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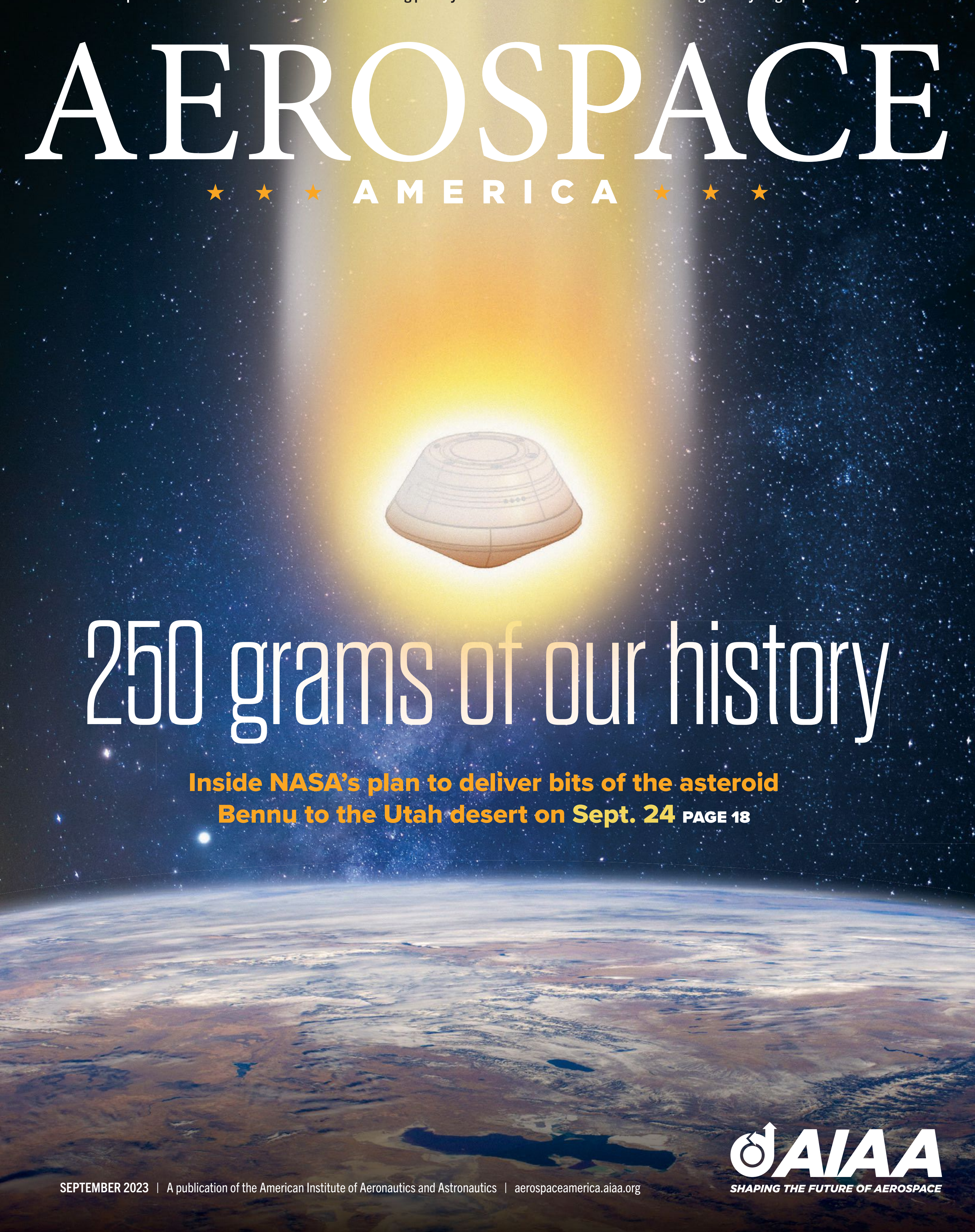

250 grams of our history

Inside NASA's plan to deliver bits of the asteroid Bennu to the Utah desert on Sept. 24 PAGE 18

