National Aeronautics and Space Administration

NASA KNOWLEDGE JOURNAL

Office of the Chief Knowledge Officer

"To capture and share what we know now to ensure mission success."

NASA KNOWLEDGE **JOURNAL**

ISSUE NO. 3

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On the cover: While preparing to expand human presence deeper into the solar system, Astronaut Tracy Caldwell Dyson looks back at Earth through a window in the Cupola of the International Space Station. The artist's depiction features NASA's Space Launch System and a human on Mars.

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WELCOME FROM

NASA's Chief Engineer

NASA's Office of the Chief Engineer and the Human Exploration and Operations Mission Directorate partnered with Marshall Space Flight Center and the University of Alabama in Huntsville to host a pilot knowledge sharing event in November 2016. The Human Spaceflight Knowledge Sharing Forum brought together individuals responsible for shaping NASA's future over the next 10 to 20 years to focus on technical best practices and lessons learned from human spaceflight missions.

With participation from over 100 speakers, panelists and attendees representing NASA centers, mission directorates, human spaceflight programs, NASA's Technical Authorities, commercial contractors and partners, and academia, we were able to achieve our goal of collaboratively identifying and discussing applicable lessons from previous human spaceflight mission successes and failures.

The knowledge shared by these individuals during the two-day forum is invaluable, and the event sponsors and participants want to disseminate the information to a broader audience in an effort to positively impact mission success. This issue of the *NASA Knowledge Journal* is a compilation of articles aimed at sharing knowledge with individuals who were unable to attend.

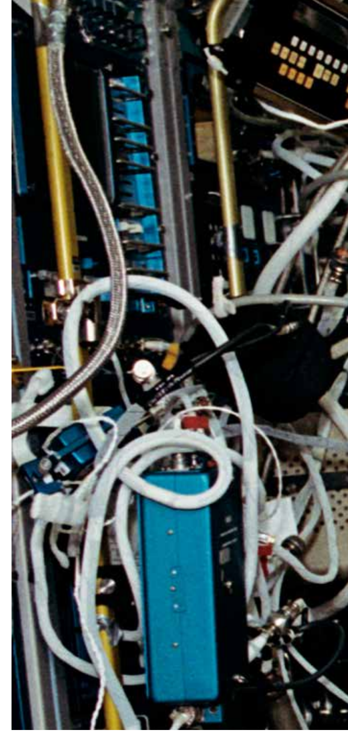
The forum drew attention to the human element of human spaceflight with sessions led by NASA's Chief Health and Medical Officer and an Astronaut. One panel explored shared accountability with commercial partners. We looked at innovation, integration and the future of space communications, and examined three of NASA's top technical risks -- micrometeoroids and orbital debris, parachute systems and composite overwrapped pressure vessels. The journal articles summarize the knowledge sharing forum and include web addresses for video of many of the forum sessions.

This journal highlights critical knowledge shared at the forum among colleagues representing multiple disciplines. I hope the journal provides useful insight and that you will embrace knowledge sharing by passing along pertinent information you find here to your team members. For more information on how to receive print or electronic copies of this or previous issues of the journal, please visit the km.nasa.gov website.

Warmly,

Ralph R. Roe, Jr.
NASA Chief Engineer

Human-Centered Design



STS-58 Payload Commander Rhea Seddon spins the Spacelab Life Sciences rotating chair as Payload Specialist Martin Fettman serves as a test subject during a medical research mission in 1993.

NASA Chief Health and Medical Officer James Polk shared lessons learned about the human element of spaceflight. "The human system is the only system in engineering that you can't take to failure," said NASA Chief Health and Medical Officer James Polk, D.O., at NASA's recent Human Spaceflight Knowledge Sharing Forum.

"I am horribly jealous of the folks in engineering who can take a part and stress it and break it, and take 50 parts and get little dots on a graph to figure out where that part breaks," said Dr. Polk. "I can't do that to [Astronaut] Kjell Lindgren. I can't take him and see where he breaks or where he fails. It's generally frowned upon to do that on a human system."

Polk spoke candidly about the tension between the medical and engineering communities when defining requirements for space missions. "You guys hate it when I say, 'It depends,' because you want a firm number or requirement. I've had engineers say, 'It looks like this in the textbook.' Well, that's not what it looks like when you're actually doing the surgery," he said.

