National Aeronautics and Space Administration

Academy Sharing Knowledge
ask

The NASA Source for Project Management and Engineering Excellence | APPEL

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Photo Credit: NASA

ON THE COVER

On July 31, 2011, Expedition 28 astronaut Ron Garan looked out his window aboard the International Space Station and saw the moon. In fact, he saw it sixteen times. "We had simultaneous sunsets and moonsets," said Garan. For him and the rest of the station crew, this extraordinary event is a daily occurrence. Since the station orbits Earth every ninety minutes, each day the crew experiences sunrise, sunset, moonrise, and moonset about sixteen times a day.

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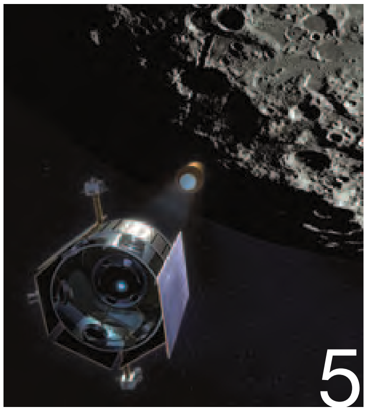

ask

Issue No. 44

The Academy of Program/Project and Engineering Leadership (APPEL) and *ASK Magazine* help NASA managers and project teams accomplish today's missions and meet tomorrow's challenges by sponsoring knowledge-sharing events and publications, providing performance enhancement services and tools, supporting career development programs, and creating opportunities for project management and engineering collaboration with universities, professional associations, industry partners, and other government agencies.

ASK Magazine grew out of the Academy and its Knowledge Sharing Initiative, designed for program/project managers and engineers to share expertise and lessons learned with fellow practitioners across the Agency. Reflecting the Academy's responsibility for project management and engineering development and the challenges of NASA's new mission, *ASK* includes articles about meeting the technical and managerial demands of complex projects, as well as insights into organizational knowledge, learning, collaboration, performance measurement and evaluation, and scheduling. We at APPEL Knowledge Sharing believe that stories recounting the real-life experiences of practitioners communicate important practical wisdom and best practices that readers can apply to their own projects and environments. By telling their stories, NASA managers, scientists, and engineers share valuable experience-based knowledge and foster a community of reflective practitioners. The stories that appear in *ASK* are written by the "best of the best" project managers and engineers, primarily from NASA, but also from other government agencies, academia, and industry. Who better than a project manager or engineer to help a colleague address a critical issue on a project? Big projects, small projects—they're all here in *ASK*.

You can help *ASK* provide the stories you need and want by letting our editors know what you think about what you read here and by sharing your own stories. To submit stories or ask questions about editorial policy, contact Don Cohen, Managing Editor, doncohen@rcn.com, 781-860-5270.

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In This Issue

One of NASA's stated goals is to "expand scientific understanding of the earth and the universe in which we live." Advancing science has been a primary aim of the agency's from the beginning; its contributions to science are too numerous and varied even to begin to list. This issue of *ASK* includes several articles that focus not on the science itself, but on how much NASA's scientific accomplishments depend on close cooperation among the scientists, engineers, and managers who share responsibility for its missions.

In his "From the Academy Director" reflections, Ed Hoffman describes the conflicts among those groups in the first project team he worked with as a new hire at Goddard—how hard they found it to function as a team. Recognizing that essential work happens when these communities interact, he quickly saw the importance of bringing them together around the one goal they shared: a successful mission.

Jeffrey Hoffman, the subject of this issue's interview, is a Massachusetts Institute of Technology scientist and a veteran astronaut who has helped explain some of the benefits and limitations of research in space to scientists and clarify science needs to astronauts and operations staff. He talks about the change in focus and operational flexibility needed to realize the International Space Station's great potential for scientific discovery.

It is hard to imagine a more vivid demonstration of scientific discovery hinging on excellence in engineering and management than Daniel Andrews's story of LCROSS's "bad day," when an unanticipated expenditure of propellant almost ended the spacecraft's mission to measure water ice in a crater at the moon's south pole. And the NEAR story ("Rendezvous with an Asteroid," by Andrew Cheng) takes us back to the scientific and engineering challenges and accomplishments of NASA's first Discovery Program mission—a demonstration of how much can be done on a relatively tight budget when the team is dedicated, ingenious, and united.

In "Putting the Science Back in Rocket Science," Glen Robertson argues for a refocusing on science—devising and testing new ideas—in the field of rocket propulsion, which he believes has been dominated in recent years by an engineering emphasis on reliably putting old ideas into practice.

Some of the articles here are not explicitly about science, but they touch on the essential elements of cooperation that have made and will continue to make NASA science possible. Jim Hodges's report on the Dream Chaser and Haley Stephenson's story about keeping space station operations going during Hurricane Ike—as well as pieces about wiki use at NASA, decision-making styles, and encouraging systems thinking—illustrate, in different ways, the importance of communication and the sharing of expertise. Most of all, they show the importance of a shared passionate commitment to mission success.

Don Cohen
Managing Editor

From the Academy Director

Action at the Boundaries

BY ED HOFFMAN

Many years ago, I was hired to design and implement strategies that supported teams at Goddard. Because performance happened at the team level, the idea was to complement traditional individual-development activities with team support.

NASA's grand science challenges depend on engineering expertise to design and build the needed instruments and sound project management to ensure overall value and execution. I have always been fascinated by what happens when these communities come together. It is at these organizational boundaries and interfaces that projects are tested for strength, teamwork, and resilience.

My first project team was responsible for a large science program led out of Goddard. The project manager asked me to design a retreat with the ambiguous aim of creating more of a "total team." I was assured that the team was composed of the best and hardest-working engineers and scientists around. The issue was how people interacted when they came together. Arguments, threats, even fights over priorities were not uncommon. Progress was made when the groups returned to their local work.

My project manager sponsor believed in the potential value of the team retreat but kept asking, "How much time will this take? Can you do it in half the time? Is there a way you can show us a return on investment?"

My interactions with the engineers were mostly positive but initially skeptical. They were interested in anything that could improve performance; time was important but less of a driver. "If you have something that makes us better, let's do it," they said, but if they didn't see value they would—at best—ignore the activity entirely.

The scientists informed me that the whole notion of "team" was suspect. Science, I was told, happened at the edge of rebellion; conformity to team norms and roles was the enemy of scientific discovery. The only communities scientists recognized were other scientists. One scientist asked, "What do you notice in my dress?" I looked at his shorts, sneakers, and T-shirt. Before I could answer, he told me, "My clothes represent my difference. I am deliberately unlike anyone else around here." In other words, get the engineers and project managers to work as a team, but leave us alone.

I wondered what planet I had landed on. My retreat sponsor was increasingly worried about taking time away from the project. The engineers were creative and playful, but skeptical. The scientists were offended by the very notion of team building.

I saw that I needed to better understand the challenges, rhythms, and dynamics of a complex project. Generic team-building tools would never accomplish anything. I learned, too, that the key to bringing these groups together was to focus on mission success.

The interplay of scientists, engineers, and managers—the interaction at the boundary that determines success or failure—is influenced by their natural dependencies, passions, and animosities. The only way those players can develop the communication, integration, and trust required to truly work as a team is to unite them in pursuit of a common goal: meeting the epic challenges of NASA's great science missions. ●

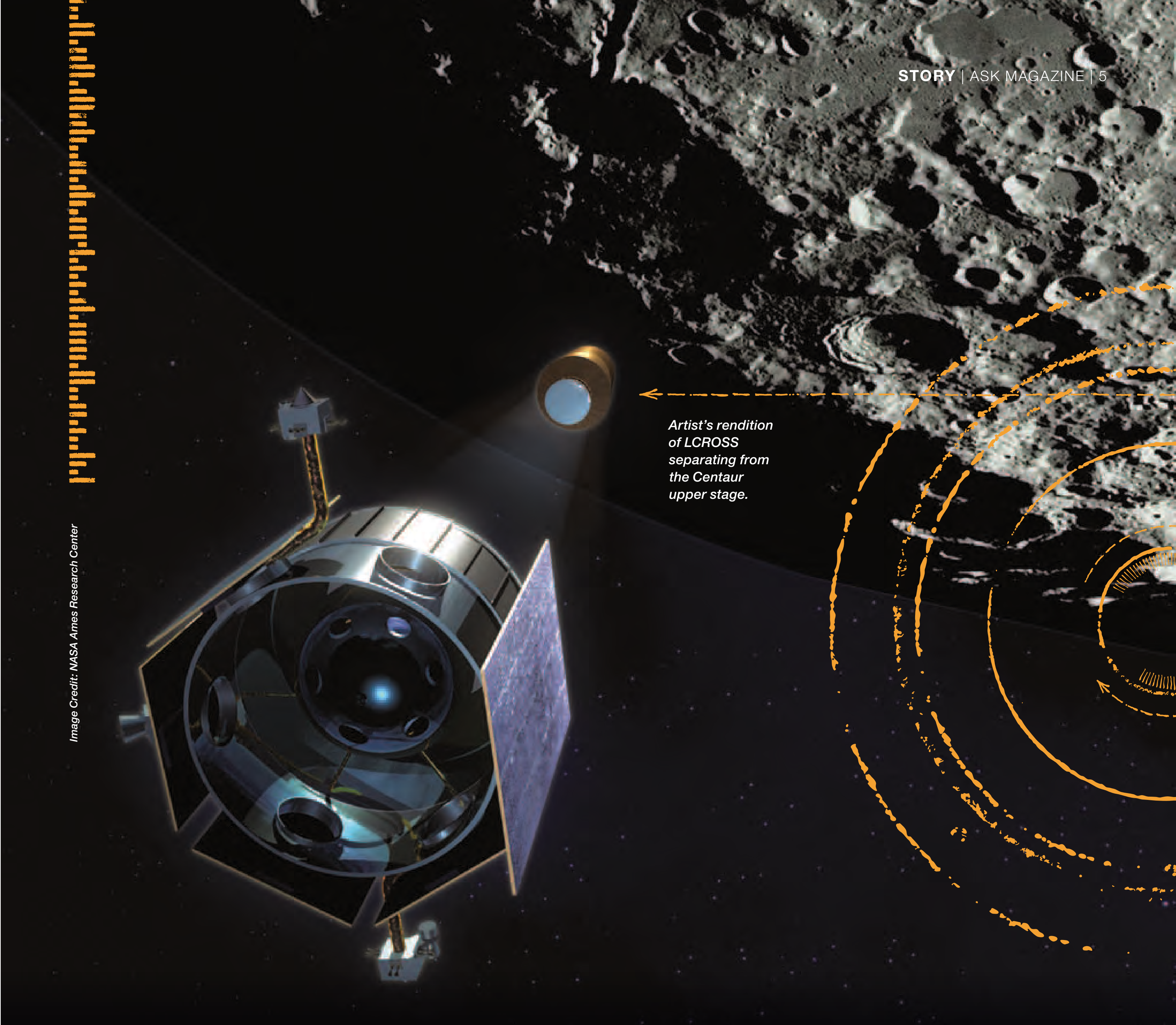


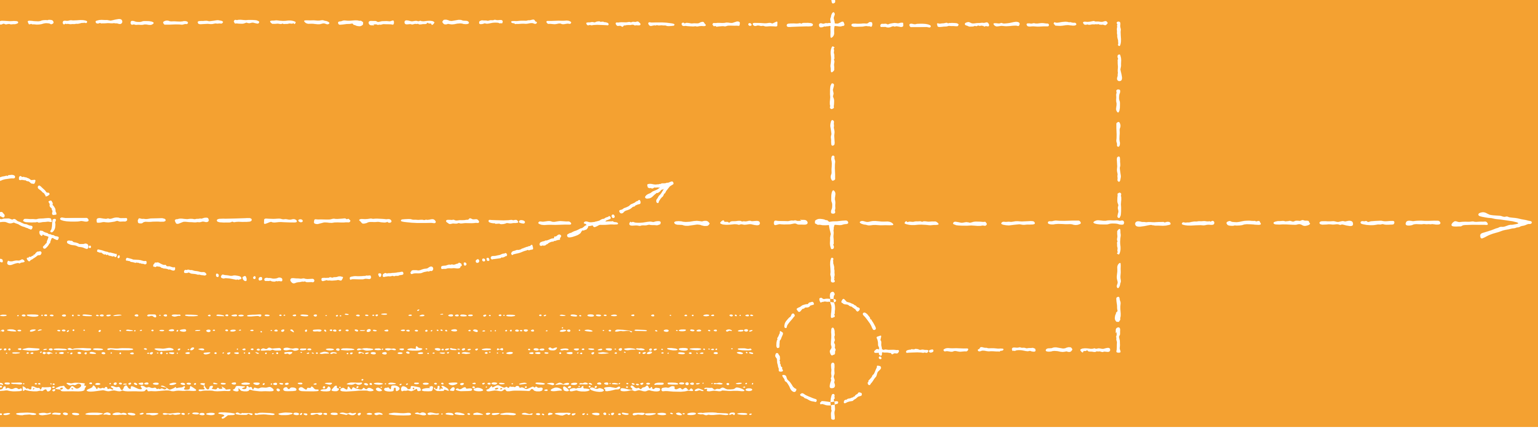
Image Credit: NASA Ames Research Center

Artist's rendition of LCROSS separating from the Centaur upper stage.

MANAGING THE BAD DAY

BY DANIEL ANDREWS

It's 3:30 a.m. on Saturday, August 22, 2009. My cell phone rings. As the project manager for the Lunar Crater Observation and Sensing Satellite (LCROSS), I was used to sleeping with the phone near my bed ever since launch. The LCROSS operations team was preparing to do a spacecraft-orientation maneuver, turning the cold side of the spacecraft to the sun to burn off any residual ice remaining on the Centaur upper stage—what we called a "cold-side bake." I was planning to go in and observe the activities later that morning. The phone had never rung this early before.



"Project, this is Mission," the LCROSS mission ops manager (MOM) stated.

"Go, Mission," I replied.

MOM indicated the team had just gotten "acquisition of signal," which means the operations crew had reestablished communication with the spacecraft after a planned period of no communication. MOM told me that once spacecraft telemetry began flowing, the ops team discovered that a very large amount of propellant had been mysteriously consumed while the spacecraft was out of view of the ground stations.

MOM explained, "When we acquired the spacecraft, we discovered that the thrusters were firing almost continuously and believe a substantial amount of propellant was consumed." I asked if we knew if we had enough propellant remaining. "We do not yet know if we have enough propellant to finish the mission—working it now," replied MOM. "The thrusters are still firing, and we are trying to get that stopped."

It was clear that if we hadn't scheduled an early-morning activity when we did, we would have consumed all the propellant and lost the mission. Furthermore, if we didn't get it stopped immediately, we'd lose the mission anyhow.

This was LCROSS's bad day.

I got dressed and headed in to the mission ops control room at Ames Research Center and learned the thruster firing had stopped after a commanded power-cycling of the spacecraft's inertial reference unit, or IRU. The IRU is standard spacecraft equipment used to measure the spacecraft's velocities so its attitude can be controlled. The ops team discovered that an IRU fault flag was set. After some consideration, the team issued a reset command, which cleared the fault and halted the thruster firings, returning the spacecraft to its normal condition.

Later analysis revealed that when the IRU fault occurred, the autonomy and fault management system appropriately kicked in, no longer trusting the IRU for velocity feedback and switching to the star tracker's velocity feedback. For (then) unexplained reasons, this changeover drove the attitude control system to fire the spacecraft thrusters at an extraordinary rate. The spacecraft ultimately consumed some 140 kg of propellant, leaving a mere 60 kg to finish the mission.

It eventually turned out that two root causes led to this event and our subsequent challenges:

1. **IRU configuration error:** A spurious, short-lived error on the IRU was interpreted as a more serious fault by the spacecraft fault-management system because the IRU fault-flag update rate and the autonomy and fault management sampling rate were not properly synced, leading the autonomy and fault management system to believe a persistent error was present and to subsequently switch to the star tracker for velocity measurements. This issue alone wouldn't have been a problem.
2. **Star tracker velocity noise:** Since star-tracker measurements compute velocity from the spacecraft position relative to the stars, the computations can be noisy, or jittery, which is why IRUs are employed for velocity measurements. The noise levels were within manufacturing specifications, but our high-performance spacecraft attitude-control system was sufficiently sensitive to think the noise was velocity error and tried to control it when it should have ignored it. This led to the excessive thruster firings and propellant consumption.

LCROSS formally declared a spacecraft emergency with NASA's Deep Space Network, given the spacecraft's precarious condition. With this declaration, all missions using the Deep Space Network have an understanding to yield their communications pass time to a mission in danger. This enabled LCROSS to have near-continuous communication with the ground, limited only by geometric constraints of the spacecraft's position relative to ground stations on Earth.

As it turned out, one of those outages was again coming, so we needed to put some protections in place just ten hours after

Photo Credit: NASA/Jack Pfaller

LCROSS and LRO are installed inside their fairing.

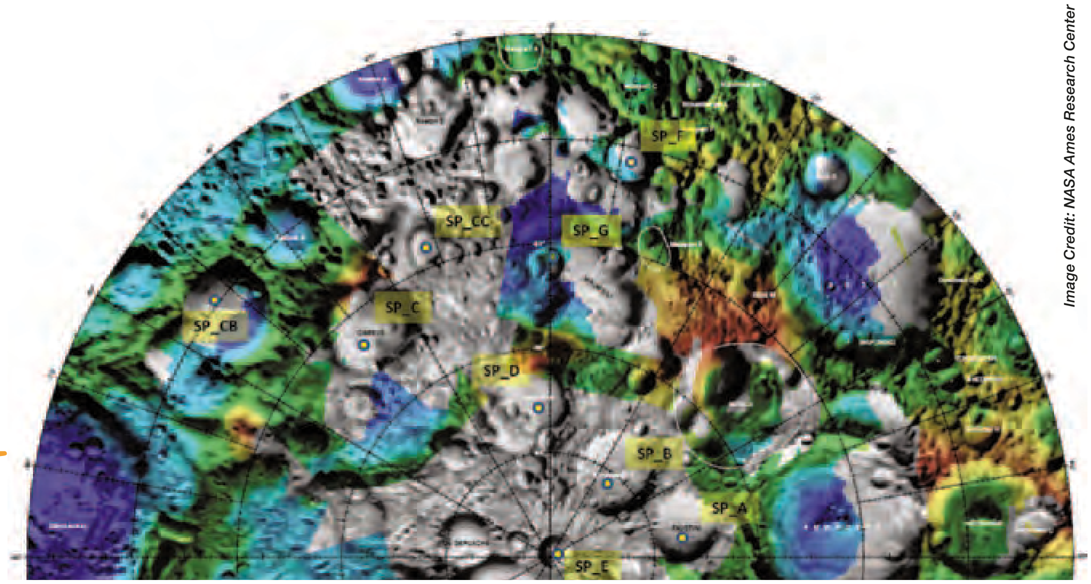


Image Credit: NASA Ames Research Center

LCROSS candidate impact craters.

discovering the anomaly. Our plan was to update the persistency with which the IRU fault was monitored so a spurious fault would not throw us into another costly propellant-consumption situation. Then we went dark again and crossed our fingers.

From Anomaly to Recovery

When communications were reestablished, we discovered there had been no further incident. We had made it through, but this was the beginning of a new operational environment for LCROSS as we moved from anomaly to recovery. This required serious triage. Here were the steps we took:

1. **Stop the bleeding.** The mission is over if you cannot stop the elevated rate of consumption of a finite resource like propellant. Electrical power can be renewed through solar arrays, but there is no mid-air refueling of spacecraft propellant. We needed to stop the propellant consumption ASAP.
2. **Make it through the night.** We needed to survive upcoming known communication outages caused by orbital geometries. We needed a way for the spacecraft to monitor when excessive firing occurred and prevent further consumption *automatically*.
3. **Ensure long-term health.** Once you are out of imminent danger, how do you ensure finishing the mission? What are the tasks remaining and the risks of executing them? How far do you go with analysis, simulations, and other risk-mitigation means? At what point does the risk of human error become greater than the technical risk associated with the spacecraft?
4. **Address the root cause (if you can).** Discover the specific cause for the incident. Is there anything that can be done to prevent this in the future? Is there a way to fix it, or only ways to avoid the circumstances that led to it?

The Project Manager's Role

Along with this triage process, the operations team's most important job, the project manager takes on a new series of responsibilities when a mission has a "bad day."