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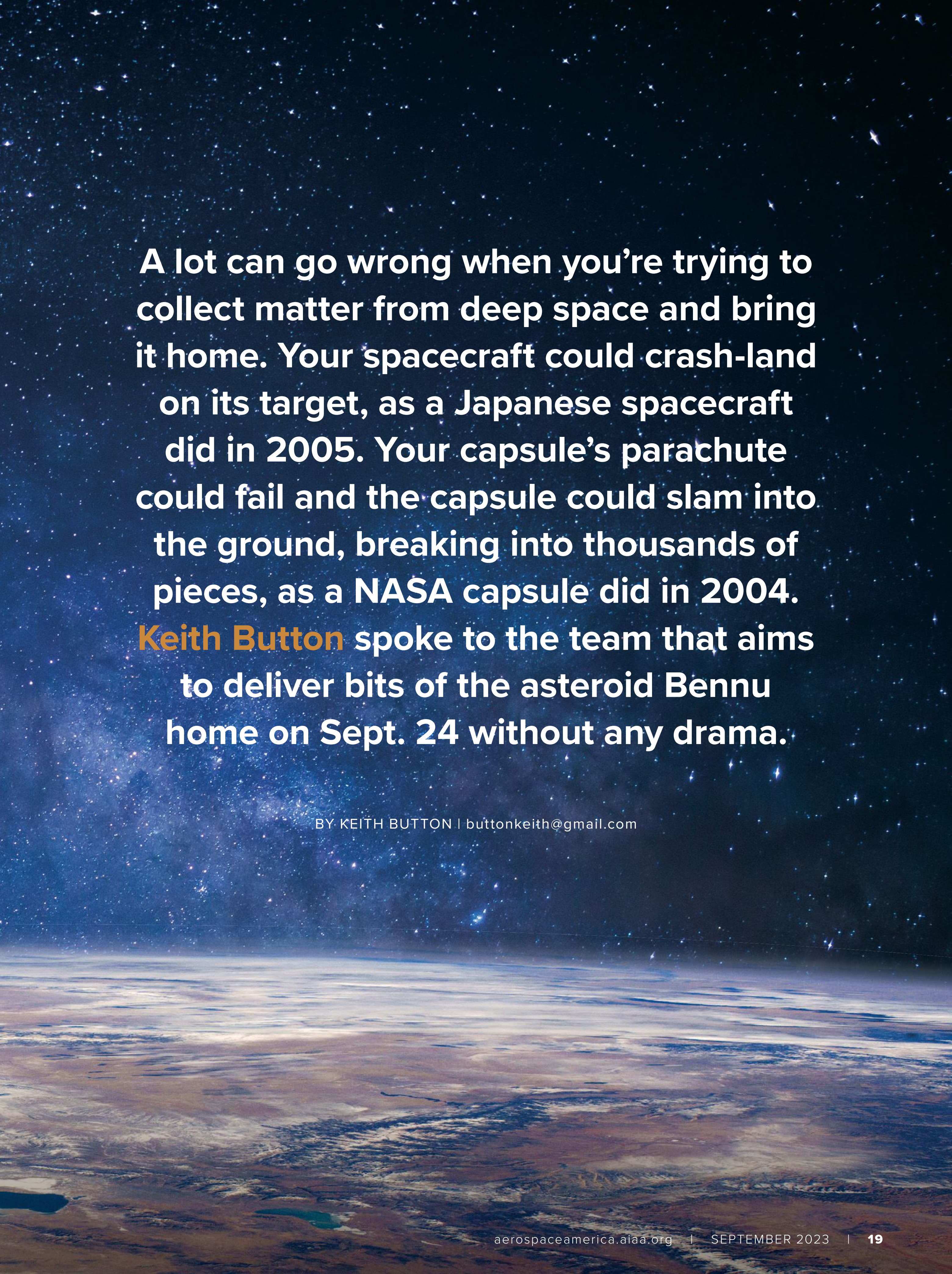

A lot can go wrong when you're trying to collect matter from deep space and bring it home. Your spacecraft could crash-land on its target, as a Japanese spacecraft did in 2005. Your capsule's parachute could fail and the capsule could slam into the ground, breaking into thousands of pieces, as a NASA capsule did in 2004. Keith Button spoke to the team that aims to deliver bits of the asteroid Bennu home on Sept. 24 without any drama.