He addressed some of the differences between how doctors and engineers think. "You design your systems. We actually have to reverse engineer nature to understand the system," said Polk. "You use quality-controlled components. There isn't anything quality-controlled about the human body. You use established frameworks and employ physical laws, and we have to discover the concepts in qualitative relationships as we go."

Polk's passion and compassion came through as he recounted the unenviable responsibility of dealing with tragic loss of life when accidents occur. "In meetings, when folks start to talk about graphs and lines and loss of crew, we will purposely inject somebody's name into the discussion just to make sure that folks realize what's at risk here. I try to put a face on this," he said. "At the end of the day, my job is to make sure the astronaut survives."

Polk is responsible for the oversight of health and medical activities at NASA, including medical aspects of all national and international NASA missions involving humans. He led a forum session on "Human Factors/Human-Centered Design: What Did We Think and Do?" and shared his experiences and perspectives on human factors and medical lessons learned from decades of human spaceflight data and research.

PHYSIOLOGIC CHALLENGES

The human body always tries to reach homeostasis, an equilibrium with its environment, which is hard in microgravity. Polk said a lot of medical lessons were learned through Mercury, Gemini, Apollo and the Space Shuttle Program, but the International Space Station (ISS) presented totally different physiologic challenges that occurred as a result of increased time in microgravity.

A new understanding of Visual Impairment and Intracranial Pressure (VIIP) is one of the biggest lessons learned through medical evaluation of ISS crew members. About 40 percent of the astronauts who spend a couple of months on ISS complain of vision change. Through 3 Tesla MRI and other diagnostic test results, Polk and his medical colleagues at NASA observed changes in the optic nerve that goes from the brain to the eye, and a flattening in the back of the eye along with choroidal folds -- similar to wrinkled carpet -- in the back of the retina. The medical doctors initially thought the problem was caused by fluid changes that occur on orbit, but then realized the vision problems sometimes linger several years after spaceflight. NASA has initiated clinical and research protocols to acquire and analyze data on all astronauts to define the exact origin of the potentially harmful vision changes and is seeking possible preventive measures.

Polk also shared lessons learned about Space Adaptation Syndrome, formerly called Space Motion Sickness, which he says has "absolutely nothing to do with motion." In the early days of spaceflight when the vomiting, queasiness, disorientation and headaches were thought to be motion-related, the prevailing assumption was that astronauts could be conditioned by spinning in a centrifuge in preparation for spaceflight. But they still got sick.

Polk explained why approximately 78 percent of astronauts get Space Adaptation Syndrome. "You have about 112 signals that come up to your brain that tell you where you are at any moment in time to allow you to walk or ride a bicycle, etc., and stay upright. But after eight minutes of

Dr. J.D. Polk.

spaceflight, in the most exciting ride of your life, you get up. Your partner is upside down, so your eyes say, 'Wait a minute. That's not right. Your semicircular canals, which have fluid in them, now are floating. The fluid is floating and it's not moving around in the same direction that it did on Earth. You don't have any pressure on the balls of your feet or your heels because you're floating. You don't have any pressure on your rear end because you're no longer sitting on your seat. Your Golgi tendon apparatus doesn't have the stretch on it," Polk said. "All of a sudden, 112 confusing signals come to your brain, and your brain says, 'I don't know what just happened, but I'm going to throw up.'" He said fewer incidents of the syndrome occur with capsules -- such as Mercury, Gemini and the planned Orion crew vehicle -- than on space shuttle and ISS because the brain is deciphering fewer mismatched cues, such as an astronaut upside down.

SPACE MEDICINE CHALLENGES

Among the unique challenges of space medicine is research. "Normally, when we do research in medicine, we'll do something at the Cleveland Clinic or similar institution with about 2,000 patients and we can get a really good 'n' number," said Polk. "With space medicine, unfortunately, one is a control, two is a series, and three is a prospective randomized trial."