Inform and Manage the Stakeholders

Understandably, stakeholders get very engaged after an anomaly. They want to help ensure the mission. The morning of the anomaly, I followed established procedures to call the various stakeholders and inform them of what had happened. Shortly after those notifications went out, the Ames center director and most of his directors arrived at the ops control room with bags of breakfast food and drinks, a gesture much appreciated by the team. And we were grateful that leadership understood the team needed to be given room to work.

I provided frequent stakeholder updates on findings and progress, in person and via e-mail for the broader agency audience, with a brief daily status teleconference by the MOM. E-mail updates were nearly hourly in the beginning, dropping to updates at shift changes near the end of our emergency. My deputy project manager and I tag teamed to cover shifts in the mission ops control room, writing a summary and publishing it to the stakeholders at shift changes, keeping the stakeholders informed and comfortable.

Protect the Team from External Distraction

The LCROSS team was of course attempting to get back to more normal operations as soon as feasible after the anomaly. Center management demanded that additional controls be put in place to protect the remainder of the spacecraft's propellant; however, this challenged the team at a time when they were stressed and fatigued—our staffing plan was not designed to support 24-7 operations. It is the project manager's job to try to manage stakeholders to a consistent level of risk tolerance, despite the strong drive to eliminate future risk, which is not possible. This mission had grown to be very important to many, but reason and balance needed to prevail.

Steer Parties Away from Hunting for the Guilty

Once you stop the bleeding, questions naturally begin to surface about why the anomaly occurred. These queries, while important to understanding your continuing risk, should not distract the team from focusing their attention on continuing the mission. I had to push back on this questioning to prevent the team from getting frustrated or distracted.

Handle the Press

When a spacecraft experiences an anomaly, you have to be available to the press. The traditional media want to know all the details and can turn against you if they suspect you are holding back; openness is important. The blogosphere is different in that their "facts" come from unknown sources and their conclusions are sometimes based on personal agendas. We handled the press with frequent phone interviews and updates to the project web page. I conducted about ten phone interviews in two days.

Watch for Things Getting Complicated

After the anomaly, engineers worked through the data and invented responses, but engineers (like me) are predisposed to solving problems and have a tendency to create complex, multilayer solutions to stomp out the risk of reoccurrence. Discussions would work their way from one incremental fix to another, arriving at complex fixes and patches that would move the team far from its operations training and might not be testable. This complexity growth actually *grows risk* that the system will become so sophisticated it will be prone to operator error or create unforeseen interactions. In the heat of battle, there needs to be someone who keeps an eye on the risk of the solution. There were a couple of times when I would ask, "Do we need to go that far, or can we live with just the first corrective measure?" We would usually agree we could accept the residual risk after addressing the

Photo Credit: NASA/Dimitri Gerondidakis

On Launch Complex 41, the Lunar Reconnaissance Orbiter and LCROSS are moved into the mobile service tower.

(Left to right) John Marmie, Jack Boyd, Lewis Braxton III, Tina Panontin (standing), Pete Worden, and Chuck Duff celebrate LCROSS's separation from the Centaur upper stage.

Photo Credit: NASA/Eric James

principal problem. Missions have been lost because smart people did well-intended things that made problems worse.

Watch Operations Console Staffing

Because the LCROSS team was small, we had the project systems engineer staff the systems engineering console station. The project systems engineer would take one shift, and his deputy would staff the other shift. The idea seemed sensible—why not put your most competent systems engineer right in the middle of the action? I later realized that having your project systems engineer on the console removes him from his normal responsibilities—that you still need. Yes, you benefit from having your lead systems engineer monitoring the spacecraft, but he needs to sleep as well and is less able to participate in important assessment and planning activities, making him unavailable to advise you with his technical assessments and recommendations. I would not organize staff this way again.

Watch for Crew Fatigue

Hardworking, dedicated people get tired. Our cost-capped mission was not designed for post-anomaly staffing demands. A small number of people were covering an extraordinary number of hours. Their work was impressive, but fatigue inevitably sets in. You need to balance attacking technical problems with the growing operational risks associated with fatigue. I saw heads bobbing while on console as people fought back sleep; I saw people struggle to complete thoughts during shift-handover discussions. There was also growing stress at home for many who were working difficult hours. It was essential to remediate the problem as soon as possible.

Meeting the Challenge of the Bad Day

The LCROSS team behaved remarkably through its bad day. The triage process was exactly the right mix of urgency and focus, which comes from many, many operational rehearsals where the team trains for what is supposed to happen and even what is not supposed to happen. Of course, you cannot afford to spend unending money training for a low-cost mission, which means you need to focus not on the specifics of what could go wrong, but on your behavior and process when something goes wrong.

The project manager has many responsibilities when a bad day happens. You will depend on individual and team capabilities, training, and roles in ways that are hard to describe. You know that you must trust the team's abilities and judgment, but also watch for signs, both within the team and outside, of good intentions yielding problematic results. You must be reasonable and evenhanded, understanding that you cannot eliminate risk. The bad day is a time when a mission team shows what it is really made of. The LCROSS team earned its stripes on its bad day and through the end of what became an amazingly successful mission, redefining mankind's understanding of the moon—at a bargain price. ●

DANIEL ANDREWS has managed diverse and eclectic projects at NASA for twenty-four years, including the risk-tolerant pathfinder, LCROSS. Favorite motto: "Take calculated risks. Be willing to change course. Keep moving."

FROM THE SOVIET UNION TO NASA:
An Intern's Journey

BY ALINA ZATER

Photo courtesy Alina Zater

My name is Alina Zater, and I'm a senior at American Public University, where I'm soon to earn a bachelor of science in space studies.

Photo courtesy Alina Zater

I was born in Ukraine (the former Soviet Union) to a family through which a deep and inspiring passion for the space industry has coursed like fire from grandfather to uncle, mother, and into me. For nearly twenty-three years, I've been a naturalized U.S. citizen, and it's been here in America where, through hard work fueled by an insatiable hunger, my long-held dreams to be a part of the space industry and the NASA family have begun to see the light of day.

The fire in my grandfather's heart ignited a hunger to reach for the heavens long before Russia began to develop its space agency. He worked as a test pilot in the Soviet Union's military, where his life epitomized the idea of "pushing the envelope." He was known to speculate about how it would be to one day fly among the stars. During such moments, the light from the fire within gleamed in his eyes. His work eventually included being responsible for capability testing of spacesuits and new hardware. The tests provided valuable information that contributed greatly to the Soviet space program.

My grandfather's fire passed like a torch to his son, my uncle, igniting in him an overwhelming desire to become a cosmonaut. My uncle studied hard in school and, to the great joy of his family, was accepted into the Cosmonaut Training Program. Unfortunately, a debilitating fear of heights eliminated him from the program. His phobia was an unconquerable obstacle to attaining his dream to fly beyond Earth's atmosphere. Unwilling to give up on his heart's desire, he completed his master's in engineering and won a position among the team responsible for building the vehicle that would deliver others to space. If he couldn't get there himself, he reasoned, he'd do all he could to get someone else there in his stead. His passionate drive and desire to succeed earned him the opportunity to work directly under Sergey Korolev, father of the Russian space program. My uncle's love for and dedication to the program brought him the honor of being considered one of Korolev's most valued engineers.

The fire then passed to my uncle's little sister, my mother, sixteen years his junior. He exposed her to the space industry when she was young, enthralling her immediately. Growing up, she had the opportunity to attend political and space-industry-related briefings and dinners. While most teenage girls collected the records or posters of pop stars, my mother collected all the cosmonaut memorabilia she could get her hands on.

Math and chemistry came naturally to her, and, though she was given an opportunity to attend the Moscow School of Engineers, my mother decided to focus on chemistry. Landing a position in the space agency's chemistry department, she worked with a team of chemists to develop the protective layer later used for all the Russian space and military rockets.

I WONDERED HOW A GIRL FROM THE FORMER SOVIET UNION COULD EVER BE ACCEPTED IN THE AMERICAN SPACE INDUSTRY.

From my mother the fire passed to me. Despite the torch's burning within my heart, as a young girl I limited myself due to a lack of confidence. I wondered how a girl from the former Soviet Union could ever be accepted in the American space industry. Even if accepted, would I have the wherewithal to succeed in such an intense field? Allowing my apprehensions to control my decision making, I pursued paths unrelated to the space industry.

That said, I did take on opportunities that presented themselves. I earned an associate of science degree in computer networking; soon after, I earned an associate of art. I married. I worked in several intellectually challenging and rewarding industries that helped mold me into the person I am today—for instance, when I trained emergency room doctors. But a lack of satisfaction left me feeling incomplete.

I could not escape a strong sense of destiny pulling me inextricably toward my heart's passion: space. The flame of my family's torch seemed to only intensify with the passage of time. All I wanted to do was pick that torch up and run with all my might.

Fate, it would seem, removed the excuses I had used to procrastinate. Like so many during these tough economic times, I found myself suddenly out of work, a result of company downsizing. Instead of seeing this event as devastating, I saw it as an opportunity to give my dream a chance. With the unconditional, loving support of my husband and family, I went back to school to earn an advanced degree in space studies.

When researching where to enroll, I found the American Public University System, a 100-percent online school with a space studies program. Intrigued but cautious, I called to inquire further. I spoke with Dr. Ford, the director of the information technology and science department. His availability and his passion for the space industry and the university's program served as an accelerant to my own passion and removed concerns I may have had about matriculating with an online-only university.

I enrolled and started courses the very next semester, a decision that's proven every day since to be one of the most rewarding I've ever made. And considering my love for this country, the gift of opportunity it provides for all of us to obtain our dreams, I find it an honor to be a part of a university with such a fitting name.

Now I'm only three classes away from graduation. Since I started this journey during the spring 2011 term, I had the life-impacting privilege to be accepted into and complete an internship at the Johnson Space Center in Houston. Sponsored by NASA's largest nationwide internship program, the Undergraduate Student Research Program, I was assigned to the distance learning team in the Mission Operations Directorate (MOD) Spaceflight Training Management Office. The distance learning team develops a next-generation online learning experience for astronauts, flight controllers, and instructors. My

While most teenage girls collected the records or posters of pop stars, my mother collected all the cosmonaut memorabilia she could get her hands on.

And from here … the future: as big and unlimited with opportunity for discovery as space itself.

Photo courtesy Alina Zater

mentor, Valerie Gordon, says, "Spaceflight training is a complex, heavily integrated activity, requiring efficiency in both planning and execution to meet flight dates and timely certification requirements for crew and MOD personnel." The goal of this project is to provide on-demand training. To accomplish this goal, the distance learning team converts classroom content into a fully web-based environment, creating interactive, media-rich lectures and multimedia presentations. Students are able to access training content at any time, assisting them in gaining and maintaining proficiency of both technical and soft skills required for spacecraft mission operations.

Arriving at MOD, my first assignment was to learn four separate lesson-development programs, of which three were new to the entire team. As I became comfortable with the programs, I contributed improvement insights and guidance for their future use. Additionally, I performed ongoing configuration control of available lessons, ensuring that the programs presented up-to-date material and all technological aspects of the lessons worked properly.

In the beginning, I received and successfully completed a number of small projects, allowing me to foster credibility and trust with my mentors. My hard work paved the way to an incredible opportunity to lead the development effort of a key product for the distance-learning department and the Spaceflight Training Management Office. I directed the development of a cutting-edge, interactive, online-based training lesson that now serves as a prototype for introducing the current technological capabilities of our department. The prototype combined several traditional classroom lessons into one distance-learning course.

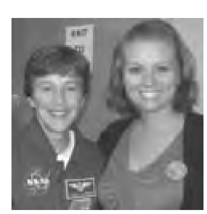
I worked closely with subject-matter experts to ensure that the progress of the lesson development adhered to a planned time frame, achieving completion in time for the exhibit at the end of my spring term. My enthusiasm for this industry and passion for my work assisted in me being nominated for and winning the "Outstanding Intern" award of spring 2011.

My experience at Johnson was life changing. The people and their knowledge of and passion for the industry provided an experience that solidified my dream into reality. The successes of my internship have boosted my confidence and stoked the passion within me. It's a passion shared with kindred spirits among a community of people who have become friends and my extended family.

I believe my drive for excellence in my school work, the successes of my NASA internship, and my passion have contributed to earning my second, current internship opportunity, which I recently began at the Kennedy Space Center, working for the Academy of Program/Project and Engineering Leadership in the Academy Center for Excellence.

And from here … the future: as big and unlimited with opportunity for discovery as space itself. ●

ALINA ZATER is a student of American Public University Systems and is pursuing a bachelor's degree in space studies. She is currently completing her second internship at NASA with the Academy of Program/Project and Engineering Leadership after a successful spring internship at Johnson Space Center, where she won the "Outstanding Intern" award for her accomplishments.



INTERNATIONAL LIFE SUPPORT

BY KERRY ELLIS

Supplying oxygen is only one of many life-support necessities for human spaceflight, but it's obviously one of the most vital. The main oxygen-generation system aboard the International Space Station has a backup system to ensure breathable air is always available. It is known by various names: the solid-fuel oxygen generator, or SFOG; Vika; and TGK, an acronym for the Russian name of the system. In September 1999, one year before Expedition 1 was to launch the first crew to station for an extended duration, the TGK was undergoing urgent testing in Moscow because of a life-threatening accident.

Photo Credit: NASA

Astronaut Edward T. Lu, Expedition 7 NASA ISS science officer and flight engineer, eats a meal in the Zvezda service module on the station. The TGK system can be seen in the upper left without the ceramic mitigation screen in place.

Photo Credit: NASA

Cosmonaut Sergei K. Krikalev works with the European Space Agency Matroshka radiation experiment in the Zvezda service module of the International Space Station. In the upper right of the foreground is the TGK backup oxygen system, with the ceramic mitigation screen in place.

Originally designed by the Russian Federal Space Agency, Roscosmos, the TGK provided additional oxygen for the Mir space station when more than three people were on board. It created oxygen by igniting a solid, oxygen-rich compound within a canister, commonly referred to as a "candle." About the size of a fat spray can, one candle contains nearly a liter of lithium perchlorate and, when burned, could provide enough oxygen for one crewmember for one day. The same system exists on civilian aircraft, using smaller candles per row to provide oxygen if those yellow masks pop out from the overhead compartment.

Since the TGK had been tested and proven, first by the Russian space agency and then by NASA when plans for the International Space Station (ISS) assembly were being drawn up, the newly formed international team agreed it was the best supplemental-oxygen system available. During the assembly process, most of the TGK system—renamed the SFOG within NASA—launched to the ISS.

In February 1997, a TGK candle aboard Mir malfunctioned and burst into flame. The metal tube that contained the reactive, oxygen-producing chemicals inside the candle began to burn in the increased oxygen concentration, launching globules of molten, flaming metal into zero gravity that splattered onto the opposite bulkhead. The fire was a "raging blowtorch," according to American astronaut Jerry Linenger, who was on board during the accident. "I've never seen smoke spread like it did on Mir," he said.

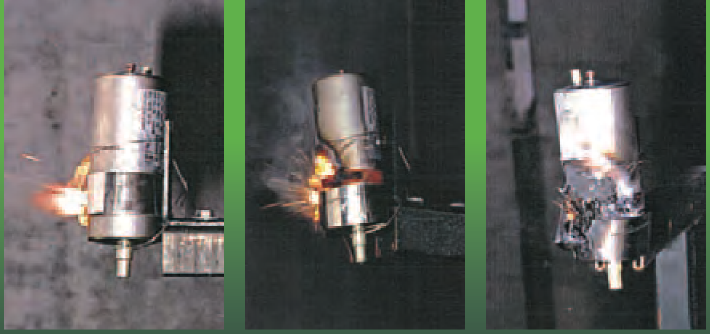
Crewmembers used three fire extinguishers to put out the fire, adding clouds of steam to the smoke filling the cabin. Russian cosmonaut Aleksandr Lazutkin recalled the accident in a BBC documentary: "When I saw the ship was full of smoke, my natural reaction was to want to open a window. And then I was truly afraid for the first time. You can't escape the smoke. You can't just open a window to ventilate the room."

Those involved in the still-developing ISS immediately shared the fear of the system having a similar accident aboard station, and both NASA and Roscosmos began their own investigations. Since all evidence of what had caused the mishap had burned during the incident, those on the ground had no definitive proof of what had gone wrong.

Meeting in Moscow

In the two years following the accident, after testing other options and designing their own alternative, NASA determined the TGK was still the best option available for the backup oxygen system. During that time, Russia worked to improve the safety of the candles and to develop a fire-resistant screen to help mitigate a fire in case another candle malfunctioned. To learn more about their improvements and mitigation efforts, NASA sent a team to Moscow.

David Urban, a microgravity scientist from Glenn Research Center, and Harold Beeson, an expert on materials flammability



After igniting a contaminated candle, a fire begins and progresses (from left to right) to a flame jet, then slows down until the fire stops.

in high-oxygen conditions from White Sands Test Facility, arrived as part of that team in August 1999. Frank Buzzard, who was then the ISS chief engineer, paved the way for the new collaboration to go as smoothly as possible.

"The culture there is very different than NASA," said Urban, "things that are beyond the language. In a NASA meeting, you would have a printed copy of PowerPoint slides in front of you. In Moscow, a question would be asked, and one piece of paper would come out of a folder to circulate around the table and then go back."

There was also a delicate political balance to maintain. "You didn't want to be the ugly American that's standing back and saying, 'You had a failed system,'" Beeson explained. "We wanted to make sure that we could build the team that was trying to solve this problem, with everybody's focus on the problem and not on assigning blame."

"We had to convince them that we were there to work with them and not there to shoot the system down," added Urban. Part of showing their support for all the work the Russians had done was to refer to the system by its original Russian acronym, TGK, instead of the NASA acronym, SFOG.

The team needed to collaborate well, and quickly. The remainder of the TGK system and additional candles were already on board the first Progress spacecraft to supply the ISS.

In an attempt to foster good relationships at the outset, the NASA contingent would invite their Russian teammates to lunch each day. "It took us a week to get them to let us eat with them," recalled Urban. The first day the NASA team arrived, the Russians said they should plan for lunch and recommended a restaurant. "We all loaded up into the van when lunchtime came and pulled up outside the restaurant. We get out, and none of them come in. Fortunately, astronaut Sandy Magnus was there, who spoke more Russian than the rest of us, so she helped us interpret."

Urban and Beeson quickly learned that the restaurant was not affordable for their Russian teammates, but the Russians were unwilling to take their NASA colleagues to their cafeteria. A few days later, they visited a remote testing site. "The guy who ran the site had been to NASA in Cleveland, so he was more comfortable with us, and we went to the cafeteria," said Urban. "That was great."

"When we actually went to their cafeteria and were able to eat with them, sit down with them, that helped," added Beeson. "A meal is always a good thing to share."

The working relationship among the team swiftly improved after that. Urban explained, "We'd built a familiarity, they were relaxing, we had spent some time together and communicated during meetings."

The plan that then developed included the Russian team preparing four TGK cassettes designed to ignite while NASA's White Sands Test Facility would make several copies of a TGK simulator that could be burned up in testing. The Russians would provide a test facility, the protective screen, and support staff to operate the experiments. White Sands had to create a simulator that captured the major features of the TGK and would interface with the Russian system. Paralleling these decisions were discussions about providing support analysis of the heat and product released from an event of this type. This would allow them to more easily share the results of their respective testing.

"Everybody came to understand that this event was something that could happen again," said Beeson. Because most of the TGK was already in space and limited funds prevented Russia from building an on-the-ground fixture for testing, NASA would build the test system and Russia would provide the candles and fire-mitigation screen they had developed. In one month, they would bring the pieces together to see how the modified TGK performed.

Testing with Limited Time

NASA's team had a little over one month to design, build, test, and ship a TGK test unit to Moscow. Since the original TGK evidence had burned up on Mir, NASA's microgravity and combustion experts had to first recreate the accident as best they could. This would allow them to verify if the protective screen the Russians designed for the system would successfully mitigate a fire.

Russia's extensive testing after the Mir fire resulted in several theories about the cause of the accident, but the definitive cause

Photo Credit: NASA

Astronaut Jay Apt looking at a solid-fuel oxygen generator like the one that caught fire on Mir.

could never be known since the fire destroyed the evidence. "They found two techniques that would do it, and one of them they thought was more plausible than the other," explained Urban. "Either they had a small piece of material in the ignition system that was mismixed so it had more energy-producing material that would cause the reaction to run away, or they had a small amount of contamination inside the canister—such as a four-square-centimeter piece of rubber glove folded in between the interior and side wall. There were people wearing rubber gloves when making the canisters, so they believed that was the obvious cause." Using these theories provided a basis for the joint NASA–Roscosmos testing.

