JUNE 8, 2011

AUDIT REPORT

OFFICE OF AUDITS

NASA'S MANAGEMENT OF THE MARS SCIENCE LABORATORY PROJECT

OFFICE OF INSPECTOR GENERAL

National Aeronautics and
Space Administration

REPORT NO. IG-11-019 (ASSIGNMENT NO. A-10-007-00)

Final report released by:

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Inspector General

Acronyms

ATLO	Assembly, Test, and Launch Operations
FY	Fiscal Year
IPAO	Independent Program Assessment Office
JPL	Jet Propulsion Laboratory
MMRTG	Multi-Mission Radioisotope Thermoelectric Generator
MSL	Mars Science Laboratory
NPR	NASA Procedural Requirements
P/FR	Problem/Failure Report
SAM	Sample Analysis at Mars
SA/SPaH	Sample Acquisition/Sample Processing and Handling

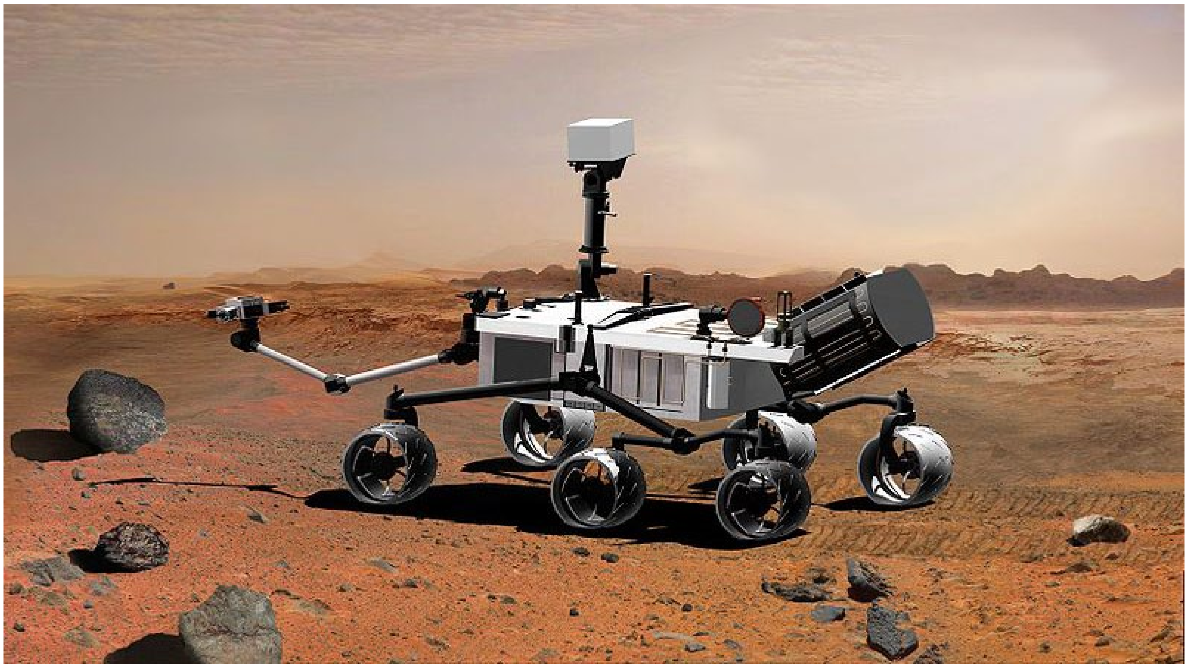
OVERVIEW

NASA'S MANAGEMENT OF THE MARS SCIENCE LABORATORY PROJECT

The Issue

The Mars Science Laboratory (MSL), part of the Science Mission Directorate's Mars Exploration Program (Mars Program), is the most technologically challenging interplanetary rover ever designed. This NASA flagship mission, whose life-cycle costs are currently estimated at approximately $2.5 billion, will employ an array of new technologies to adjust its flight while descending through the Martian atmosphere, including a sky crane touchdown system that will lower the rover on a tether to the Martian surface.[1] Contributing to the complexity of the mission are the Project's innovative entry, descent, and landing system; the size and mass of the rover (four times as heavy as the previous Martian rovers Spirit and Opportunity); the number and interdependence of its 10 science instruments; and a new type of power generating system.

Figure 1. Artist's Concept of the Mars Science Laboratory Rover on the Surface of Mars



Source: http://marsprogram.jpl.nasa.gov/msl/images/PIA09201-br2.jpg (accessed May 4, 2011).

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[1] Flagship missions are missions with costs exceeding $1 billion.

The primary objective of the Mars Program is to determine whether Mars has, or ever had, an environment capable of supporting life. In pursuit of this objective, the MSL rover – known as Curiosity – will assess the biological potential for life at the landing site, characterize the geology of the landing region, investigate planetary processes that influence habitability, and analyze surface radiation. NASA's Jet Propulsion Laboratory (JPL) is responsible for development and management of the MSL Project.

Due to planetary alignment, the optimal launch window for a mission to Mars occurs every 26 months. MSL was scheduled to launch in a window between September and October 2009. However, in February 2009, because of the late delivery of several critical components and instruments, NASA delayed the launch to a date between October and December 2011.

This delay and the additional resources required to resolve the underlying technical issues increased the Project's development costs by 86 percent, from $969 million to the current $1.8 billion, and its life-cycle costs by 56 percent, from $1.6 billion to the current $2.5 billion. If the Project is delayed to a late 2013 launch window, NASA's costs would further increase, at least by the $570 million that would be required to redesign the mission to account for differences in planetary alignment and the Martian dust storm season.

The following timelines show the Project's phases, major milestones (Figure 2), and life-cycle cost estimates (Figure 3).

Figure 2. MSL Project Timeline Overview

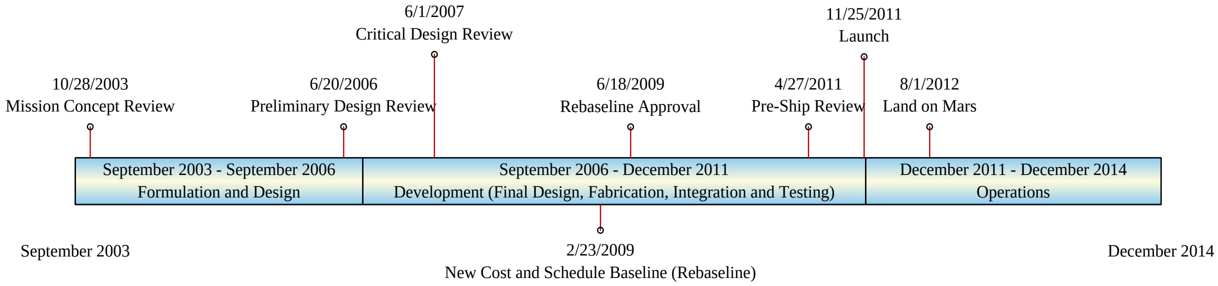
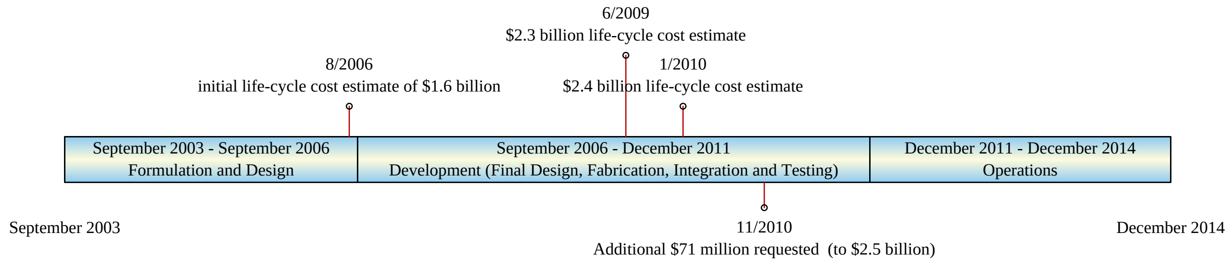


Figure 3. MSL Project Life-Cycle Cost Timeline



In light of the importance of the MSL Project to NASA's Mars Program, the Office of Inspector General conducted an audit to examine whether the Agency has effectively managed the Project to accomplish mission objectives while meeting revised cost and schedule projections. See Appendix A for details of the audit's scope and methodology.

Results

We found that the MSL Project has overcome the key technical issues that were the primary causes of the 2-year launch delay. Additionally, as of March 2011 all critical components and instruments have been installed on the rover. Project managers expected to complete integration of equipment by May 2011 and ship MSL to Kennedy for flight preparation by June 2011.

However, of the ten issues Project managers identified as contributing to the launch delay, as of March 2011 three remained unresolved: contamination of rock and soil samples collected by the Sample Acquisition/Sample Processing and Handling (SA/SPaH) subsystem and development of flight software and the fault protection systems.[2] The resolution of these and other issues that may arise during final integration is likely to strain the already limited margin managers built into the Project's schedule to allow for unanticipated delays. Moreover, since November 2009 this schedule margin has been decreasing at a rate greater than planned.

In addition, approximately 1,200 reports of problems and failures observed by Project personnel remained open as of February 2011. If these reports are not resolved prior to launch, there is a possibility that an unknown risk could materialize and negatively affect mission success.

Finally, since the 2009 decision to delay launch, the Project has received three budget increases, most recently an infusion of $71 million in December 2010. However, in our judgment because Project managers did not adequately consider historical cost trends

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[2] Fault protection enables an instrument or system that does not operate as expected to operate at a reduced level rather than fail completely.

when estimating the amount required to complete development, we believe the Project may require additional funds to meet the 2011 scheduled launch date.

Remaining Unresolved Technical Issues. Although Project managers have overcome the majority of technical issues that led to the launch delay, as of March 2011 three significant technical issues remain unresolved. In addition, management is evaluating the mission impact of unexpected degradation of the MSL's power source, the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG).[3]

One major issue contributing to the 2-year delay was the late delivery of the rover's SA/SPaH subsystem, which will acquire soil and rock samples from the Martian surface and deliver them to other instruments on the rover for analysis. During testing of the SA/SPaH, managers discovered particulate contamination of samples. Program managers told us that this issue would not present a mission-level risk because any contaminants could be filtered through data processing. As of March 2011, Project managers said they have identified and validated a method to minimize contamination of samples and have nearly completed implementing the solution. However, we remain concerned because remaining work on the SA/SPaH is not due to be complete until June 2011, when the rover is due for delivery to Kennedy Space Center for final integration and assembly.

The two other major unresolved issues are the development of flight software and fault protection systems. The onboard computer will use the flight software to direct MSL's flight. The fault protection system is an engineering design that will enable MSL's instruments and equipment that do not perform as expected to continue operating at a reduced level rather than fail completely.

As early as May 2009, MSL's Standing Review Board expressed concern about delays in development of flight software and fault protection systems and we are concerned that their development remains incomplete.[4] As of March 2011, the majority of the software needed for launch, cruise, entry, descent, and landing was developed. However, the software was not expected to be delivered until May 2011 and Project managers stated that work on software required to operate the rover on Mars would be completed after launch. In addition, as of March 2011, 13 of the 16 necessary fault protection related tasks had been completed and the remaining 3 were in progress.

Because of technical issues related to these three and other items, Project managers must complete nearly three times the number of critical tasks than originally planned in the few months remaining until launch. As shown in Table 1, Project managers had planned to have all critical tasks (except for Kennedy Space Center operations) completed by April

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[3] The MMRTG provides power by the natural degradation of the radioactive material, plutonium-238 dioxide. The material has naturally decayed during the 2-year launch delay. In addition, environmental testing has shown some power degradation anomalies that are yet to be resolved.

[4] The Standing Review Board is an outside group of experts convened by NASA to monitor the status of a program or project. The Board periodically conducts independent reviews of performance related to cost, schedule, technical, and other risks.

