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The Dragon roars

Mars Science Laboratory: Going for a touchdown
A conversation with Norman R. Augustine

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Mars Science Laboratory

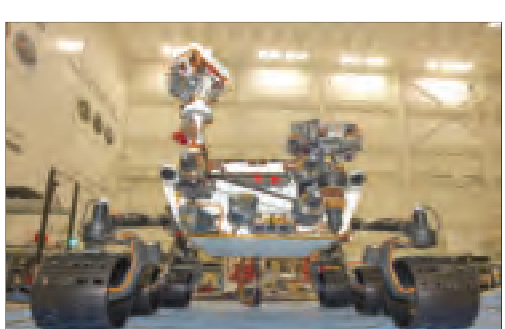
Going for a touchdown

NASA's Mars Science Laboratory, launched last November, carries Curiosity, a large Mars rover with equipment more advanced than any that has reached the planet before. The program has faced major challenges, but by far the greatest will be the scorching entry, descent, and landing, scheduled for early August. Whether it succeeds or fails, the mission will have far-reaching ramifications for the U.S. planetary exploration program.

Mars is soon to receive a visitor from afar—space machinery sent from Earth to probe the planet with instruments far more capable than any previously launched to the forbidding Martian landscape.

Sent aloft on November 26, 2011, the Mars Science Laboratory (MSL) totes a car-sized rover called Curiosity, slated to land in early August at Gale Crater on the planet's south equator. The nuclear powered megarover is fully equipped to assess whether Mars ever was—or might be—an ecofriendly environment capable of supporting microbial life, and to determine the planet's habitability.

Curiosity underwent mobility testing inside the Spacecraft Assembly Facility at Jet Propulsion Laboratory.



The process of getting the MSL program off the ground was a saga in itself. Cash infusions were needed during both the mission's difficult birth and years of development and testing. Technical snags delayed its sendoff in 2009. Meanwhile, its cost skyrocketed to some $2.5 billion, including $1.8 billion for spacecraft development and science investigations, plus additional dollars for launch and operations.

MSL morphed into a 'flagship' mission at a time of tightening NASA budgets and a

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Curiosity touches down on the Martian surface. The MSL mission's EDL phase will begin when the spacecraft reaches the Martian atmosphere, about 81 mi. above the surface of the Gale Crater landing area, and ends with the rover safe on the surface of Mars. Credit: NASA/JPL-Caltech.

restructuring of the agency's entire Mars exploration enterprise.

Scientifically, the mission continues the thematic sequence of 'follow the water' and 'follow the minerals' on Mars. Now, however, it has become part of an unfolding bureaucratic tale of 'follow the money' and 'follow the confusion' as NASA determines how best to proceed with post-MSL exploration of the planet.

The high-profile adventure could end in a smashing success...or a smash-up on the Martian surface. Either way, it may set in motion a new chapter in exploration of that enigmatic world.

Down and sound

Curiosity's wheels-down meeting with Mars is set for the night of August 5 PDT, when its two-year primary mission of scrutinizing the planet will begin. The mobile laboratory will head for Gale Crater to probe that area's present and past environments, conducting 10 science investigations. Its robotic arm will drill into rocks, scoop up soil, and ingest samples into internal analytical instruments.

Getting down and sound on Mars will entail using active guidance for improved accuracy. Then, in the first Martian 'soft landing,' a Sky Crane will reel out Curiosity for touchdown. MSL's great mass prevented engineers from using airbags for delivery.

Using steerable engines, MSL's descent stage will slow the nested rover down, to eliminate the effects of any horizontal winds. When it has been slowed to nearly zero velocity over the Martian landscape, the rover will be released from the descent stage. A Sky Crane bridle system made of

by Leonard David
Contributing writer

This Mars Descent Imager (MARDI) downward-looking camera will take about four frames per second at nearly 1,600 by 1,200 pixels per frame for about the final two minutes before Curiosity touches down on Mars. Malin Space Science Systems supplied MARDI and two other camera instruments for the mission.

nylon cords will spool out the rover to the ground. Curiosity's wheels and suspension system, which double as the landing gear, pop into place just before touchdown. The metric-ton rover is to be set down at a velocity of roughly 1.7 mph.

When the spacecraft senses touchdown, the connecting cords between rover and Sky Crane will be severed, with the descent stage rocketing out of the way and crashing some distance away.