Once the test fixture was completed, NASA shipped it to Moscow in a 4 x 4 x 6–foot crate. "The TGK itself is not a huge unit," Beeson explained, "but we had to design and put together the test stand and holders for the canisters. We had to include a way to interface our ignition system with their canisters, and also ship all our tools and instrumentation. We needed to measure thermal levels so we could understand if their mitigation screen was getting too hot. We shipped everything, including our welding goggles, because this is molten metal burning, and you don't want to be viewing that with your naked eye."

The NASA team reunited with their Russian teammates in Moscow in mid-September, where all the pieces would finally come together for joint testing. Astronauts and cosmonauts who had experience with the TGK provided their insight as well. This included astronaut Sandy Magnus, who was assigned as a "Russian Crusader" in 1998 and had been traveling to Russia to support hardware testing and products development, and cosmonaut Aleksandr Lazutkin, who had witnessed the 1997 Mir fire. "He came in for a short period of time to view the videos of fires we had created at White Sands, and he was able to say, 'That's what that fire looked like in Mir,'" said Beeson. This helped confirm that they were creating a fire large enough and hot enough to stress the system and mitigation screen.

The screen itself was made of ceramic and provided a housing, much like a fireplace, to control any fire that might occur and contain molten metal that could fly off a burning canister. It covered the back, sides, and bottom of the system and included a front screen to prevent spatter but allow oxygen to filter through for the igniting spark required for the candle. The screen withstood the joint testing in Moscow, but the team discovered an issue with operating procedures the Russians had provided for the screen.

"The original operations concept required the astronauts to have the fireplace screen at the ready, but they wouldn't necessarily attach it unless they had a fire event," said Beeson. "We questioned that. And once we lit off the first canister, it became clear to the Russians that it was not going to be an appropriate operations concept. They saw just how much molten, burning metal was coming off the canister." As a result, the operations concept changed. Once the astronaut placed the candle in the TGK, he or she would install the screen before igniting the canister.

A little over one year later, in October 2000, Expedition 1 launched with the first crew to take up residence aboard ISS. And while the TGK system has changed a little over the years, it has not experienced a fire since its installation on the station.

A Memorable Beginning

The ISS did not have a smooth start. When the program was announced, Russia was still recovering from the social and political turmoil of *perestroika*, the United States did not have long-duration human spaceflight experience, and both countries were figuring out how to work together after the end of the Cold War. But amid such chaos, individuals from NASA and the Russian Federal Space Agency were able to create cohesive teams. Ensuring the TGK was safer and ready to sustain life aboard the biggest, newest internationally collaborative effort was just one of many instances of this teamwork.

"There's things in your career that you really remember," said Beeson. "This is one of those. I really felt like I had a direct contribution to the astronauts' safety, which is so important to us. And understanding this failure and successfully working with our international partners to mitigate it was a memorable event. We worked with a great team." ●

INTERVIEW WITH Jeffrey Hoffman

BY DON COHEN

Currently a professor in the Department of Aeronautics and Astronautics at MIT, the Massachusetts Institute of Technology, Jeffrey Hoffman flew on five shuttle missions as a NASA astronaut, including the first Hubble repair mission. He also served as NASA's European representative for four years. Don Cohen spoke with him at his office at MIT.

COHEN: You were a scientist first and then an astronaut. How did that come about?

HOFFMAN: I've been interested in space since I was a little kid. When the first astronauts began to fly, I was excited by the idea of flying in space, but I had no desire to be a military test pilot. I took an astronomy course in college, found that I liked it, and went on for a PhD in astrophysics. I was most interested in high-energy aspects of physics for two reasons. I liked the space connection, the fact that you had to go above the atmosphere. And, because we were looking at these wavelengths for the first time, you were almost guaranteed to make interesting discoveries. I was involved in the discovery and elucidation of the nature of X-ray bursts, work I did with Walter Lewin.

COHEN: And you need to get above the atmosphere to study those wavelengths?

HOFFMAN: Absolutely. For my PhD thesis, we flew gamma-ray detectors in balloons. That was before we realized that you can't do gamma-ray astronomy from balloons: you need more exposure time. Now we do it from satellites, of course. Here at MIT we had our own SAS-3—small university-class satellite—we operated out of the control room at MIT. The commands went to Goddard to send up to the satellite, but it was our satellite, and we determined what commands should be sent. I was also project scientist for the high-energy X-ray experiment on the first

THERE ARE MANY SCIENTISTS designing space experiments WHO REALLY don't appreciate THE LIMITATIONS AND ALSO SOME OF THE special opportunities THEY WOULD HAVE.

high-energy astrophysical laboratory, HEOA-1. I've always followed the space program. When I read that NASA was going to need quite a few new astronauts for the shuttle and that they were looking for scientists, engineers, and doctors, not just for test pilots, I figured, "Why not have a go?" I put in my application and was fortunate enough to be selected in the first round. I was in the first group of shuttle astronauts that showed up for work in 1978.

COHEN: Did being in space live up to your expectations?

HOFFMAN: Yes, both the physical and psychological experience *and* the interesting work that I got to do up there. I was very fortunate in having a lot of different and interesting missions to work on. My career coincided with the heyday of the Space Shuttle as a multipurpose vehicle. I was on missions that launched satellites, did medical experiments, did tethered satellites, materials sciences, and, of course, the Hubble rescue mission.

COHEN: What are the benefits of having a scientist in space?

HOFFMAN: I think the most valuable thing was the work I did with scientists on the ground preparing experiments to go into space, being able to use my understanding of the environment of the shuttle in space to help them plan experiments. I worked with scientists in many different fields. Every time I got involved in a new project, it was like being a graduate student all over again, trying to understand what they were doing. I've always felt comfortable having a foot in both the science and engineering worlds, even when I was working with sounding rockets and satellites. Being able to work in both disciplines is important. There are many scientists designing space experiments who really don't appreciate the limitations and also some of the special opportunities they would have. When you're doing laboratory science in space, the deeper your understanding of the experiment, the more likely you are to be able to recognize unusual results and take advantage of the serendipity that is a part of most laboratory science. That was very difficult in a Spacelab-type mission because everything was so tightly programmed. You had to do what you were supposed to do and then shut down that experiment and go on to the next one. We didn't have the luxury of turning people loose in the laboratory. NASA is very good at running missions: organizing an EVA [extravehicular activity] or planning for the visit of one of the supply ships. But a laboratory has to be run with flexibility, with rapid response. You need procedures, but you need the flexibility to know when to change things. That's something I hope some day we'll be able to get to in the space station.

COHEN: How did your astronaut experience help scientists who had never flown?

HOFFMAN: I was not the only one who felt it was important to get the astronaut perspective to scientists. There were a number of us—Franklin Chang-Diaz, Bonnie Dunbar, Rhea Seddon—who formed what was called the Science Support Group. We produced a movie where we went through some of the problems that people don't understand—simple things like handling fluids, for example, because people didn't plan on the unusual types of fluid behavior. Experiments can go awry because of that. And thermal control. Particularly in the early days, we lost a lot of locker experiments because of thermal problems. There is no density-driven convective cooling in weightlessness. Also things involving cabling could cause problems. Cables have a life of their own in space. You need to design systems so you can set them up and take them down without spending hours controlling all these things that are floating around. Little parts floating away can ruin your day. There are things you can do to avoid that, but you have to think of them beforehand.

COHEN: So, for various reasons, good communication between scientists and astronauts is important.

HOFFMAN: Right now, the system places as many barriers as possible between the scientists and the crew. During some of the older Russian missions—I think they still do it this way—it was a requirement that the scientists be there to talk with the crew. At least, that is what some of the Russian scientists told me. We don't allow that. A scientist has to put in a request to get something to the crew, and that has to be sent to the PAYCOM [payload command], and the PAYCOM, who is not a scientist and may not have a deep understanding of the science, has to transmit that up to the crew. It's not the way laboratories should work.

COHEN: Like a game of telephone, where you lose the message in translation.

HOFFMAN: You got it. People guard the air-to-ground loops very carefully. They don't want people getting on who don't have proper protocols. But frankly it's easier to teach a scientist how to talk over the air-to-ground loops than it is to teach a contractor or someone working at the PAYCOM console to be a scientist. Verbal communication is part of it. The training is much more important. The amount of time the crew can spend getting to know the scientists and understand the science that is supposed to be done is far more critical than the conversation back and forth.

COHEN: Do you think we're getting better at using the space station for research?

HOFFMAN: A lot of people are working very hard to increase the efficiency of research operations on the station. We're only just starting the operations phase of the space station. It took years before we really learned how to operate the shuttle efficiently. We're pushing in the right direction, but it takes time. There are cultural gaps that have to be bridged. I hope we can do it successfully. At the moment the crews are still overscheduled. I think that maybe the biggest challenge that faces the space station program, at least from the scientific point of view, is transforming the station from a construction project into a flexible, working, scientific laboratory.

COHEN: The construction is essentially finished …

HOFFMAN: Yes, but the crew is still incredibly busy taking care of the station. People are trying to figure out how to get more crew time available, and not just time on orbit. When crews trained for Spacelab missions, they spent a lot of time with the scientists. In many cases, they were personally invested in the experiments, because they had spent time in the laboratories, they knew what the scientists were trying to achieve. I think that made a big difference in the success of many Spacelab experiments. Crews are so overwhelmed with training responsibilities now—just the basic stuff you've got to do in Russia, plus learning the European module, the Japanese module, robotics training, EVA training. The crew has basically been pulled out of the kind of science training that was a part of Spacelab missions, to the detriment of space station science.

COHEN: The tradition of astronauts working closely with scientists goes back to geologists training Apollo astronauts.

HOFFMAN: And that made a huge difference. You don't get it by magic. It requires training time.

COHEN: What are the potential advantages of science in space?

HOFFMAN: In many cases, weightlessness improves the precision with which you're able to make measurements. I remember an experiment where one of the limitations in the lab was the pressure gradient in a fluid caused by gravity. In space, you have no pressure gradient so you can get an order of magnitude improvement in the precision of the measurement. I think there are planned experiments for atomic clocks up in orbit. Because you don't have atoms falling out of the field of view of the exciting lasers because of gravity, you can observe them for a much longer time and that gives you better precision. The hope is that we'll get maybe an order of magnitude improvement in our ability to measure time. Whenever we make an improvement in our ability to measure time, it ends up having technological spinoffs, GPS being the most obvious example. In other cases, you're trying to look at phenomena which flat-out don't exist on the ground. That's probably where serendipity is going to be even more important.

COHEN: What kinds experiments would you personally like to see happen at the space station?

HOFFMAN: Telling time better is probably at the top of the list for me, if only because there have been so many benefits from telling time better in the past. Demonstrating the efficacy of the station as a useful investment for our country is probably going to come from biotechnology. I was in Houston last weekend at the International Space Medicine Summit. They announced that they are reactivating the bioreactor program, which I think has a tremendous potential for health. If it turns out that this bioreactor research in orbit can lead to better vaccines and medicines and treatments, that's the sort of thing that the public will really respond to. What goes on in laboratories doesn't make the news, except when they make major discoveries. We hope there are going to be some significant discoveries from the space station.

COHEN: Would you explain how a bioreactor works?

HOFFMAN: Everyone knows about petri dishes for growing tissue cultures. You can put a little bit of substance into a petri dish to see if it has antibiotic effects, but you can't grow three-dimensional tissue, which is the way tissue exists in our body. Think of a bioreactor as a cylinder which rotates. It's filled with a liquid and you can put in nutrients as required. You put tissue in suspension in the liquid and the tissue can then grow three-dimensionally.

COHEN: And the advantage of having a bioreactor on the space station is what?

HOFFMAN: Suppose you have a bit of liver tissue. It starts to grow. As it gets bigger, it sinks toward the bottom. So you rotate the bioreactor so it's at the top again. It's continually falling through the liquid and it continues to grow. The problem is, as it gets bigger and bigger you have to rotate faster and faster to counteract the settling forces. Eventually you build up shear forces, which will rip the material apart. So there's a limit. In space, where you don't have the settling, these three-dimensional tissue cultures can be grown much bigger. That's been demonstrated. The original work was done up on the Mir station. They've actually seen vascularizaton of tissues; they've grown knee cartilage, liver cells, cancer cells. You can then use these to test drugs. If you can get good three-dimensional human tissue to test on, you could save one or two years in the development of a drug. At $100 million a year—my understanding is drug development can cost that much—that's enough to finance experiments up in space. Assuming that we can do them quickly. That's part of the other challenge I mentioned before: turning the station into a working laboratory. If the pharmaceutical company or a research university comes up with something they'd like to test and they've got to wait three years in the queue, you've lost it.

I THINK THAT MAYBE THE biggest challenge THAT FACES THE space station program, AT LEAST FROM THE SCIENTIFIC POINT OF VIEW, IS transforming THE STATION FROM A CONSTRUCTION PROJECT INTO A flexible, working, scientific laboratory.

COHEN: **Do you think the station has a role to play in future space exploration?**

HOFFMAN: I very much believe in the space station as preparation for long-duration spaceflight, and I hope we will take up that mantle again.

COHEN: **And fly to Mars some day?**

HOFFMAN: The more we learn about Mars the more fascinating a place it is in terms of geological history, potential for biology, and resources. For long-term activities on Mars, we need to be able to do ISRU, *in situ* resource utilization. All explorers have lived off the land. The first time we go there, we'll take everything we need, just like the first time we went to the moon, but for longer-term exploration we need to learn how to use the local resources. That's absolutely critical. It makes a huge difference in terms of the ultimate cost as well, if you can make your own oxygen and rocket fuel. We need to do that first on the moon. There are differences between the moon and Mars, but would we really rely on surface operations that we've never tested out on another heavenly body the first time we go to Mars? I don't think there needs to be a permanently manned moon base; I don't want to see us build another space station there. Let's remember that we can operate equipment on the moon telerobotically from the earth. The Mars rovers have to be pretty much autonomous, and when they run into problems, they have to shut down and wait for advice, whereas we can keep things running 24-7 if we want to on the moon, and periodically visit to set them up, make repairs, do whatever you have to do for operations while they're building up supplies. We need to do that before we are ready to go to Mars. We also need to develop and demonstrate the capabilities for deep-space travel. That's where visits to asteroids come in, because you don't have to land on them. We don't now have the technological capability to do entry, descent, and landing on Mars with human-class vehicles. I think we can develop at least the entry capability with experiments in the upper reaches of the earth's atmosphere, which I know NASA is thinking about, but we've never had successful demonstrations. So there's a lot that has to be done before we go to Mars. ●

The Dream Chaser: BACK TO THE FUTURE

BY JIM HODGES

The first time Mark Sirangelo saw the model on which Sierra Nevada's Dream Chaser is based, in 2005, it was in the corner of a huge hangar at NASA's Langley Research Center in Hampton, Virginia. "It was covered with dust and other things I'd probably better not mention," said Sirangelo, who heads Sierra Nevada Space Systems.

It also was in the way.

"People were moving it around to get to other things," said John Martin, part of Langley's Vehicle Analysis Branch and chief liaison between the center and Sierra Nevada. "To be honest with you, people were kind of annoyed with it. It had been there a good twelve to fifteen years."

"It" was an approximately 30-foot-long wooden model of the HL-20 ("HL" for "horizontal landing"). The model had been waiting for SpaceDev—since bought by Sierra Nevada—to use it as the basis for the company's entry in NASA's commercial crew-vehicle development sweepstakes. The winner will ferry astronauts to and from the International Space Station, replacing a service that will be performed at great cost to the United States by Russia's Soyuz now that the Space Shuttle program has ended.

Sierra Nevada has won awards totaling $130 million in two NASA commercial crew development competitions so far with Dream Chaser or—as it's still called at Langley—the HL-20. And the company has inherited a mature model with a mountain of data and pictures, along with technical advice from some of the NASA people who derived that data and took those pictures.

The HL-20 mock-up in front of Langley's hangar.

Photo Credit: NASA

Building on the Past

"A lot of people told us we needed to get a clear sheet of paper and start all over again," said Sirangelo. "We decided we didn't want to do that. We wanted to build on something."

In Dream Chaser's past is the intriguing story of how the idea for the HL-20 came to Langley in the first place. On June 3, 1982, as the Cold War was winding down, a Royal Australian P-3 Orion reconnaissance plane was patrolling in the Indian Ocean, near the Cocos Islands, when it saw a Soviet ship struggling to capture an object in the water and bring it aboard.

That object, the BOR-4, was an unmanned prototype spacecraft used to test heat-shield ideas for what the Soviets envisioned would be their space shuttle program. As the space plane bobbed in the ocean, cameras aboard the P-3 captured the scene.

"It really was a 'Keystone Kops' thing," said Del Freeman, then an engineer at Langley and involved in a NASA program to develop a space taxi at the time. He also was one of the few at the center then with a high enough security clearance to view the pictures brought to Hampton by U.S. intelligence agents.

Pictures of the BOR-4, both in the water and also being hauled aboard the ship, showed an approximate center of gravity that proved to be a starting point for Langley to "reverse engineer" an 11-inch cherrywood model that underwent helium tests in some of the center's wind tunnels. (Using helium makes high-speed testing at room temperature possible.)

More models—some bigger—were built and more tests were made. Eyes were opened.

"From day one, the thing had excellent entry characteristics, from Mach 20 down to high transonic speeds," Freeman said. "The characteristics were really good."

More tests showed that the plane had a natural trim point and needed little control surface deflection to remain stable. Wing-like fins along each side of the craft acted as a nozzle, forcing air onto a short, vertical tail.

"We realized that that little, teeny tail was in a high-dynamic position so that [it] could be smaller," Freeman said.

More tests were carried out, and the Langley engineers saw the influence of an earlier American craft, the HL-10, on the Soviet design. It had been part of NASA's "lifting body" program that began in the 1950s, then went out of vogue when the agency adopted the Space Shuttle configuration in the 1970s.

The HL-20 was funded for tests, including some involving human access and egress in which NASA's first chief technologist, Bobby Braun—then a young engineer—took part. But money waned, along with interest in a space taxi. It took some maneuvering to get funding for students from North Carolina State and North Carolina A&T to build the wooden model that Sirangelo and others from SpaceDev found in Langley's hangar that day in 2005.

After delving deeper, "we realized that the vehicle was one of the most tested and reviewed vehicles that had never flown," Sirangelo said. "Among its missions, it was initially meant to be the lifeboat to the space station."

It could be yet.

Sharing NASA's Knowledge

After taking the model and a mountain of NASA data to its Colorado facility, Sierra Nevada talked with several Langley engineers who had worked on the HL-20. A few are still at the center. Most have retired, but were eager to be involved.

"The HL-20 had the best combination: a lot of history, a lot of testing done on it," said Sirangelo. "Also, the people who worked on it are still alive and engaged, so we had a chance to get that history."

Among those people are former Langley aerodynamicist George Ware, who led the wind-tunnel testing of the HL-20, as he had the HL-10 a generation earlier. Another is Bruce Jackson, who worked on approach and landing simulations for the HL-20 and serves as a technical advisor for the Dream Chaser in those areas.

"They've taken the data from NASA and refined it," said Jackson. "They've built outlines from what we did and have conducted new wind-tunnel tests. But it's still the HL-20, with some small differences." Among them are a slightly different wing shape and a hatch that's been moved.

Sierra Nevada also has former astronaut Jim Voss, its director of special projects, working on the Dream Chaser project. "That helps because he understands the NASA side, at least from the developmental standpoint, and just how the NASA system works," Martin said.