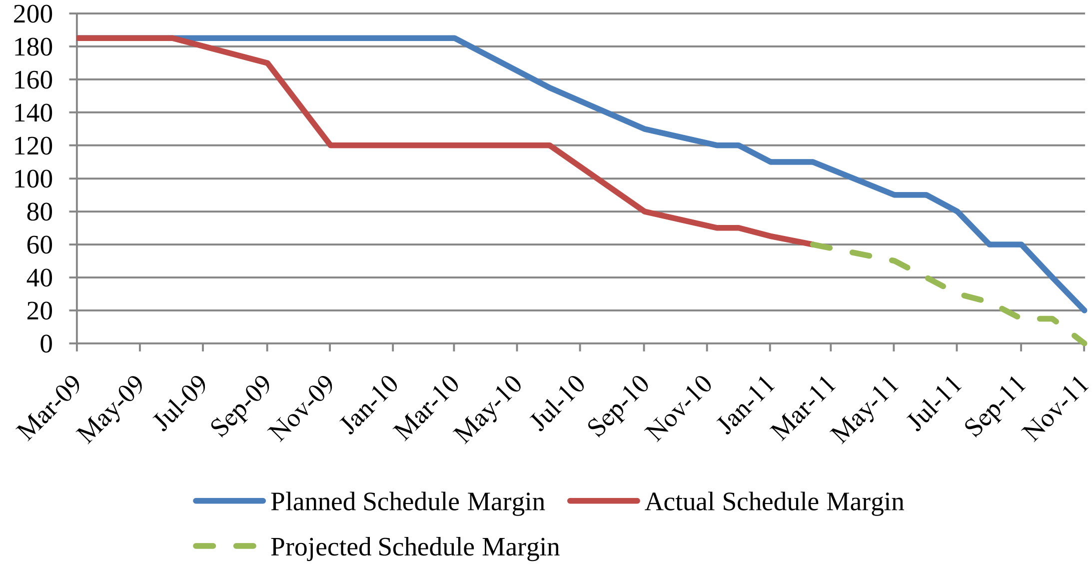
2011. However, when they revised the schedule in November 2010, that date slipped by 3 months to July 2011. Furthermore, the February 2011 revision shows that seven critical tasks have been further delayed. Coupled with the decreasing schedule margin described below, we are concerned that management may be pressured to reduce mission capabilities in order to avoid another 2-year delay and the at least $570 million in associated costs.

Table 1. Critical Tasks for Completion Prior to Launch

	Planned Completion Date		
Task	**Feb. 2009 Plan**	**Nov. 2010 Plan**	**Feb. 2011 Plan**
Mechanical	June 2010	January 2011	March 2011
Payload	May 2009	January 2011	May 2011
SA/SPaH	February 2010	May 2011	June 2011
Avionics	June 2010	March 2011	May 2011
Launch Vehicle	April 2011	April 2011	April 2011
Flight Software	June 2010	May 2011	May 2011
Assembly, Test, and Launch Operations	January 2011	May 2011	June 2011
Testbeds	April 2010	June 2011	July 2011
Guidance, Navigation, and Control	December 2010	July 2011	July 2011
Kennedy Operations	September 2011	November 2011	November 2011
MMRTG	April 2011	April 2011	June 2011

Accelerated Schedule Margin Decrease. To allow for unanticipated delays, NASA routinely builds a margin of extra time into project development schedules. We found that for MSL this schedule margin has eroded at a rate slightly greater than planned and that as of February 2011 only 60 margin days remained (see Figure 4).

Figure 4. Comparison of Planned Schedule Margin to Actual



When the launch was rescheduled in 2009, Project managers programmed 185 margin days into the development schedule. However, since November 2009 the Project has been consuming margin days more quickly than managers expected as a result of the number and complexity of technical issues needing to be resolved. Although managers expressed confidence that the remaining schedule margin would be adequate to address the risks having potential schedule impact that they have indentified, the rate of schedule margin decrease concerns us because the inherent complexity of the MSL Project increases the likelihood that additional issues will arise in final testing and integration.

Project Management Did Not Effectively Assess or Prioritize the Risks Identified by the P/FR Process. Problem/Failure Reports (P/FRs) are generated when individuals working on a project observe a departure from design, performance, testing, or other requirements that affects equipment function or could compromise mission objectives. P/FRs may range from minor issues with negligible effects to potential "red flag" issues with significant or major effects, up to and including a loss of mission.

We found that MSL Project managers did not consistently identify and assess the risks associated with P/FRs. For example, during our audit fieldwork in June 2010, the Project's P/FR database contained 983 open P/FRs. We found that the Project had not conducted a preliminary risk assessment or assessed potential cost and schedule impacts for 71 of these open P/FRs.

We also found that the number of open P/FRs increased between February 2010 and February 2011. For example, when we conducted a detailed analysis of the database in June 2010, 983 P/FRs were in open status. By February 2011, that number had increased to 1,213. Moreover, during this period the average time a P/FR remained open was 1.2 years, and P/FRs with higher degrees of risk – including significant and potential red flag reports – remained open on average approximately 1.6 years.

Project managers expressed confidence that they will close those P/FRs that require resolution before the launch date, noting that P/FRs involving flight software can be resolved after launch. However, as discussed above, because Project managers have not assessed the risk associated with all open P/FRs, we remain concerned that they do not have sufficient information to assess whether these P/FRs could negatively impact safety, cost, or mission success and may not have allocated sufficient resources to address them. Our concern is heightened by the increasing number of open P/FRs, the fast approaching launch date, and the amount of time that it has taken Project managers to close P/FRs in the past.

Project Funding May Be Inadequate. The Project achieved several important technological successes over the past 2 years, including delivery and acceptance of the actuators (motors that allow the rover and instruments to move), avionics, radar system, and most of the rover's instruments. However, Project managers did not accurately assess the risks associated with developing and integrating the MSL instruments and did not accurately estimate the resources required to address these risks. Consequently, the cost of completing development and the Project's life-cycle costs have increased.

In August 2006, NASA estimated the life-cycle cost for MSL as $1.6 billion. After launch was rescheduled for 2011, Project managers developed a new schedule and cost baseline for the Project, adding $400 million to complete development. Estimated life-cycle costs for the Project increased to $2.3 billion in fiscal year (FY) 2010 and to $2.4 billion in FY 2011. In November 2010, the Project requested an additional $71 million, which brought the total life-cycle cost estimate to the current estimate of approximately $2.5 billion. The extra money was obtained by reprogramming funds in the FY 2010 Mars Program budget, identifying additional funds from the Planetary Science Division in FY 2011, and addressing the balance in the FY 2012 budget request.

The primary causes for the most recent cost escalations were:

- increases in the validation and verification and testing programs;
- problem resolution;
- funding of the assembly, test, and launch operations (ATLO) team for a post-shipment delay period;
- impact on Kennedy Space Center operations due to delaying the launch to November 2011; and
- P/FR and other paperwork closure.

In our judgment, even Project management's most recent estimate may be insufficient to ensure timely completion of the Project in light of the historical pattern of cost increases and the amount of work that remains to be completed before launch. For example, when NASA rescheduled the launch to 2011, Project managers estimated the cost to complete development at $400 million and maintained $95 million of unallocated reserve at the Program level. However, this level of reserve turned out to be insufficient and the estimated cost to complete development was increased by $137 million, from $400 million to $537 million, in December 2010.

Our analysis of the Project's current estimate to complete development indicates that even the $537 million figure may be too low. Our analysis is based on the earned value management system budget data and estimates of the additional work that will be needed to address unknowns. We estimate that $581 million may be required – $44 million more than management's latest estimate. Based on our calculations, unless managers request additional money the Project may have insufficient funds to complete all currently identified tasks prior to launch and may therefore be forced to reduce capabilities, delay the launch for 2 years, or cancel the mission.[5]

Conclusion. Historically, NASA has found the probability that schedule-impacting problems will arise is commensurate with the complexity of the project. MSL is one of NASA's most technologically complex projects to date. Accordingly, we are concerned that unanticipated problems arising during final integration and testing of MSL, as well as technical complications resulting from outstanding P/FRs, could cause cost and schedule impacts that will consume the current funding and threaten efforts to complete development and launch on the current schedule. Similarly, we are concerned that the limited remaining schedule margin may increase pressure on NASA to accept reduced capabilities in order to meet the approaching launch window and avoid another 2-year delay that would require significant redesign at a cost of at least $570 million or cancel the mission.

Management Action

To minimize the risk of missing the upcoming launch window and incurring the resultant costs, NASA's Associate Administrator for the Science Mission Directorate should reassess the sufficiency of the Project's funding based on our calculations. In addition, the MSL Project Manager should allocate additional resources to expeditiously close all outstanding P/FRs that could impact mission success.

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[5] Our $581 million calculation is an overall estimate based on the average efficiency of Project management's work performed since February 2009 and includes items that did not increase in cost and items that may have substantially increased in cost above the average. We considered the Project's cost in aggregate and did not attempt to segregate the impact of individual items on work performance efficiency and cost to complete project development (see Appendix D).

In response to a draft of this report, the Associate Administrator for the Science Mission Directorate concurred with our recommendations and stated the Directorate had been conducting weekly monitoring and ongoing assessments of the Project's funding status, expenditures, and remaining work (see Appendix E for the Agency's response). According to these assessments, the Project's budget, coupled with $22 million in Directorate-held reserves, will be sufficient for MSL to achieve a timely and safe launch. In addition, the Associate Administrator stated that MSL Project management has developed a plan to address all open P/FRs and expected to close all relevant P/FRs by the time of the MSL launch.

We consider the Associate Administrator's comments and proposed actions to be responsive to our recommendations. The recommendations are resolved and will be closed upon completion and verification of the proposed corrective actions.

Other Matters of Interest

On May 20, 2011, subsequent to the issuance of a draft of this report, an incident occurred during flight system assembly that had the potential of causing damage to MSL system components. Due to a crane operator's error, the spacecraft's backshell (the part of the spacecraft structure designed to decelerate the spacecraft and protect its contents from overheating during entry into the Martian atmosphere) and the support cart the backshell was attached to were pulled off the ground for a few seconds. At the time, on-site personnel reported that they did not hear any noises (pops or creaks) from the backshell.

MSL Project managers stated that the incident did not appear to have placed excessive loads on the backshell, and subsequent visual inspections and "tap testing" of the backshell did not reveal any damage. In addition, the contractor compared the loads from the incident with the expected flight loads and concluded that the backshell had not been damaged. As of June 2, 2011, it was unclear whether the incident will have any impact on the Project's cost and schedule.

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INTRODUCTION

Background

The Mars Science Laboratory (MSL), part of the Mars Exploration Program (Mars Program), is one of NASA's flagship missions with life-cycle costs currently estimated at $2.5 billion.[6] MSL is currently scheduled to launch in a window between November 25, 2011, and December 18, 2011; land on Mars in August 2012; and operate on the surface of the planet for a minimum of 1 Martian year (approximately 2 Earth years).

The Mars Program seeks to understand if Mars has, or ever had, an environment capable of supporting life. To answer this question, NASA plans to place a rover – known as Curiosity – on the surface of Mars to assess the biological potential at the landing site, characterize the geology of the landing region, investigate planetary processes that influence habitability, and analyze surface radiation. This roving science laboratory includes 10 advanced research instruments (described in Appendix B) that will collect Martian soil and rock samples and make detailed measurements of element composition, elemental isotopes and abundance, mineralogy, and organic compounds.

The MSL rover is engineered to drive longer distances over rougher terrain than NASA's previous Martian rovers, Spirit and Opportunity, and unlike those rovers which relied on solar power, will use a radioisotope power system to generate the electricity needed to operate. MSL's key performance parameters are: (1) land within a 10-kilometer (6-mile) radius from a designated point on the surface of Mars; (2) acquire scientific data for 1 Martian year; (3) have a total traverse path of 20 kilometers (12 miles); and (4) select, acquire, process, distribute, and analyze 74 soil and rock samples.

The primary components of MSL are the launch vehicle (an Atlas V rocket), flight system, and the terrestrial ground-data system processing stations. The flight system consists of an Earth-Mars cruise stage, an entry-descent-landing system, and a mobile science rover with its science instrument payload.

MSL is the most technologically challenging interplanetary rover ever designed. It will use new technologies to adjust its flight while descending through the Martian atmosphere and set the rover on the surface by lowering it on a tether from a hovering descent stage (see Figure 5).

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[6] Flagship missions are missions with costs exceeding $1 billion.