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The scene unfolding on a campus TV screen was troubling.

"A train wreck," says Dante Lauretta, a University of Arizona planetary sciences professor who was among those watching the landing of NASA's Genesis capsule in 2004. It was returning after a three-year mission to collect solar wind ions. The NASA video feed showed a distant dot in the sky that came into focus as it plummeted like a flying saucer wobbling and tumbling end over end.

"I knew right away they were in trouble. You'd never want your capsule to get into the tumbling configuration," Lauretta says.

Tumbling meant that the drogue parachute and main chute had failed to deploy, so the recovery helicopter could not grasp the chute and set the capsule down gently on the desert floor. The range controller on the broadcast confirmed this: "We do not see a drogue chute. Negative drogue." The camera stayed on the capsule all the way to its impact with the ground about 30 seconds later, at 311 kph. It was embedded in the Utah desert mud like a half-buried truck wheel, cracked open with pieces scattered around.

"It was like a gut punch right below my solar plexus," Lauretta says. "All the wind just got sucked out of my lungs." He immediately thought of what his friend Donald Burnett, principal investigator for Genesis, must have been going through. He remembers thinking, "This is a bad day."

Nineteen years later, Lauretta is principal investigator for another NASA mission to deliver extraterrestrial matter to Earth — OSIRIS-REx — with a parachute landing planned for Sept. 24 in the same patch of desert: the U.S. Department of Defense's Utah Test and Training Range. At each step of the mission, he's been fixated on avoiding the pitfalls of Genesis and other missions.

OSIRIS-REx (short for Origins, Spectral Interpretation, Resource Identification, Security-Regolith Explorer) is NASA's first asteroid sampling mission. If the $1 billion mission succeeds, scientists will have 250 grams of rocks and dust from the near-Earth asteroid Bennu — about the weight of a cup of water.

"It doesn't sound like a lot, but it is huge," says Eileen Stansbery, chief of the Astromaterials Research and Exploration Science division at NASA's Johnson Space Center in Houston. By comparison, the Japan Aerospace Exploration Agency's first Hayabusa mission yielded less than 1 milligram — inadvertently gathered when the spacecraft crash-landed on the asteroid Itokawa — and Hayabusa2 collected 5 grams from the asteroid Ryugu.

From direct samples, "you can tell the pressures and temperatures at which specific mineral components were born, and that tells you when and how in the evolution and formation of our solar system a particular body was formed," says Stansbery, who headed the team that recovered the broken Genesis capsule and its collector plates.

How Earth formed is among the questions that scientists hope to explore with the study of the Bennu sample. Where Earth acquired its water and organic (carbon) molecules — the ingredients that made life possible — is still an open question. Because Bennu orbits the sun on nearly the same path as Earth's orbit, the asteroid is a potential window into how Earth coalesced 4.5 billion years ago from debris and possibly from planetesimals that were about the same distance from the sun.

Earth and these original ingredients are like a chocolate chip cookie that has already been baked, says Beau Bierhaus, a Lockheed Martin planetary scientist on the OSIRIS-REx team.

"All of the original ingredients that went into making the Earth in some sense are still kind of there, but they've just been baked up to the point that we don't know what the source material may have been like," he says. Bennu could show scientists what the cookie dough looks like without baking, or heating from Earth's core, in this analogy.

Scientists have tried to discern similar answers about Earth's origins from meteorites, but that material has been altered by the heat of reentry and contaminated by terrestrial material and water, like cookie dough that's been dropped on a dirty floor, Bierhaus says.

Nearly any material from a carbon-rich asteroid like Bennu wouldn't survive entry into Earth's atmosphere — it would burn up — unlike meteorites that originated from metallic asteroids, for example.