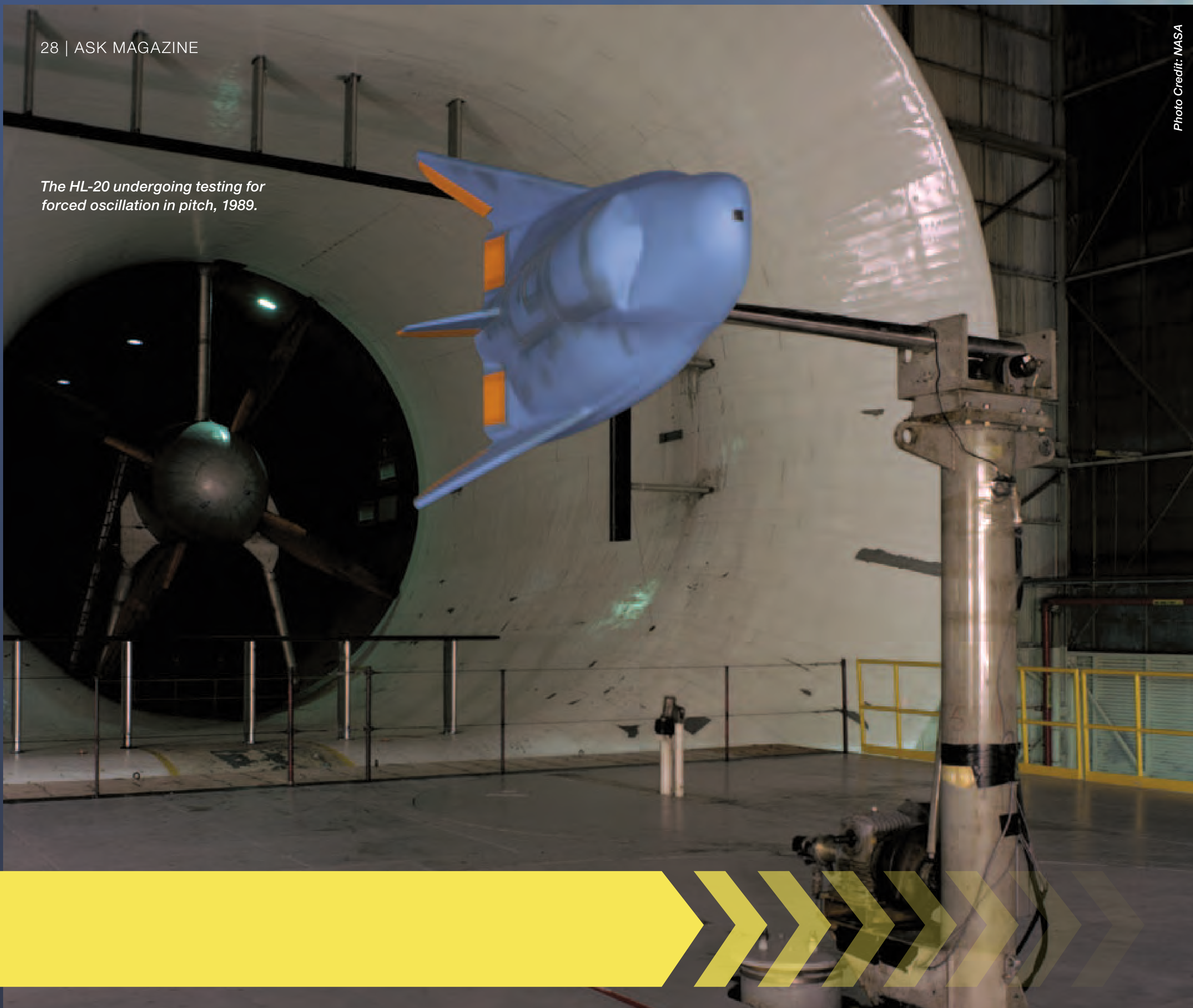
Langley engineers and retirees are involved in Sierra Nevada–funded work, such as wind-tunnel tests, liftoff tests, simulations and guidance, and navigation and control support. An aero-heating analysis is planned. They also helped develop a cockpit simulator at Sierra Nevada's facility. It largely replicates one that still exists at Langley.

"We had a full-motion simulator here, and we've managed to keep it alive over the years," said Martin. "The cockpit is generic, but the software has been used with students. We've even kept HL-20 as a problem for students, so it's been kept alive as a case study all those years."

On June 23 of this year, Sirangelo, Voss, and others from Sierra Nevada came back to Langley, took a turn on the simulator, and stayed around to host a reception for those who worked on the HL-20 all those years ago.

Photo Credit: NASA

Langley volunteers, wearing flight suits and helmets, were put through a series of tests with the craft placed both vertically and horizontally to simulate launch and landing attitudes.



The HL-20 undergoing testing for forced oscillation in pitch, 1989.

Photo Credit: NASA

"I had made a promise that if we ever got to the point where the program was beginning to go to the next level, that we would find a way to come back and thank all of those people who enabled this," Sirangelo told the group.

"You'd be surprised at how little it's changed," he added of the Dream Chaser. "The more we got into it, the more we realized how smart you all were."

Ahead is a drop test from a helicopter or airplane in late 2012, a suborbital test in 2013, and an orbital test in 2014, depending on how Dream Chaser and Sierra Nevada progress through NASA's winnowing-out process for its space taxi.

For many who worked on the HL-20 two decades ago, the Dream Chaser offers a chance to finish what they started. "Everybody who worked on it realized what an outstanding opportunity it offered NASA," Jackson said. "It ought to have a chance to fly."

Sirangelo invited the Langley engineers to Dream Chaser's first launch, offering a chance for affirmation of the HL-20.

"That would be a very rewarding feeling," Martin said. "I'm very fortunate. I'm involved in something in the very forefront of technology, but I'm riding on the shoulders of some people who made this possible."

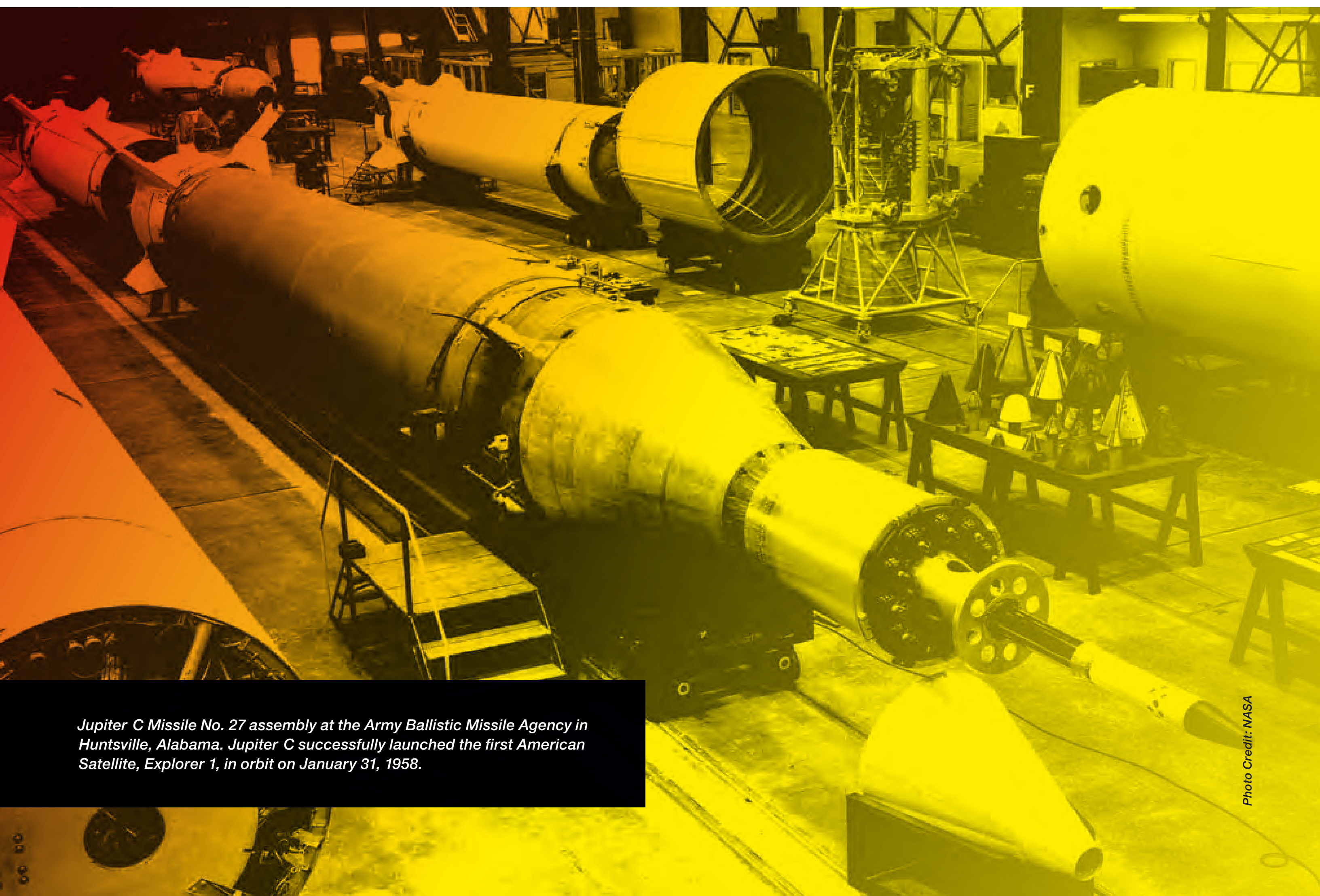
And, to some extent, Sierra Nevada is, too. ●

Former *Los Angeles Times* reporter **JIM HODGES** is managing editor/senior writer of the *Researcher News* at NASA's Langley Research Center.

Fluids Management for Affordable Spaceflight

BY RUSSEL RHODES

There is more to a ballistic rocket than hardware and software. Think about all the fluids required to power its systems. There's a lot more than "rocket fuel" involved, especially as these systems grow increasingly complex to meet the innovative demands of groundbreaking science and exploration. Not accounting for fluids early in development can create complex systems integration and management issues later on and dramatically increase operating costs. Designing for efficient fluid management will be an important element of making future spaceflight reliable and affordable.



Jupiter C Missile No. 27 assembly at the Army Ballistic Missile Agency in Huntsville, Alabama. Jupiter C successfully launched the first American Satellite, Explorer 1, in orbit on January 31, 1958.

Photo Credit: NASA

BECAUSE ROCKETS REQUIRE SUCH PRECISION EQUIPMENT, THE FLUIDS THAT POWER THEM ALSO HAVE TO BE PRECISE. THIS MEANS THE FLUIDS HAVE TO BE PURE, CAREFULLY CONTROLLED, AND VERIFIED TO MEET DESIGNERS' SPECIFICATIONS.

In the early years, flying a rocket required only propulsion fluids, a coolant, air-bearing gas for the guidance system, and sometimes hydraulic fluid for the controls system. The Jupiter rocket, for example, used only eight fluids in the mid-1950s. Compare that with the Space Shuttle, which required twenty-seven fluids (fifty-four if you include the cleaning and testing fluids involved) with 102 locations, and you can begin to see that the complexity of fluid management and the cost of preparing a vehicle for launch drastically increased in just a few decades.

Because rockets require such precision equipment, the fluids that power them also have to be precise. This means the fluids have to be pure, carefully controlled, and verified to meet designers' specifications. In the beginning, the Army Ballistic Missile Agency Missile Firing Lab—which was later transferred to NASA—relied on the air force to perform this verification. Once Kennedy Space Center was developed, NASA assumed these responsibilities, but our efforts were not organized efficiently. With little technical management oversight, each systems engineer had to ensure the fluid verification was completed for his or her particular system. This worked well enough when less than a dozen fluids were required, but our leap into human spaceflight quickly expanded the number of required fluids.

With the age of Apollo came the need for fluids for life-support systems. At the same time, launch-vehicle systems became much more complex, relying on multiple stages to push humans into space. And those different stage elements weren't required to use the same fluids. With the number of fluids growing rapidly and no integration or technical oversight of fluids management at the program level, keeping the fluids pure and the system clean quickly became a greater issue.

In one case, filters were not performing as predicted. These spacecraft filters were recleaned at Kennedy and given a 10-micron rating, but they were discharging much larger-diameter particles, which would cause component failures. During the resulting failure investigation, we discovered the filter manufacturer was performing the assembly in an uncontrolled environment, trapping contaminates in the filter. Recleaning the filters failed to remove these trapped particles, and they would end up shedding during operations to contaminate the system. This problem was resolved by having the filter manufacturer change its processes to first clean the double-Dutch-twill filter cloth with other filter parts and then assemble the filter in a clean-room environment.

The Apollo-era practice of taking fluid samples at the flight-to-ground interface when servicing operations began was another important contamination-control requirement that would have caused issues if implemented on the Space Shuttle program. Launch-vehicle personnel realized that obtaining samples at the ground interface was not a practical or safe way to verify large cryogenics systems because the launchpad area was always cleared of all personnel before servicing the vehicle. To solve this issue, they developed a technique to sample fluids in the ground-servicing container instead and then carefully control the environment when the fluids were later transferred to the flight vehicle. This approach, along with the use of a qualified final filter, proved to be a technically adequate solution and was later written into a single procurement-and-use control document. This allowed for consistency in keeping fluids clean and verified across an entire program.

Additional changes required for fluid management became more evident as NASA transitioned from Apollo to the Space Shuttle. The shuttle program was to be managed from a lead center with responsibilities divided among the NASA spaceflight centers. Because the lead center knew there would be many fluids required to support the shuttle flight system, the management team wanted visibility into and control of the procurement and use of all fluid commodities.

The result was a single document describing an integrated approach, by subsystem, to controlling all fluids used by the shuttle elements. There was never any disagreement on using a single document to provide a uniform and consistent method for

The first Space Shuttle external tank   the main propulsion test article rolls off the assembly line on September 9, 1977, at Michoud Assembly Facility in New Orleans, Louisiana. The tank contains two tanks, one for liquid hydrogen and one for liquid oxygen, and a plumbing system that supplies propellant to the main engines of the orbiter.

Photo Credit: NASA

managing all fluids, but there were differences in the approach to this task that needed to be worked out. The three prime centers got together to work through the differences and compromise on a consistent method, relying heavily on experience to inform their decisions. For example, they invited launch-vehicle operations personnel to provide insight into the discussion since they had considerable successful experience in the field.

Tight control of procurement specifications, verification procedures, subsystem cleanliness requirements, vehicle-to-ground interface filter requirements, and the requirements for verifying a filter's design and construction integrity, to name a few, were necessary due to the shuttle system's complexity. The final document not only defined requirements to help keep the very complex shuttle system free from fluid contaminants, it also established a common language to help avoid misunderstandings since every NASA center has its own unique terminology. Identifying terms such as bubble point—the minimum gas pressure (in inches of water) required to overcome surface tension at a filter's interface when it is submerged—and silting—an accumulation of minute particles sufficient to interfere with sample analysis—helped prevent misunderstandings among the team.

The shuttle Space Transportation System required fifty-four fluids in total, and each flight required servicing for twenty-seven of them located within sixteen system groups, which had between them fifty-six subsystems needing fluid service. The magnitude of managing the procurement and use of all these fluids was much greater than the Jupiter vehicle system.

Why were so many different fluids required? First of all, the shuttle system was especially complex because it had broad applications. Also, flight systems are traditionally designed with a stove-pipe mentality: each subsystem is optimized on its own for a minimum dry weight without regard to the total vehicle system.

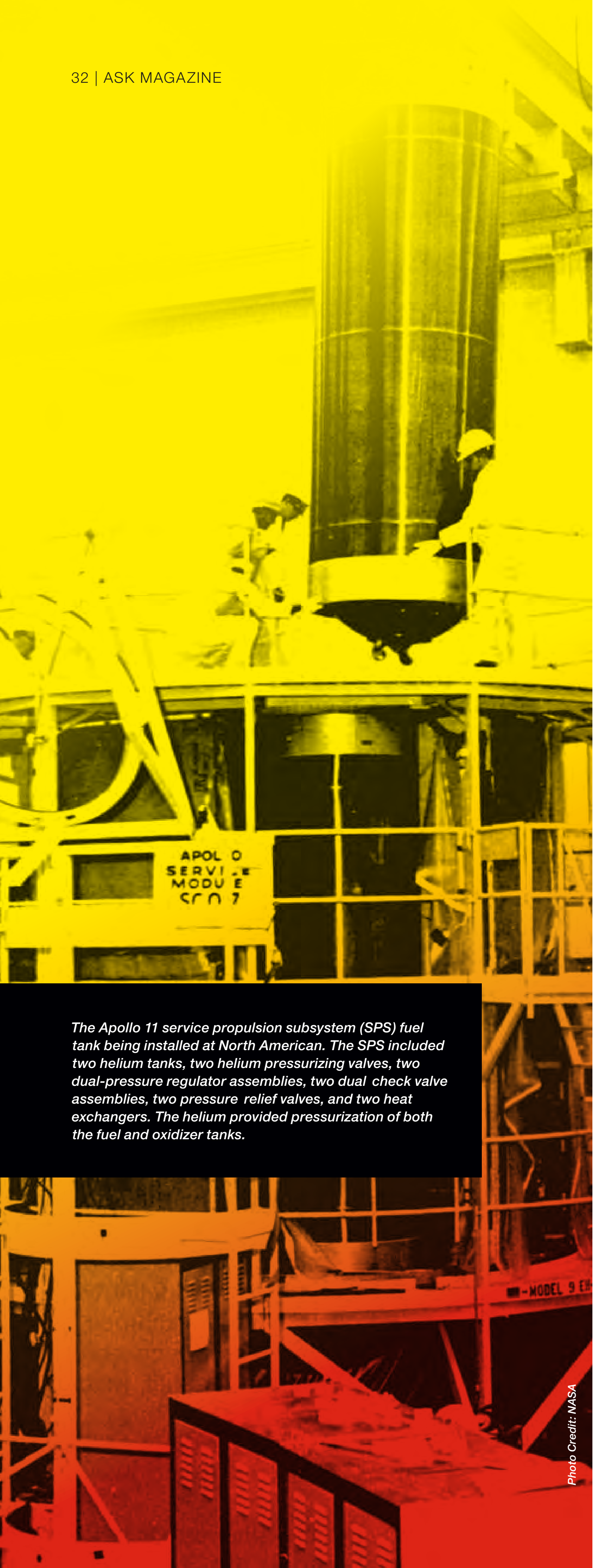
The fluid management approach to the shuttle program was very effective, but when a program requires a large number of fluids, recurring operations costs will also be large. Unique subsystems drive the requirements for many labor-intensive operations, reducing the productivity of the flight system by increasing ground-servicing time, which also increases cost. In addition to this direct cost impact, the logistical relationship among fluid management, flight hardware, and ground-servicing hardware grows increasingly complex.

For comparison, the Constellation program's expendable cargo launch vehicle, designed for fewer capabilities than shuttle, had sixteen systems identified for fluid servicing, including thirty-seven subsystems that needed fluid service every flight. During the program's preliminary design review, there were fifteen different fluids identified for servicing and twenty-two fluids that required procurement-and-use control. Many of these systems were not fully defined at this phase of the program, so the list of fluids was expected to grow.

The Ares I design team did take fluid control into consideration, planning for the booster thrust-vector control and reaction control systems (RCS), as well as the upper-stage RCS, to use a common hydrazine fluid. The fluid choice ended up being very toxic, unfortunately, but at least it was only one fluid for several propulsion functions.

Often in designing and developing these systems, the focus is on performance, optimizing each subsystem independently without regard to the integrated system. If we continue to focus only on performance, we should not expect anything different in terms of the product's affordability. If we want an affordable solution, we must change our development process.

At present, a commercial launch-vehicle supplier has provided an example of integrating common functions on a vehicle, which reduces flight-to-ground interfaces as well as overall flight and ground hardware. The vehicle stores cold helium gas on the vehicle itself, which provides flight pressurization for both the fuel and liquid-oxygen tanks. The only flight-to-ground interface required would be for filling the cold helium bottles on the vehicle. This system provides pre-pressurization for the fuel and liquid-oxygen tanks as the bottles



The Apollo 11 service propulsion subsystem (SPS) fuel tank being installed at North American. The SPS included two helium tanks, two helium pressurizing valves, two dual-pressure regulator assemblies, two dual check valve assemblies, two pressure relief valves, and two heat exchangers. The helium provided pressurization of both the fuel and oxidizer tanks.

Photo Credit: NASA

AS WE READY OURSELVES FOR THE NEXT LEAP IN SPACEFLIGHT, BOLD LEADERSHIP CAN EMPOWER PERSONNEL TO DESIGN FOR AFFORDABILITY AND SUSTAINABILITY— AS WELL AS INNOVATIVELY.

are refilled during the final phase of preflight. The NASA cargo launch vehicle also used cold helium gas to pressurize the liquid-oxygen tank during flight, but it required an additional interface to provide pre-pressurization to each of the liquid-oxygen and fuel tanks. The commercial vehicle's approach would provide considerable savings in the recurring cost of spaceflight.

With a national policy directive advising NASA to focus on improving and achieving affordability and sustainability, minimizing the total number of fluids required for launch would be one way to create substantial savings. To help achieve these savings, fluid control and servicing should be integrated into design considerations earlier on—and across an entire system, not just individual elements. Concept development should consider life-cycle cost and not just minimum dry weight. If weight removal is needed to meet performance objectives after the design architecture has been selected, designers could look at manufacturing processes or material selection for reduced dry-weight solutions. Integrating major functions could also help reduce the number of flight-to-ground interfaces that require fluid servicing for every flight, further reducing costs.