Figure 5. MSL Mission Overview

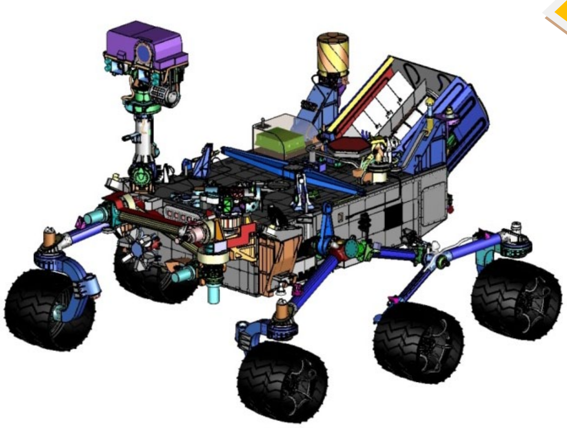
CRUISE/APPROACH
- Approximately 9 months in route
- Approach starts 5 days before entry

ENTRY, DESCENT, AND LANDING
- 15 minutes
- Direct Entry
- Communication provided by ultra-high frequency link to different relay orbiters, based on latitude

Source: NASA/Jack Pfaller (KSC-2009-3750)

LAUNCH
- Nov.–Dec. 2011 Launch
- Atlas V launch vehicle

SURFACE MISSION
- August 2012
- 1 Mars year prime mission
- 900 kilogram (kg) rover
- mobility capability of 20 kilometers
- Approx. 100 kg payload of instruments and support tools
- Radioisotope Power Source



The NASA Associate Administrator for the Science Mission Directorate is the programmatic authority for the MSL Project. NASA's Jet Propulsion Laboratory (JPL) is responsible for performing overall system design and integration. In addition, five other NASA Centers support MSL:

- Ames Research Center – provides the Chemistry and Mineralogy (ChemMin) instrument and elements of the Ground Data System and supports entry descent and landing systems engineering and verification;
- Goddard Space Flight Center – provides the Sample Analysis at Mars (SAM) instrument;
- Johnson Space Center – supports entry descent and landing systems engineering and delivers guidance, navigation, and control algorithms;
- Kennedy Space Center – supports final integration, assembly, and launch; and
- Langley Research Center – supports entry descent and landing systems engineering and delivers guidance, navigation, and control algorithms.

Three foreign government space agencies – the Russian Federal Space Agency, the Spanish Ministry of Education and Science, and the Canadian Space Agency – the Department of Energy, and a number of subcontractors also contribute to the MSL Project.

Cost and Schedule History. Due to planetary alignment, the optimal launch window for a mission to Mars occurs every 26 months. Originally, MSL was to launch between September 2009 and October 2009. In February 2009, NASA delayed the launch 2 years to a window between October and December 2011. The delay resulted from unresolved technical issues that caused several critical components and instruments to miss their delivery dates. For example, actuators (motors that allow the rover and instruments to move) and avionics missed scheduled delivery dates by 11 and 4 months, respectively.

The 2-year delay and the additional resources required to resolve the underlying technical issues increased the Project's development costs from $969 million to $1.8 billion or 86 percent, and its life-cycle costs from $1.6 billion to $2.5 billion or 56 percent.[7] Table 2 shows the Project's cost increases since 2006.

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[7] As required by the NASA Appropriation Act of 2005, NASA notified Congress in December 2008 that MSL had exceeded its schedule baseline by more than 6 months and its cost baseline by more than 15 percent.

Table 2. MSL Project Cost Summary (millions)

Phase	**Initial Cost Estimate per 2006 Project Plan**	**Proposed FY 2012 Budget**	**Funds Expended as of December 2010**
Formulation (Phases A and B)	$ 515.1	$ 515.5	$ 515.5
Development (Phases C and D)	968.6	1,802.0	1,609.9
Operation (Phase E)	158.5	158.8	
Life-Cycle Cost	$1,642.2	$2,476.3	$2,125.4

Objectives

The overall objective of this audit was to examine whether NASA has effectively managed the MSL Project to accomplish its mission objectives while meeting revised schedule and cost milestones. We also reviewed management's cost estimate and its process for identifying, reporting, and mitigating risks. See Appendix A for details of the audit's scope and methodology, our review of internal controls, and a list of prior coverage.

UNRESOLVED TECHNICAL ISSUES CONTINUE TO STRAIN LAUNCH SCHEDULE MARGIN

As of February 2011, MSL's remaining schedule margin was 60 days and more tasks remained to be completed prior to launch than managers had planned. Specifically, the Project had 11 outstanding tasks to be completed in 2011 as opposed to the 4 tasks managers had planned as of February 2009. This increase occurred because of continuing technical challenges that are still being resolved. Although NASA expects that the remaining schedule margin will be sufficient to complete the remaining tasks, in our judgment, the margin may not be sufficient to provide management with the flexibility to resolve unanticipated issues that typically arise in the integration and testing of complex projects like MSL. Consequently, to meet the launch schedule and avoid the more than $570 million in additional costs a delay would engender, Project managers may have to accept greater risks than anticipated related to safety, cost, and the completion of mission objectives.

Schedule Margin and Remaining Technical Issues

Project managers include a schedule margin to allow for resolution of unanticipated issues that arise during project development. The size of the schedule margin varies depending on a project's potential for unforeseen issues such as failures during testing, procurement-related delays, resource availability problems, and new technology challenges. When NASA rescheduled the MSL launch in 2009, the Project's schedule margin was 185 days. As of February 2011, managers planned to have 110 days of remaining schedule margin, but only 60 days of margin remained.

Remaining Unresolved Technical Issues. Project management has overcome most of the technical issues that were the primary causes of the 2009 launch delay. For example, the actuators have been redesigned, manufactured, and delivered, and the technical issues related to developing a subsystem for gas removal for the Sample Analysis at Mars (SAM) instrument were resolved and the SAM installed on the rover in January 2011.[8] However, of the ten issues identified as contributing to the decision to delay the launch, three remained unresolved as of March 2011: contamination of rock and soil samples collected by the Sample Acquisition/Sample Processing and Handling (SA/SPaH) subsystem and development of flight software and fault protection systems.

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[8] SAM is designed to identify materials that contain the element carbon, including methane, that are associated with life and explore ways in which the compounds are generated and destroyed on Mars.

Project managers acknowledged that the SA/SPaH will be resolved prior to launch. However, they stated that issues involving fault protection development and flight software not related to launch can be resolved after MSL has been launched.

The immature technology and late delivery of the rover's SA/SPaH subsystem was one of the major issues that caused the 2-year schedule delay.[9] During testing, Project managers found that hydrocarbons from oil used during the manufacturing of the drill bits were being released and causing contamination of samples. As of March 2011, Project managers said they have identified and validated a solution to minimize contamination of samples and the revised drill bit fabrication was already near completion. However, we remain concerned because work on this mission-critical subsystem is still incomplete and not due for delivery until June 2011, when the rover is due for delivery to Kennedy Space Center for final integration and assembly.

The other two remaining issues are development of flight software and development of fault protection systems. Flight software will be used in conjunction with the spacecraft's onboard computer for command and control of all spacecraft activities (see Appendix C, Task 9, for a detailed description). Fault protection is an engineering fail-safe design required of all NASA flight projects that enables a system to continue operating at a reduced level rather than failing completely. During previous reviews in May 2009 and June 2010, MSL's Standing Review Board expressed concern about the late development of the resource load plan for fault protection and redundancy management.[10] MSL managers completed the fault protection design and initiated testing in November 2010. As of March 2011, MSL managers had completed development and initiated testing of most of the flight software; however, development of software to control the spacecraft and rover remained in progress.

More Recent Concerns. Project managers stated that the expected performance of the rover's power generation system, the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG), has been reduced. Thermoelectric modules inside the MMRTG, which was developed and provided to NASA by the Department of Energy, convert heat (thermal energy) from the decay of a radioisotope (plutonium-238 dioxide) into electricity. Project managers attribute some of the MMRTG's performance degradation to the natural radioactive decay that occurred during the 2-year launch delay. However, unexpected temporary reductions in the system's power output were also noted during testing that simulated the vibration and shock that MSL will experience during its entry, descent, and landing on Mars.

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[9] SA/SPaH has two primary functions, sample acquisition and sample processing and handling. Sample acquisition is accomplished by an arm that supports a percussive powdering drill, abrader, scoop, and contact instruments; the sample processing and handling performs sample transfer using door mechanisms for delivering samples to the rover's analytical instruments.

[10] The Standing Review Board is an outside group of experts convened by NASA to monitor the status of a program or project. The Board periodically conducts independent reviews of performance related to cost, schedule, technical, and other risks.

Department of Energy officials stated that the power degradation issue is unlikely to cause a catastrophic failure. However, as a cautionary measure, MSL Project managers have reduced the mission's performance capabilities to processing 28 rather than 74 soil and rock samples and to traversing 4.5 kilometers rather than 20 kilometers.

Schedule Margin Erosion and Remaining Tasks

We found that the MSL's schedule margin has eroded at a greater rate than Project managers anticipated. As of February 2011, 60 days of margin remained compared to the 110 days that had been planned (see Figure 6). In November 2009, the Project experienced a steep decline, from 185 to 120 margin days. In comparison, Project managers expected to maintain 185 margin days until March 2010. Furthermore, the gap between planned and actual margin has remained constant. To management's credit, in addition to the original margin of 105 days to allow for unforeseen issues, the Project manager held 55 days in his own reserve. In addition, the decision to schedule the launch for the latter part of the launch window provided another 25 days of margin. Without these two actions, the Project would have exhausted its schedule margin.

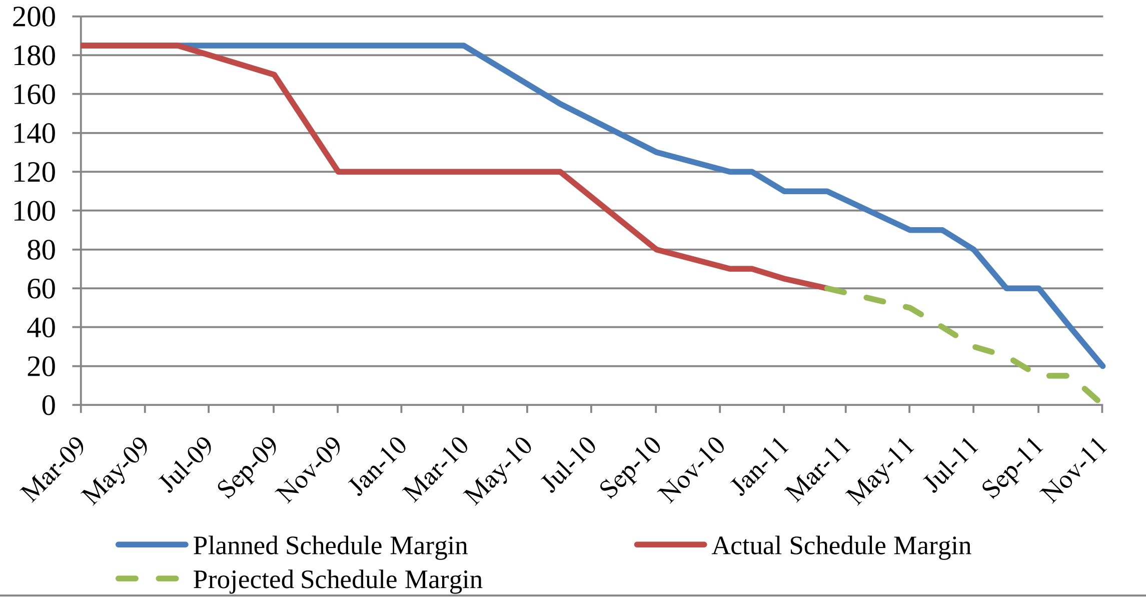


Figure 6. Plan versus Actual Schedule Margin

As shown in Figure 6, the schedule margin had the most significant decrease (60 days) starting in March 2010. This coincided with delays in delivering the Project's major components, including actuators, SAM, and SA/SPaH (see Table 3.)