"We have some meteorites on Earth that we think might be like Bennu, but they're a tiny fraction of the overall meteorite collection," Bierhaus says.

Lessons from Genesis

Though the big test will come on Sept. 24, OSIRIS-REx has so far avoided trouble. It was launched in 2016, and in 2020 reached its robotic arm down to Bennu's surface to collect rocks and dust. If all goes as planned, the sample will be recovered and delivered to a temporary clean room at the Utah test range, uncontaminated by earthly material. There, the sample will be wrapped and crated for a flight aboard a C-17 cargo plane to NASA Johnson the next day.

From the early days of OSIRIS-REx, Lauretta and the Lockheed Martin spacecraft designers, builders and operators vowed to learn from mistakes made on earlier robotic sample return missions, including Genesis, which Lockheed Martin also built and operated.

Ultimately, NASA recovered nearly all of the solar wind ion collection surfaces from the 14,000 broken pieces of Genesis, with ions etched deeply enough

Hard but doable: the history of robotic sampling

Over the span of six decades, robotic sampling spacecraft have brought home about 2 kilograms of material from space, including 5 grams of asteroid bits. NASA's OSIRIS-REx mission aims to increase by 50 times the amount of asteroid material available for study. What does history say about the odds of success? Nine missions out of 17 failed, and two experienced serious complications.

Country	Mission	Return Dates	Purpose	Outcome
China	Chang'e 5	Dec. 17, 2020	Return lunar regolith from the Mons Rümker volcanic mound northwest of the moon's equator.	Landed in the Inner Mongolia region of northern China via parachute with 1,730 grams of lunar dirt and rocks.
Japan	Hayabusa2	Dec. 6, 2020	Return rocks and dirt from near-Earth asteroid Ryugu.	Landed by parachute in Australia with 5 grams of material, 540 milligrams of which were shared by the Japan Aerospace Exploration Agency with NASA, which plans to return the favor and share a portion of the OSIRIS-REx samples with JAXA.
Russia	Fobos-Grunt	August 2014 (planned)	Return 200 grams of soil from Phobos, one of the two Martian moons.	Became stranded in Earth orbit when the Fregat upper stage did not fire its engines. In early 2012, the spacecraft reentered the atmosphere.
Japan	Hayabusa	June 2010	Return samples from near-Earth asteroid Itokawa.	Landed by parachute in Australia carrying about 1 milligram, 15,000 grains. The collecting mechanism was damaged during its first sampling attempt, but scientists believe some particles were pushed into the sample container during the impact with the asteroid.
U.S.	Stardust	January 2006	Collect particles from the tail of comet Wild 2 and from space dust.	Landed in the Utah desert by parachute with 10,000 particles larger than 1 micrometer from Wild 2, plus separately collected samples of space dust, including seven rare microscopic particles that dated back to the origins of the solar system.
Genesis	U.S.	September 2004	Collect solar wind ions.	Drogue and main parachute failed to deploy, foiling plans for a helicopter to swoop in with a dangling hook and snatch the chute and gently lower the capsule to the ground. The capsule impacted the ground at 311 kilometers per hour in the Utah desert, but scientists salvaged most of the samples.
Soviet Union	Luna missions	1969-1976	Return samples of lunar dirt and rocks.	A combined 301 grams of lunar soil was returned. Eleven Luna probes were launched; three managed to deliver samples to Kazakhstan. Some failed in spectacular fashion: Luna 18 crashed some 500 kilometers from the Apollo 11 site while Armstrong and Aldrin were on the moon.

SOURCE: Beyond Earth: A Chronicle of Deep Space Exploration, 1958–2016

into the metal plates not to be disturbed by contaminants from the crash. Even so, 2004 was a discouraging year for Lauretta, then the deputy principal investigator, and colleagues, who were trying to win approval for their mission to Bennu on the heels of the Genesis crash. The team's first proposal was rejected by NASA.

"We got hammered on engineering, and Lockheed is our aerospace provider, and they just crashed in the desert," Lauretta says.

