October 2012

AEROSPACE AMERICA

Curiosity on the move

Declassifying the space race: Part 2

High stakes for human-rating spacecraft

A PUBLICATION OF THE AMERICAN INSTITUTE OF AERONAUTICS AND ASTRONAUTICS

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Curiosity on the red planet

It was nothing short of an engineering tour de force: NASA's Mars Science Laboratory (MSL) and its 1-ton Curiosity rover successfully touched down on the red planet's Gale Crater on August 5, after a 36-week sojourn from Earth.

The on-target, wheels-down landing of the nuclear-powered Curiosity meant that the largest rover ever sent to another planet had settled into place and was on task to start a multiyear science study of enigmatic Mars. But getting the $2.5-billion mission up and running, as well as down and dirty on the Martian surface, was preceded by a terrorizing, seven-minute, death-defying dive through the planet's atmosphere.

What made the touchdown traumatic was the need for several cutting-edge technologies to work perfectly. All were part of an intense entry, descent, and landing (EDL) phase relying on a sequence of 76 pyrotechnic blasts, a guided entry, supersonic parachute deployment, and the use of a descent-stage 'rocket backpack' teamed with a Doppler radar system built especially for the mission. Called the Sky Crane, this hovering platform—which had never been field tested—was used to enable a 'soft-landing' on the Martian surface.

Engineers at JPL celebrate the landing of Curiosity. The rover touched down on Mars the evening of August 5. Image credit: NASA/JPL-Caltech.

Curiosity's assignment is clear cut: To survey its surroundings and investigate whether or not environmental conditions on Mars have favored development of microbial life on that faraway world.

Following the landing, President Barack Obama saluted the achievement: "The successful landing of Curiosity—the most sophisticated roving laboratory ever to land on another planet—marks an unprecedented feat of technology that will stand as a point of national pride far into the future. It proves that even the longest of odds are no match for our unique blend of ingenuity and determination."

"If anybody has been harboring doubts about the status of U.S. leadership in space," said John Holdren, the president's science adviser, at a postlanding JPL news conference, "well, there's a 1-ton automobile-size piece of American ingenuity…and it's sitting on the surface of Mars right now."

The euphoria of the moment brought flag-waving and tears of triumph for hundreds of scientists and engineers gathered at JPL, where Curiosity was designed, developed, and assembled. It is also the rover's mission control site. Buoyed by the feat, more than one voice was heard to declare: "Mars is ours!"

Heartbeat tones

"It was a great day on Mars," says JPL's Alan Chen, operations lead for EDL. "We had an incredibly clean ride…we traveled over 350 million miles on the way to Mars, and we missed our entry target by only about a mile."

by Leonard David
Contributing writer

Mars is ours!

Triumphant shouts erupted at mission control on August 5 as images began arriving from the Martian surface—confirmation that NASA's Mars Science Laboratory and its Curiosity rover had touched down on the planet safely. A landing tour de force and an automobile sized rover with a suite of advanced instruments are ushering in a new era in planetary exploration, experts say.

A network of orbiters—NASA's Odyssey and Mars Reconnaissance Orbiter, and ESA's Mars Express—plus several ground stations back on Earth, supported the MSL landing. Heartbeat and informational tones from MSL during EDL enabled an early reconstruction of how things transpired.

Entering Mars' atmosphere at about Mach 24, then slowing down to just under Mach 2, MSL/Curiosity pulled a little over 11 Earth *g*s, says Gavin Mendeck, an EDL team member from NASA Johnson. "If you were a human riding onboard it would be a little bit of a rough ride. Fortunately, Curiosity is made of some pretty sturdy stuff, and she handled that just fine," he says.

The spacecraft executed three bank reversals in the Martian atmosphere to target itself to the desired landing spot, although a tail wind may, in part, have contributed to a downrange misdistance of 1.5 miles, says Mendeck.