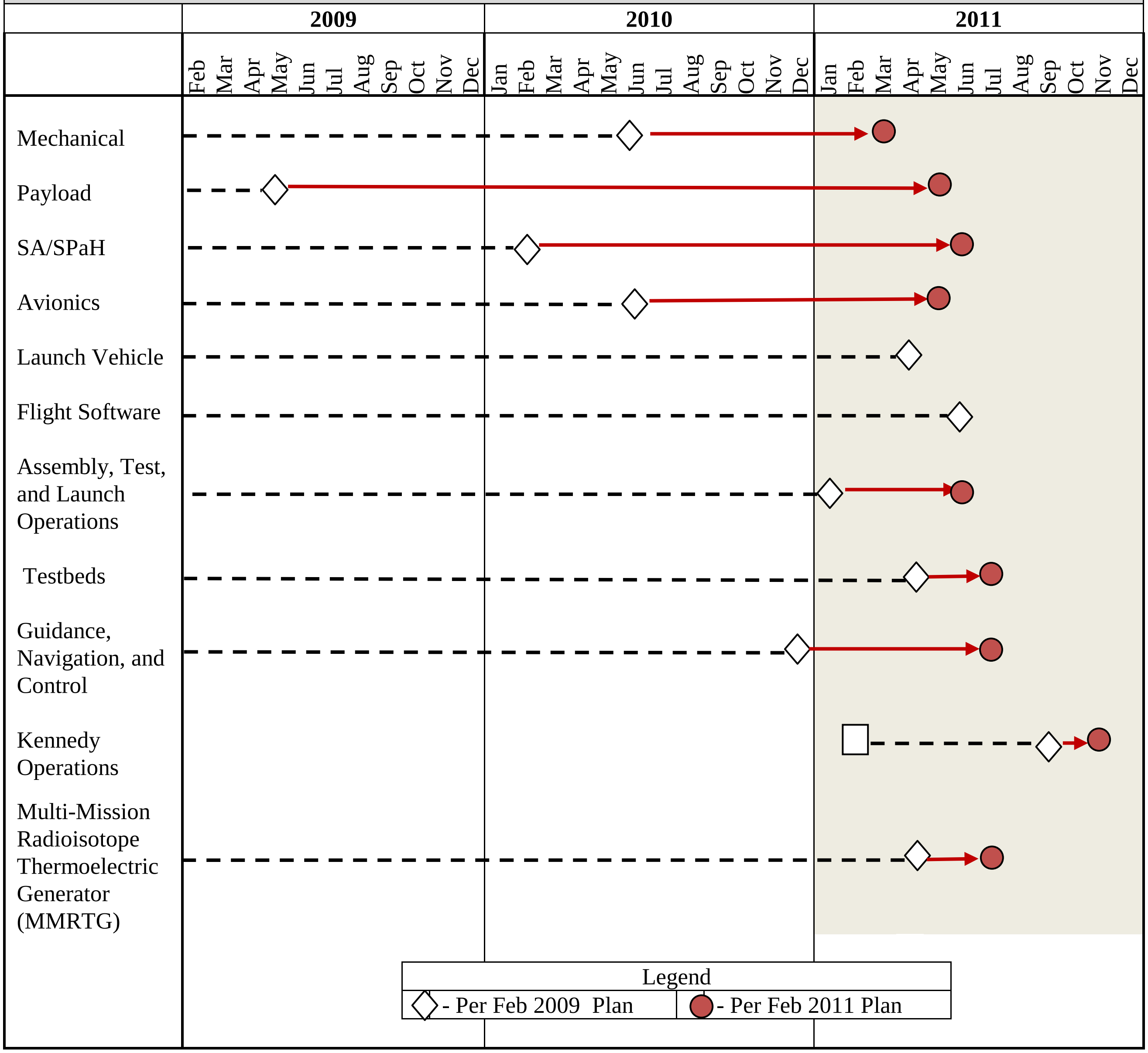
Table 3. MSL Major Components Delivery Schedule

Component	*Estimated Delivery Dates* Per 3/09 Status Review	Per 6/09 Status Review	Per 11/09 Status Review	*Actual Delivery Date to Assembly and Testing*	Delay Since Initial Status (in months)
Actuators	7/22/2009	10/16/2009	1/27/2010	7/8/2010	11
Avionics					
power assembly	10/19/2009	1/15/2010	1/7/2010	1/13/2010	2
motor control	1/29/2010	1/29/2010	3/2/2010	6/3/2010	4
compute element	3/3/2010	3/3/2010	5/10/2010	5/12/2010	2
analog module	6/3/2010	6/3/2010	6/8/2010	10/25/2010	4
SA/SPaH	5/28/2010	6/8/2010	8/20/2010	8/12/2010	2
Radar	5/20/2009	11/9/2009	12/11/2009	3/4/2010	9

Project managers expressed confidence that the current schedule margin would be adequate to address all risks to schedule identified to date. However, we are concerned that the complexity of the Project, the outstanding technical issues that remain to be resolved, and the problem/failure reports that still need to be closed (see discussion below) will increase the likelihood that unanticipated issues will arise during final testing and integration, which the current schedule margin will be inadequate to accommodate.

Delays in development and delivery of critical project components and subsystems have contributed to erosion of the schedule margin. As seen in Figure 7 these delays pushed the completion of critical tasks into 2011 and therefore closer to the launch date. When the original launch delay was approved in February 2009, the project budgeted 185 margin days (top blue line in Figure 6) and the corresponding launch-related tasks were scheduled for completion as shown in white in Figure 7.

Figure 7. Comparison of Critical Tasks Timeline
(see Appendix C for task descriptions)



As shown in Figure 7, in February 2009 managers planned to complete 4 tasks in the final 11 months prior to launch. However, by February 2011 this list had grown to 11 tasks. As discussed previously, delays in development and delivery of critical components and subsystems postponed these tasks closer to the launch date. When these deliveries were delayed, the completion dates for the tasks were extended into 2011 causing the Project to lose margin days (red line in Figure 6). These extended tasks are adding to those that Project managers previously planned for 2011 including:

- Mechanical assembly and electrical integrations;
- Rover rework, including major instrument and component installation;
- Software updates;
- Drill rework (part of SA/SPaH), requiring complete turret deintegration and reintegration;
- Environmental testing;
- System and functional testing;
- Rover descent stage fit check;
- Mass Property Measurements;
- MMRTG installation (mechanical and electrical);
- Pack and ship to Kennedy Space Center; and
- Final processing at Kennedy and integration on the launch vehicle.

With only 60 margin days remaining for calendar year 2011, Project managers have limited flexibility to address any significant new problems that may arise as the Project is integrated and prepared for launch. Unforeseen incidents – such as the one that occurred on May 20, 2011, when a crane operator's error resulted in unplanned inspections and assessments of MSL's backshell to determine whether it was damaged – have the potential to erode schedule margin and affect the schedule.[11] Missing the current launch window would result in another 2-year delay at a cost of at least an additional $570 million or mission cancellation. Moreover, we are concerned that as the schedule margin tightens NASA will face increased pressure to reduce capabilities relative to the mission objectives.

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[11] The spacecraft backshell is designed to decelerate the spacecraft and protect its contents from aerothermal heating during entry into the Martian atmosphere. The crane operator lifted the backshell and the support cart it was attached to for a few seconds. Subsequent visual inspections and "tap testing" of the backshell did not reveal any damage.

ADDITIONAL RISKS ASSOCIATED WITH CLOSING PROBLEM/FAILURE REPORTS

Project managers did not consistently identify and assess cost and schedule risks associated with problem/failure reports (P/FRs). Consequently, cost reserve and schedule margins may not be adequate to accommodate the potential impacts of these risks. A large number of P/FRs remain open and resolving them may result in increased costs and delays due to unanticipated problems.

Problem/Failure Report Associated Risks and Closures

JPL requires a formal problem/failure reporting and analysis program to support flight project hardware and software developments. The program requires the cognizant engineer to review P/FRs and assign a preliminary risk rating within 10 days of occurrence of the incident for early identification of potentially significant issues.[12] MSL Project managers developed a problem/failure reporting process to address problems and concerns attributed to technical uncertainties identified during development of the MSL. These reports range from minor issues with negligible effects to "red flag" issues with significant or major effects up to and including a loss of mission. An example of a minor P/FR is the correction of language in a test procedure. An example of a red flag issue is the unexpected powering down of MSL's main onboard computer during a critical phase of the mission. In such a situation, the computer may lose memory of the last action performed, which could lead to unintended actions resulting in hardware or software failure and the inability to achieve mission objectives.

MSL Project Management Did Not Effectively Assess or Prioritize the Risks Identified by the P/FR Process. During fieldwork, in June 2010, there were 2,085 P/FRs on record for the MSL Project, with 1,102 closed and 983 open. We found that 71 of the open P/FRs had not received the required preliminary risk assessment. In the absence of these assessments, Project managers may not have allocated sufficient resources to address these P/FRs.

Problem/Failure Reports Were Not Closed in a Timely Manner. We analyzed P/FR database trends from June 2010 to February 2011 and found that although the number of open P/FRs as a percentage of the whole was decreasing, the absolute number of open P/FRs increased. Specifically, as of February 24, 2011, the number of P/FRs had increased to 2,865, of which 1,652 were closed and 1,213 open. Figure 8 shows a trend of steady increase in P/FRs while Table 4 shows that more than 42 percent of the Project's P/FRs remained open as of February 2011.

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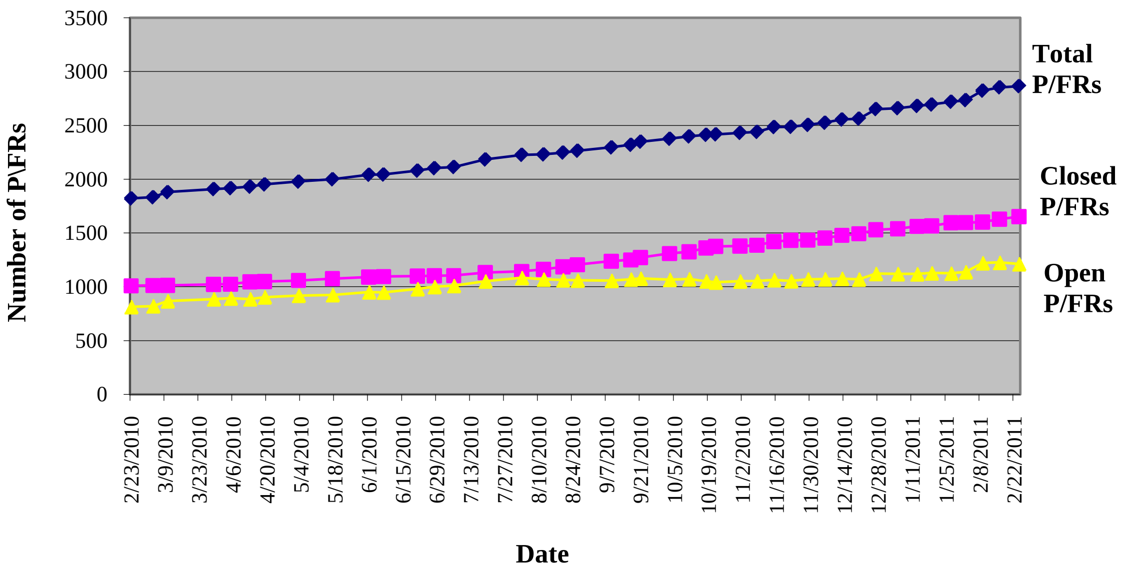
[12] JPL Rule 73472, Section 5.10.15, "Preliminary Risk Rating."

Figure 8. MSL Problem/Failure Report Trend



Source: MSL Project Quarterly Status Report February 2011

Table 4. MSL P/FR Progress Snapshot

As of Date	Total	Increase from previous month	No. of Closed P/FRs	Increase of P/FRs Closed	No. of Open P/FRs	Net Incr (Decr) of Open P/FRs	Open P/FRs to Total P/FRs
6/21/10	2,085		1,102		983		47 percent
7/19/10	2,184	99	1,132	30	1,052	69	48 percent
8/20/10	2,248	64	1,185	53	1,063	11	47 percent
9/17/10	2,320	72	1,250	65	1,070	7	46 percent
10/18/10	2,413	93	1,360	110	1,053	(17)	44 percent
11/15/10	2,485	72	1,421	61	1,064	11	43 percent
12/20/10	2,563	78	1,493	72	1,070	6	42 percent
1/27/11	2,720	165	1,595	117	1,125	48	41 percent
2/24/11	2,865	145	1,652	57	1,213	88	42 percent
Total Increase		780		550		**230**	

The trend also shows that the number of P/FRs has increased by about 1,000 over the 12-month period between February 23, 2010, and February 24, 2011. Both the trend line and the 8-month snapshot show that while an increasing number of P/FRs were closed over this period, the total number of P/FRs grew at a faster rate. Our review of the June 2010 P/FR database also found that, on average, P/FRs remained open for 1.2 years and that those concerning potentially red flag issues remained open on average for 1.6 years.