Unknown unknowns

Following a very complete development cycle, MSL went through an extremely inclusive test program as well. The EDL (entry, descent, and landing) was more in-depth and broader in scope than previous Mars missions, says MSL's project manager, Peter Theisinger, at NASA JPL. "We're pretty confident with respect to EDL," he says.

"I think landing on Mars is, of course, in a class by itself," he adds. "MSL is clearly much more complex [than earlier vehicles] and can carry out much more ambitious science. We're confident in what we have done. The thing that will catch us, of course, will be the unknown unknowns… or if we have a one-off problem."

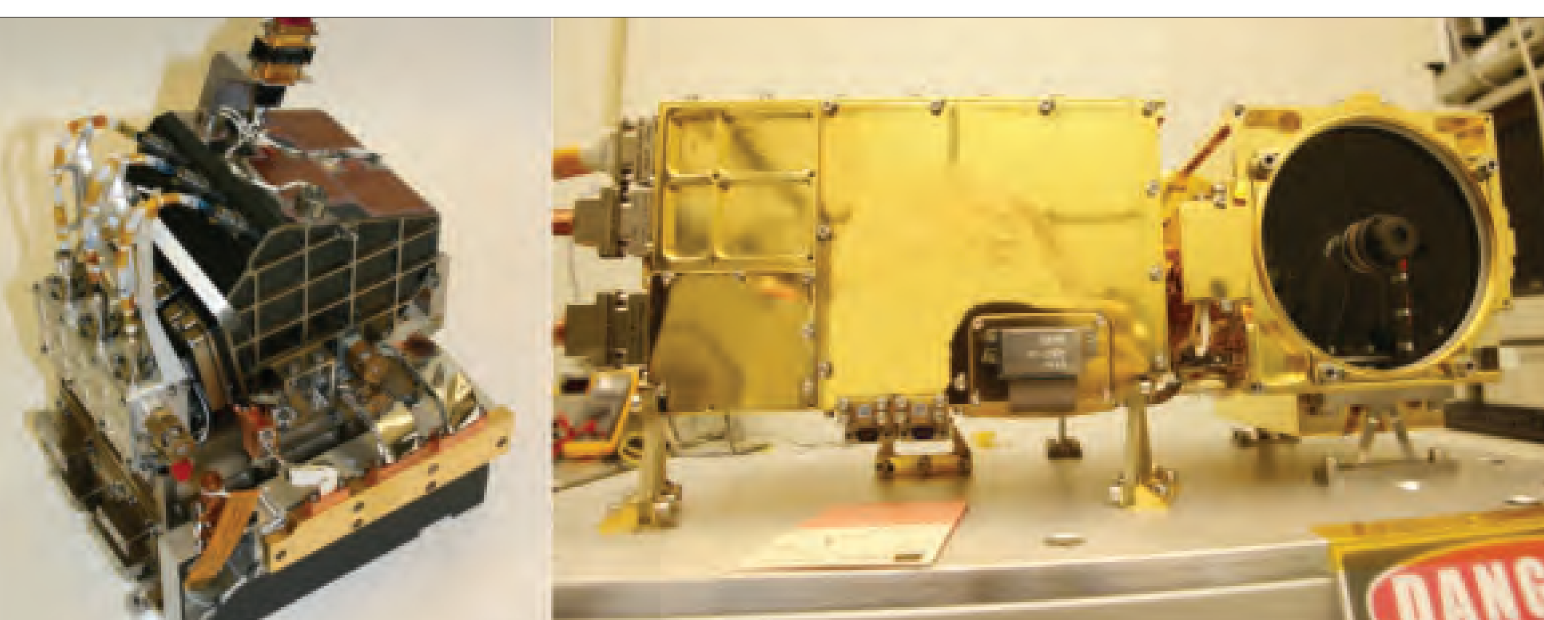
EDL testing on Earth, Theisinger admits, can go only so far. The ultimate EDL will be at Mars itself and will take place there in its entirety for the first time.

"You cannot test as you fly the EDL environment at Mars. We did separation tests and drop tests, too, and we flew MSL's radar on helicopters and F-18s. We tried to simulate cable cutter events," Theisinger notes. But the new environment of Mars is "much more dynamic in reality" than what can be approximated on the ground, he says. "So flying through for the first time will be the proof of the pudding for sure."