As we ready ourselves for the next leap in spaceflight, bold leadership can empower personnel to design for affordability and sustainability—as well as innovatively. Including integration design and fluid management is just one way to help achieve these objectives and make future spaceflight more affordable for government and industry alike. ●

RUSSEL RHODES has been employed for more than fifty years at Kennedy Space Center. During this time, he has been engaged in the design, development, testing, and operation of ballistic missiles and space transportation systems, and has specialized experience in space vehicle propellant loading, cryogenic, hydraulics, high-pressure gases, and other propulsion systems.

Government and Academia Study Systems-Thinking Development

BY DANIELLE WOOD, HEIDI DAVIDZ, DONNA RHODES, AND MARIA SO

How do NASA's systems engineers develop the skills they need to think effectively about the complex systems they develop? How do people outside formal systems-engineering roles improve their ability to see connections across subsystem and organizational boundaries? What can NASA management do to facilitate the development of systems thinkers in its workforce? A collaboration between NASA and a university research group addressed these challenging questions.

The questions were tackled as part of the doctoral dissertation of Heidi Davidz while she was a PhD student in the Engineering Systems Division at the Massachusetts Institute of Technology (MIT). Working under Professor Deborah Nightingale, Dr. Donna Rhodes, and other faculty, Davidz devised interview and analysis methods that approach the issue both qualitatively and quantitatively. She interviewed 205 engineers at ten organizations, primarily in the aerospace industry.

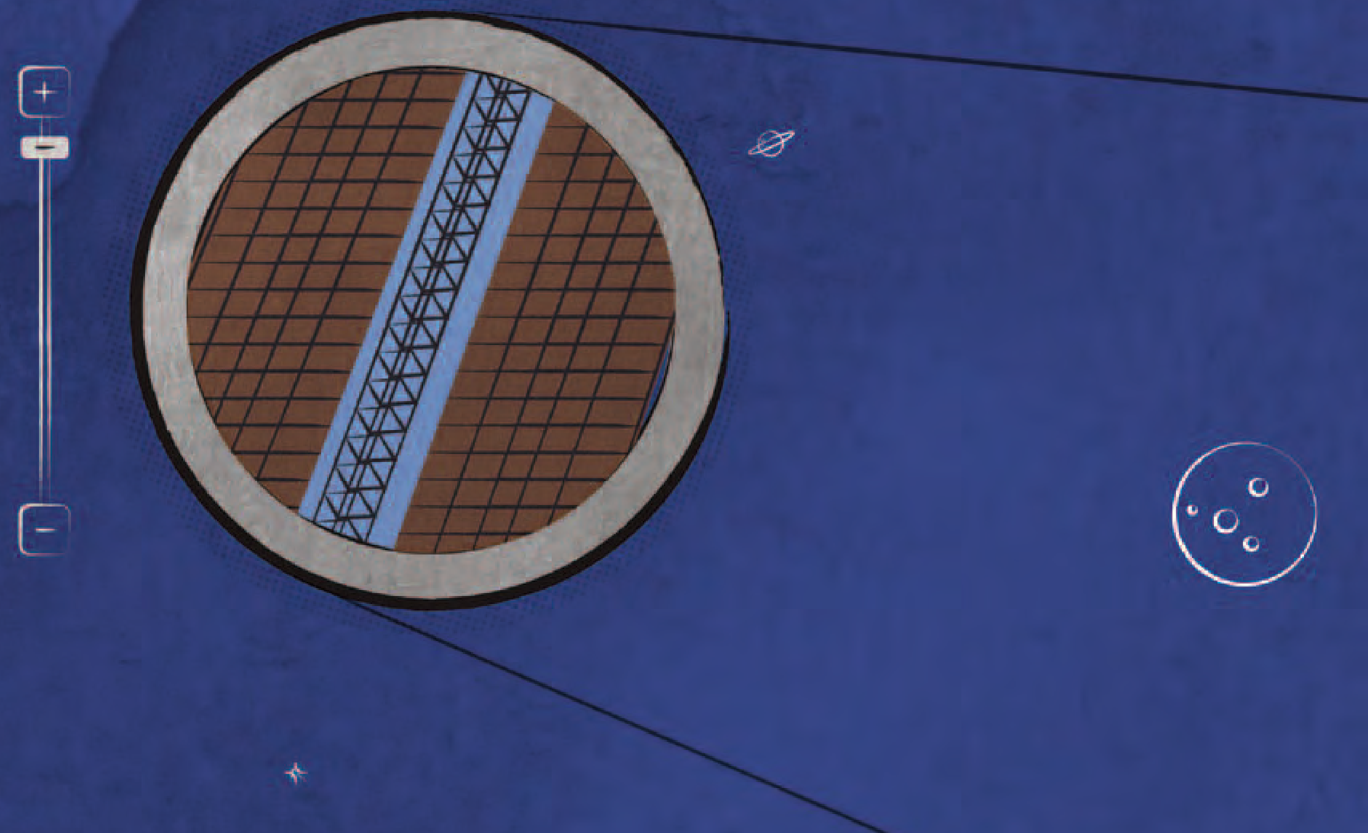
Another MIT student, Danielle Wood, used Davidz's methods to explore the development of systems thinking among engineers at NASA's Goddard Space Flight Center. Wood's project was part of a collaboration between Maria So (then chief of the Mission Systems Engineering Branch) and Dr. Rhodes of MIT's Lean Advancement initiative and Systems Engineering Advancement research initiative. As a branch chief and line manager for about fifty senior system engineers at the time, So's responsibilities included caring for the professional development of Goddard's core systems professionals. She was also involved in several NASA activities aimed at improving systems engineering methods, including participating in the NASA Systems Engineering Working Group, shaping a NASA systems-engineering leadership development program, and updating the NASA Systems Engineering Handbook.

So and Rhodes invited Wood to carry out data collection and analysis for a systems-thinking study at Goddard based on the work of Davidz. In early 2007, Wood interviewed thirty-seven Goddard employees in four categories: senior systems engineers, junior systems engineers, senior technical specialists, and expert panelists. The expert panelists were senior leaders in the systems engineering community at Goddard. The core interview questions asked participants to define systems thinking and name enablers or barriers to the development of systems thinking in engineers. The results show that at Goddard, as in other parts of the aerospace industry, the key enablers of systems-thinking development are experiential learning, personal characteristics, and environmental effects.

Experiential Learning

Davidz's doctoral study emphasized the importance of experiential learning in developing systems thinking. Interviewees from Goddard and the broader industry study cited valuable learning from both work and general life experience. A relatively high percentage of respondents (30 percent) at Goddard said that exposure to systems thinking and to the relationships between subsystems helped develop systems thinking. Specifically, they mentioned the opportunity to see other capable engineers successfully implementing systems engineering tasks. As one respondent said, "I got to work on projects where I had senior engineers who were willing to teach and who modeled the behavior that I needed to learn."

One supervisor modeled systems thinking for his team when testing and qualifying equipment. As one interviewee recalled, "He always asked about how their work would affect the whole mission." About 21 percent mentioned that it is valuable to experience a variety of roles. At Goddard, this often means rotating to various subsystems within a satellite mission team. One engineer was thankful for experience in design, testing, and project management—even when the role did not suit him.



He noted, "I tried design and realized I was not a designer." Sometimes a team leader helped engineers find new roles that were opportunities for learning. One engineer reported that her mentor "basically fired [her] off the Hubble Space Telescope project so [she] would get some experience." She eventually saw this as a favor. It was also helpful for one of the engineers to work on three small explorer satellites "in the span of eight years and see three of them launch."

Some members of the Goddard team (27 percent) gave examples of formal systems-engineering training programs, such as Goddard's SEED (Systems Engineering Education Development) and JumpStart initiatives. Engineers in the SEED program benefit from a combination of courses and rotational assignments designed to increase their exposure to the work of the overall satellite team. JumpStart, a program initiated by So, allows senior technical specialists to move directly into a systems role without formal training. Goddard interviewees also found short courses to be helpful.

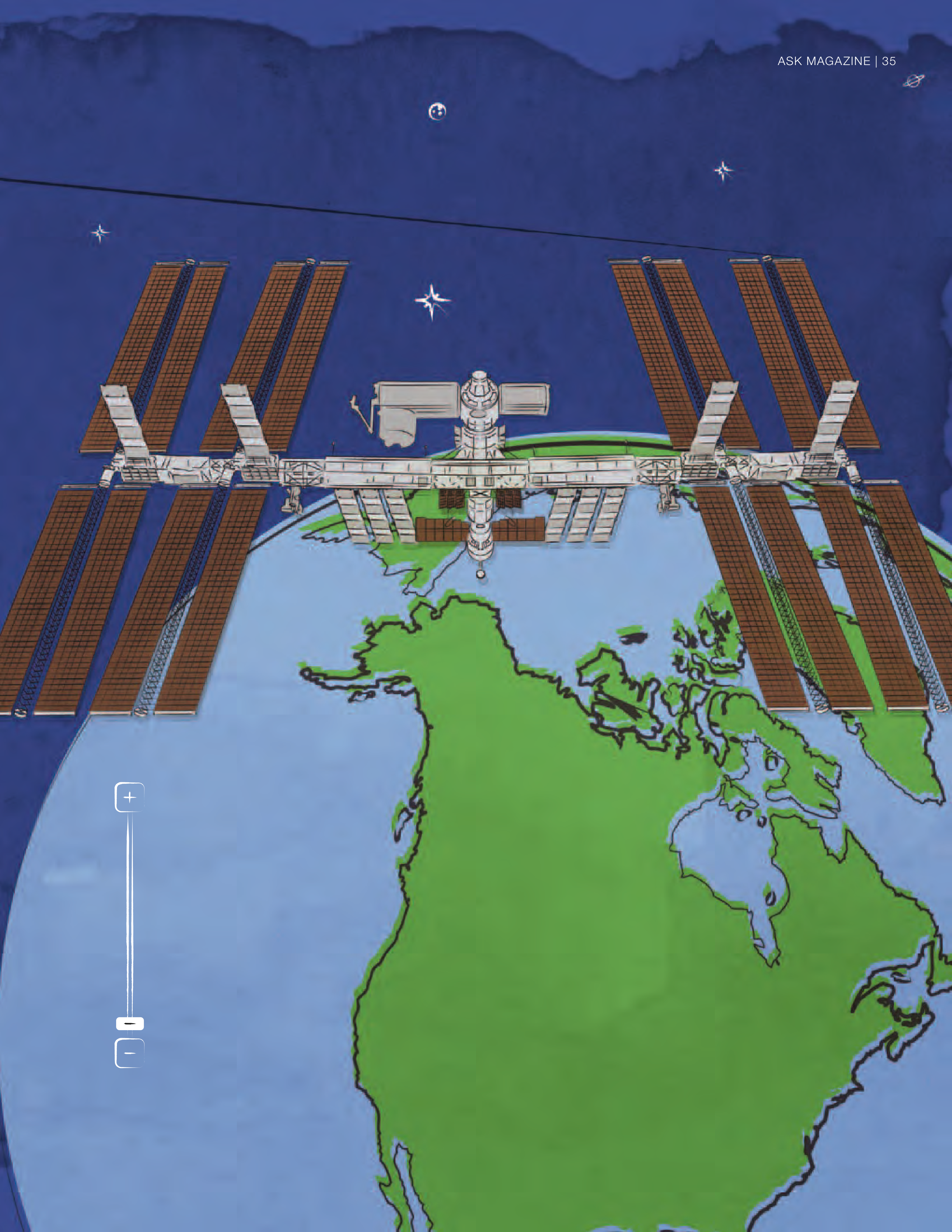
One person specifically appreciated a course because it took him away from his routine for a week, and another appreciated a course that gave guidance on opportunities to move within his organization. For one interviewee, the key aspect of a training course is working through case studies that expose engineers to areas with which they are unfamiliar "because systems engineering is about constantly running into stuff you know nothing about." Some subsystems—for instance, the onboard computer and attitude control system—naturally interface with many other systems on a satellite. Working on a team that works closely with many other teams can also help enable systems thinking (according to 15 percent of the Goddard respondents).

Recognizing the value of experiential learning to the development of systems thinking will encourage both engineers and their managers to harness opportunities for learning by experience.

Personal Characteristics

Results from the Goddard interviews supported Davidz's conclusion that personal characteristics also influence the development of systems thinking in engineers. Many of the Goddard engineers (42 percent) stressed that systems thinking develops best when a person is not prone to "bench-level" thinking about their specific subsystem or task. Some interviewees (15 percent) proposed that certain people have an innate desire and ability to do systems-level work. This may be seen as a desire to understand how the parts of a system interact (18 percent), a desire to experience new things periodically (12 percent), or a natural tendency toward big-picture thinking (36 percent). One respondent said, "I'm unhappy when I see something and don't understand it."

The Goddard team proposed that systems thinkers may also be good at interacting with people (27 poercent), communicating (21 percent), thinking logically (18 percent), and staying open to new ideas (21 percent). All these qualities are facilitated by humility and a willingness to ask questions. One person commented that in transitioning from a role as a subsystem expert to a systems engineer "you have to be willing



DAVIDZ'S RESULTS UNCOVERED SOME ISSUES THAT WERE NOT OFTEN MENTIONED BY THE GODDARD TEAM. SCHEDULE AND COST CONSTRAINTS AND MISALIGNED ORGANIZATIONAL INCENTIVES CAN BE CHALLENGES TO EXERCISING SYSTEMS THINKING.

to lose some depth in order to gain some breadth." Several ideas from the Goddard study were similar to Davidz's results, especially the concept that systems engineers often have an inherent or developed sense of curiosity and a tendency to think of the big picture. One enabler that came out of Davidz's study, not commonly mentioned at Goddard, was a tolerance for uncertainty.

Engineers and managers can use these ideas to foster systems-thinking development in their teams. People who seem to naturally have systems-thinking ability can be moved into positions with systems responsibility. People who may not have some of these innate characteristics but still need to apply systems thinking for their work may be candidates for an intervention via experiential learning. Someone in the study saw a teammate grow in this way. "One of the engineers I worked with … had been an analyst and became a subsystem lead. I would ask him questions that would cause him to go back and revisit his assumptions. Soon, he started to anticipate my questions. This is an example of training via exposure to the bigger picture."

Environmental Effects

According to the Goddard community and Davidz's doctoral results, the environment in which an engineer works also influences the development of systems thinking. Systems thinking can be enhanced by an engineer's relationships with individuals, the immediate organization, and the broader community. Close relationships with mentors and supportive management play an important role (as seen in 21 percent of Goddard responses). Mentors can help people see their own potential for systems thinking, as in the case of the interviewee who said, "The key enabler was a mission systems engineer who said that he thought I would be good as a systems engineer. I said no three times, but I'm happy I said yes." One person was thankful for a mentor who shared lessons from his own experience: "Having somebody who is twenty years more experienced than you sit down for an hour of relaxed conversation … I cannot put a value on what those lessons meant." Twelve percent of the Goddard interviewees mentioned that engineers benefit from managers who explicitly value the development of systems thinking.

Similarly, a narrow interpretation of an engineer's role by their organization discourages systems-thinking development. One interviewee recalled that people discouraged him from thinking creatively when he tried to consider possible implications to changes in his flight software: "People said things like, 'Don't worry about that aspect—that's not your area.'" Another interviewee noted that the role of a systems engineer can be limited to "clerk" if all he does is write requirements and track their completion. Such a concept does not contribute to systems-thinking development.

Systems thinking is also fostered by a surrounding community that has a systems understanding. One example is teams that invited all the subsystem leads to be part of the systems-engineering group. As some Goddard leaders noted, community understanding is aided by the growing recognition of systems engineering as a formal discipline. An organizational culture that values people with diverse experience also contributes to systems engineering skills. For example, people are better able to develop as systems thinkers when the organizational culture makes it possible to rotate among various job activities. A few people from Goddard noted that organizational pressure for engineers to stay in their disciplinary area could hinder that development.

Davidz's results uncovered some issues that were not often mentioned by the Goddard team. Schedule and cost constraints and misaligned organizational incentives can be challenges to exercising systems thinking. The Goddard expert panelists gave examples of organizational tactics to foster systems thinking that included encouraging risk taking, giving awards for systems thinking, and providing funding for exploring new ideas.

Follow-Up to the MIT–Goddard Study

The MIT team—Rhodes, Davidz, and Wood—delivered the results of the Goddard interviews to So, the Mission Systems Engineering Branch, and the director of Engineering via a report and presentation. So's team took some immediate steps to respond to the research. They saw the need to ensure that the mission systems engineers in So's organization had a variety of mission experiences and communicated with each other about their projects. So addressed this by ensuring that systems engineers served on peer-review panels to missions outside their main assignments and by establishing small discussion groups where systems engineers could share knowledge. Goddard also continued to benefit from a monthly systems-engineering seminar in which speakers from inside and outside NASA shared about issues in the field. So continued to be involved with NASA's wider activities to improve systems engineering, helping to develop the Project Management and Systems Engineering Competency Models.[1]

The *Goddard–MIT Systems Thinking Study* provided great benefits at low cost to the participants. The relationship between Goddard and MIT was mutually beneficial. Goddard's Mission Systems Engineering Branch gained from access to the expertise and research effort of MIT. Rhodes's research group was able to validate their research results by extending the scope of investigation to include government engineers. Wood, as a young master's student, profited from the exposure to NASA and the research training. She went on to follow Davidz's footsteps and pursue a PhD within MIT's Engineering Systems Division. So and Rhodes continued to find ways to work together through student projects. Another MIT student, Caroline Lamb, also worked with So's team for the data collection for her doctoral dissertation (completed in 2009). In her doctoral work, Lamb built on Davidz's definition of systems thinking and explored the dynamics of collaborative systems thinking at the team level. One of Lamb's case studies was the GOES-R satellite team at Goddard. The results of this study were featured in a paper coauthored by NASA and MIT.

As So reflected, this project brought intellectual value to Goddard's systems engineering community. It also stands as a shining example of government collaboration with academia. The government does not always have the financial or personnel resources to do exploratory studies about important issues like the development of systems thinking. Academic organizations bring expertise and effort, and benefit from access to NASA's practitioners. The team hopes that this project will be a model for future useful collaborations. ●

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MARIA SO is the deputy director for the Safety and Quality Assurance Directorate at Goddard Space Flight Center. Previously, she was with the Mission Engineering and Systems Analysis Division, first as the senior technologist, then associate branch head of the Earth Science Systems Engineering Branch, branch head of the Mission Systems Engineering Branch, and associate division chief. She is a member of the AIAA Space Systems Technical Committee, INCOSE, and IEEE.

1. See www.nasa.gov/offices/oce/appel/pm-development/pm_se_competency_framework.html.

WEATHERING IKE

BY HALEY STEPHENSON

Operating the International Space Station under normal circumstances is challenging. Doing it during the third-costliest hurricane to hit the United States is another story.

Hurricane Ike covers more than half of Cuba in this image, taken by the Expedition 17 crew aboard the International Space Station from a vantage point of 220 statute miles above Earth.

Photo Credit: NASA

Natural disasters are not usually performance-threatening obstacles to space-exploration missions—budgets and technical problems are more frequent showstoppers. On September 9, 2008, when Hurricane Ike was headed for Houston, it had been at least two decades since the last big storm hit Johnson Space Center. Ike was the third storm in four weeks to trigger an emergency response, compelling hurricane-fatigued area residents to evacuate or hunker down to ride out the storm. The last concern for most local residents was the International Space Station (ISS).

That was not the case at Johnson, which was busy with operations for ongoing missions and preparations for future ones. NASA astronaut Greg Chamitoff was aboard the ISS on Expedition 17 with two cosmonauts; Progress and Soyuz vehicles were scheduled to dock and undock from the ISS in early September; and STS-125 was slated to launch October 8 for the final servicing mission of the Hubble Space Telescope.

Ike was so huge, the crew aboard ISS was unable to fit the entire hurricane in one photo. Before it made landfall, a "Rideout" team was in place to maintain necessary operations within Johnson, which includes the ISS Mission Control Center (MCC). This meant maintaining vital servers and coordinating station operations. NASA Flight Directors Heather Rarick and Courtenay McMillan, along with their teams, were tasked with sustaining ISS operations from remote locations throughout the storm.

A Four-Week Dress Rehearsal

Emergency-response plans are regularly rehearsed, but chances to execute and learn from the real thing are fortunately few and far between. Events including September 11, 2001, and Hurricane Lili in 2002 drove the development of improved backup plans in the event that ISS operations were jeopardized.