The unresolved P/FRs we reviewed were in various stages of the reporting process. About one-third of the open P/FRs were in the final (signature) phase, which Project managers said they expected to close with minimal effort. In addition, Project managers said they felt confident that they could close all of the P/FRs that must be closed to proceed to launch before the scheduled launch date, noting that those involving flight software can be closed after launch. However, we are concerned that 20 of 30 significant or potential red flag P/FRs that were open as of April 2011 involve flight hardware that could present significant challenges to mission success. Furthermore, as previously stated, at least 71 P/FRs were not properly assessed, leaving open the possibility of unknown risks that could impact mission success or result in unanticipated cost growth.

Recommendations, Management's Response, and Evaluation of Management's Response

Recommendation 1. The MSL Project Manager should ensure that the required preliminary risk assessments are completed on all P/FRs and identify required resources to resolve the identified problems.

Management's Response. The Associate Administrator for the Science Mission Directorate concurred, stating that the MSL Project Manager has engaged senior JPL management to use lab resources to assess and ensure rapid disposition of all open P/FRs. In addition, senior P/FR team leads have been identified for all critical areas, with daily tracking and weekly reporting on the resolution progress.

Evaluation of Management's Response. Management's proposed actions are responsive; therefore, the recommendation is resolved and will be closed upon completion and verification of the proposed corrective actions.

Recommendation 2. The MSL Project Manager should develop a plan to address all open P/FRs. The plan should prioritize P/FRs commensurate with their severity, provide a schedule for completion, and establish realistic resource requirements to ensure a timely and safe launch.

Management's Response. The Associate Administrator concurred, stating that Project management had developed such a plan in March 2011. Based on improved P/FR closure progress to date, Project management expected the plan would lead to closure of all relevant P/FRs by the time of the MSL launch.

Evaluation of Management's Response. Management's proposed actions are responsive; therefore, the recommendation is resolved and will be closed upon completion and verification of the proposed corrective actions.

PROJECT MANAGEMENT CONSISTENTLY UNDERESTIMATED THE COST TO COMPLETE MSL

Project managers have increased cost estimates for MSL multiple times since inception of the Project. Since February 2009, the Project has received three budget increases totaling $137 million, including a $71 million increase in December 2010. Even with these increases, we are concerned that based on historical cost trends and the remaining work to be completed, funding for MSL may still be insufficient to meet the 2011 launch schedule. In our judgment, in order to meet the scheduled launch date without reducing scope, the Project may require additional funding.

Project Management Consistently Underestimated Costs

MSL's 2-year launch delay and the additional resources required to resolve the underlying technical issues increased the Project's development costs from $969 million to $1.8 billion (86 percent) and the corresponding life-cycle cost estimate from $1.6 billion (per the May 2006 project plan) to $2.5 billion. Moreover, the current development and life-cycle cost estimates reflect three separate increases over the past 2 years. Since the launch was delayed in February 2009, the estimated cost to complete development has increased by $137 million, including an additional $71 million – consisting of $36 million in identified work and a $35 million reserve – in December 2010. In addition, Mars Program management set aside $22 million as Program Office reserve that has not been specifically allocated to the MSL Project.

Growing Cost Estimates. Following the decision to delay MSL's launch, Project managers established a new schedule and cost baseline taking into consideration the work required to meet the 2011 launch date. This February 2009 rebaseline included a $400 million estimate to complete the remaining work through launch (the development phase). In May 2009, NASA's Independent Program Assessment Office (IPAO) projected that development costs would likely exceed the Project's revised estimate by $65–$95 million and could exceed the estimate by up to $107 million.[13] At that time, the Mars Program Office set aside a $95 million Program Office reserve. However, 1 year later the IPAO and JPL's independent cost assessment both showed a risk that the $495 million cost estimate would be insufficient. See Table 5 for their estimates.

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[13] The IPAO provides independent life-cycle reviews and assessments of the technical, schedule, cost, and risk posture of proposed and ongoing projects to provide objective advice to the Agency Program Management Council.

Table 5. Independent Cost Estimates			
	Low	**Mostly Likely**	**High**
IPAO Assessment as of June 2010	$484 million	$495 million	$520 million
JPL Independent Assessment as of May 2010	$498 million		$511 million

Although the IPAO's most likely estimate remained at $495 million, its "high" estimate increased to $520 million. JPL did not offer a "most likely" estimate, but its independent assessments at the low end exceeded the $495 million estimate by $3 million and its "high" figure exceeded the estimate by $16 million.

See Table 6 for details of the Project's history of cost increases through December 2010.

Table 6. MSL Cost Estimates Since 2009 Launch Delay
(Estimated Cost to Complete Project Development)

Date of Cost Estimate	**Estimated Cost to Complete** (in millions)	**Main Factors Driving Cost Growth**
February 2009	$ 400	• SAM development activity • flight systems development activity: actuators; avionics; SA/SPaH subsystem; and radar • late subsystem deliveries • launch vehicle
June 2009	+ 32 432	• This increase resulted from a review by the Standing Review Board and NASA management of the Project reserve level and risks. The major technical drivers remained the same as above.
November 2009	+ 34 466	• SAM development activity • flight system development activity: actuators, avionics, SA/SPaH subsystem, and radar • late subsystem deliveries
December 2010	+ 71 $ 537*	• increases in the validation and verification program and test program • funding of the ATLO team for a post-shipment delay period. • increase in Kennedy operations cost estimate for the change in the launch date to November 2011 • P/FR resolution and other paperwork closure

* In December 2010, management for the Mars Program set aside an additional $22 million as unallocated reserve. This amount is a Program Office reserve that was not allocated to MSL and is not included in the figures above.

Budget May Be Inadequate. In November 2010, managers requested an additional $71 million, which brought the development cost estimate to $537 million and the total life-cycle cost estimate to $2.5 billion. The Agency Program Management Council approved the request in December 2010.[14]

The November 2010 request consisted of $36 million to complete the then current scope of work plus $35 million in reserve. Managers developed the $36 million estimate by conducting a bottom-up review of the remaining work and the $35 million figure by calculating 20 percent reserve levels based on the total estimated cost ($175 million) as of September 2010 to complete the Project's development phase.[15] In addition, Project managers said they validated the reserve requirement by using various cost projection approaches.

However, in our judgment, in light of the Project's historical pattern of cost increases and our analysis of the Project managers' cost estimates, current funding may be insufficient to ensure the Project meets the 2011 launch date. In June 2009, the Mars Program Office set aside a $95 million reserve; however, this reserve has proved insufficient to cover the current $137 million cost increase needed to complete the development phase.

Our analysis indicated that the Project's $537 million estimate to complete development may still be insufficient to fund the Project through launch. We recomputed a cost to complete estimate by factoring in cost increases associated with the additional work requirements added since February 2009 to address technical issues identified during development and determined that $581 million was required – $44 million more than the current estimate.[16] (See Appendix D for details of our computation.)

Although Project managers have received three funding increases since February 2009, Figure 9 illustrates that the schedule margin gap between planned and actual number of days available has not decreased. Accordingly, it appears that Project management has consistently underestimated the amount of resources necessary to complete tasks in accordance with the schedule. In addition, because we are concerned that the probability of unforeseen problems will increase commensurate with the complexity of the project and that issues discovered during integration and testing or as a result of closing the

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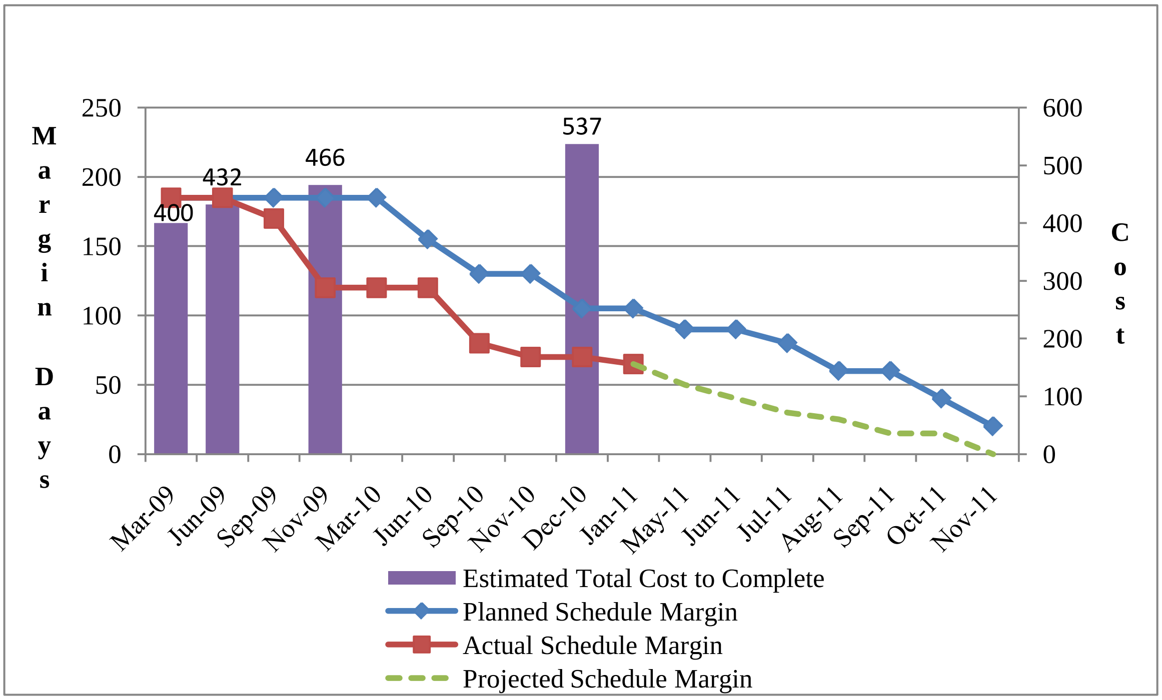
[14] The Agency Program Management Council is NASA's senior management group, chaired by the NASA Associate Administrator or his designee, responsible for reviewing formulation performance, recommending approval, and overseeing implementation of programs and projects according to Agency commitments, priorities, and policies.

[15] Managers applied the 20 percent based on guidance in JPL's *Flight Project Practices*, a set of project management best practices.

[16] Our $581 million calculation is an overall estimate based on the average efficiency of Project management's work performed since February 2009 and includes items that did not increase in cost and items that may have substantially increased in cost above the average. We considered the Project's cost in aggregate and did not attempt to segregate the impact of individual items on work performance efficiency and cost to complete project development.

outstanding P/FR issues will consume all of the current funding and reserve, thereby potentially jeopardizing the scheduled launch.

Figure 9. Comparison of Schedule Margin Reduction to Estimated Total Cost to Complete



Funding limitations may also increase pressure on Project managers to reduce science capabilities or accept a higher level of risk in order to avoid further delay. Rescheduling launch from 2009 to 2011 added approximately $900 million to the Project's life-cycle cost estimate, and any further delay to 2013 or 2014 would only add to that figure. According to Program managers, in addition to added administrative and maintenance costs, such a delay would require the spacecraft's cruise and descent stages be redesigned to accommodate differences in planetary alignment and the Martian dust storm season. This redesign alone would cost approximately $570 million.

Recommendation, Management's Response, and Evaluation of Management's Response

Recommendation 3. The Associate Administrator for the Science Mission Directorate should reevaluate the Project's history of cost estimation, reassess the sufficiency of available reserves, and adjust funding accordingly.

Management's Response. The Associate Administrator for the Science Mission Directorate concurred and stated that the Directorate's ongoing assessments indicated that the Project's budget coupled with $22 million in Directorate-held reserves would be sufficient for MSL to achieve a timely and safe launch. In addition, the Associate Administrator said the Directorate was conducting weekly monitoring of the Project's funding status and expenditures.

Evaluation of Management's Response. Management's proposed actions are responsive. Although the recommendation is resolved, it will remain open pending our review and analysis of management's assessments of the sufficiency of its reserve funding.

APPENDIX A

Scope and Methodology

We performed this audit from May 2010 through April 2011 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.

We performed work at JPL and at NASA Headquarters, Washington, D.C. We obtained, reviewed, and analyzed Federal, NASA, and JPL policies and procedures relating to space flight program and project management, including the NASA Authorization Act of 2005 (Public Law 109-155), NASA Procedural Requirements (NPR) 7120.5D, NPR 8000.4A, Science Mission Directorate Management Handbook, and JPL Rules and Internal Standard Operating Procedures. We also reviewed NASA contract NAS7-03001 to determine contractual requirements for JPL operations. We interviewed management officials from the Science Mission Directorate's Independent Program Assessment Office, and JPL MSL Project management. We discussed areas related to MSL's rebaseline process, management oversight tools and processes, current project status, and issues that impact delivery delays and potential launch delays.

