orbit.

^d 1999 Mars missions includes Mars Climate Orbiter and Mars Polar Lander, which carried a pair of microprobes called Deep Space 2.

^e Climate Orbiter was lost upon arrival on 9/23/1999 and Polar Lander/Deep Space 2 was lost upon arrival on 12/3/1999.

APPENDIX C: EVALUATION OF DESIGN METRICS

We obtained the status and discussed the top five design readiness metrics with Project managers to evaluate Project performance and design readiness as measured against the metrics discussed in the Background section of this report (see Table 6). Factors such as where the Project was in its life cycle or whether or not the project was heavily based on heritage technologies influenced how projects tracked the design metrics.³⁹

Table 6: Design Readiness Metrics

Metric	Status	Evaluation
Percentage of verification and validation plans complete at PDR and CDR.	The verification and validation completion status will not be tracked at the system level until after CDR.	Not applicable at the time of review.
Definition of the project's top level requirements, that define mission success criteria and are imposed by NASA, to requirements at the subsystem level by the time of PDR.	Eight mission success criteria for the Mars 2020 mission have been defined.	Top level requirement and mission success criteria have been defined.
Maturity of critical technologies TRL 6 by PDR.	As of November 2016, at close of audit fieldwork, five of seven critical technologies had not reached TRL 6. In December 2016, Project personnel updated the TRL status of all seven critical technologies to 6.	All seven critical technologies should have been at TRL 6 by PDR - February 4, 2016. However, five critical technologies are still below TRL 6 as of November 2016.
Percentage of actual mass margin versus planned mass margin.	Mass margin is at 4 percent.	Actual mass margin is 4 percent and the required mass margin is 3 percent. Mass was 3,393 kg with an allocation of 3,540 kg for cruise stage; entry, decent, and landing system; and landed mass.
Level of funding reserves and schedule margin at various points in the development life cycle.	The mission's funding profile was identified as a risk going into KDP-C but was corrected at that time. Project management believes the current profile is adequate.	Not considered an issue at this time.
Engineering drawings should be releasable by CDR to lower the risk of subsequent cost growth and schedule.	As of June 2016, only 4,200 of the 9,000 estimated drawings (47 percent) required were ready for release.	Not likely to meet the 90 percent best practice by CDR – February 2017.

Source: Based on information provided by Mars 2020 Project management.

³⁹ NASA, "Systems Engineering Handbook" (SP-2007-6105, December 2007).

APPENDIX D: MANAGEMENT'S COMMENTS

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



JAN 26 2017

Reply to Attn of:

Science Mission Directorate

TO: Assistant Inspector General for Audits
 FROM: Associate Administrator for Science Mission Directorate
 SUBJECT: Agency Response to OIG Draft Report, "Audit of the Mars 2020 Project"
 (A-16-008-00)

NASA appreciates the opportunity to review and comment on the Office of Inspector General (OIG) draft report entitled "Audit of the Mars 2020 Project" (A-16-008-00), dated December 22, 2016.

In the draft report, the OIG makes four recommendations addressed to the Associate Administrator for Science Mission Directorate (AA/SMD), intended to assist the Project in achieving its technical objectives, meeting milestones, and controlling costs.

Specifically, the OIG recommends the AA/SMD direct the Mars 2020 Project Manager to:

Recommendation 1: Ensure the technology readiness level (TRL) of critical technologies and the rate of releasable engineering drawings meets established criteria before the Project completes its upcoming Critical Design Review (CDR).

Management's Response: NASA concurs with this recommendation in that projects should achieve an acceptable level of maturity prior to CDR. As of December 2016, Mars 2020 has demonstrated acceptable technology readiness level (TRL-6) maturity for all critical technologies.

Approximately 68% of the flight hardware engineering drawings are releasable as of the end of 2016, with a projected ~80% of such drawings being releasable by the time of the Project CDR. Design maturity is also captured in computer-aided, design-based models. Based on the above and satisfactory progress demonstrated through Phase C peer reviews and subsystem CDRs, NASA assesses that Mars 2020 has achieved an acceptable rate of releasing engineering drawings to proceed to CDR. If any corrective action leading up to Project CDR is required, NASA will undertake such actions as expeditiously as possible.

Estimated Completion Date: March 30, 2017

Recommendation 2: Develop alternative plans to minimize changes to the overall science mission, Project cost, schedule, and scope if current risks to the actuators, mass growth, MOXIE, and Sampling System are realized.

Management's Response: NASA concurs with this recommendation in that projects should establish mitigation plans for key risks. Project management practice is to monitor and assess risks based on likelihood and impact if realized. Mitigation plans are identified to respond to those risks.

Estimated Completion Date: March 30, 2017

Recommendation 3: Assess the effectiveness of a less detailed Integrated Master Schedule (IMS) and make timely adjustments if required.

Management's Response: NASA concurs with this recommendation and will conduct an assessment of the Mars 2020 IMS. NASA will continue to monitor the project's schedule and management practices at regular project status reviews and life-cycle reviews. If any corrective action is required, NASA will undertake such actions as expeditiously as possible.

Estimated Completion Date: March 30, 2017

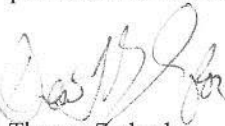
Recommendation 4: Work with international partners facing funding issues, including developing alternate options to mitigate delivery delays and potentially reduce technical capability or non-inclusion of the instruments.

Management's Response: NASA concurs with this recommendation in that Projects should resolve funding issues on international contributions and hold descope and backup options.

Estimated Completion Date: March 30, 2017

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

Once again, thank you for the opportunity to review and comment on the subject draft report. If you have any questions or require additional information regarding this response, please contact Peter Meister on (202) 358-1557.



Thomas Zurbuchen

APPENDIX E: REPORT DISTRIBUTION

National Aeronautics and Space Administration

Acting Administrator
 Acting Deputy Administrator
 Acting Chief of Staff
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 Director, Office of Acquisition and Sourcing Management

Congressional Committees and Subcommittees, Chairman and Ranking Member

Senate Committee on Appropriations
 Subcommittee on Commerce, Justice, Science, and Related Agencies
 Senate Committee on Commerce, Science, and Transportation
 Subcommittee on Space, Science, and Competitiveness
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(Assignment No. A-16-008-00)