NASA mitigates the risk of losing ISS command and control in Houston through redundancy. A smaller version of mission control in Moscow serves as one backup, though its capability is limited by the use of ground-based stations, which can only transmit data when the ISS flies over their antennae. The Backup Control Center (BCC) at Marshall Space Flight Center provides more functionality today, but it was still in the process of being configured in May 2008. Even with two backups, Johnson seeks to avoid losing Houston's capability. "Once you swing away from Houston," said Rarick, "it takes a long time and effort to swing back."

Enter the BCC Advisory Team, or BAT, a mobile squad dispatched to undisclosed locations to carry out ISS operations. This team can quickly provide command and control capability if MCC is unable to do so. It was dispatched when Ike started on its path straight for Houston (twelve days after Hurricane Gustav, which arrived twenty days after Tropical Storm Edouard). In addition, McMillan flew to Marshall to lead the BCC team. Rarick joined BAT outside Austin, Texas, to provide data and

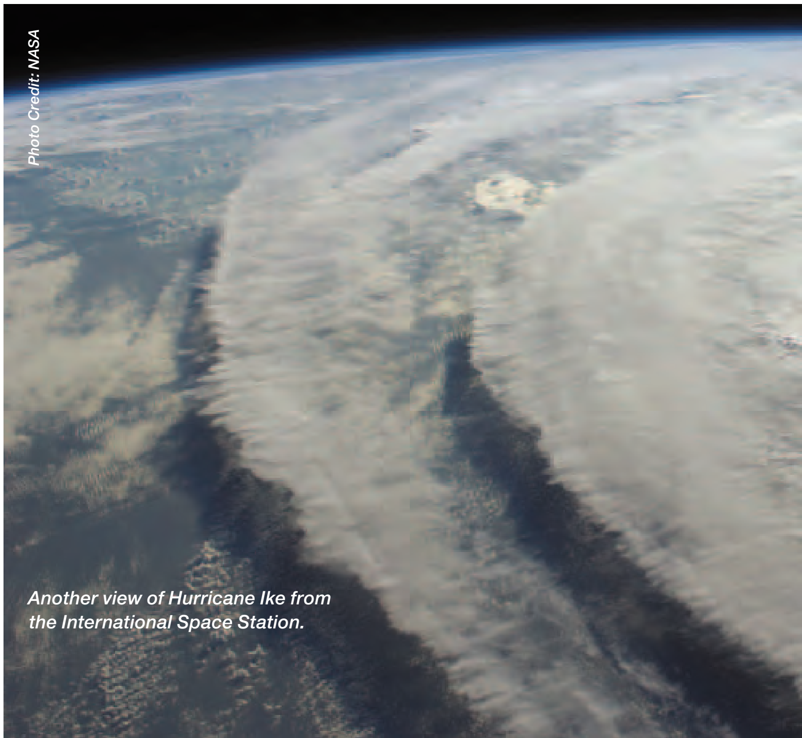


Photo Credit: NASA

Another view of Hurricane Ike from the International Space Station.

plans already in progress to support the current astronaut team on ISS and overall ISS system status and plans. “Once BAT is operational, then we just sit and wait until all MCC operations in Houston are handed over to BAT,” said Rarick.

No, No! Don’t Shut *That* One Down.

Hours before the storm struck, BAT set up their mobile mission control in a small hotel conference room. Two digital clocks, labeled “GMT” and “CST” with yellow Post-It notes, were at the front of the room. They were operational. Outside, parents, children, and pets lined the hotel halls, seeking refuge from the storm. None would have guessed what this team was doing.

The first half hour of every morning was rough. “At 8:00 a.m., the hotel guests would get up and check their e-mail, check the Internet, and then we’d drop off [lose the connection],” said Rarick, referring to the effects caused by the short surge in online traffic at the hotel. “We would have to reestablish our Internet link, and we’d be fine most of the day.”

Although BAT had a backup—using the BCC team at Marshall—the international partners didn’t. Computers in Houston were essential to providing command and control from the international partners to ISS. This was a major reason to keep Houston up and running for as long as possible. McMillan made constant calls to the hurricane Rideout team about the status of various computers and servers. Some had to be covered with plastic wrap; others had to be shut down entirely because of water leaks in the roof. Whenever Rideout delivered updates about equipment that had to be taken offline, McMillan recalled, “We’d think, ‘No, no! Not *that* one.’”

Progress on a Schedule

As Ike approached Houston, BAT had gone west, the BCC team had gone east, and a Russian Progress vehicle had launched. Progress began its journey to the station on September 10. While the vehicle didn’t dock until after the storm passed, Houston’s MCC was still not operational when it did. Ike’s timing was less than ideal.

Docking a Progress spacecraft to the ISS is a critical operation that involves conducting thermal analysis and reorienting the solar arrays, among other things. The ISS flies at an inclination of 51.6 degrees, which creates a tough thermal environment. Changes in temperature can cause structures like the solar-array longerons (the long, sturdy rods that support the arrays) and equipment positioned outside the ISS to expand or contract. “We go through larger hot and cold periods than we originally planned for some space station hardware,” explained Rarick. “So when we have to configure for a docking, we have to do thermal analysis.” This thermal analysis has to be done on a specific Houston computer.

To obtain the details needed, the thermal analysis team had to get creative. In order to communicate, the team had to relocate to an out-of-the-way coffee shop to get a Wi-Fi connection. “We had to send them the information needed to run the analysis back in a deserted office,” said Rarick. “They would get the computer up and running, do all the analysis, and tell us if the plan was thermally acceptable.”

Additionally, a Progress vehicle approaches the ISS in such a way that its thrusters can damage the solar arrays if they are not moved. But reorienting the solar arrays usually decreases the amount of energy they can acquire, which means instituting energy management procedures. Mission control powers down certain modules to conserve energy prior to an event. It is a complex maneuver, explained Rarick: “One loss of one computer and we can’t put our solar arrays in the right position.”

Preparations like prestorm covering of electronic equipment and mitigation after Ike's passage were vital to preventing major damage at Johnson Space Center. Here, workers are in the center's Mission Evaluation Room after the storm.

Photo Credit: NASA

For these events, there is always full redundancy in MCC. But the BAT did not have the necessary redundancy in its systems. At the time, BCC didn't either, but it had some redundancies that BAT didn't. BAT handed over control to McMillan. "Realistically, we were going to get into the situation eventually," said McMillan about the Progress docking, which turned out to be successful. "The fact that we got into this situation right out of the gate took a lot of us by surprise."

Space Station Aside

Station operations, computer servers, and buildings make up one part of the emergency-response plan; taking care of families, relatives, employees, children, and pets is the other. "Getting your house ready is no easy task," said Rarick. "Literally, you go through your house and say, 'What do I care about?'"

Evacuation isn't easy. Aside from two minor freeways, I-45 is the one and only major highway leading out of Houston. "Pick the wrong way, and you're still in the hurricane," said Rarick. "People get hurt, pets get lost, homes are destroyed, valuables are lost."

Most of all, Rarick and McMillan appreciated having information. "All of us were just glued watching the news, trying to figure out what was going on," recalled McMillan. "After Ike's landfall, I was incredibly impressed by how the management team, not just the management but the team as a whole, back in Houston pulled together to get information and help each other out."

Volunteer crews deployed around the community to clear driveways, cut down tree debris, share generators, or visit homes to send status reports back to families who couldn't return yet. Some areas didn't get power back for weeks. Stagnant water provided a breeding ground for mosquitoes. Dead animals had to be removed. Homes had to be salvaged and communities rebuilt.

"There was a huge effort, and it was very well organized. NASA management teams put volunteers on teams, called you, and told you where to show up and what to do," said Rarick. "It was significant. Those of us who were unable to return home were well taken care of."

Ready for the Next Time Around

Johnson Space Center (JSC) received praise for its response to the destructive storm. "The JSC team did an outstanding job of preparing prior to the storm and recovery afterwards. Through these difficult experiences, our collective knowledge was expanded," wrote Mike Coats, center director of Johnson, in a lessons-learned report on Ike.

"Most of the stuff that became lessons learned were holes that we didn't anticipate or didn't fully understand," said Rarick, "not because of a lack of preparation."

… PREPAREDNESS LEVELS HAVE PREDETERMINED SCHEDULES, BUT HURRICANES DON'T.

One of the biggest lessons Ike brought to light was about orchestrating center preparedness. Starting with Level 5 (the beginning of hurricane season in May) and ending with Level 1 (the hurricane has arrived), Johnson had choreographed the preparation of all the center's assets. These preparedness levels have predetermined schedules, but hurricanes don't.

Mission control has a large stack of evacuation checklists. "Everyone pulls out the procedure, we walk through them, and we track when they are done," Rarick explained. They are systematic and vigilant with these checklists. A problem arises when the predetermined level says it takes twenty-four to thirty-eight hours to complete, but the storm changes pace and cuts the available time to four hours. Said Rarick, "You have an expectation, and you go into work one day and you think, 'OK, we're on Level 4. How do we get to a Level 3 late today or tomorrow?' Suddenly, it's late afternoon and JSC is at Level 3, but MCC isn't."

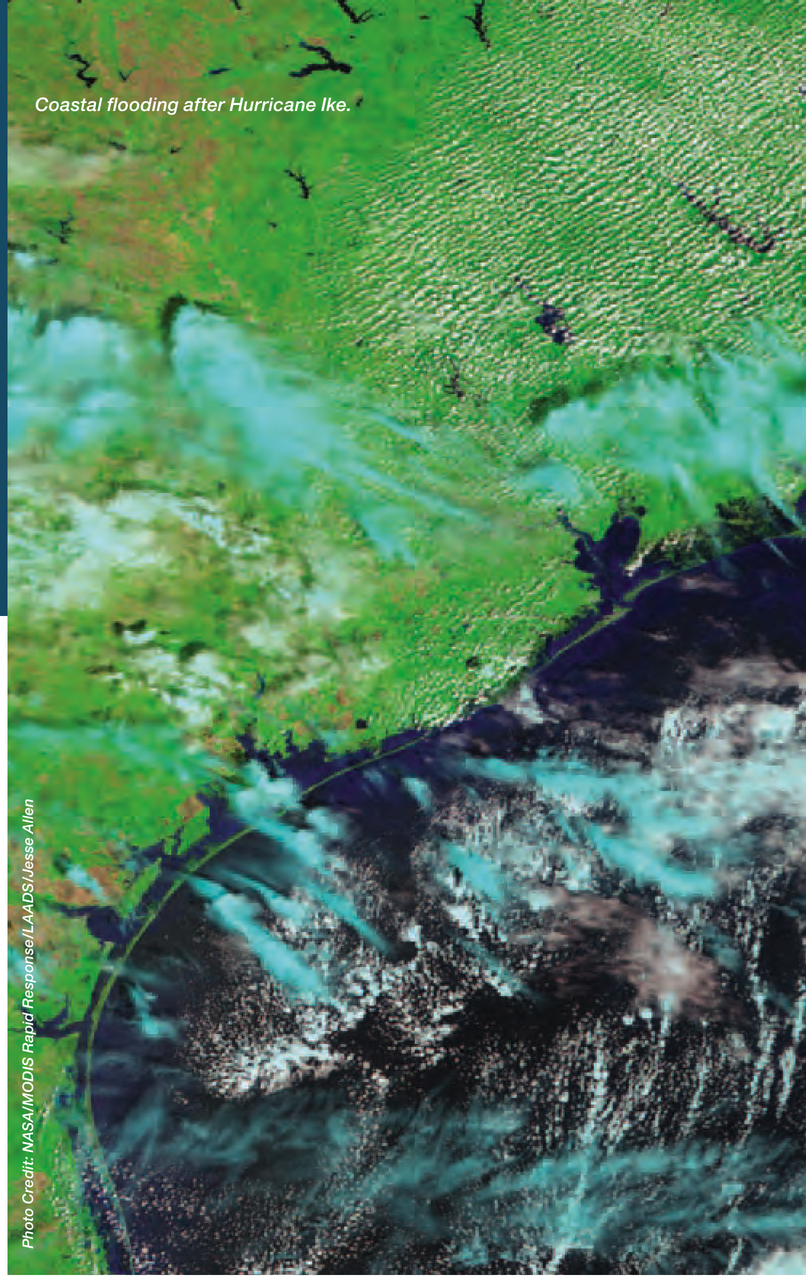
"We spent a lot of time, starting in early 2008, to really go through those procedures with the new [BCC] capabilities in mind to try to figure out what was the best way to choreograph all of that," added McMillan. "We had done that previously when we just had BAT." Even then there were things they didn't foresee. "After Ike, we went back and made some changes to the procedures because of things that we had learned," said McMillan.

Other lessons ranged from information technology and connectivity issues to maintaining employee contact information and making sure there was enough staffing. "When Ike came around, the good news was we had done this in terms of actually putting people in place," said McMillan. A team was dispatched for one night during Gustav, which diverted to Louisiana instead. The bad news, she continued, was that the "one-night Gustav" mentality was still in place when Ike hit, but the BCC team was dispatched for more than a week, supporting operations around the clock, and shift backup couldn't come fast enough. The team is now more cognizant of the importance of having enough available personnel to reduce shift length and provide relief.

While procedures for center shutdown are practiced annually, aftermath recovery was not as well developed. Tracking down the right personnel to access specific systems for contracts, funding, and procurement needed for center recovery and rehabilitation was a challenge. "It's difficult to plan for the multitude of outcomes," said Rarick.

Being adaptable and maintaining a global view of the situation was difficult but essential to everyone involved. "The exchanges that we had with the center ops folks were really interesting," said McMillan. "They really had to think about what type of information they needed to convey to center ops in order for it to mean something in terms of evacuation readiness. Those of us in space station aren't used to having to think about things like the team that's working on the roof of whichever building. Meanwhile, the center ops folks are not used to worrying about whether or not the right server is up to support a Progress docking. There were a lot of conversations where we ended up looking across the table at each other saying, 'Huh?'"

"Even though we had set up a plan and prepared for everything, it was the ability to make changes at the last minute, or accommodate whatever narrow situation you were in to find a way through it, that made it successful," said Rarick.



Coastal flooding after Hurricane Ike.

Photo Credit: NASA/MODIS Rapid Response/LAADS/Jesse Allen

Viewpoint: Putting the Science Back in Rocket Science

BY GLEN A. ROBERTSON

One hundred years from now there will exist technologies that today's science fiction writers have yet to dream of. Many of these technologies will come from theories, ideas, and concepts that are laughable today.

Modern rocketry (since 1900) came about through the innovation of people seeking new knowledge. These individuals were more scientist—creating theories of propulsion and testing hypothoses—than engineer. As rocketry moved into the space arena, this discipline of building launch vehicles became known as rocket science. But is rocket science really science?

Science refers to the disciplines and professions that acquire knowledge based on scientific methods, including the development of theories, the derivation of mathematical formulations, or the research of these theories and derivations, which provides an organized body of knowledge containing the natural laws and physical resources gained through such research.

In the early days of rocketry, all we had to go on was science. Rockets didn't exist, and the kinks of mechanical flight were still being worked out. There was no common idea of what a rocket should or could be. The field was open for interpretation and experimentation. As a result, the forms of early rockets varied widely. Some worked better than others, but as soon as one worked even a bit, its function would be tinkered with and refined, or changed outright. It entered an engineering stage.

Engineering refers to the disciplines and professions that apply scientific knowledge in order to design and implement materials, structures, machines, devices, systems, and processes that realize a desired objective and meet specified criteria (such as missions). As the physics of propulsion became more common knowledge and rocketry moved into formal long-range weaponry, government entities needed engineers to design and build rockets that could withstand the rigorous environment in which these weapons were placed.

What we needed was reliability, not creativity. The scientific portion of rocket science was slowly edged out of the definition and practice. Rocket science became a discipline of technological refinement and not one of scientific innovation. We developed a stronger mind-set to build things than to discover and advance our knowledge.

The fundamental problem of space exploration today is that spacecraft-propulsion technologies drive everything else that can be done in space. Given the current engineering mind-set, today's "rocket scientists" are encouraged to use what is known, resulting in heritage engineering. This culture forbids a realistic path to the discovery of new propulsion technologies through scientific methods. If future spaceflight is to be radically changed and improved upon, we need a new discipline to provide that path.

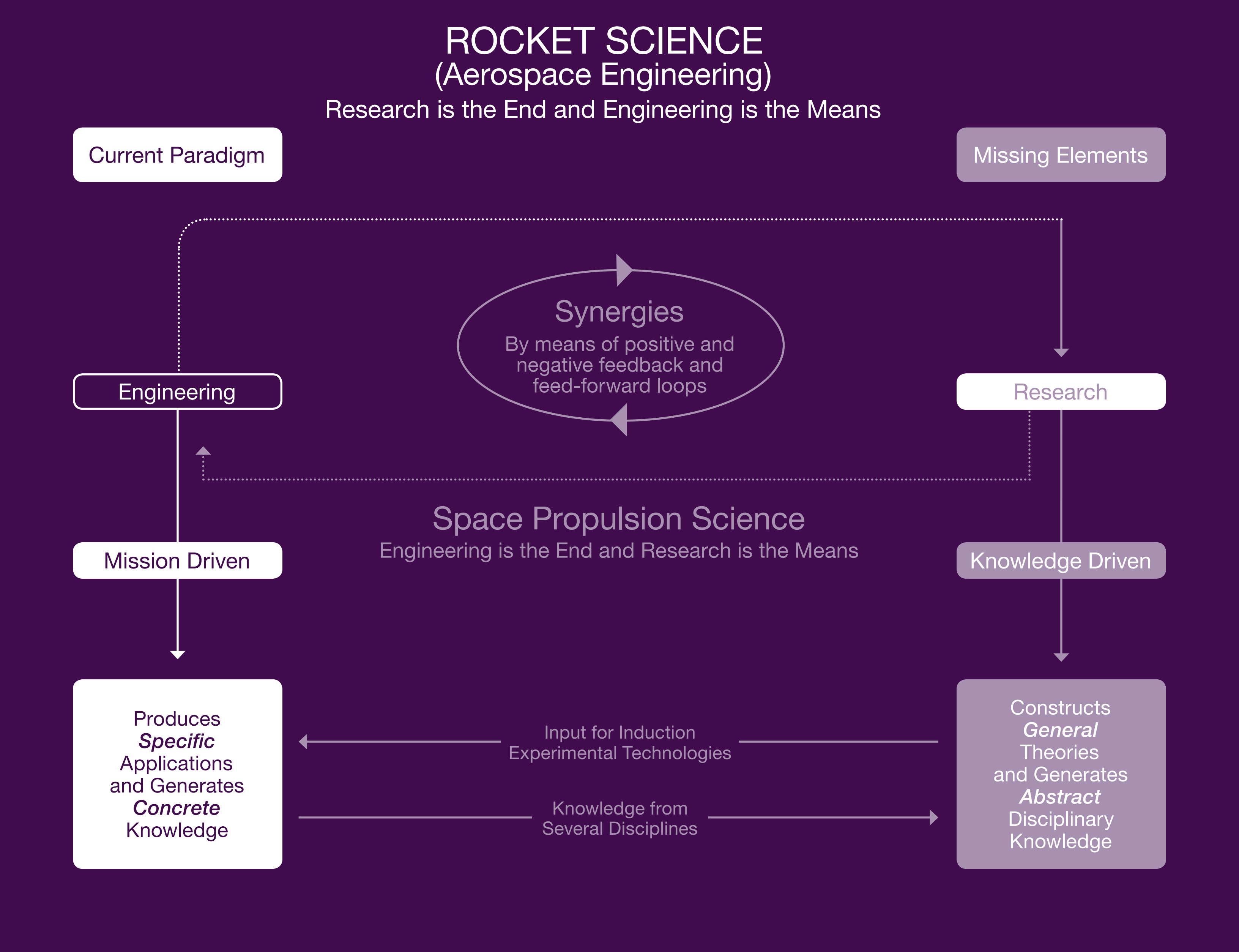
What we need is not rocket science, but space-propulsion science.

Space-propulsion science would involve developing new theories, deriving new mathematical formulations, or researching new concepts derived from these theories and derivations. The aim would be to provide scientific knowledge that engineers can use to design future launch and space vehicles. To my knowledge, this discipline—as defined here—is nonexistent in today's society, even though there are practitioners such as the Tau Zero Foundation and the Defense Advanced Research Projects Agency's 100-Year Starship Study.

This new discipline would offer a radical, counterintuitive view that technology advancement can be learned and intentionally carried out by individuals and teams with the proper knowledge base and organizational commitment. Furthermore, space-propulsion science would encourage breakthrough performances that could make an individual or organization extraordinary, rare, and gifted.