Parachute deployment decelerated MSL from roughly Mach 1.7 to subsonic speeds, gauged to be Mach 0.7, notes JPL's Devin Kipp, a member of the EDL team focused on the parachute descent. "Not a lot of exciting things happened, because everything was right down the pipe of what we expected—but that's how we want it," he says.

Powered descent and maneuvers made by Sky Crane to spot-land Curiosity onto Mars went according to script, says JPL's Steve Sell, who was in charge of powered flight within the EDL group. "From data received so far, we flew this right down the middle. It's absolutely incredible to have worked on a plan for so many years and then just see everything happen exactly according to plan," says Sell. One by one, the shedding of all the contingency plans as the data came in "was like weights being lifted off our shoulders."

Parking lot landing

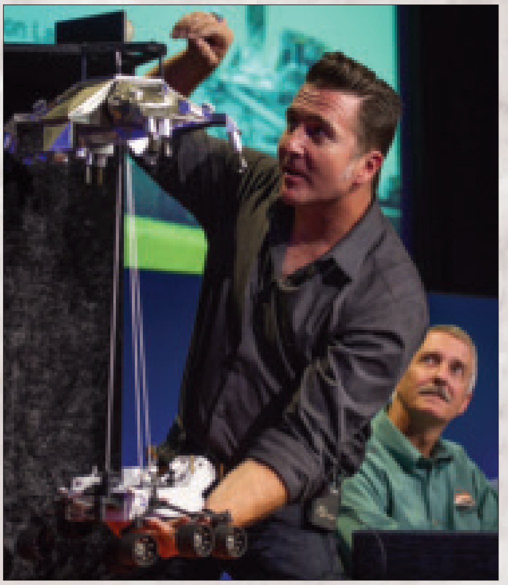
Using eight throttleable engines, the Sky Crane gently lowered Curiosity to a final stop. The crane's bridle system, made of nylon cords, spooled out the rover to the ground. The rover's wheels and suspension system served as the landing gear. When Curiosity sensed touchdown, the connecting cords between rover and Sky Crane were cut. Still carrying a large reservoir of fuel, more than projected, the descent stage performed a flyaway maneuver, crashing at 100 mph some 600 m away from Curiosity's landing spot, Sell says.

A best estimate of the rover's speed at touchdown puts it at 0.75 m/sec (1.7 mph) vertical and 0.04 m/sec (0.09 mph) horizontal, as reported by the flight software. In other words, Curiosity's wheels first met Mars at a slow walking speed.

The rover's safe and sound touchdown benefited from scientists' having chosen a place with a nice flat landing pad right next to it, Sell concludes. "The science store they wanted to go to had a parking lot."

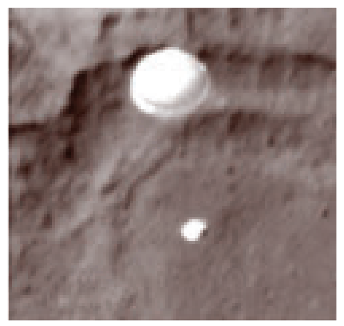
In a masterpiece of sharpshooting camera work, NASA's

This is a portion of the first color 360° panorama from Curiosity. The mission's destination, a mountain at the center of Gale Crater called Mount Sharp, can be seen in the distance, to the left, beginning to rise up. Blast marks from the rover's descent stage are in the foreground. Credit: NASA/JPL-Caltech/MSSS.



Adam Steltzner, JPL's Mars Science Laboratory EDL phase lead, demonstrates how the spacecraft lands the rover during a pretouchdown briefing. Credit: NASA/ Bill Ingalls.

Mars Reconnaissance Orbiter (MRO) spotted Curiosity descending under its parachute. MRO's High-Resolution Imaging Science Experiment (HiRISE) camera captured the image while the orbiter was listening to transmissions from Curiosity. The feat was a repeat performance for MRO, which in 2008 had captured a much similar view of NASA's Phoenix lander enroute to its Mars touchdown.