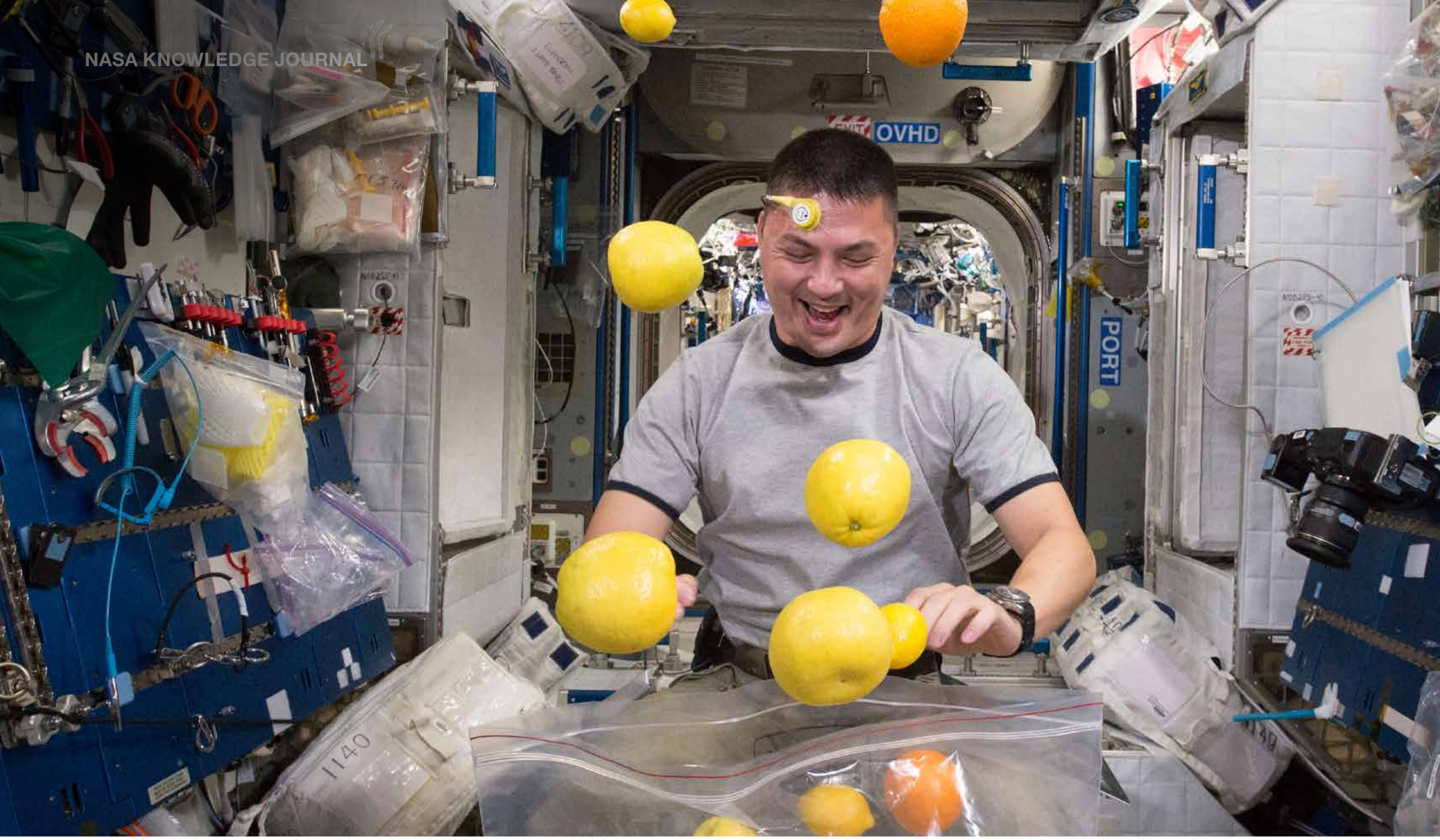
Another challenge has been long-term health care for crew members. Space travelers are at higher risk for radiation-induced cancer, bone loss and fractures, and a variety of health issues. Polk's predecessor, Richard Williams, M.D., has been a longtime proponent of legislation to provide lifetime comprehensive health care for former astronauts. In March 2017, Congress passed and the President signed the To Research, Evaluate, Assess, and Treat Astronauts Act, also known as the TREAT Astronauts Act, as part of the NASA Transition Authorization Act of 2017 -- allowing NASA to treat former astronauts for medical issues that may have resulted from spaceflight.