On top of that, still percolating in memories was the loss of NASA's Mars Climate Orbiter, which in 1999 missed its orbit altitude and disintegrated in the Martian atmosphere due to a navigation error caused by one team using metric units and another using English units. Also in 1999, Mars Polar Lander crashed during its descent when its main engines shut down prematurely.

"There were a lot of failures in planetary science," Lauretta recalls.

▲ OSIRIS-REx team members conducted rehearsals at the Utah Testing and Training Ground, where the craft is due to land on Sept. 24. With a mock capsule, they practiced assessing the capsule for damage and packaging it for transport via helicopter to a nearby clean room (next page). There, the container would be opened to extract the asteroid sample.

NASA/Keegan Barber

But Lauretta's mentor, Michael Drake, who was principal investigator at that time, flipped the perspective: The Genesis crash was good news, he told Lauretta, because their team would learn from the mistakes, not repeat them and grow stronger because of them.

"He was right about that. We studied that failure intensely," says Lauretta, who became principal investigator in 2011 when Drake died of cancer.

The design of the OSIRIS-REx capsule is similar to that of Genesis: It is intended to detach from the top deck of the OSIRIS-REx spacecraft about four hours and 97,000 kilometers before the capsule's landing in Utah. Once detached, the capsule will be autonomous; it won't be able to receive any commands from the ground. Should the detachment not work, the spacecraft would be put in a backup orbit for a second attempt in September 2025. If all goes as planned, though, the capsule will enter the atmosphere and release the drogue and main parachute that will carry it to the desert floor. (Unlike Genesis, no helicopter is involved at this point.) Meanwhile, the spacecraft will maneuver to continue in an orbit around the sun.

After the Genesis crash, the NASA-convened investigative board traced the cause to the mission's autonomous flight phase. Four spring-loaded switches, each the size of the metal cylinder on the eraser end of a pencil, were supposed to initiate a timer that would trigger pyrotechnics to release the capsule's parachutes. But the switches were installed backward, so the weighted plungers inside the switches couldn't press down in response to the capsule's deceleration as it entered the atmosphere. The electrical circuit needed to arm the timer could not be completed.

Lockheed Martin engineers installed the switches backward because that's how they were drawn in the blueprints. The lesson for OSIRIS-REx — besides the obvious, "Don't install the switches backward" — was to test the entire assembly that contains the switches for its pyrotechnics under the most flight-like conditions that can be reproduced. Genesis planners hadn't done that. The error went undetected in part because of a "lack of involvement" by the Jet Propulsion Lab managers, the board concluded.

To simulate flight conditions, the OSIRIS-REx team decided to test the trigger assembly under the same g-forces expected during reentry. In early 2016, they took the assembly from Lockheed Martin's facility in Littleton, Colorado, to the Geotechnical Centrifuge Laboratory at the University of Colorado Boulder, about an hour away.

"You put an astronaut on a centrifuge to make sure that they can survive the launch environment and the reentry conditions. We put our return capsule through the centrifuge for exactly the same reason," Lauretta says.

But the process would be more complex. From earlier tests, they had determined that they also needed to cancel out the 1-g effects — Earth's natural gravity — for the centrifuge to realistically mimic reentry forces, says Josh Wood, who led OSIRIS-Rex's system design at the time.

The solution: They attached the loaf-of-bread-sized trigger assembly to a plate that would spin it like a Lazy Susan as the centrifuge arm spun the unit. The spinning of the plate would cancel out the lateral g-forces. They ran the centrifuge to replicate the full range of g-forces the capsule would experience during entry, a maximum of 40 gs. The results showed that the trigger assembly would work as planned.

They also tested the switches that must react when the capsule impacts the ground, sparking another pyrotechnic device that shoots a knife through the bridle connecting the capsule to the main chute. That step ensures that if it's windy, the capsule isn't dragged across the desert surface. And they also tested the capsule's aeroshell on a larger centrifuge with a 5.5-meter arm.