Curiosity underneath its parachute was photographed by the MRO's HiRISE camera. Image credit: NASA/JPL/University of Arizona.

"The MSL parachute image turned out just as I had hoped," says Alfred McEwen, University of Arizona in Tucson, HiRISE principal investigator. "The brightness levels of both the parachute and Mars surface were also very close to our predictions, and we had no saturation," he says.

The image shows the supersonic parachute fully inflated and performing perfectly. Details such as the band gap at the chute's edges, and the central hole, are also clearly visible.

McEwen tells *Aerospace America* that the odds of capturing the shot were a little lower for MSL's skydive than for Phoenix—a 60% rather than 80% chance, according to the known errors—although the chances of a mistake were lower because he and his team had done this kind of camera work before.

"I also wasn't surprised at the detail," he says, "because I had ground-test images of the parachute that I reduced to the expected HiRISE scale, and the real thing looked very similar. I had hoped we would be extremely lucky and capture it in our narrow color swath. But that didn't happen, because MSL landed east of the center of their predict by more than 600 m…the half-width of our color swath."

That MRO picture, likely taken 40-50 sec after parachute deployment, speaks volumes, notes JPL's Kipp. "It tells a whole lot about how the parachute performed. It's got its inflated shape perfectly. You can see the dark area at the top of the parachute, which is the vent that lets some air escape through the top. The shape is exactly what we expected to see. You don't see any apparent damage…we see a perfectly functioning parachute that looks exactly like we thought," he says. "That's good news."

Jitters at JPL

Before MSL began its nose-dive into the Martian atmosphere, the EDL jitters at JPL were palpable.

"We definitely did all we could, says Richard Kornfeld, deputy EDL phase lead for validation, during a prelanding interview. "We took all the problems and decomposed them. Obviously, this is a more complex mission than in the past."

Curiosity was the fourth Mars lander mission for Kornfeld, a veteran of the Spirit and Opportunity touchdowns as well as Phoenix and now MSL. "What impressed me more about this one is its complexity…and with that comes a complex test program, along with the complexity of the team to understand all the aspects of everything," he says.

"We pushed the envelope, and the team has set new standards. That builds confidence, but no guarantee for the future. We continue to perfect the tools. The flight test data you get from previous missions, well, they are worth gold," Kornfeld says.

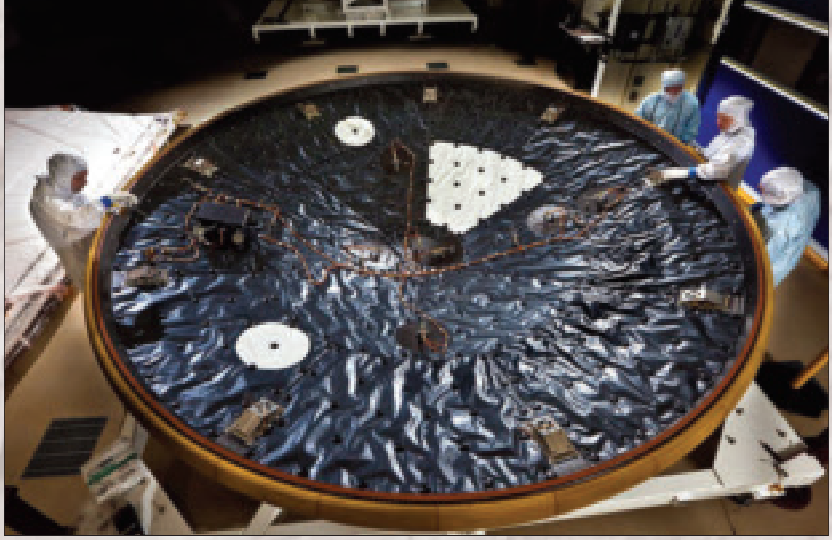
Personally for Kornfeld, the entire EDL sequence did equate to seven minutes of nail-biting terror. More specifically, he felt great anxiety about the powered descent of the Sky Crane, because of "its novelty and its first-time use," he says.