MEDICAL RISKS

Radiation risks during long-duration spaceflight garner a lot of media attention, but Polk says he's more concerned about long-term risks of radiation than immediate effects during the mission. In fact, he said this is where the mindset between physicians and engineers differs the most because the mission is over for engineers when the wheels stop. For physicians, the mission continues for the remainder of the astronaut's life as they monitor health conditions that could be related to spaceflight.

During his forum presentation, Polk emphasized the importance of human system integration and said it has to be improved. "We've seen in multiple different areas where human factors were ignored. What we typically do is look at the spaceflight environment, try to reduce the hazards, look at the evidence base in medicine, and through the Human Research Program try to reduce those risks to try to implement standards and requirements and then mitigate them for any remaining risk that comes on," he said.

It shouldn't be an easy conversation, according to Polk, who resolutely explains medical risk to program managers. "We should cuss and discuss and get heated in arguments because the risk is really high on the other side if we screw this up. And I don't want that to be an easy, amiable, 'love you, man' conversation. It's supposed to be hard," he said. "I want the program manager to be awake at 2 o'clock in the morning thinking about whether or not this was the right decision. There are some risk trades and some very difficult discussions to have. It's not going to be easy, and it's not supposed to be."



Own the Onboard Perspective

Astronaut Kjell Lindgren provided a crew member's perspective of human spaceflight lessons learned. Lindgren began his Human Spaceflight Knowledge Sharing Forum presentation by expressing appreciation to the Chief Medical Officer and forum attendees for their advocacy for the crew and their work to make sure missions are safe and successful. He emphasized the importance of incorporating human factors and concerns early on in the design of procedures, software and equipment. "As we think about future vehicles and future missions, just own the onboard perspective. Utilize the human factors, folks," he said during his forum presentation. "It pays absolute dividends in the end so that we don't have to do the workarounds."

Lindgren's "Crew Office Lessons Learned" presentation at the forum included snapshots of his own human spaceflight experience. He flew on Expedition 44/45, logged 141 days in space, and participated in two spacewalks and more than 100 different scientific experiments. Lindgren was selected as an astronaut in 2009 as one of 14 members of the 20th NASA astronaut class. He holds a Doctorate of Medicine from the University of Colorado and is board certified in emergency and aerospace medicine.

He says it's "absolutely amazing" to work in the challenging space environment. "That work is critically important," he said. "We feel like we are doing work that is important to our future in the solar system and to the lives back here on Earth. And having meaningful work is critically important."

NASA Astronaut Kjell Lindgren.

NASA Astronaut Kjell Lindgren corrals the supply of fresh fruit that arrived at the International Space Station in August 2015.

He said the International Space Station (ISS) is a great place for long-duration crews to live and work. "The truth of the matter is that we're at the 90 to 95 percent solution on the space station now for many things. We've been doing this for 16 years," said Lindgren. "But it is still like going camping." He cited examples such as the lack of a dedicated hygiene area and not having a variety of food.

BALANCED TRAINING

One of the lessons learned is that balanced training is important. Crew training for a six-month mission is a one-and-a-half to two-year process, and some details trained on the ground are lost months later when the activity is performed on orbit. Lindgren said most crew members think training could be more efficient. Specifically, he noted that significant time is spent on topics not used on orbit and that classroom PowerPoint presentations are the hardest to recall. He said robotic simulations, training in the Neutral Buoyancy Laboratory, and other activities that build muscle memory skills are more easily recalled. He said emergency response and critical ops training is important, and that the crew also must maintain a high level of proficiency in ISS systems and maintenance, extravehicular activity, robotics, and Soyuz systems and flight procedures (in Russian).

"I think one of the biggest surprises for me when I got to the space station -- and this was a pleasant surprise -- is that there is nothing that I was asked to do that I did not feel competent or prepared for," said Lindgren. "That speaks to a terrific training process, probably a little bit of over-training. But it meant that we were checking all of the boxes, and that's a good place to be."

The Johnson Space Center Flight Operations Directorate, which is responsible for providing trained astronaut crew members for NASA human spaceflight programs, is working toward day-in-the-life type training and routine operations training. Lindgren said short videos that offer a brief overview of simpler procedures are very effective on ISS.