Project Technical Risk. We reviewed JPL Rules 35506 "Anomaly Resolution" and 73472 "JPL Problem/Failure Reports, Preparation and Review Guidelines" to understand the standards for effective anomaly reporting and resolution for JPL flight projects and the preliminary rate rating process. We interviewed JPL MSL Mission Assurance personnel to understand P/FR processing. To determine whether MSL Project management had effectively identified and assessed technical risk, we reviewed the status of P/FRs as of August 2010. We analyzed the P/FR database and historical trend for the 8-month period of June 2010–February 2011. We also selected 20 P/FRs based on the significance of the areas affected by the problem or failure and evaluated the P/FR reporting, analyzing, testing, and closing process.

Project Schedule Estimating. We reviewed planning documents for the February 2009 rebaseline, Project status reports since the rebaseline, and Headquarters Project reviews since the rebaseline. We obtained an understanding of major issues that caused the 2-year delay. To determine the adequacy and effectiveness of the Project's schedule control procedures, we reviewed instrument delivery schedules and critical path timelines and compared them with the rebaseline planning documents. We also analyzed schedule margin trend since rebaseline and compared the actual schedule margin with the planned schedule margin.

Project Cost Estimating. To determine the adequacy and effectiveness of the Project's cost control procedures, we analyzed the cost growth trend since rebaseline and main factors driving cost growth. We reviewed JPL's current cost estimate method and recomputed a cost to complete estimate by factoring in cost increases associated with the additional work requirements (due to scope adjustments).

Use of Computer-Processed Data. We used computer-processed data to perform this audit. JPL reportable incidents involving design, development, and testing of flight-configured hardware and software were reported to the problem/failure reporting and analysis program. Although we did not test the general or application controls of this program we did compare the information in the key data fields with our sample of P/FRs and supporting documents for the data and determined that the data was valid and reliable to support our objectives and conclusions.

Review of Internal Controls

We reviewed the internal controls associated with MSL Project management's assessment of cost and technical risk that could impact the near-term launch schedule. We noted concerns as discussed in the report. Our recommendations, if implemented, should address the concerns.

Prior Coverage

During the last 5 years, the Government Accountability Office (GAO) has issued three reports of particular relevance to the subject of this report. Unrestricted GAO reports can be accessed over the Internet at http://www.gao.gov.

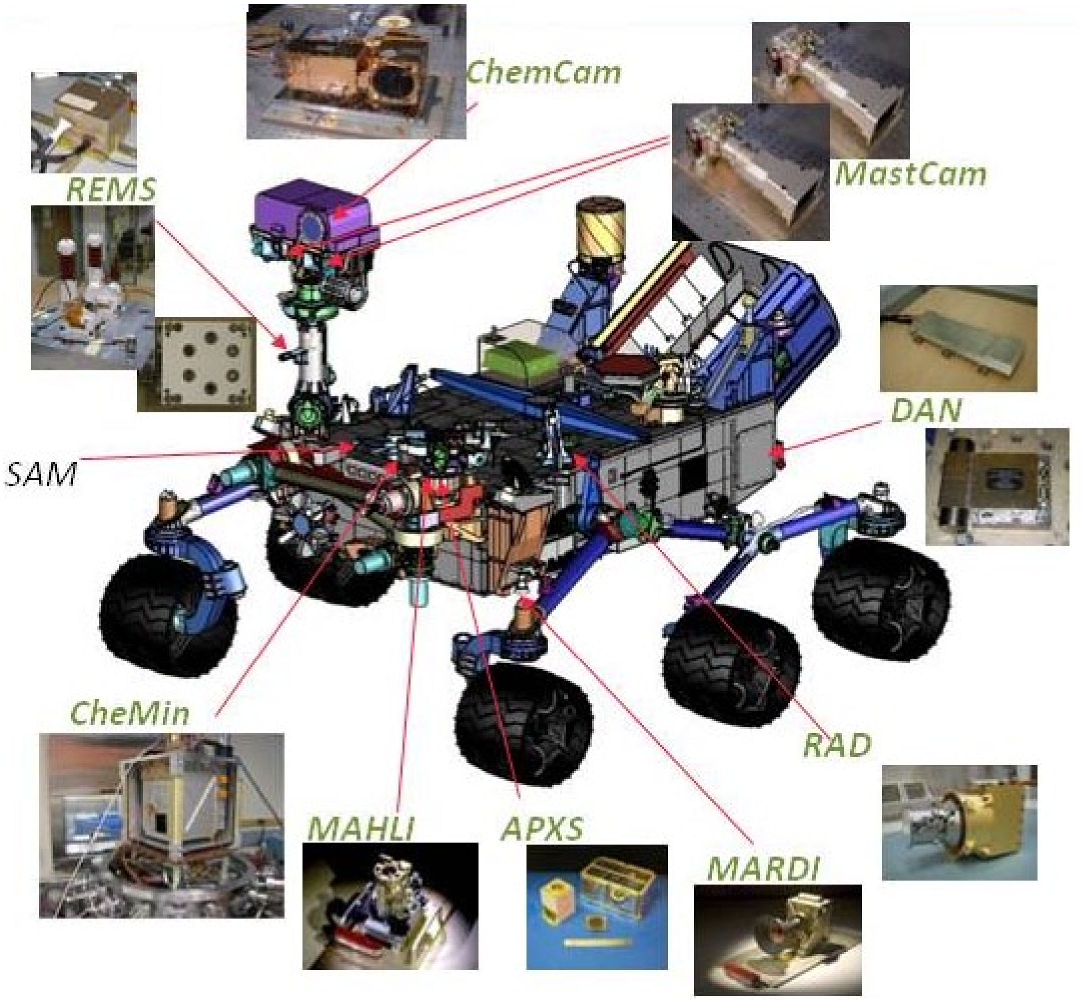
"NASA: Assessments of Selected Large-Scale Projects" (GAO-10-227SP, February 2010)

"Information Technology: Agencies Need to Improve the Implementation and Use of Earned Value Techniques to Help Manage Major System Acquisitions" (GAO-10-2, October 2009)

"NASA: Projects Need More Disciplined Oversight and Management to Address Key Challenges" (GAO-09-436T, March 2009)

PAYLOAD DESCRIPTIONS

Figure 10. Rover Payloads



Source: Status Report from Program Executive

To accomplish the science goals of the MSL mission, the rover carries a science payload with instruments sponsored by NASA and others contributed by international partners. These instruments are roughly divided into 4 categories. Table 7 identifies the instruments and their categories.

Table 7. Instrument Descriptions

Category/ Instrument	**Functional Description**	**Supporting Organization**
Remote Sensing/ Mast Camera (MastCam)	MastCam will take color images and color video footage of the Martian terrain. Like the cameras on the rovers that landed on Mars in 2004, the MastCam design consists of two camera systems mounted on a mast extending upward from the MSL rover deck (body). The MastCam will be used to study the Martian landscape, rocks, and soils; to view frost and weather phenomena; and to support the driving and sampling operations of the rover.	Malin Space Science Systems (Subcontractor)
Remote Sensing/ Chemistry and Camera (ChemCam)	Looking at rocks and soils from a distance, ChemCam will fire a laser and analyze the elemental composition of vaporized materials from areas smaller than 1 millimeter on the surface of Martian rocks and soils. An onboard spectrograph will provide detail about minerals and microstructures in rocks by measuring the composition of the resulting plasma – an extremely hot gas made of free-floating ions and electrons. ChemCam will also use the laser to clear away dust from Martian rocks and a remote camera to acquire detailed images. The camera can resolve features 5 to 10 times smaller than those visible with cameras on NASA's two Mars Exploration rovers that began exploring Mars in January 2004. In the event the MSL rover cannot reach a rock or outcrop of interest, ChemCam will have the capability to analyze it from a distance.	Los Alamos National Laboratory (Subcontractor)
In-Situ/ Mars Hand Lens Imager (MAHLI)	MSL will carry its own equivalent of the geologist's hand lens, MAHLI. MAHLI will provide earthbound scientists with close-up views of the minerals, textures, and structures in Martian rocks and the surface layer of rocky debris and dust. The self-focusing camera, roughly 4 centimeters wide (1.5 inches), will take color images of features as small as 12.5 micrometers, smaller than the diameter of a human hair. MAHLI will carry both white light sources, similar to the light from a flashlight, and ultraviolet light sources, similar to the light from a tanning lamp, making the imager functional both day and night. The ultraviolet light will be used to induce fluorescence to help detect carbonate and evaporite minerals (minerals that form by coming out of solution when water evaporates), both of which indicate that water helped shape the landscape on Mars. MAHLI's main objective will be to help the MSL science team understand the geologic history of the landing site on Mars. MAHLI will also help researchers select samples for further investigation.	Malin Space Science Systems (Subcontractor)
In-Situ/ Alpha-Particle X-ray Spectrometer (APXS)	APXS will measure the abundance of chemical elements in rocks and soils. APXS will be placed in contact with rock and soil samples on Mars and will expose the material to alpha particles and X-rays emitted during the radioactive decay of the element curium.	Canadian Space Agency (CSA)

Category/ Instrument	**Functional Description**	**Supporting Organization**
Analytical/ Chemistry and Mineralogy Instrument (CheMin)	CheMin will identify and measure the abundances of various minerals on Mars. Examples of minerals found on Mars so far are olivine, pyroxenes, hematite, goethite, and magnetite. Minerals are indicative of environmental conditions that existed when they formed. For example, olivine and pyroxene, two primary minerals in basalt, form when lava solidifies. Jarosite, found in sedimentary rocks by NASA's rover Opportunity on Mars, precipitates out of water. Using CheMin, scientists will be able to study further the role that water played in forming minerals on Mars. Different minerals are linked to certain kinds of environments. Scientists will use CheMin to search for mineral clues indicative of a past Martian environment that might have supported life.	NASA Ames Research Center
Analytical/ Sample Analysis at Mars (SAM)	The SAM instrument suite will take up more than half the science payload on board the MSL rover and feature chemical equipment found in many scientific laboratories on Earth. SAM will search for compounds of the element carbon, including methane, that are associated with life and explore ways in which they are generated and destroyed in the Martian ecosphere. A suite of three instruments, including a mass spectrometer, gas chromatograph, and tunable laser spectrometer, SAM will also look for and measure the abundances of other light elements, such as hydrogen, oxygen, and nitrogen, associated with life. The mass spectrometer will separate elements and compounds by mass for identification and measurement. The gas chromatograph will heat soil and rock samples until they vaporize, and will then separate the resulting gases into various components for analysis. The laser spectrometer will measure the abundance of various isotopes of carbon, hydrogen, and oxygen in atmospheric gases such as methane, water vapor, and carbon dioxide. These measurements will be accurate to within 10 parts per thousand.	NASA Goddard Space Flight Center
Environmental/ Radiation Assessment Detector (RAD)	RAD will be one of the first instruments sent to Mars specifically to prepare for future human exploration. RAD will measure and identify all high-energy radiation on the Martian surface, such as protons, energetic ions of various elements, neutrons, and gamma rays. That includes not only direct radiation from space, but also secondary radiation produced by the interaction of space radiation with the Martian atmosphere and surface rocks and soils. RAD will also assess the hazard presented by radiation to potential microbial life, past and present, both on and beneath the Martian surface. In addition, RAD will investigate how radiation has affected the chemical and isotopic composition of Martian rocks and soils.	Southwest Research Institute (Subcontractor)