Sky Crane evolved over many years, says Rob Manning, MSL's chief engineer at JPL. But bringing the 'rover on a rope' idea to fulfillment did not come easy.

"I've always been a fan of the whole closed-loop control architecture. Early on there were a few of us who realized that we could control the horizontal velocity as well as the vertical velocity with this simple two-body control system," Manning tells *Aerospace America.* "Architecturally, it all made so much sense to some of us, because there's a natural evolution from Viking, Mars Pathfinder, Mars Exploration Rovers, and to some extent Phoenix. They are not different architectures; they are all interconnected. So it was a natural synergy in the ideas and the equations of motion. The physics, the things that we're trying to protect ourselves from, they all converged to make this architecture come true."

Sky Crane meant "putting your propulsion system on your roof, and just flipping it around so the payload is below," Manning says. "I think it was one of the most innovative parts of MSL. It certainly is the most revolutionary architectural transformation."

Concerning Curiosity itself, Manning says one of the challenges is that the rover flew the entire MSL configuration on its own. "So what is Curiosity's specialty? Is it a pilot? Is it a hypersonic entry vehicle? Is it an interplanetary navigator spacecraft? Is it an all-terrain vehicle…what the heck is it? That transformation…that overloading of functionality has been the bane of my life," he admits. "A lot of that has made me very nervous over the years, to get all these functions to work on the same computers, the same input/output, and especially to get the resources to test it all."



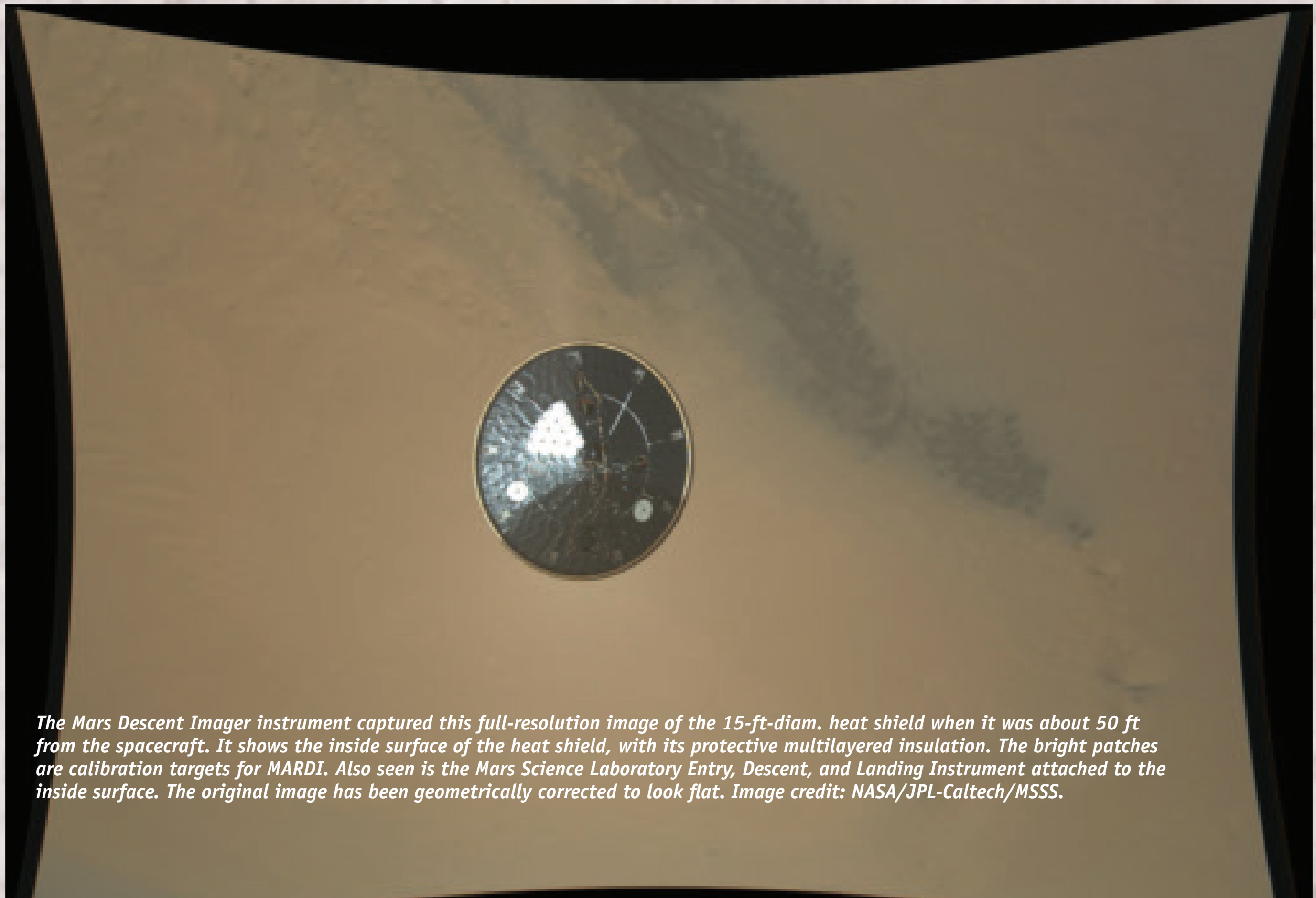
The heat shield for MSL was the largest ever built for a planetary mission. Credit: NASA/JPL-Caltech/Lockheed Martin.