MINIMIZING MISTAKES

Lindgren noted that since the human spaceflight equation includes humans, mistakes will happen on the ground and on orbit, but said the key is learning from the mistakes, sharing lessons learned from mistakes, and avoiding repeat mistakes. In addition to training, he said good communication, teamwork and procedures are the main mechanisms the team uses to minimize the frequency, effect and severity of mistakes to keep from putting the crew or the spacecraft at risk.

Lindgren recalled a mistake he made while changing a cable on the Advanced Resistive Exercise Device (ARED) on ISS. After spending two hours installing the cable, Lindgren called to notify ground controllers the C-clamp wasn't working according to procedure. He had mistakenly grabbed a left-sided cable for the right side of the device and was advised to uninstall it.

"That sounds like a pretty trivial and minor thing. And in the scope of things, it was. But from a crew perspective, man, I beat myself up over that for hours," said Lindgren. "You've got to get to a point, like with all mistakes, that you say, 'OK, I made a mistake. Now it's time to fix it, and move on.' But you recognize you're living in this fishbowl. Everybody's seeing you make this dumb mistake. And it's important to be able to compartmentalize that stuff."

TEAMWORK

Lindgren said crew teamwork -- "that desire to help each other out" -- as well as teamwork with the ground is absolutely critical to good performance on orbit. He said he was delighted with the relationship with the ground team. "We believed that the ground had our priorities in mind. We trusted them. And that all came from very good communication," he said.

Crew members have a great relationship with their training teams as a result of spending many hours working together over the course of two years of training. "But with the ops team, we don't work with them until we get on station. And now we have this 250-mile gap between us," said Lindgren. "So, intentionally getting together before flight, getting to know the flight director and all the discipline leads is very important for on-orbit operations."

The crew is able to communicate with the ground 80 to 90 percent of the time. Lindgren says the excellent communication capability enhances teamwork. "I think just adopting that posture of 'Call anytime' is super important," said Lindgren. "There's this idea of 'Don't bother the crew.' But we want that feedback. We want to do a good job for the team."

He said international partnerships are absolutely essential. "I think that the greatest benefit that this program has provided is that international piece," said Lindgren. "The International Space Station is a testament to what our countries are able to accomplish when we work together. We have created something remarkable."

Kjell Lindgren's forum presentation on Crew Office Lessons Learned: http://go.nasa.gov/2jjEQN6