So why aren't we pursuing this, and why does a profession that uses brute force to overcome gravity not try to understand it?

TO INVENT AND DEVELOP GENUINELY INNOVATIVE PROPULSION SYSTEMS, WE NEED TO BRING IN SCIENTISTS STUDYING THE THEORIES, IDEAS, AND CONCEPTS THAT TODAY MAY SEEM FOOLISH OR IMPRACTICAL.



The answer is simple: most new ideas, concepts, and theories lack a fundamental engineering value that could be applied today and be justifiable up the current management chain. For rocket science and space-propulsion science to develop future spacecraft-propulsion systems, there needs to be a means to unite them. Such a union can be made using the similarity between design and research, as engineering is, in effect, a form of design.

Engineering and research are characterized by iterative cycles of generating ideas and testing them against reality. Scientists and engineers both use generative and evaluative thinking, but scientists stress the evaluative thinking (by logic, deduction, explicit definitions, verbal notations, etc.) while engineers focus on the generative thinking—which is usually associative, analogical, and inductive—using loose definitions supported by visual representations such as sketching, diagramming, and prototyping. A visual schematic of the most fundamental relationships between engineering and research as it applies to space propulsion is shown on the facing page, with the current paradigm shown in white and the missing elements in light purple.

From a management viewpoint, this figure implies that organizations that pursue only rocket science—especially the aerospace-engineering components—need to develop smaller, but mirroring, space-propulsion-science components. Such development should include the following elements to help ensure a successful marriage between the discplines:

- Provide funding sources outside engineering missions
- Separate line management, beginning at the directorate level, to ensure survivability
- Engage upper-management support that is sustainable through the hard times as well as the good
- Ensure mutual respect and collaboration are maintained across the engineering and research components, and allow a better future for both

This is not to say the aerospace community is not doing a great job or that engineers are not knowledge-driven, but integrating *definable* knowledge-driven entities such as space-propulsion science within an aerospace organization would provide a faster path to future propulsion technologies.

In other words, for NASA to stand out as a leader in exploring the dreams of tomorrow, the agency must support and investigate scientific-technology innovations in propulsion (and other areas). To invent and develop genuinely innovative propulsion systems, we need to bring in scientists studying the theories, ideas, and concepts that today may seem foolish or impractical. Discover one, allow engineering to develop it, then continue pursuing the next innovation.

The NASA Office of the Chief Technologist has already started down this path. Programs like the NASA Innovative Advanced Concepts may even support space-propulsion science. It is unclear whether their ideas will expand across the agency, however, without clearer organizational synergies between space-propulsion scientists and aerospace engineers.

To quote Dennis Bushnell, chief scientist of NASA's Langley Research Center, "It takes three thousand new ideas to find one good one." We must be able to investigate ideas before they can be used. We'll have new technologies when engineers are able to work on the new concepts scientists provide and turn those concepts into reality. ●

Note: This is an excerpt from Glen A. Robertson's "The Death of Rocket Science in the 21st Century," published in Physics Procedia *in late summer 2011.*

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Why Wikis at NASA?

BY JON VERVILLE, PATRICIA JONES, AND MARK ROBER

How Does a Wiki Work?

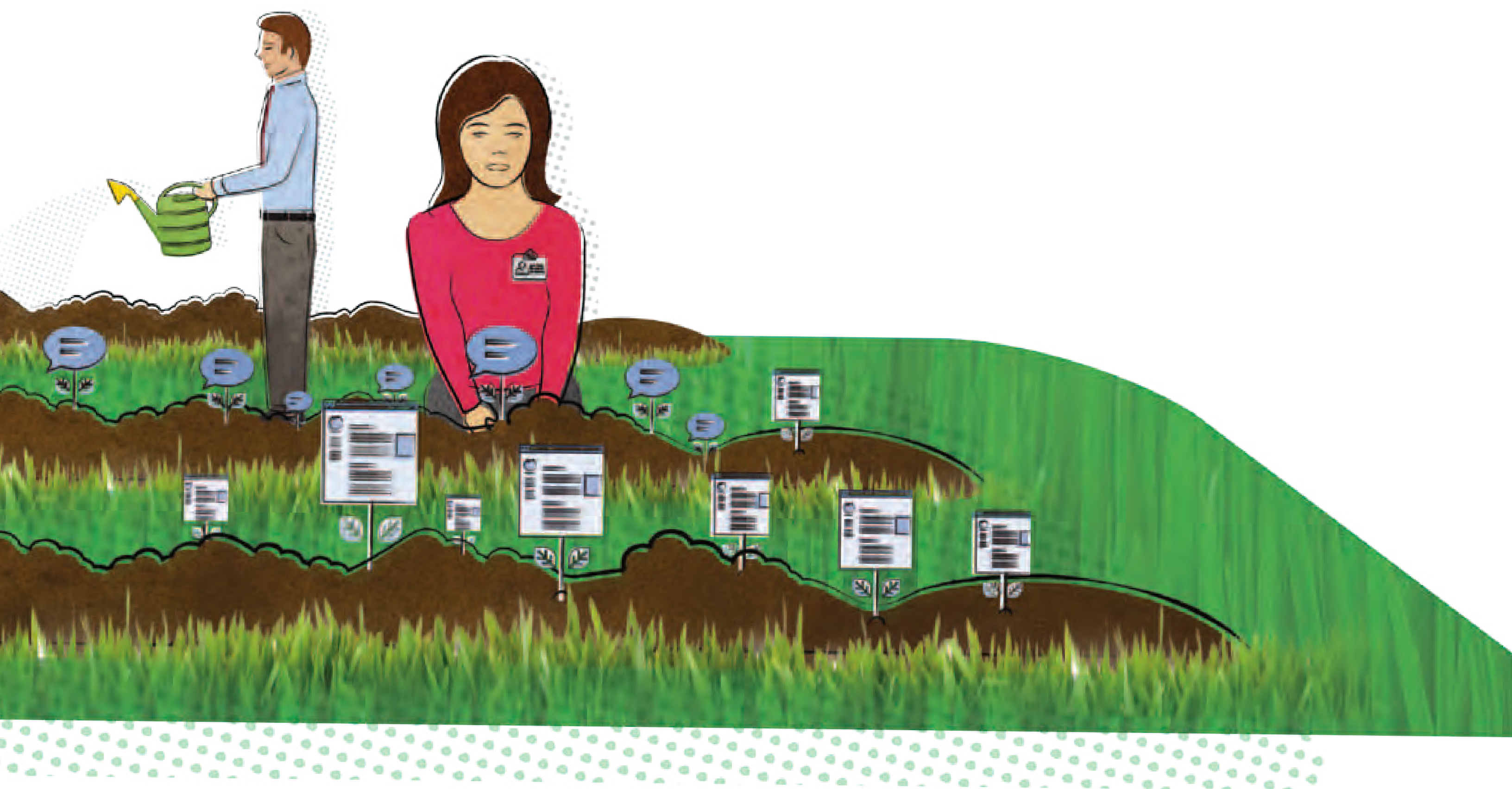
A wiki is a web site that can be edited by its users. It tracks sitewide activity (typically called "recent changes") and individual page history, provides profiles, and retains authorship information about every change. This enables community cleanup and policing of the site, generally called "wiki gardening." With a wiki, there is no need for a flurry of e-mail to go around to discover who has the most recent version; a central wiki page incorporates all the changes made along with information about when and by whom they were made.

The ability to go into a site and easily update and enhance material is the game-changing feature of wikis. Since it is done through the user's web browser, no special software needs to be installed. Of course, the openness to editing that makes wikis a powerful tool for collaboration also raises concerns. What about "contributors" who maliciously or ignorantly falsify content? That problem does occur on fully open sites like Wikipedia, but all the wikis at NASA we have encountered are open only to a NASA network. And they all require users to log in to make changes. This ensures that everyone is accountable for their activity, eliminating the Wikipedia problem.

Some Cases

The potential value and ease of use of wikis do not mean that they are readily embraced by people who have never used them before. These brief examples suggest some of the

The NASA workforce is hungry for ways to improve collaboration. Wikis can help—and are helping—to do that. These powerful tools exist at every NASA center and across many levels of organizations, from wikis running on a temporary server for a team of five to others for the benefit of an entire field center. There are grassroots, bottom-up systems, originating to meet a particular need for a specific project or group. There are top-down institutional systems, provided for the benefit of a larger organization. Among other uses, they are helping project managers promote better communication within their teams, and engineers collaboratively document the results of their work.



work that needs to be done to make them an effective tool in NASA organizations.

Goddard's AETD Wiki (go.usa.gov/8mb)

The engineering wiki within the Advanced Engineering and Technology Directorate (AETD) at Goddard Space Flight Center had humble beginnings. It started as a grassroots effort in October 2009 within a group of about thirty engineers, the Microwave and Communication Systems Branch, under the name CommWiki. The leadership of the directorate heard about the work being done and wanted to learn more about it. Along with a team of other young professionals, Jon Verville put together a slide presentation that answered the question, "If this tool were to be deployed across the directorate for all our engineers, what would it look like?" At this presentation, funding for one full-time government employee and procurement of wiki software was approved.

From the beginning, the main purpose of the AETD Wiki was to capture "information living in experts' e-mail inboxes, binders, loose papers, and brains" and enhance collaboration among engineers at Goddard. After receiving resources and developing a basic charter, the team decided that the best approach would be to choose a few suborganizations within AETD for a pilot study to gauge interest and learn how to adapt the tool to the organization. Five branches were chosen for the nine-month pilot study that ran from March to December of 2010.

These branches had very differing levels of success. Much of that difference depended on cultural factors, so we determined early on that it would be crucial to make as personal a connection as possible with each branch to identify and address these cultural factors.

One notable example was the Materials Engineering Branch (MEB). Even before the pilot officially launched, the MEB branch head, Mike Viens, had heard of the wiki. He was very enthusiastic and invited Verville to introduce the branch to the tool at the next all-hands meeting. The presentation was greeted with quite a bit of skepticism about both the utility and value of the tool, given the extra burden it could impose. During this first introduction, Verville discussed the philosophical and technical aspects of wikis. Viens continually pushed the idea of using the wiki in many different settings. His championing of the tool was tremendously important.

LEVERAGING EXISTING STORES OF INFORMATION TURNS OUT TO BE A GREAT WAY TO SEED INFORMATION INTO A WIKI.

That summer, Viens had two interns devote nearly all their time to adapting existing material to the wiki. Much of this material was in the form of a handbook, the Materials Selection Guide, that had not been updated for more than ten years. The interns designed the way the material, information, and data would be presented and cleaned it up in order to make it accessible and usable on the web.

Leveraging existing stores of information turns out to be a great way to seed information into a wiki. Once this information was posted, the branch wiki saw a large increase in activity and additional contributions. Since NASA engineers have so much information to deal with, we found that organizing this material around the way the engineers think is critical to their being able to find what is relevant to them.

When our engineering directorate needed an intranet site for hosting material, they asked Verville to show them what the wiki could do. He prototyped some pages, which is very easy in a wiki, laying out the structure of the pages and doing some basic HTML/CSS coding so that it matched the look and feel of some other pages AETD had developed. The wiki is now the place where the directorate posts all the information they wish to share internally on the web. Directorate staff now easily keep the material up to date because they no longer need to rely on web developers to make changes.

JPL Wired (go.usa.gov/8mW)

JPL Wired is a Wikipedia-style online resource customized for and written by Jet Propulsion Laboratory (JPL) employees. Even though the staged rollout to the entire lab is not complete, it is open and ready to be used by anyone at JPL. The "big picture" goal is to capture all the great information that people have stored on their hard drives, in their file cabinets, or in their heads and put it in "the cloud" so everyone can have access to it. JPL Wired has been in a beta/live mode since early 2010 and now has more than 740 articles. It has had 38,180 site visits and 157,771 article views since February 2010.

A few distinct challenges emerged from the introduction and expansion of the wiki. Some key roles are important to success. These include a wiki champion—someone in management who has the authority to push the project, to get behind it and promote its use. The champion should be a respected individual. There also need to be people who will do the day-to-day "dirty work." Also, it can be challenging to get people to edit other people's material. The culture in general is reluctant to correct others' work because people know each other (unlike Wikipedia where other editors are just another screen name). This is especially true if the original author is highly respected or considered an expert. Other users will readily change obvious things like an incorrect phone number but hesitate to edit important content. Some power users, those who will make changes, did emerge. Letting them share their stories about how it works to edit someone else's material has helped free up others.

It is not easy to maintain the grassroots culture of a wiki with management support that conveys it as something valued by the organization. Having a system that management encourages the use of yet does not stifle from oversight is a difficult balance to maintain. Management must be willing to talk about and encourage the use of a system they may not be able to control.

Keys to Wiki Success

Experiences from these case studies and others in our Wiki Case Study Library suggest some practices and principles that groups developing and supporting wikis need to consider. These are some of the most critical:

- Wikis work best when they solve a problem that is evident to most of a group.
- Wiki use needs to replace an existing work process, not add to work.
- Wikis need advocates and advertising.
- Seeding the wiki with valuable content helps jump-start the process; with a blank page, no one knows where to start.
- Gradual growth is fine, and starting small helps a core group of users become accustomed to the wiki (think pilot study).
- A wiki that serves a niche need is okay; it does not need to be all things to all people.

Any great technological or societal change requires the alignment of technology, economy, and culture. The technology must be reliable and usable; the economics of adopting it must make sense; the organization or society must be culturally ready to adopt it. Our goal is to spread the stories of managers, engineers, and scientists who have adopted wiki technology and achieved a new level of collaboration, innovation, and efficiency. Wiki technologies have proven themselves to be usable, robust, and affordable. With wikis and other collaborative technologies springing up around NASA, we believe the technological, economic, and cultural forces have aligned to make us a more highly collaborative culture. We are excited about the conversation that can develop through uniting those who read this article and have a genuine need for better collaborative technologies. Please visit our wiki at go.usa.gov/8mC and join our mailing list at nasa-wikis@lists.nasa.gov. ●

SOME NASA WIKI CASES

Here are some quotes from our case study gallery, which you can visit by following the links or using your smartphone and scanning the QR codes.

SYSTEMS WIKI, LANGLEY RESEARCH CENTER (GO.USA.GOV/8m2)

To drive adoption, the Space Mission Analysis Branch has started defining uses for which the wiki is the primary, and preferably only, documentation location, which they refer to as official uses. Once an official use is defined and enforced, system adoption occurs more rapidly as people have to use the wiki to either add or view content. For example, since Space Mission Analysis Branch leadership declared the wiki the official repository for software documentation, a gradual transition of documents has occurred.

ROBOTIC SERVICING WIKI, GODDARD SPACE FLIGHT CENTER (GO.USA.GOV/8mT)

If something on the wiki wasn't accurate, it was the subsystem lead's responsibility to make sure it was changed immediately. Team members were constantly told by the project manager to put information on the wiki; otherwise, it didn't exist to him. It was this type of top-down encouragement to use the wiki that enabled the team to see its power of collaboration. Team members that were initially reluctant came around very quickly to its uses and benefits.

RENDEZVOUS WITH AN ASTEROID

BY ANDREW CHENG

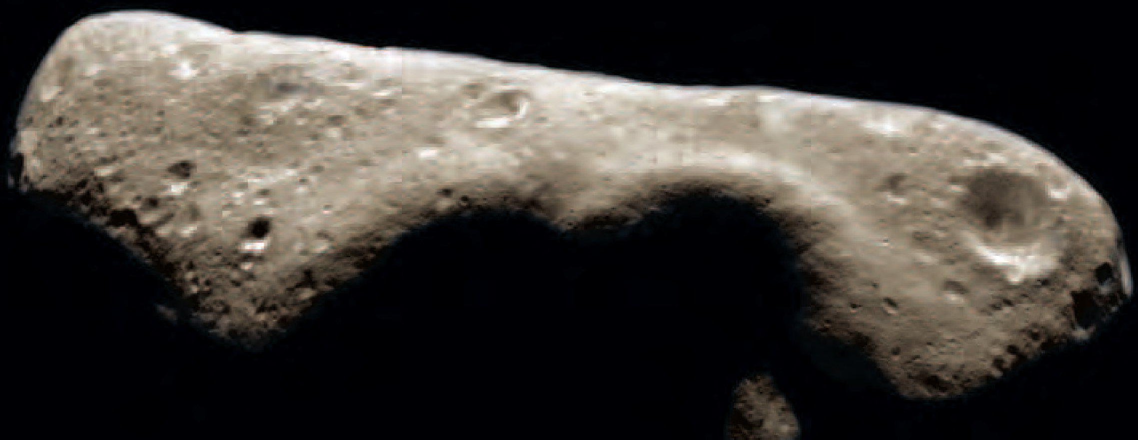


Photo Credit: NASA

This image mosaic, taken earlier in the NEAR mission, shows Eros's southern hemisphere, offering a long-distance look at the cratered terrain where the spacecraft touched down.

NEAR was the Near-Earth Asteroid Rendezvous, the first launch in NASA's Discovery Program—and the first dedicated asteroid mission. The plan was to insert the vehicle into orbit around Eros, one of the larger near-Earth asteroids. Not everything went according to plan.

NEAR was the first planetary mission by the Johns Hopkins University Applied Physics Laboratory (APL). And NEAR was probably the first NASA mission on which the Internet was widely used. I remember being called in to my management's office and being asked, "How come I don't have a file of all the letters and announcements and schedules that I sent out to my science team?"

And I said, "Oh, I'm not doing that. I'm using e-mail."

"Using e-mail?"

Not that management wasn't aware of e-mail, but, in 1993, it was a bit innovative to rely on it instead of printed paper.

NEAR was also the first mission with an open-data policy. Previous missions, like Galileo, had a one-year proprietary data period; investigators owned the data for that year and often were reluctant to let other people use it. We were the first mission that had to agree up front to an open-data policy with no proprietary period. Our scientists—in fact, the whole science community—was not used to that idea. In their view, they were investing years to build the instruments and develop the mission, and then wouldn't receive any reward for the effort.

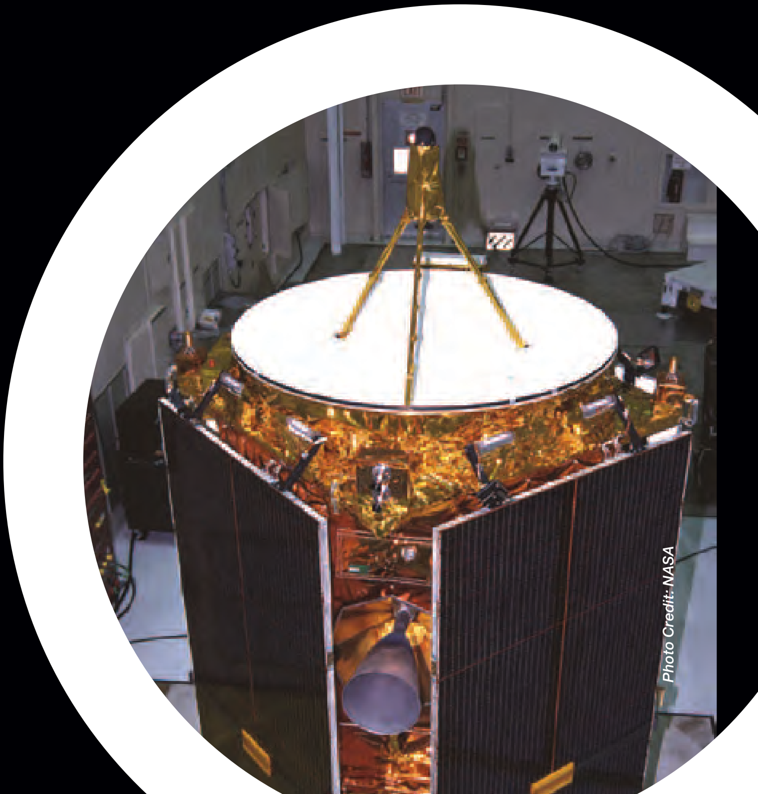
Without a proprietary period, and with the rapid release of all data, scientists anywhere in the world would be able to glean new scientific results and potentially scoop the mission investigator team. But our experience on NEAR, and subsequently on numerous other missions, alleviated this concern. Mission investigators are familiar with the mission, the instruments, and the science issues, and they have dedicated funding to analyze the data. Given those advantages, they are rarely, if ever, scooped. Science missions with open-data policies are now standard for NASA.