Miracle of engineering

With each Curiosity image received, the call to get moving is perceptible. Despite the rover's first-rate health, a lengthy, step-by-step commissioning of the mobile robot has taken priority. "Be patient with us, please," says MSL project manager Pete Theisinger, "because we will be patient with Curiosity."

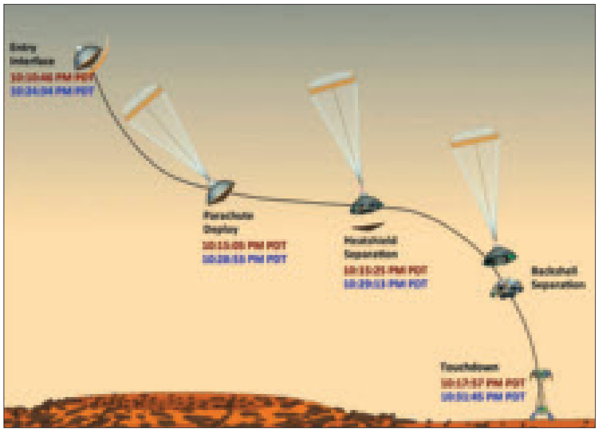
Caltech's John Grotzinger, MSL chief scientist, is leading some 400 researchers on the mission that now must interact with Mars, and 300 or more engineers who will operate Curiosity over the years ahead.

Shortly after the landing, Grotzinger first pointed to an area excavated by the blast of MSL's descent-stage rockets. With the loose debris blown away by the rockets, details of



The Mars Descent Imager instrument captured this full-resolution image of the 15-ft-diam. heat shield when it was about 50 ft from the spacecraft. It shows the inside surface of the heat shield, with its protective multilayered insulation. The bright patches are calibration targets for MARDI. Also seen is the Mars Science Laboratory Entry, Descent, and Landing Instrument attached to the inside surface. The original image has been geometrically corrected to look flat. Image credit: NASA/JPL-Caltech/MSSS.