Micrometeoroids and Orbital Debris

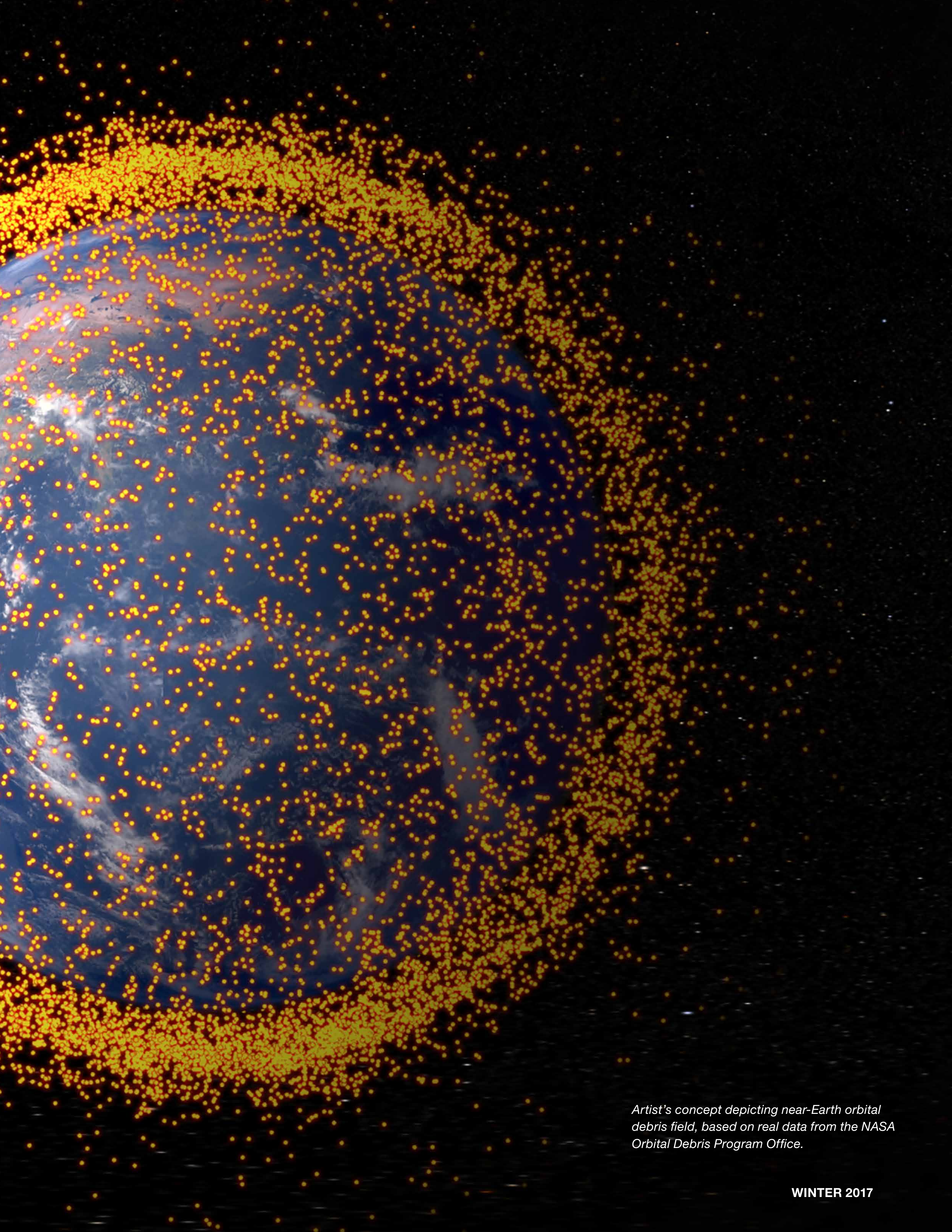
Risk associated with micrometeoroids and orbital debris (MMOD) was a key topic of discussion at NASA's 2016 Human Spaceflight Knowledge Sharing Forum. The No. 1 risk for NASA's human spaceflight programs, including Orion, is MMOD. Due to the danger MMOD poses to space missions, NASA invests significantly in investigating the potential risk from micrometeoroids -- natural objects typically comprising particles originating from asteroids or comets -- and man-made orbital debris such as decommissioned satellites, rocket bodies, thermal blankets and even objects as tiny as paint flakes that could cause catastrophic damage when hurtling through space at speeds up to 44 miles (70 kilometers) per second.

Mike Squire, Principal Engineer in the NASA Engineering and Safety Center (NESC), presented an MMOD overview as part of the Human Spaceflight Knowledge Sharing Forum panel on "Using Lessons Learned to Mitigate NASA's Top Technical Risks." Squire said orbital debris is more of a concern for spacecraft in orbit about the Earth than micrometeoroids because there's more of it.