Category/ Instrument	**Functional Description**	**Supporting Organization**
Environmental/ Mars Descent Imager (MARDI)	Knowing the location of loose debris, boulders, cliffs, and other features of the terrain will be vital for planning the path of exploration after the MSL rover arrives on Mars. MARDI will take color video during the rover's descent toward the surface, providing an "astronaut's view" of the local environment. As soon as the rover jettisons its heatshield several kilometers above the surface, MARDI will begin producing a five-frames-per-second video stream of high-resolution, overhead views of the landing site. It will continue acquiring images until the rover lands, storing the video data in digital memory. After landing safely on Mars, the rover will transfer the data to Earth. In addition to helping Earthbound planners select an optimum path of exploration, MARDI will provide information about the larger geologic context surrounding the landing site. It will also enable mappers to determine the spacecraft's precise location after landing.	Malin Space Science Systems (Subcontractor)
Environmental/ Dynamic Albedo of Neutrons (DAN)	One way to look for water on Mars is to look for neutrons escaping from the planet's surface. Cosmic rays from space constantly bombard the surface of Mars, knocking neutrons in soils and rocks out of their atomic orbits. If liquid or frozen water happens to be present, hydrogen atoms slow the neutrons down. In this way, some of the neutrons escaping into space have less energy and move more slowly. These slower particles can be measured with a neutron detector. The MSL rover will carry a pulsing neutron generator called DAN that will be sensitive enough to detect water content as low as one-tenth of 1 percent and resolve layers of water and ice beneath the surface. Albedo is a scientific word for the reflection or scattering of light.	Russian Space Agency
Environmental/ Rover Environmental Monitoring Station (REMS)	REMS will measure and provide daily and seasonal reports on atmospheric pressure, humidity, ultraviolet radiation at the Martian surface, wind speed and direction, air temperature, and ground temperature around the rover. Two small booms on the rover mast will record the horizontal and vertical components of wind speed to characterize air flow near the Martian surface from breezes, dust devils, and dust storms. A sensor inside the rover's electronic box will be exposed to the atmosphere through a small opening and will measure changes in pressure caused by different meteorological events such as dust devils, atmospheric tides, and cold and warm fronts. A small filter will shield the sensor against dust contamination. A suite of infrared sensors on one of the booms will measure the intensity of infrared radiation emitted by the ground, which will provide an estimate of ground temperature. These data will provide the basis for computing ground temperature. A sensor on the other boom will track atmospheric humidity. Both booms will carry sensors for measuring air temperature.	Spanish Space Agency (INTA)
Source: http://mars.jpl.nasa.gov/msl/mission/instruments/		

TASK DESCRIPTIONS

Table 8. MSL Project Task Descriptions

	Task	Task Description
1	Propulsion	The MSL propulsion subsystem comprises two independently operated subsystems: cruise stage (CS) propulsion and the descent stage (DS). The CS propulsion subsystem is used to perform attitude control and delta-V functions during the cruise to Mars, while DS propulsion is used to carry out a soft landing of the rover on the surface of Mars.
2	Thermal	The flight system thermal control subsystem provides in-flight active and passive thermal control hardware that maintains flight hardware within allowable temperature limits during prelaunch, launch, cruise, and landed operations.
3	Telecom	All MSL communications are handled through the telecommunications subsystem. This subsystem receives and demodulates uplink commands, transmits science and engineering data, and provides coherent two-way tracking and ranging. The telecommunications subsystem is composed of a complete ultra-high frequency (UHF) subsystem to handle proximity link communications with NASA assets in orbit around Mars (Mars Reconnaissance Orbiter, Odyssey) and also a complete X-Band subsystem that handles communications directly with Earth. The UHF subsystem spans the rover, DS, and the Backshell/Parachute Cone Stage of MSL and is used during Entry, Descent, and Landing (EDL) and rover surface operations. The X-Band subsystem spans the rover, DS, Backshell/Parachute Cone Stage, and CS of MSL and is used during CS, EDL, and rover surface operations.
4	Mechanical	There are three work breakdown structure elements in this category: aeroshell, parachute, and motor actuators/gearboxes. The aeroshell is a scaled Viking heritage heatshield and thermal protection system (TPS), 4.75 meters in diameter. The descent phase of MSL begins after guided atmospheric entry, with the aeroshell having passed through peak heating and peak deceleration. Stowed at the top of the backshell is a Viking heritage parachute scaled up to 22.5 meters in diameter, to accommodate the significantly heavier mass of MSL. The supersonic parachute is deployed via the mortar in the backshell.

	Task	**Task Description**
	(Mechanical, continued)	The rover mechanical subsystem provides the basis for integrating all of the other rover subsystems and payload elements. In addition to the internal and external accommodation of instruments, the mechanical subsystem is responsible for the large number of deployments that bring the rover to its full functionality.
5	Payload	See Appendix B.
6	SA/SPaH	The Sample Acquisition/Sample Processing and Handling (SA/SPaH) subsystem is fully responsible for the acquisition of rock and regolith samples from the Martian surface and the processing of these samples into fine particles that are then distributed to the analytical science instruments, SAM and CheMin. The SA/SPaH subsystem is also responsible for the placement of the two contact instruments, APXS and MAHLI, on rock and soil targets.
7	Avionics	All onboard command and data handling is hosted by the avionics subsystem. Avionics also contains solar power generation and all onboard primary power bus regulation, motor control, pyrotechnic device control, and primary power distribution functions. Its performance is critical to collection, storage, processing, and distribution of engineering and science data, commanding for all subsystems, and attitude control during cruise, EDL, and rover surface operations. It is also critical for supplying power to the entire flight system.
8	Launch Vehicle	The launch vehicle for the MSL mission will be an Atlas V (541), which consists of a Common Core Booster (CCB), four solid rocket boosters (SRB), and one Centaur III with a 5.4-m diameter payload fairing. The Atlas V launch vehicle system is based on the 3.8-meter (12.5-foot) diameter CCB powered by a single RD-180 engine. The Atlas 541 is provided to NASA by United Launch Alliance. Launch of the MSL spacecraft will be from Launch Complex-41 at the Cape Canaveral Air Force Station in Florida. The launch services contract for MSL is managed by NASA's Launch Services Program Office at Kennedy Space Center.
9	Flight Software	The flight system software is composed of seven functional domains: avionics interface, infrastructure interface, flight and ground interface, guidance/navigation and control, mobility, payloads and articulation, and high-level system behaviors. MSL flight software (FSW) is defined as all software that executes in the Rover Compute Element (RCE) flight computer. Specifically excluded from this definition is device-resident firmware, software that executes in the resident central processing units of the science instruments, test software, simulation software, ground operations software, and mission support software.

	Task	Task Description
	(Flight Software, continued)	The RCE is the key element of the MSL avionics subsystem, which entirely controls the MSL spacecraft. Rover flight software is the software in the main computer of the rover that monitors the status of the flight system during all phases, checks for the presence of commands to execute, maintains a buffer of telemetry for transmission, performs communication functions, and checks the overall health of the spacecraft. Central control of the entire flight system is under control of the flight software running in the RCE, the same architecture as was used for the Mars Exploration Rover (MER) mission. Additionally, the internal architecture of the flight software is also inherited from that mission.
10	Assembly, Test, and Launch Operations (ATLO)	This task involves flight system verification, integration, and testing. Specifically, ATLO accomplishes flight system integration, assembly, and launch execution, as well as the planning and test procedures associated with those activities.
11	Testbeds	The MSL Project will have access to three system testbeds for the conduct of the mission. Developed and certified prior to launch, after launch, these facilities are available for the verification of uplink products and procedures (often for first-time events, as well as for others when time permits) as well as for troubleshooting and anomaly resolution during flight operations. Two of these testbeds are stationary (non-mobile) but support limited surface phase testing via simulated mobility and terrain interactions and instrument simulations. The higher fidelity system is named the Mission System Testbed (MSTB), which has the most complete complement of hardware models available. An additional stationary testbed, the Flight Software Testbed (FSWTB), is also available, but with some hardware components only represented as software simulations. The majority of launch, cruise, and EDL testing will take place on these platforms. Additionally, a mobile testbed, the Vehicle System Testbed (VSTB) is available for surface phase testing, including mobility, of the SA/SPaH hardware and engineering models of the payload instruments. The VSTB does not support launch, cruise, or EDL testing.
12	Guidance, Navigation and Control (GN&C)	The flight system GN&C supports the Cruise Phase and uses the Mars Pathfinder/MER heritage star scanner and the Adcole sun sensor package. Cruise navigation comprises orbit determination and propulsive maneuver design. Orbit determination responsibilities include determining the trajectory of the spacecraft and predicting atmospheric entry condition and delivery accuracy. Propulsive maneuver design responsibilities include designing trajectory

	Task	Task Description
	(GN&C, continued)	correction maneuvers to achieve the desired atmospheric entry conditions and calculating mission statistical change in velocity (speed) and propellant requirements. During approach and entry phases, GN&C will de-spin the entry body and turn the capsule to the entry attitude. After successfully slowing the EDL system down, the parachute is deployed, and the front aeroshell is separated, the rover radar begins radar acquisition of the surface and computation of relative velocity GN&C for a rover may be equated to the "eyes" of the rover. The rover attitude control subsystem consists of two major elements: • The engineering camera subsystem, which is responsible for providing the surface system with images and from which 3D terrain information can be derived. • The rover's Inertial Measurement Unit, which is used to support rover navigation of traverses and to estimate tilt on the Martian surface.
13	Kennedy Operations	The MSL Flight System will arrive at Kennedy's Payload Hazardous Servicing Facility in a somewhat preassembled state. The flight system and mechanical and electrical ground support equipment will be configured for a post-shipment system test. Following completion of the system test, all flight segments will start the closeout process in preparation for final flight assembly. Upon completion of the rover and descent stage (DS) closeout activities, the DS propellant tanks will be loaded and then the rover and DS will be mated to form the powered descent vehicle (PDV). The PDV is installed inside the backshell and then the heatshield is mated to the backshell to form the entry vehicle (EV). Once completed, the EV is mated to the CS and then the CS propellant tanks are loaded. Following the execution of launch configuration mass property measurements and a final limited electrical functional test of the flight vehicle, the MSL spacecraft enters the Atlas launch vehicle flow.
14	Multi-Mission Radioisotope Thermoelectric Generator (MMRTG)	This is a U.S. Department of Energy radioisotope power supply that will generate electricity from the heat of plutonium's radioactive decay. This type of power supply could give the mission an operating lifespan on Mars' surface of a full Martian year (687 Earth days) or more.

COST PROJECTION APPROACHES

Approach 1

Cost projection reflects historical increases to the scope of work, inefficiencies, and a performance trend factor. Our calculations are based on the cost estimates from the February 2009 rebaseline when the estimated cost to complete development was projected to be $400 million. We assumed that any changes from that estimate forward would be attributed to unexpected work (due to technical problems) and efficiencies in performance of the work. Note that the mission deliverables were not changed.

1. Amount of work: The amount of work required to meet the established deliverables for work performed by JPL increased by $75 million, from $325 million in February 2009 to $400 million in September 2010 – a 23.1 percent increase. We applied the same percentage increase to the initial budget of $400 million and concluded that the cost estimate should have been $492 million. [$400 million X 1.231 = $492 million]

2. Efficiency factor: Project management's performance measurement process calculated an 11 percent inefficiency rate for the Project through September 2010. We applied the same inefficiency factor to our adjusted cost from step 1 above. [$492 X 1.11 = $546 million]

3. Performance trend factor: Project management determined that performance is degrading at a rate of 6.4 percent since February 2009 (date of rebaseline). We applied this performance trend factor to our adjusted cost from step 2 above. [$546 million X 1.064 = $581 million]

Our estimate represents a rough order of magnitude considering Project management's history of underestimating the work requirement. Instead of estimating work requirement and reserve separately, we made a projection based on total work history. Our estimate is not based on a scientific assessment of the work.

Approach 2

$$\left(\frac{\begin{array}{c}\text{February 2009 BAC}\\ \text{(\$325 million)}\end{array} \;\text{X}\; \left(\frac{\begin{array}{c}\text{September 2010 BCWP}\\ \text{(\$262 million)}\end{array}}{\begin{array}{c}\text{September 2010 BAC}\\ \text{(\$401 million)}\end{array}} \right)}{\begin{array}{c}\text{September 2010 ACWP}\\ \text{(\$291 million)}\end{array}} \right)$$

- BAC (budgeted at completion) 2009 – the estimated cost to complete development at the start of the 2-year delay in February 2009.
- BAC 2010 – the adjusted estimated cost to complete development on September 2010, which included adjustments to the scope of work required to meet the established deliverables.
- BCWP (budgeted cost of work performed) 2010 – the expected cost, based on the February 2009 cost estimate, of the work actually performed through September 2010.
- ACWP (actual cost of work performed) 2010 – the actual cost of the work performed through September 2010.