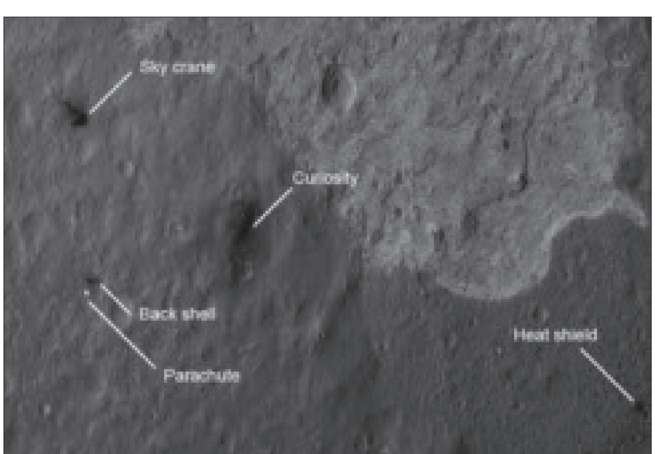
This graphic shows the times at which NASA's Curiosity rover hit its milestones during its entry, descent, and landing on Mars. The times at which the events actually occurred are in red; the times at which Earth received confirmation that they occurred are in blue. All times are listed in Pacific Daylight Time. Credit: NASA/JPL-Caltech.



the underlying material can be seen. Of particular note is a well-defined topmost layer that contains fragments of rock embedded in a matrix of finer material.

Catching Grotzinger's eye in the larger panorama of landscape relayed from Curiosity is how Earthlike the scene appears. "You would really be forgiven for thinking that NASA was trying to pull a fast one on you…and [that] we actually put a rover out in the Mojave Desert and took a picture.

"I think for us at this point as scientists we haven't even scratched the surface," he says. "It is a miracle to us. We have chosen this place as a result of scientific deliberation. This EDL system for the first time in the history of landed missions allowed the science community to choose between four [landing site] options."



The four main pieces of hardware that arrived on Mars with Curiosity were spotted by MRO's HiRISE camera, which captured this overhead image about 24 hr after the landing. The heat shield was the first piece to hit the ground, followed by the back shell attached to the parachute, then the rover itself, and finally, after cables were cut, the Sky Crane flew away to the northwest and crashed. Relatively dark areas in all four spots are from disturbances of the bright dust on Mars, revealing the darker material beneath. Curiosity is approximately 4,900 ft away from the heat shield, about 2,020 ft away from the parachute and back shell, and roughly 2,100 ft away from the discoloration consistent with the impact of the Sky Crane. Credit: NASA/JPL-Caltech/University of Arizona.

Grotzinger reflected on the first images of Curiosity's wheels firmly on the ground. "You know you've landed on Mars. No semaphore tones, no people jumping up and down; you actually see a picture of the surface of the planet with a spacecraft on it. And that is a miracle of engineering."

During its fifth day on Mars, Curiosity underwent a planned 'brain transplant'—that is, transitioning to a new version of flight software on both of the rover's redundant main computers. "We're wiping away all of the cruise and entry, descent, and landing software and making room for the software needed to perform the exciting portions of the surface mission ahead," reported Jessica Samuels of the MSL engineering operations team. The new software, she said, is better suited for Mars surface operations such as driving, or using Curiosity's robotic arm and drill. It also includes advanced image processing to check for obstacles as the rover motors about on Mars.

Mobile analytical laboratory

"In my view, the historic landing of the MSL mission's Curiosity rover was beyond transformational," says James Garvin, chief scientist at NASA Goddard. A member of the MSL science team, Garvin has a long association with the project, as the first MSL program scientist, as one of the mission's founding fathers starting in January 2001, and as a participant in MSL's payload definition and selection.