NEAR was also one of the first faster-better-cheaper missions. We advocated for less than thirty-six months' development, and we actually delivered in twenty-seven. We also came in below our cost cap, which was $150 million. One reason for this success is that we were able to work the way we had always done at APL, even though this was a new type of mission. That was a good lesson: you really don't want an implementing institution to completely change the way it does business. Even if nobody knew at the time what we were getting into.

When we started mission implementation in 1993, no one had any idea how to operate a spacecraft around a small body. That was the biggest leap into the unknown for NEAR. Even though we had identified the target asteroid, we didn't know its mass. Because of that, there was no way to simulate orbital operations. Things you take for granted today, in terms of simulating navigational accuracy and showing that you can obtain all the promised measurements, we couldn't do because we had no idea what the orbits were going to be like. It was worse than that, actually, because APL, it turned out, had no idea how to operate a planetary mission. We had to learn on the fly.

Our original plan was to approach the asteroid very slowly and remain at a high altitude—where irregularities in the gravitational field due to the non-spherical shape of the asteroid would be less important—until we gained enough knowledge to orbit at a low altitude, which was required for many of the key measurements we wanted to obtain. Our original plan changed.

There's folklore that says the job of a mission or program manager or project scientist is to just say no—that when requirements are set they're set. Real life is not like that. On NEAR, we had a bunch of things we agreed to that were not in our original plan. Flying by Mathilde—to explore a C-type asteroid (meaning its surface is believed to have a high concentration of carbon) for the first time and obtain great science—was one of them. We had to spend extra fuel to get there and undertake operations we had never tried before. And then we agreed to fly closer to Eros than we'd ever intended to or guaranteed we would, and finally land on the asteroid.



The NEAR spacecraft undergoing preflight preparation in the Spacecraft Assembly Encapsulation Facility-2 at Kennedy Space Center.

Image Credit: JHUAPL/Goddard SVS/NASA

High-resolution surface images and measurements made by NEAR's Laser Rangefinder have been combined into this visualization based on the derived 3-D model of the asteroid.

The final mission operations ended up being the Mathilde encounter, Earth flyby, the Eros flyby—which was supposed to be the rendezvous, but we missed—the Eros rendezvous insertion, the asteroid landing, and then the science operations.

Learning from Problems

The changes, and our first miss of the Eros rendezvous, ended up being good news. Since we were learning on the fly, we learned more the longer we flew. After we failed to get into orbit as originally planned, we flew by Eros and made preliminary measurements of its mass and shape. This information allowed us to simulate orbital operations, which we couldn't do before because the information didn't exist. When we returned to Eros in February 2000 and entered orbit, we were able to descend to a low altitude quickly and make all the planned measurements (plus more) as a result.

That first flyby taught us some tough lessons, too. When we started the second burn of the spacecraft's main bipropellant engine, it shut down after one second. This brought back memories of what happened on Mars Observer, which was lost during the second burn of its big bipropellant engine. And we didn't know what had happened on NEAR.

Miraculously, NEAR recovered twenty-seven hours later. The spacecraft contacted Earth and indicated the battery was fully charged. It was in sun-safe mode, but fine. But what actually happened?

We were only able to recover the first forty-something minutes of events that led to the shutdown. After that, we don't really know what happened because low voltage detected on the spacecraft shut off the solid-state recorders, and the data were lost. So we don't know what happened toward the end, but we understood the series of errors leading up to that time—starting with how the spacecraft was fundamentally put together. Its construction had many advantages for the mission, but it also contributed to the shutdown.

The main engine was perpendicular to the main load-bearing structure, so when we fired the engine, the structure flexed just enough to create a false reading of lateral thrust on an accelerometer, and that's what shut us down. The data by which an analyst could have predicted this would happen was actually available but had not been seen or acted on by the right people in order to set the accelerometer's threshold properly.

Once the burn was shut down, an automatic command was supposed to place the spacecraft into an Earth-pointing safe mode. It turned out that the command script programmed this maneuver to be done with thrusters, but the same script also disabled the thrusters. So the command was initiated with thrusters but used momentum wheels when the thrusters were disabled. The wheels didn't have enough torque to stop us in the proper attitude, so we overshot. And because the spacecraft didn't stabilize at the Earth-pointing attitude, it went again to a sun-pointing safe mode. It didn't stabilize immediately in this mode, either, so it began to fire its thrusters again to compensate.

In other words, our preflight testing failed to turn up several errors. APL has a deeply ingrained culture of test as you fly, fly as you test. Nevertheless, at least four errors were not turned up by our testing. The right tests—of the guidance system, the autonomy system, the operations scripts—were not done. That's what caused our problems.

Still, NEAR was designed with enough back-up systems and redundancy that it recovered from the anomalies. We don't know exactly how it recovered, but when it contacted Earth twenty-seven hours later, the battery was fully charged and the spacecraft was in a nominal state.

There were a number of lessons to be learned there: the way the ops team should operate, the way operations scripts are tested, the way the guidance system is tested before launch. We took those lessons to heart because they showed us where we needed to improve. Since then, we routinely perform the tests that would bring out issues like those experienced on NEAR, and we have not had any similar anomalies on subsequent missions.

Success

Many things also went right. Achieving the first landing on an asteroid is one of them. Another was a magnificent science return that exceeded all expectations.

Our second rendezvous burn occurred at the beginning of 2000, only a few months after the losses of the two Mars '98

These images of Eros were acquired by NEAR on February 12, 2000, during the final approach imaging sequence prior to orbit insertion.

Photo Credit: NASA

spacecraft. Things that happen to other projects can have a big effect on you, and that's exactly what happened to us. The Mars '98 missions were lost, and NEAR was about to make its second attempt to get into orbit around Eros, after screwing up the first one. You can imagine the kind of scrutiny we were under, and the interest we got from Headquarters—exactly the kind of interest you don't want.

When the time came for us to land NEAR, Headquarters said no, you're not landing the spacecraft. Instead, we were allowed to command the spacecraft to "descend to the surface," because descending to a surface does not necessarily mean a safe, soft landing.

When our ops team announced that the spacecraft was on the surface and we were still in contact with it, it took a while for that news to sink in. There was a stunned silence in the room, with all our VIPs looking around nervously. It succeeded? Yes, it did!

Because it was the first launch of the Discovery Program, everybody needed NEAR to be successful. Obviously, APL needed it because it was our first planetary mission. NASA needed it to enable the Discovery Program to establish that it was a credible, useful, important thing to do with Congress and with the Administration. The community needed it because there was great science to be had.

To help us succeed, we had strong support from Headquarters. At the time, the Discovery Program Office at Marshall Space Flight Center did not exist, so we worked directly with the program executives at Headquarters, and we had a good relationship with them. That relationship was—and is—key to helping missions proceed smoothly.

Getting the team to truly be a team is also important. Science, engineering, and management are separate disciplines, but they all have to be pulling in the same direction or you cannot succeed. Nobody can do the mission by themselves. You need the whole team. There were many instances on NEAR, from getting to launch on time and within budget to overcoming the problems that arose in flight—like the 1998 burn anomaly—where the difference between success and failure was, simply, the team.

And it isn't enough for the leadership team to know what the requirements are; your whole team needs to understand them deeply. Not only what they are literally, but where they come from and how they bear on what the mission is supposed to be doing. The subsystem leads and even the people at lower levels than that should understand them, too, because they make decisions every day. If they don't understand your requirements, they may create a problem you won't find out about for a long time. Or they may have a better solution to offer that fulfills the intent of the requirement. It must be okay to ask questions and bring up issues, even about subjects that may be outside one's discipline.

Many lessons are learned over and over again. It's not that we're stupid and never learn from the past, but when you're going to new places, doing new things, and making discoveries, you often run into old problems in new guises. Technical circumstances, political environment, external environment, and program management are always changing. So when the gremlins show up on your program, they may look different from the ones people saw before, even though they are fundamentally the same. The challenge is to recognize those similarities earlier so you can apply lessons learned to fix them with less pain than your predecessors. ●

ANDREW CHENG is the chief scientist for the Space Department at the Johns Hopkins University Applied Physics Laboratory, where he serves as the department's external liaison for space science and provides independent science advice and strategic vision to lab and department leadership. He was the project scientist for the Near-Earth Asteroid Rendezvous mission, which was the first to orbit (and eventually land on) an asteroid.

Managing Stakeholder Styles to Optimize Decision Making

BY VANIA NEVES

We make many decisions every day. Should we wait patiently for the green light to cross the street or risk an accident? Should we buy something we want or save money for the future? We also make decisions with other people. When planning a vacation with friends or family, the group has to decide on destination, route, dates, costs, transportation, hotels, and attractions. Sometimes planning is easy and the result is a pleasurable outing for everyone. At other times, some members of the group take too long to agree about the trip details; in the end, some may decide not to travel together as they realize they have different objectives. The complexity and flexibility of decision making is directly related to the objectives and characteristics of each individual.

Similar situations occur during program and project execution. Project decisions can become especially tough when they involve many people. The individual perspectives and behaviors of various stakeholders can create differences of opinion and may raise political issues and spark conflict between different organizational environments. When a project team is geographically dispersed, these complexities are likely to increase. So what can program and project managers do to avoid or minimize problems in such situations?

There is no simple formula for success, but proper communication and stakeholder management can reduce the negative effects of bad decisions or long, drawn-out decision-making processes. For complex programs and projects, mapping psychological characteristics, including decision-making styles and personal motivators, provides guidance on how and what to communicate to stakeholders.

Stakeholder Analysis

Focusing exclusively on execution rather than paying attention to removing barriers in the project environment may not bring the expected efficient and effective results. Communication gaps are one of those barriers, especially in large projects. As part of project communication planning, it is a good practice to carry out an accurate and systematic stakeholder analysis by identifying and understanding who the people involved in the project are, what their organization positions and project roles are, their contact information, how they feel about the project, what they expect, what their interests are, what their influence levels are, and whether they are internal/external, neutral, resistors, or supporters. Additionally, it is useful to identify how key decision makers are likely to respond in various situations, given their decision styles.

Understanding Stakeholder Decision Styles

Mapping likely reactions to a given situation requires a common-sense understanding on decision style models. A good approach is offered by Rowe and Boulgarides in *Managerial Decision Making: A Guide to Successful Business Decisions.*

They define decision style as the way in which a person perceives information and mentally processes it to come to a decision. Decision style reflects a person's cognitive complexity and values. Understanding stakeholder decision styles is a valuable part the stakeholder management strategy.

The Decision Style Model

Rowe and Boulgarides identify four styles: directive, analytic, conceptual, and behavioral. Individuals usually exhibit a combination of these styles, though one or more may dominate.

- **Directive:** This individual has a low tolerance for ambiguity and low cognitive complexity. The focus is on technical decisions based on little information, few alternatives, and minimal intuition, resulting in speed and adequate solutions. Generally directive individuals prefer structured and specific information given verbally.
- **Analytic:** This individual has a much greater tolerance for ambiguity than the directive one and also has a more congnitively complex personality that leads to the desire for more information and consideration of many alternatives. This style enjoys problem solving and strives for the maximum that can be achieved in a given situation. Generally, such people are not rapid decision makers; they enjoy variety and prefer written reports. They enjoy challenges and examine every detail in a situation.
- **Conceptual:** This individual has both cognitive complexity and a people orientation and tends to use data from multiple sources and consider many alternatives. Concepual decision makers have a long-range focus with high organizational commitment. Generally they are creative and can readily understand complex relationships.
- **Behavioral:** Although this individual has low cognitive complexity and uses low data input, he or she has a deep concern for the organization and people. Behavioral decision makers tend to have a short-range focus and use meetings for communicating. They provide counseling, are receptive to suggestions, persuasive, and willing to compromise.

Using stakeholder analysis, the project manager, with the project team's support, can create a stakeholder management strategy for gaining support or reducing obstacles.

Applying the Decision Style Model

Managing a virtual program team to integrate the information technology (IT) infrastructure of two merging companies provided an opportunity to confirm the value of this approach. This IT-integration program included an infrastructure project, a commercial systems project, and a manufacturing systems project. In the planning phase, several integration options were designed to fit business and technical assumptions. A lot of money was required to implement any of the options of full, medium, and minimum IT integration. (Doing nothing was the low-cost option.)

Full integration would replace all the acquired company's systems and infrastructure with the owner company's IT infrastructure. This option would produce merger benefits anticipated by the commercial units of both companies, but it was not aligned with the manufacturing unit's strategy of keeping both companies' manufacturing environments running with minimal changes and investments.

Medium integration would be similar to full integration but with no changes in manufacturing systems. This option would support expected commercial benefits and be consistent with manufacturing strategy. It would, however, mean extra work for a few people due to a lack of some process automation.

Minimum integration would apply mandatory changes to the acquired company's IT infrastructure to meet the new company's standards. It would mean faster implementation and would fit into manufacturing strategy, but it would not support expected commercial benefits.

The decision-making process to select the integration option was as difficult as the program execution. Having these clearly defined steps and requirements was essential to our success:

- A robust merge-and-acquisitions framework. This made the team aware of the steps to follow and how to contact subject-matter experts to provide guidance when needed.
- Clear definitions of roles and responsibilities. This kept the team committed to and focused on program goals.
- Mapping stakeholders' expectations and motivations and

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identifying the decision makers were critical to support the stakeholder management strategy.
- As specified in the communication plan, we held regular team virtual meetings tailored for different audiences.
- All required technical and functional specialists were invited to support the design for the integration.
- Workshops with business and technical teams from both companies were held for gathering business requirements and identifying key risks for the integration.
- Integration options and budgets were submitted to senior management for approval.

Given the program's complexity, the budget required, and the decision's impact on the business of both companies, new stakeholders from higher levels of the organization joined the program approval committee partway through the process. As they were not familiar with the project's history, some of them asked for new integration options based on new assumptions. It became clear that the decision-making process would take longer than expected.

The program approval process would have been an endless journey if we had not adjusted our communications to respond to these new demands. Using the decision style model, I mapped the potential dominant decision styles and updated the program stakeholder management strategy. Before the final session for program approval, we held individual and group meetings and teleconferences tailored to the stakeholders' interests and influences on the project. To the overall presentation with the integration options and rationale for each of them, we added additional appropriate information and adjusted emphasis to match stakeholder styles. The majority of senior stakeholders had conceptual, analytic, and directive decision styles.

The main concern of the stakeholders with an analytic style was understanding the financial impacts in detail. Our supporting materials were therefore related to on-time costs, ongoing costs, and the net present value of each integration option.

For stakeholders with a directive style, who were concerned about understanding overall integration scenarios in a concise and objective way, we provided a matrix and summary that went straight to the point. We showed integration level, scope, pros and cons, risk impact, and costs for each option.

The stakeholders with a conceptual style were concerned about financial impact as well, but their questions also addressed long-term benefits, risks, and impact on both the organizations and their people. For them, in addition to the big picture provided by the matrix with a summary of integration options, we used supporting material with long-term effects, such as the high risks of implementing a minimum integration or doing nothing. Those options would not give the acquired company the benefits of the owner company network and services, so although low or no investment would be done in the short term, in the medium term they would need additional budget to remediate their IT environment. In addition, the new company's business would not benefit from up-to-date technology.

In the end, senior management approved the medium integration option proposed by the program team. They agreed that the preferred integration strategy was the most cost-effective option and aligned with the owner company's IT target architecture, which would support both commercial requirements and future manufacturing strategies. Like a group that works to decide on a joint plan for a trip, these executives only reached a common decision when the advantages, disadvantages, and risks involved were communicated in ways that matched their decision styles.

In other words, we were successful because we were able to adjust communication channels and messages to match stakeholders' behaviors and interests. We accelerated and improved the decision-making process by giving stakeholders information in the ways they could best process it. ●

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The Knowledge Notebook

Indicators

BY LAURENCE PRUSAK

How do you evaluate a situation quickly—in seconds or minutes? Do you think it through systematically, evaluating the evidence at hand, weighing all the inputs and coming to a coherent and cohesive conclusion? Probably not, unless what goes on inside your head is a lot different from what goes on in mine. We all make speedy judgments of many kinds when we first visit a new country, enter a company or agency new to us, or visit a project team. So how do we do it? What goes into quick evaluations that retain their force for longer than we might care to admit?

How we make these judgments is, and has been for quite a while, the subject of much speculation and even some science. But one aspect of the issue mostly missing from this literature is useful to think about: the role of indicators.

Indicators come in all forms and styles and are often used to explain past events (lagging indicators) or to predict future ones (leading indicators). Many people use them in their work, be it in market research, economic planning, logistics, project analysis, or other professions. But we all use them every day—often without thinking about which ones we have adopted or developed and how we use them. Let's say you are visiting a friend in his office. As you walk over to his desk or cubicle you undoubtedly register how his colleagues are dressed, how old they are and how busy they appear to be, the lighting and noise level, the age and aesthetics of the office furniture, and maybe twenty other factors you take in in a few seconds. What do you do with all these inputs? Research shows that you interpret these indicators and use them to make a judgment based on your own values, experiences, and general knowledge of the place. It all happens in a few seconds and usually occurs semiconsciously or unconsciously.

I have asked several consultant friends of mine how long it takes them to arrive at some sort of conclusion about a company they are visiting for the first time. The consensus from these experienced folk is anywhere from five to twenty minutes. And they almost always find that these first impressions prove to be correct over time.

The indicators we deploy are self-generated and of course subject to change with our own changing views and circumstances. One indicator that I frequently use to judge a country's intellectual level is how many and what sort of books are being sold at its airports. I have been positively impressed by small Indian cities that had selections of real literature and serious social science and political commentary. These books sold well, too. The opposite experience has happened to me in even large cities in Latin America where the offerings, even in Spanish, are thin and dispiriting.

When I recently mentioned this to a colleague, however, he pointed out that although Boston, where I live, has a reasonably active intellectual environment, there are no good bookstores in the airport. The books for sale at airport newsstands are what you might expect them to be almost anywhere—escapist fare to while away the hours of a long flight.

A little digging showed me that in India the books are subsidized by the government and so airport shops have financial encouragement to offer them. In Boston, one vendor runs all the newsstands and has little incentive to offer anything but bland thrillers and romances. The same is true at Heathrow in London, by the way. And in Latin

America, in general, serious logistical and financial factors work against a more varied diet of books being offered.

So, in this case, my indicator was not really a valid clue to the local intellectual level. I needed to re-evaluate it in light of what I learned about why the shops offered what they did.

This sort of thing is interesting (I think) but probably not earthshaking. But some faulty indicators do make a huge difference and can cause considerable damage. For instance, governments base policies on indicators such as Gross National Product, household income, and other such mechanisms that can be quite misleading. A most interesting example is the fact that personal wealth, long seen as an indicator of happiness, just isn't. It turns out that there is little correlation between the two. Nigeria turns out to be a pretty happy place compared with the United States, whose wealth per capita dwarfs it. Another example in the news nearly every day is using the amount of money spent on health or schooling as indicators of good results (even though some countries that spend half of what the United States spends per capita on health have demonstrably better results).

What is the value of all this to project managers, engineers, and others not in the business of setting government policy? It leads to the idea that we all need to recognize the indicators we use to make judgments and question the assumptions they are based on to avoid or reduce errors that can harm our work and our personal lives. What seems obvious often isn't even true. Taking a conscious and critical look at how you make judgments can help make your judgments better. ●

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What's Next for NASA?

The end of the Space Shuttle program marks the end of an era for NASA, but not the end of NASA's ambitious goals for space exploration, aeronautics, science, and technology. In July, NASA Administrator Charles Bolden spoke about the agency's future: "As a former astronaut and the current NASA Administrator, I'm here to tell you that American leadership in space will continue for at least the next half-century because we have laid the foundation for success—and failure is not an option." To learn more about NASA's future and to hear Administrator Bolden's full speech, visit www.nasa.gov/about/whats_next.html.

International Space Apps Challenge

Demonstrating its commitment to the Open Government Partnership, NASA will work with space agencies around the world to coordinate an International Space Apps Challenge to be held in 2012 that will encourage scientists and citizens from all seven continents—and in space—to create, build, and invent new solutions to address challenges of global importance. The unique challenges posed by spaceflight often result in solutions to issues we see every day on Earth, and developing these solutions can be expedited when leveraging the expertise and entrepreneurial spirit of those outside government institutions. To learn more about the upcoming challenge, visit open.nasa.gov/appschallenge.

NASA Internships

Want to learn more about NASA from the inside? NASA offers several educational opportunities for students, including internships at its field centers. To find out more about available internships, visit www.nasa.gov/offices/education/programs/descriptions/Students-rd.html. Have ideas about additional educational opportunities you'd like to see NASA offer? Submit them at www.nasa.gov/offices/education/about/ideas.html.

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