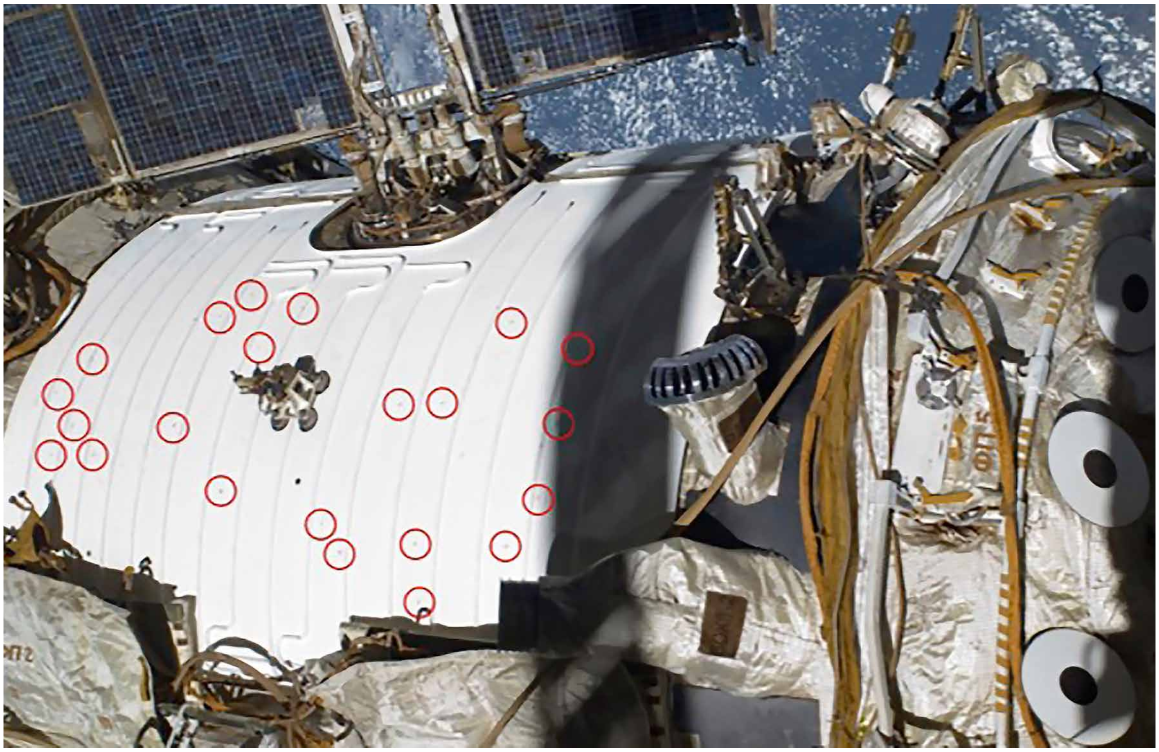
"We had no idea that the MMOD population was going to grow by orders of magnitude today and continue growing in the future," said Squire. "So, the risk is only getting worse."

The Department of Defense Space Surveillance Network tracks objects as small as 4 inches (10 centimeters) in diameter in low-Earth orbit and about 1 yard (1 meter) in geosynchronous orbit. The DOD network currently tracks more than 21,000 objects. Squire said objects smaller than 4 inches are the biggest concern since they can't be tracked but can still cause significant damage.

Orbital debris travels up to 33,500 mph (approximately 54,000 kilometers per hour), fast enough for even a relatively small object to damage a satellite or spacecraft. Micrometeoroids can move at speeds 10 times higher than orbital debris.



Artist's concept depicting near-Earth orbital debris field, based on real data from the NASA Orbital Debris Program Office.



Multiple impact sites on ISS service module shown as an example of human spaceflight MMOD damage.

RISK AND MITIGATION

Squire shared high-level MMOD lessons learned and emphasized the importance of direct measurement. “By direct measurement, I mean either getting your hands on a piece of space hardware that flew and was brought back, and it has impact damage, and being able to analyze that and incorporate that data, or, alternatively, having sensors in orbit that are able to detect impacts and feed that information back down to the ground,” said Squire during his forum presentation.

He said evidence began mounting during the Gemini era that orbital debris was starting to be a problem, and the understanding of the magnitude of the problem increased during the Apollo and space shuttle years. Squire said the technical community has a relatively good understanding of the orbital debris environment around the International Space Station (ISS) and space shuttle altitudes because of direct measurements performed on radiator panels, windows and hardware that have been brought back down from orbit. Beyond that region, he said extrapolation and various assumptions come into play, but that different orbital debris models are generally in agreement that the peak in orbital debris appears at an altitude of approximately 435 to 500 miles (700 to 800 kilometers), highlighting why it’s important to get assets into the higher region and get more direct measurements.

Squire explained why the latest NASA Orbital Debris Engineering Model -- ORDEM 3.0 -- shows higher risk than previous models. The new model incorporates recent events such as the Chinese anti-satellite test and the Iridium-Cosmos collision that were not in the previous model. Based partly on an NESC recommendation, ORDEM 3.0 also includes a population of higher density particles, such as stainless steel, which inflict more damage when they hit a spacecraft and therefore elevate the risk numbers above the older model that assumed all debris particles were aluminum, which has a lower material density than steel.