"This remarkable and unprecedented feat of spaceflight engineering was significant in that it culminated the implementation stage of a science-guided Mars Exploration Program that was forged from the ashes of NASA's failed Mars '98 missions and put into place in fall of 2000," Garvin tells *Aerospace America.*

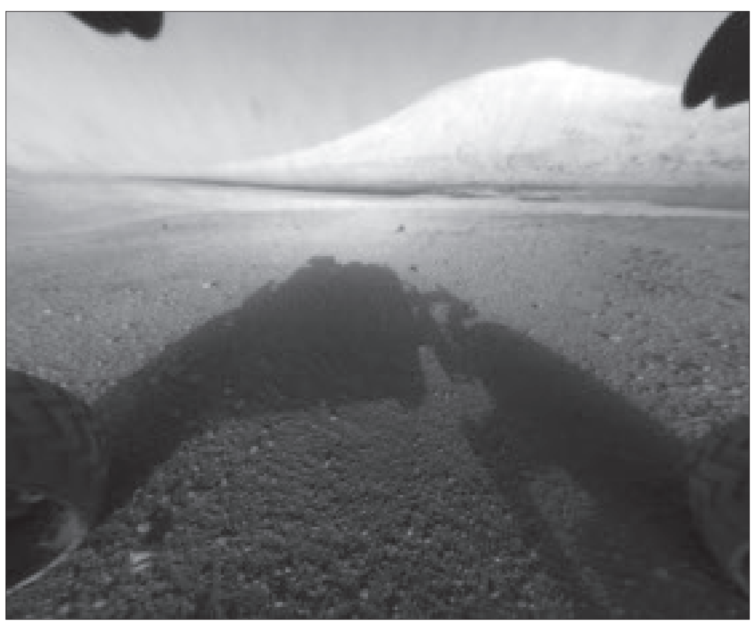
By serving as a "surface observatory," MSL has ushered in a new era, Garvin declares. "Having a mobile analytical laboratory, with field science instruments that far exceed what traditional field geologists here on Earth would carry, is truly transformational," he says. For example, Curiosity's CheMin (chemistry and mineralogy) and SAM (sample analysis at Mars) instruments provide capabilities that typically require Earth laboratories far away from field exploration, "and yet on Mars we have them 'on our back' ready to go," he notes.

Furthermore, Curiosity carries specialized 'eyes' and compositional sensors that are better than the hand-lens and rock ham-

A chapter of the layered geological history of Mars is laid bare in this postcard from Curiosity, where we see the layers at the base of Mount Sharp, the rover's eventual science destination. Image credit: NASA/ JPL-Caltech/MSSS.

mers used on Earth by geologists. Engineers at JPL worked with rover instrument developers across the U.S., Canada, Russia, France, Germany, Spain, and Finland.

"We are finally beyond the era of the classic robotic field scientist, and now, on the surface of another world, we have a capability better than what we routinely use to explore the Earth! All of this in less than a decade of Mars program evolution and execution," Garvin exclaims.



This image, taken by Curiosity, shows what lies ahead for the rover—its main science target, informally called Mt. Sharp. The rover's shadow can be seen in the foreground, and the dark bands beyond are dunes. Rising up in the distance, Mt. Sharp, the highest peak, at a height of about 3.4 mi., is taller than Mt. Whitney in California. The Curiosity team hopes to drive the rover to the mountain to investigate its lower layers, which scientists believe hold clues to past environmental change. Image credit: NASA/JPL-Caltech.

MSL has opened another new era, he adds: that of accessing locations where the 'science pull' is remarkably rich. Curiosity is factory loaded with gear to study the history of past environments on Mars, and of the preservation potential (or lack of potential) for chemical or compositional indicators of ancient habitats.

"We have *never* been able to access any places as exciting as the Gale Crater region," says Garvin. It is an amazing location, rich in known scientific targets worthy of intensive exploration, he believes. He says this is the first time since the 1972 Apollo 17 Moon landing that "we know we are in one of the best places in the solar system to conduct pathfinding new science!"

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In many ways, the Mars Science Laboratory can be viewed as a down payment on the day when humans set foot on Mars.

Says Garvin, "MSL could be the stepping stone to give us confidence that people can get to Mars, and to showcase for everyone that the U.S. space program is up to the task. I can only imagine the day when women and men land on Mars equipped with MSL-like robotic 'assistants' to explore other compelling sites on the red planet. Like the first ships arriving on the shores of North America, Curiosity's landing on Mars will catalyze human exploration of a new world."