Adding to their confidence were drop tests they had conducted two years prior with the parachute canister at Mountain Home Air Force Base in Idaho. They had a helicopter hover at 1,500 feet while dangling a 55-gallon drum, weighted to mimic the mass of the capsule, with the canister mounted on top. The hook holding the drum was released, and as the drum fell away, a line attached to the helicopter pulled the drogue chute from the canister. A few seconds later, a timer triggered the main chute to unfurl and a pyrotechnic device to fire a knife that cut away the drogue, similar to the apparatus for cutting away the capsule's main chute after landing.

These tests revealed a problem with the apparatus for cutting the drogue free: The Kevlar loop that held the drogue's bridle straps together sometimes prevented the drogue from unfurling quickly, which in turn delayed the unfurling of the main chute by about 3 seconds. They redesigned the drogue to remove a piece of Teflon tape that had held the loop rigid for easier cutting. Instead, they coated the loop in a liquid epoxy to harden its fibers, explains Sajjad Reza, who was the principal engineer for the OSIRIS-REx parachute system. After ground testing and another series of helicopter drop tests, they proved that the fix worked: The chutes deployed on time.

Prepare for landing

In July, under clear skies at the Utah test range, Lauretta wore sunglasses and a broad-rimmed cap with a neck flap as he walked gingerly through ankle-deep mud. Though strikingly similar to the desert mud that had coated the Genesis shards, this mud was created with water hauled in by a tanker truck to rehearse a what-if scenario: Retrieve the OSIRIS-REx capsule after heavy rains. This was one of nine rehearsals the team will have conducted by the time of the landing on Sept. 24 to make sure everyone knows their roles in locating, bundling and transport the 50-kilogram, car-tire-sized capsule to a hangar at the test range, where the temporary clean room has been set up.

On the day of the landing, a 10-person recovery team, including Lauretta, will wait just outside the 50-kilometer-wide ellipse where the capsule is projected to land. Once landing occurs, the members will swoop in on three helicopters, with a fourth carrying a NASA TV crew to document the recovery from the air.

Speed is of the essence to prevent or limit possible contamination. "You want to just go on muscle memory at that point," Lauretta says. "It's kind of like a race car team. When you go into a pit stop, if you rehearse everything, you get those tires replaced and the fuel thing done in seconds. As opposed to if you haven't done it, you could be wasting minutes on that."

During the mud rehearsal, Lauretta practiced his landing day role: collecting samples of soil from the landing area — mud and water, in this instance — without slipping. Technicians picked up the mock capsule from the goo, while Lauretta and others on the environmental monitoring team held vials to collect any water that drained out of the capsule as it was lifted. They also syringed up samples of water from the ground and collected mud in Teflon baggies.

On landing day, simular samples will be collected and cataloged so scientists will be better equipped to rule out the possibility that something they find in the asteroid sample isn't a contaminant from Earth.

"It's like a forensics investigation. You want to have control of the evidence all the way back," Lauretta says: a record of all the environments that OSIRIS-REx passed through, from the building of the spacecraft to the Utah landing site to the clean rooms. If a

▲ The 2004 crash of NASA's Genesis sample return capsule in the Utah desert looms large for OSIRIS-REx mission planners. Its parachutes did not deploy, and the capsule could not be caught by a helicopter as planned. The flat discs containing samples of solar wind shattered on the desert floor.

U.S. Air Force 388th Range Squadron

protein chain is discovered in the sample, for example, scientists need to determine its origin, he says. "If this was from the asteroid, this is a really huge science result. If it's from the Earth, then I just need to understand that it was contamination and not write a science paper about it."

"We have all of these witnesses to the history of the sample collection that will allow us — we expect in most cases — to be confident in our science and not have contamination fool us," he says.

On landing day, plans call for the recovery team to wrap the capsule — expected to have a temperature of about 54 degrees Celsius initially, from the heat of reentry — in multiple Teflon bags and a tarp. Then they will place it in a cargo net harness at the end of a 30-meter line for the helicopter ride to the clean room. The goal is to transport the capsule within one hour of landing, says Richard Witherspoon, Lockheed Martin's ground recovery lead for OSIRIS-REx.