The objective of the computation was to determine how much it will cost to complete the remaining work that was initially budgeted at $400 million. Our assumption was that the amount of work performed included part of the initially budgeted work, unanticipated additional work, and cost increase. Further, on the average, the rate of cost incurred was even for all three parts.

1. Determine the rate at which work is being completed. Calculated by using September 2010 (BCWP ÷ BAC) = .654.

2. Determine how much of the initially budgeted work was completed, assuming work was performed proportionally with the total work done. Calculated by multiplying rate of work completed (.654) by initial budget of $326 million = $213 million (meaning $213 million of the initial $326 million of budgeted work was completed).

3. Determine the actual cost efficiency of the work. Calculated by dividing the budgeted cost of the work completed by the actual cost of the work completed ($213 million ÷ $291 million) = .732 (meaning that for every dollar the Project has spent, 73.2 cents was spent on completing the planned work originally budgeted; the remaining 26.8 cents was attributed to price increases and to unanticipated work required to get the original work completed).

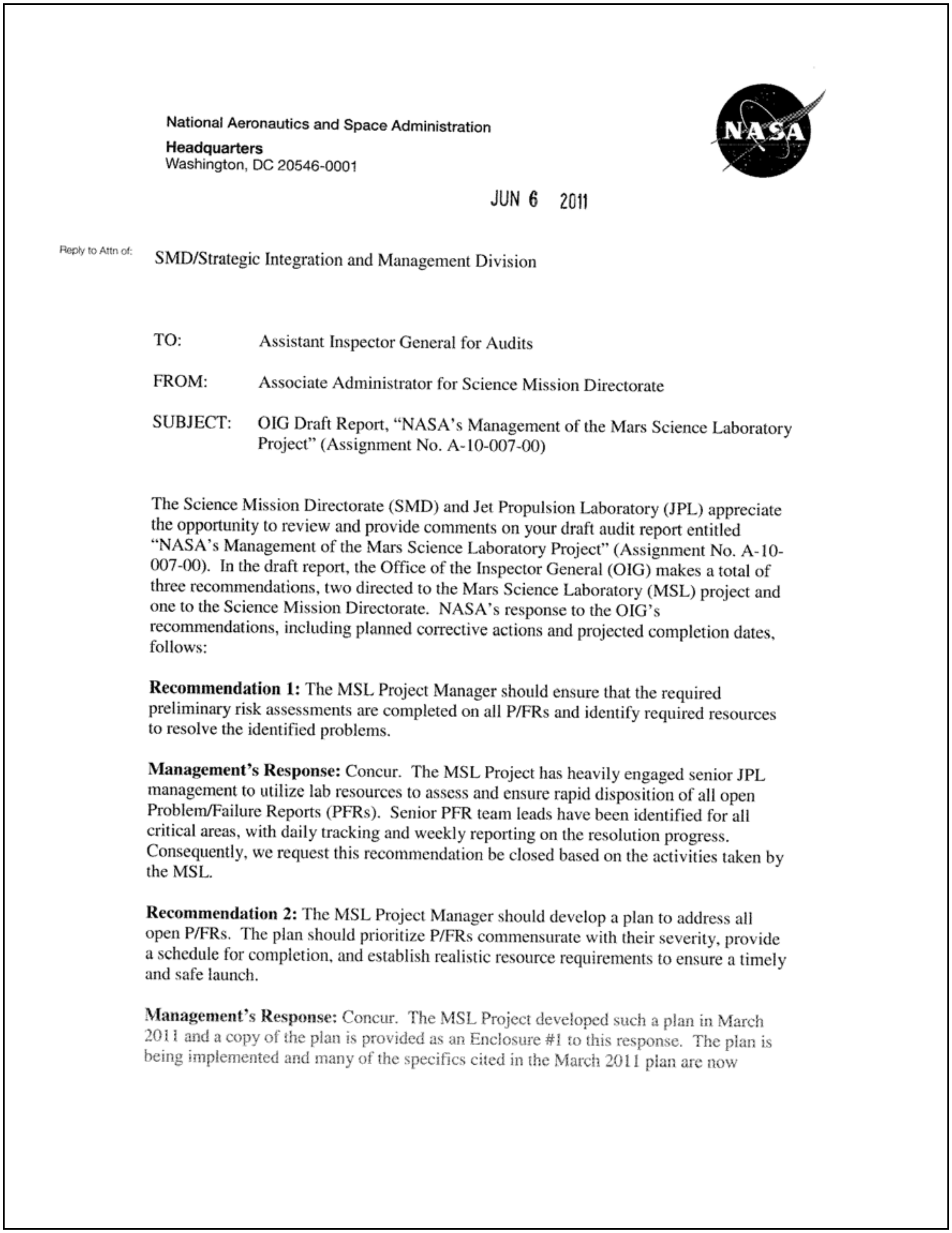
4. Determine the estimated cost to complete Project development by applying the actual efficiency:

$$\frac{73.2}{100} = \frac{\$400 \text{ million}}{\text{Projected cost to complete}}$$

   Or divide the initial cost to complete of $400 million by actual efficiency (.732) = $546 million.

5. Apply anticipated additional price increase of 6.4 percent:
   $546 million X 1.064 = $581 million.

MANAGEMENT COMMENTS



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

JUN 6 2011

Reply to Attn of: SMD/Strategic Integration and Management Division

TO: Assistant Inspector General for Audits

FROM: Associate Administrator for Science Mission Directorate

SUBJECT: OIG Draft Report, "NASA's Management of the Mars Science Laboratory Project" (Assignment No. A-10-007-00)

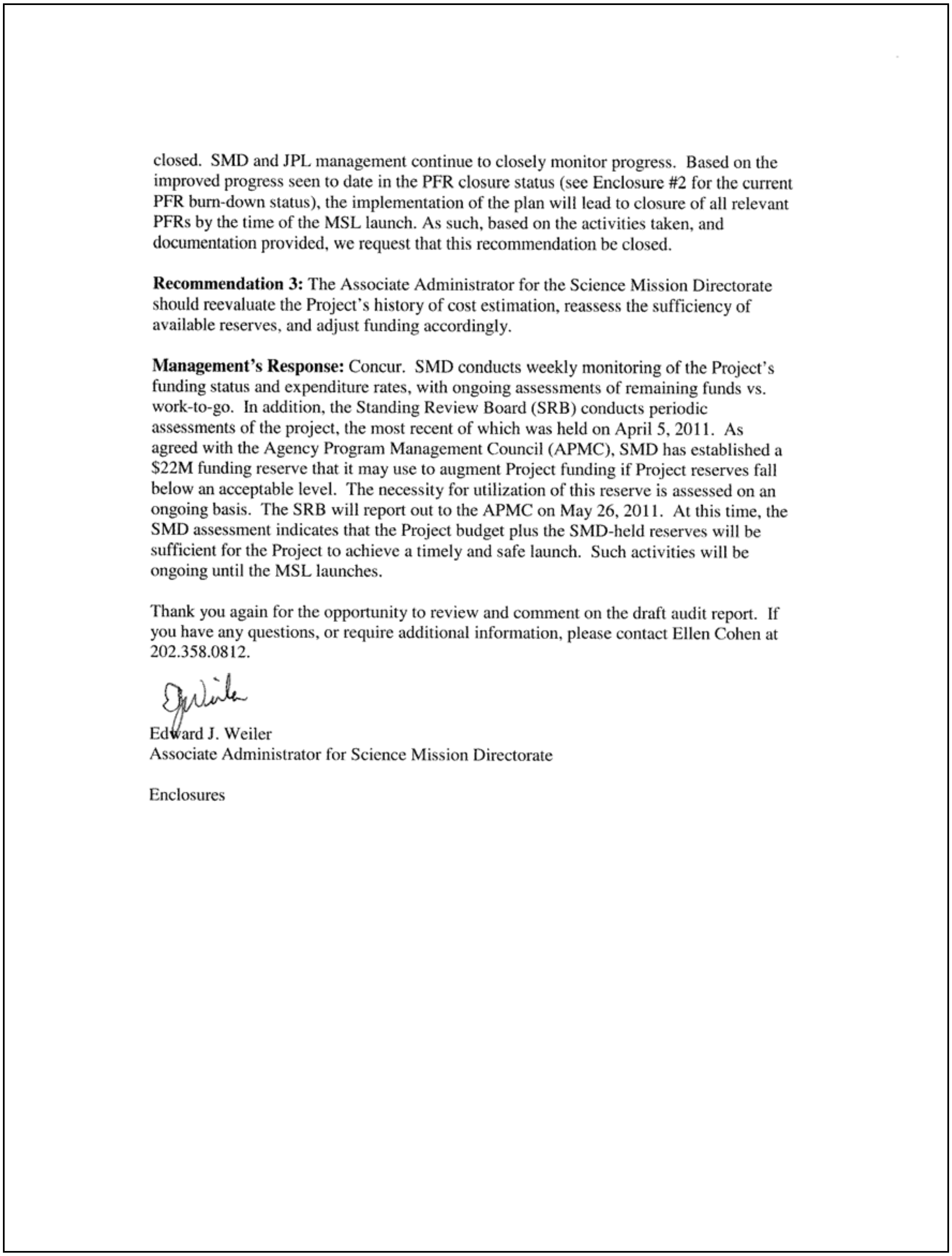
The Science Mission Directorate (SMD) and Jet Propulsion Laboratory (JPL) appreciate the opportunity to review and provide comments on your draft audit report entitled "NASA's Management of the Mars Science Laboratory Project" (Assignment No. A-10-007-00). In the draft report, the Office of the Inspector General (OIG) makes a total of three recommendations, two directed to the Mars Science Laboratory (MSL) project and one to the Science Mission Directorate. NASA's response to the OIG's recommendations, including planned corrective actions and projected completion dates, follows:

Recommendation 1: The MSL Project Manager should ensure that the required preliminary risk assessments are completed on all P/FRs and identify required resources to resolve the identified problems.

Management's Response: Concur. The MSL Project has heavily engaged senior JPL management to utilize lab resources to assess and ensure rapid disposition of all open Problem/Failure Reports (PFRs). Senior PFR team leads have been identified for all critical areas, with daily tracking and weekly reporting on the resolution progress. Consequently, we request this recommendation be closed based on the activities taken by the MSL.

Recommendation 2: The MSL Project Manager should develop a plan to address all open P/FRs. The plan should prioritize P/FRs commensurate with their severity, provide a schedule for completion, and establish realistic resource requirements to ensure a timely and safe launch.

Management's Response: Concur. The MSL Project developed such a plan in March 2011 and a copy of the plan is provided as an Enclosure #1 to this response. The plan is being implemented and many of the specifics cited in the March 2011 plan are now



closed. SMD and JPL management continue to closely monitor progress. Based on the improved progress seen to date in the PFR closure status (see Enclosure #2 for the current PFR burn-down status), the implementation of the plan will lead to closure of all relevant PFRs by the time of the MSL launch. As such, based on the activities taken, and documentation provided, we request that this recommendation be closed.

Recommendation 3: The Associate Administrator for the Science Mission Directorate should reevaluate the Project's history of cost estimation, reassess the sufficiency of available reserves, and adjust funding accordingly.

Management's Response: Concur. SMD conducts weekly monitoring of the Project's funding status and expenditure rates, with ongoing assessments of remaining funds vs. work-to-go. In addition, the Standing Review Board (SRB) conducts periodic assessments of the project, the most recent of which was held on April 5, 2011. As agreed with the Agency Program Management Council (APMC), SMD has established a $22M funding reserve that it may use to augment Project funding if Project reserves fall below an acceptable level. The necessity for utilization of this reserve is assessed on an ongoing basis. The SRB will report out to the APMC on May 26, 2011. At this time, the SMD assessment indicates that the Project budget plus the SMD-held reserves will be sufficient for the Project to achieve a timely and safe launch. Such activities will be ongoing until the MSL launches.

Thank you again for the opportunity to review and comment on the draft audit report. If you have any questions, or require additional information, please contact Ellen Cohen at 202.358.0812.

Edward J. Weiler
Associate Administrator for Science Mission Directorate

Enclosures

Enclosures omitted.

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JUNE 8, 2011

REPORT NO. IG-11-019

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In order to help us improve the quality of our products, if you wish to comment on the quality or usefulness of this report, please send your comments to Mr. Laurence Hawkins, Audit Operations and Quality Assurance Director, at Laurence.B.Hawkins@nasa.gov or call 202-358-1543.

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