MSL's Doppler radar system was fabricated specifically for the mission. Mounted on the descent stage, the radar has six disk-shaped antennas oriented at different angles. It measures vertical and horizontal velocity as well as altitude. Compared with the altitude range radars flown to Mars in the past, "it's a completely different beast," says Theisinger.

Curiosity is powered by a multimission radioisotope thermoelectric generator (MMRTG) supplied by the Dept. of Energy. The MMRTG uses a heat source that contains plutonium-238 dioxide—a non-weapons-grade form of the radioisotope—and a set of solid-state thermocouples that convert the plutonium's heat energy to electricity.

The MMRTG is loaded with 10.6 lb of plutonium dioxide, the source of the steady supply of heat used to produce onboard electricity and warm the rover's systems during the frigid Martian nights. Heat emitted by the MMRTG will circulate throughout the rover system to keep instruments, computers, mechanical devices, and communications systems within their operating temperature ranges.



The two main parts of the ChemCam laser instrument are the body unit, left, which goes inside the body of the rover, and the mast unit, which goes onto the rover's remote-sensing mast. The mast unit, 14.5 in. long, contains ChemCam's laser, imager, and telescope.

"It's an RTG/battery system," explains Theisinger. "We charge up the battery and use it for peak loads during the daylight hours, and then we go to sleep. But we're fully capable when we land, and we will rely on that capability."

The electrical output from the MMRTG charges two lithium ion rechargeable batteries. This enables the power subsystem to meet peak power demands of rover activities when the demand temporarily exceeds the generator's steady output level. The batteries, each with a roughly 42-amp-hr capacity, are expected to go through multiple charge-discharge cycles per Martian day.

At top speed, Curiosity can move across flat, hard ground at about 1.5 in./sec. However, under autonomous control with hazard avoidance, the vehicle achieves less than half that speed on average. The rover was designed and built to be capable of driving more than 12 mi. during the prime mission.

Cross-coupled complexities

"The mass and the size of MSL created cross-coupled complexities," says Matt Wallace, MSL's flight system manager at JPL. "As a result, you get to a point in all of these projects where you kind of scratch your head and ask: Are we really going to get there? But there is a feeling around here that…if it doesn't look impossible, we don't want to do it. And sometimes it's hard to know. You just have to plow forward and see where you go."

Wallace says that moving from the Mars Exploration Rovers (successfully landed in 2004) to MSL was "unquestionably more difficult than we thought."

Indeed, in early December 2008, NASA announced a slip of MSL's launch from 2009 to 2011. A host of technical issues involving devices such as mechanisms and actuators were plaguing the project, so the agency delayed the mission until the next Mars window of opportunity, to avoid a mad dash to launch.

Curiosity's drive actuators—each combining an electric motor and gearbox—are geared for torque, not speed. The Mars-cold-tolerant actuators were built for the wheels and other moving parts of Curiosity.

The two-year slip evoked a mixed response from the MSL team, Wallace recollects. "The initial response for most of the team members was disappointment. We're used to taking on aggressive tasks, getting them done, and hitting the targets. But there's also a very strong thread of quality in the product…so an element of relief that [the delay] allowed diving in deeper, penetrating the issues that were bothersome. So it was a balancing act, a mixture of feelings for sure."

End-to-end simulation

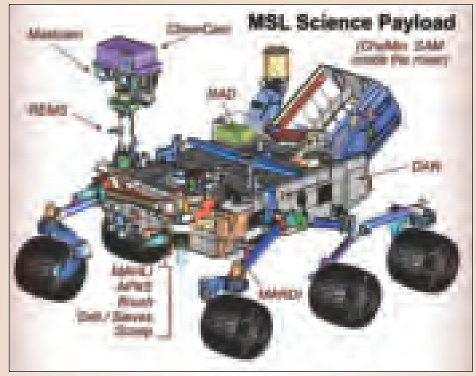
In terms of EDL, how different is MSL from past spacecraft?

"Size matters. That's the biggest thing," is the response from JPL's Al Chen, flight dynamics and operations lead for the program's EDL team. "This wasn't reinventing for the sake of reinventing. We're trying to do something fundamentally different."

"There's the 'test as you fly, fly as you test' philosophy," Chen says. "We tried to follow that with 'simulate as you fly and fly as you simulate.' Everything is heavily test based," he adds. "The key is to stitch it together with an end-to-end simulation that you believe in."