At the clean room, a team must remove the tarp and bags and disassemble the capsule. The heat shield and back shell will be pulled off to reveal the aluminum canister that contains the sample. A hollow needle and tube will be stuck into a port in the canister, starting a flow of nitrogen gas meant to keep it purged of earthly contaminants. The canister will be sealed inside four Teflon bags and a shipping container for transport the following day to its permanent clean room at NASA Johnson.

This consistent nitrogen purge is a lesson learned from colleagues on the Japanese Hayabusa missions, Lauretta says. On one of the missions, some of the asteroid sample spilled, and the team noticed it reacted with the atmosphere, changing its chemistry.

Keeping the Bennu sample in quarantine-like conditions to prevent contamination is a chief goal of the recovery team.

What about the opposite scenario — that the sample could contaminate Earth with a deadly extraterrestrial microorganism, like in Michael Crichton's bestseller, "The Andromeda Strain"?

"We do not have to worry about that," Lauretta says, due to the cosmic radiation that Bennu has been exposed to for hundreds of millions of years. The radiation "should sterilize any lifeforms that we are aware of."

Plus, Bennu's orbit around the sun crosses Earth's orbit, so rocks that the asteroid regularly throws off its surface have almost certainly already landed on Earth. NASA assessed the OSIRIS-REx mission for planetary protection concerns — contamination on Earth by a life from another world — and cleared it for unrestricted return to Earth, Lauretta says.

Meanwhile, at Lockheed Martin's OSIRIS-REx control room in Littleton, officials have rehearsed various scenarios based on previous sample return missions. Some of that planning was based on the experiences of the control room for Stardust, the Lockheed Martin-operated comet dust collector that landed safely at the Utah range in 2006. For instance, 15 minutes before the OSIRIS-REx spacecraft is supposed to release the sample capsule on Sept. 24, the batteries that power the avionics for parachute deployment must come online for the first time in seven years. When the batteries for Stardust came online, also after a seven-year hiatus, the Littleton flight operators were a little surprised by a voltage reading they saw on their computer screens. After some discussion, they determined that the batteries were working as planned, but because they had not viewed the readings and their format for seven years, there was some confusion about what they saw, says Sandy Freund, the Lockheed Martin program manager for OSIRIS-REx.

To avoid surprises on the 24th, before OSIRIS-REx was launched and the capsule avionics batteries put into sleep mode for the seven-year round trip, the team took screenshots of the capsule's normal battery voltage readings. They also created various problem scenarios with the spacecraft on the ground and took screenshots of those, such as if battery voltage was low or if cables had been severed between the spacecraft and capsule, as they are designed to do before reentry, says Freund, who worked in the control room for the Stardust and Genesis landings. They reviewed those screenshots this year to train the flight operations crew for "off-nominal scenarios" when the battery readings aren't normal.

"That way, we know there's absolutely no confusion," she says. "Although we do have a handful of people still on the team" from when OSIRIS-REx launched, "that's a long time ago and a long time ago for people to remember details like that."

Starting in January, flight operators also practiced diagnosing and solving other problems that could arise, with scenarios generated by a computer mockup of the spacecraft. For example, if the batteries show no voltage or not enough voltage to deploy the parachute, the flight operators may repeat the sequence that brings the batteries online — turning on a heater again to burn through a depassivation layer, a thin layer that forms on the batteries' electrodes when they're not in use, Freund says. Or they might try commanding the batteries to come online via a different path, such as through redundant hardware on the spacecraft.

"Ultimately, the team is going to do whatever they possibly can to get that voltage to the appropriate level," she says.

In all, the full flight operations crew was planning to run through about 30 scenario tests with the spacecraft test lab by the end of August.

As the days count down to the planned OSIRIS-REx landing, Lauretta will be rehearsing and mulling over what could go wrong. He says he has been almost obsessively rereading articles and reports about the Genesis crash and rewatching the YouTube videos of it.

"I've actually watched that footage a lot, probably too much lately," he says, maybe to prepare himself emotionally "in the event that for some reason, we're in a similar situation. I'm kind of fascinated with it at this point." ★