Chen says his team has confidence in the performance of the system. "Part of our job is to minimize the maximum risk. We've gotten everything down to acceptable levels." But there is, of course, risk involved in flying to Mars. "I'm going to feel a lot better when we see that parachute deploy…it's got to work, and I have a hard time analyz-

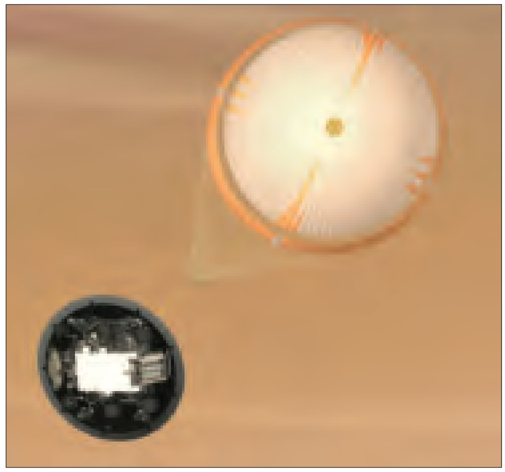
ROVER BASICS



Science instruments and other tools are placed at various locations on the car-size Mars rover, Curiosity. They are (clockwise, from upper left):

- *Mastcam, the mast camera instrument.*
- *ChemCam, the chemistry and camera instrument.*
- *RAD, the radiation assessment detector.*
- *CheMin, the chemistry and mineralogy instrument.*
- *SAM, the sample analysis at Mars instrument.*
- *DAN, the dynamic albedo of neutrons instrument.*
- *MARDI, the Mars descent imager.*
- *MAHLI, the Mars hand lens imager.*
- *APXS, the alpha particle X-ray spectrometer.*
- *The brush, drill, sieves, and scoop are tools on the rover's robotic arm.*
- *REMS, the rover environmental monitoring station.*

Curiosity will land in August near the foot of a mountain inside Gale Crater. Credit: NASA/JPL-Caltech/ESA/DLR/FU Berlin/MSSS.



An artist's concept depicts Curiosity's parachute, the largest ever built to fly on a planetary mission. Credit: NASA/JPL-Caltech.

ing it. Parachutes by their nature are an empirical thing…hard to prove they'll work from a pen and paper standpoint."

MSL's 165-ft-long parachute, the largest ever built for a planetary mission, uses a configuration called disk-gap-band. It has 80 suspension lines and opens to a diameter of nearly 51 ft. The parachute is designed to survive deployment at Mach 2.2 in the Martian atmosphere, where it will generate up to 65,000 lb of drag force.

Beating the heat

As Curiosity makes its fiery entry into the Martian atmosphere, it will be cocooned within the largest 'beat the heat' system ever hurled to Mars—an aeroshell comprising a protective heat shield and back shell. The heat shield includes an MSL EDL instrument, or MEDLI, a set of sensors that will record atmospheric conditions and judge how well the shield thwarts the searing temperatures that greet it.

This intense period begins when the spacecraft reaches the Martian atmosphere,

The heat shield for NASA's Mars Science Laboratory is the largest ever built for a planetary mission. Credit: NASA/JPL-Caltech/ Lockheed Martin.

traveling at about 13,200 mph, and ends about 7 min later with Curiosity stationary on the surface.

More than nine-tenths of the deceleration before landing results from friction with the planet's atmosphere prior to the parachute's opening. Peak heating occurs about 80 sec after atmospheric entry, when the temperature at the external surface of MSL's heat shield will be about 3,800 F. Peak deceleration occurs about 10 sec later.

MSL will make a guided entry, controlled by small rockets during its blazing fall through the atmosphere. The angle of attack will employ the highest lift-to-drag ratio ever flown at Mars. The flow around the MSL spacecraft is expected to become turbulent early in the entry. The resulting heat flux and shear stress on the heat shield will be the highest ever encountered at Mars, researchers say.

Before atmospheric entry, tungsten ballast will be tossed off the spinning spacecraft, changing its center of gravity. More ballast will be ejected to give the craft the desired angle of attack, and still more once the vehicle is through most of its hot entry, to realign it for parachute deployment.

The ballast is a set of six weights—known as entry balance mass devices (or 'the six shooter')—each weighing about 55 lb. Shedding them rebalances the spacecraft for the parachute phase of the descent.

Convergence of firsts

MSL's aeroshell/heat shield, designed by Lockheed Martin, is the largest ever built for a planetary mission, nearly 15 ft in diameter. By comparison, Apollo's heat shield measured just under 13 ft.

Using MEDLI meant drilling holes into a perfectly good heat shield. But a series of high-energy arcjet tests ensured that the sensors would not compromise its integrity and create a runaway condition, says Bill Willcockson, a senior staff member and heat shield expert at Lockheed Martin Space Systems (LMSS) near Denver.

Predictive models of MSL's entry are one thing, but MEDLI is expected to provide "real data" from the real Martian atmosphere, notes Willcockson. That information, he says, will give those designing future Mars missions added confidence in their predictions. Demonstrating guided entry onto the Martian surface is also a key to future Mars missions, one that will enable spacecraft to fly toward smaller landing zones of high scientific interest.

Spacecraft engineers stand with three generations of Mars rovers developed at JPL: Front and center is the Sojourner flight spare; at left is a rover akin to Spirit and Opportunity; to its right is a Curiosity-size test rover. Credit: NASA/JPL-Caltech.

MEDLI was developed at NASA Langley and NASA Ames. As the name suggests, its purpose is to snag a medley of engineering data from the entry sensors. The instrument suite consists of seven integrated sensor plugs and seven Mars entry atmospheric data system pressure sensors, all located on the heat shield's exterior. Mounted inside is a sensor support electronics box that provides power, signal conditioning, and analog-to-digital conversion.

The sensors' placement on the heat shield puts them right in the heart of the fire, says Rich Hund, MSL program manager at Space Systems. During the heat shield's development, he recalls, the toughest issue came late in the game. That was the decision to use a phenolic impregnated carbon ablator (PICA) thermal protection system instead of the heritage SLA-561V—the type that had flown on all of NASA's successful Mars entry missions. PICA was invented at Ames, and MSL's mission will be the material's first flight to Mars.

Ripple effects

Whether it succeeds or fails, MSL's mission will have far-reaching implications, according to Mars exploration expert Philip Christensen, regents professor of geological sciences in the School of Earth and Space Exploration at Arizona State University.

"I think that a successful landing will put Mars back in the limelight and keep the focus on sample return. So I think the ripple effect will be positive," Christensen suggests. Alternatively, an MSL crash might not be the end of the program, he says.

"Historically, failures in the Mars program have not ended it, but have led to a renewed interest in Mars and a renewed commitment by the U.S. to succeed there," notes Christensen. Examples are the U.S. Mars Observer and the Russian Mars 98 missions. "Both failures led to follow-on missions to recover the lost science. I think that the same could occur if MSL were to fail. This would be particularly true if it failed for a known, fixable cause. So much has been invested in developing the rover and the Sky Crane that I believe rational thinking would prevail, and there might likely be an investment by NASA in a second attempt to get the technology to work."

Christensen believes the public and NASA are committed over the long term to Mars activities. The program may slow down due to budget limitations, but given the investment to date, and such interesting and compelling science, the exploration will likely continue, he says.

Paving the way

Scott Hubbard, a professor in the Dept. of Aeronautics and Astronautics at Stanford University, has also considered the implications of the MSL mission. Back in 2000, Hubbard did a stint as NASA's 'Mars czar' to pick up the pieces after the back-to-back failures of the Mars Climate Orbiter (MCO) and Mars Polar Lander (MPL) in 1999.

"MSL will carry the most sophisticated scientific lab ever placed on another world. If the mission is successful it may finally allows us to detect the complex carbon compounds which are the fingerprints of life," says Hubbard. Once on Mars, Curiosity will study the planet's early history, a time when there was probably abundant water on the surface and a thicker, warmer atmosphere, he adds.

"The mission was designed to provide intensive 'ground truth' investigations that follow the very high resolution observa-

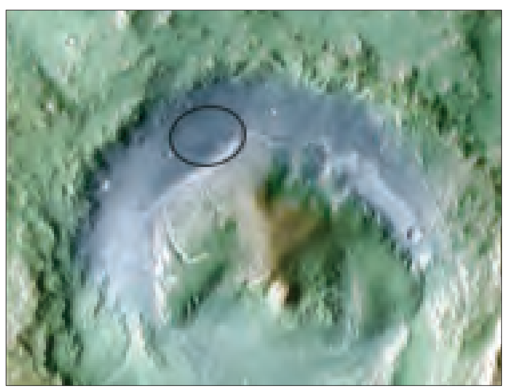
(Continued on page 49)

Touchdown
(Continued from page 35)

tions of Mars Reconnaissance Orbiter and earlier missions," Hubbard observes. "The innovative new technologies like the guided entry, Sky Crane, and sample handling tools are meant to help pave the way for a future Mars sample return."

MSL has been subject to rigorous design and testing, Hubbard says, "but Mars is hard!" Of the 44 missions to the red planet over the past 50 years, less than a third have been fully successful, he notes.

"If Mars should throw us a curve and MSL is not successful, I believe exploration *will* continue," Hubbard emphasizes. "Mars is the most Earth-like of the other planets in our solar system, the most likely to have developed life, and the most compelling target for future human exploration."



Color coding in this image of Gale Crater represents differences in elevation, with blue relatively low and tan relatively high. The vertical difference from a low point inside the landing ellipse for Curiosity to a high point on the mountain inside the crater is about 3 miles.

Historical record

Given today's tight budgets, how should MSL be viewed if it succeeds, or if it fails?

Hubbard says the administration has taken the position that it will not support any new so-called 'flagship' missions—generally viewed as costing more than $2 billion. "If MSL is a success—and particularly if evidence of organic materials is found—one would hope that NASA and the Office of Management and Budget in particular would take a fresh look at the potential of Mars exploration to answer the question: 'Are we alone?' If Mars causes the mission to have problems, I still think the red planet is so compelling that, as a nation, we can and must continue…as we did after the failures of MCO and MPL in 1999."

Holding a similar view is Roger Launius, senior curator in the Division of Space History at the National Air and Space Museum in Washington, D.C.

"With any mission, whether successful or a failure, there are always ramifications, but perhaps not in quite the way most people might think. Mission failures do not usually lead to decisions to stop undertaking exploration, as some believe," Launius says. So if MSL succeeds, everyone will cheer and press on with the program as currently defined, Launius continues. "Also, in that environment I doubt much will be said about the cost overruns on MSL. On the other hand, if it fails or is substantially degraded, the probe will be characterized as the 'troubled Mars Science Laboratory,' and most stories will probably relate the historical record of problems with the program as a preamble to whatever the current news might be," he says.

Destination: Gale Crater

NASA's July 2011 selection of Gale Crater as the landing site followed a five-year process in which some 150 Mars scientists narrowed the choice from about 60 candidate sites.

Gale Crater measures 96 mi. in diameter and holds a mound or mountain named Mount Sharp, which rises about 3 mi. above the crater floor. The slopes of the mountain are gentle enough for Curiosity to ascend, though the rover will not likely travel beyond some particularly intriguing layers near the base during the prime mission period, one Martian year (98 weeks).

Gale's low elevation relative to most of the Martian surface suggests that if Mars ever had much flowing water, some of it would have pooled inside the crater.

Like sequential chapters in a history book, the stacked layers that form Mount Sharp will present a record of the environmental conditions that prevailed when each layer was formed, scientists believe.

"Mount Sharp is the only place we can currently access on Mars where we can investigate this transition in one stratigraphic sequence," says Caltech's John Grotzinger, MSL chief scientist.

"The hope of this mission is to find evidence of a habitable environment…the promise is to get the story of an important environmental breakpoint in the deep history of the planet," he says. "This transition likely occurred billions of years ago…maybe even predating the oldest well-preserved rocks on Earth."

Day of reckoning

As MSL's day of reckoning draws closer, do its builders have lingering thoughts of carrying out more tests if the spacecraft can be brought back?

"I don't think I would want to drag it back and do more," says Theisinger. "We were very happy with the verification and validation program that we were able to run. I think we are very pleased with the quality of the vehicle that we launched. I don't think doing more on the Earth would really help us all that much," he adds.

On entry day, Theisinger says, "If we turn out to not have a good day at Mars, but we've done everything we can, that's karma. My experience with the public and everyone else is that they understand that. They won't forgive us for being stupid and for taking short cuts. But that's our job…not to be stupid, and not to take shortcuts."

In the end, Theisinger's engineering perspective is clear: "Get it down, hand the keys over to the scientists. Then say, okay, don't break it, and go do good stuff."