In addition to validating models with real-world data through direct measurement, Squire said testing is very important. Although hypervelocity impact testing is difficult and expensive, he said it is very important to be able to “see what the actual physics are when different objects are impacting different shields and different spacecraft components.”

Squire encouraged the technical community to exchange MMOD information and make a strong effort to understand huge uncertainties in different elements of the risk assessment process, including limitations of the tools, and make sure customers know that those uncertainties are going into the design process. He cautioned that it is crucial to know the difference between risk and assessed risk -- stating assessed risk can be improved by getting more

Mike Squire.

“Details matter in assessing MMOD risk. You can make very minor changes in your risk assessment, and these will end up being relatively major changes in your assessed risk. So that means you need to make sure you nail down your spacecraft configuration. Have it as accurate as possible.”

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information on the environment models and improving the fidelity of the spaceship spacecraft configuration.

“Details matter in assessing MMOD risk,” said Squire. “You can make very minor changes in your risk assessment, and these will end up being relatively major changes in your assessed risk. So that means you need to make sure you nail down your spacecraft configuration. Have it as accurate as possible. For example, know what your tank thicknesses are, how many layers of MLI (multi-layer insulation) you have, and how much area your blanket is covering, because small changes in this will make significant changes in your risk, and it will drive decisions in design.” He pointed to the importance of understanding the transition from design-based to operational-based mitigation, noting that there usually are not as many options for changes in the operational phase. Shielding augmentations have been made on the ISS, but he said adjusting attitude and orbit and similar mitigations are usually all that’s left once a spacecraft is operational.

Radiator damage caused to space shuttle Endeavour by MMOD impact during STS-118 in 2007.

Ongoing missions are not the only concern. Squire recalled the 1981 explosion of a Delta upper stage -- “just a dead derelict in orbit” launched in 1978 -- that produced about 200 pieces of trackable debris, offering the “first inkling that this was a source of orbital debris -- these dead objects up in orbit.” The Delta incident resulted in mitigation guidelines to passivate objects as necessary or make sure they don’t remain in orbit for decades after they have stopped working. Debris-on-debris impacts are accelerating, and he said that resulted in the so-called “25-year rule” that prohibits satellites from orbiting for more than 25 years in an effort to prevent additional generation of debris.

ROBOTIC MISSION APPLICATION

The focus of the knowledge sharing forum was human spaceflight, but Squire mentioned the robotic community is also seeing an increase in MMOD issues. “They’re being levied with requirements to mitigate generation of more orbital debris,” said Squire. “They have to be able to prove that they can survive their mission and be able to de-orbit after the end of their mission so they don’t generate more orbital debris.”

Squire said CubeSats are also causing concern as companies prepare to launch hundreds or thousands of the miniature satellites that could add to the growing orbital debris problem.

Mike Squire’s forum presentation on MMOD Lessons Learned: http://go.nasa.gov/2jkolAs

Mitigating the High Risk of COPVs

Composite Overwrapped Pressure Vessels, such as hydrogen or oxygen tanks, are inherently high-risk spaceflight components that demand a lot of attention to detail. The enormous amounts of energy associated with a Composite Overwrapped Pressure Vessel (COPV) automatically introduce risk that has to be mitigated. For example, a gas vessel with a volume of 1,300 cubic inches and pressure of 9,700 psi has the energy equivalent of 3.6 pounds of TNT.

As part of the Human Spaceflight Knowledge Sharing Forum panel on "Using Lessons Learned to Mitigate NASA's Top Technical Risks," Lorie Grimes-Ledesma, Chair of the NASA Engineering and Safety Center (NESC) Composite Overwrapped Pressure Vessel Working Group, presented COPV lessons learned. The working group she chairs is chartered to understand and minimize risk associated with COPV use throughout NASA. Grimes-Ledesma said failure modes are well-defined for typical use, and standards exist to capture typical approaches to mitigate the risk of failure.

NASA commonly uses COPVs for gas and propellant storage in spacecraft and launch vehicles. The vessels, designed to hold fluid or gas under pressure, consist of a thin, nonstructural liner wrapped with a structural fiber composite. Fiber-reinforced polymers with carbon and Kevlar fibers are the most commonly used composites in the vessels. The liner provides a barrier between the fluid or gas and the composite, preventing leaks and chemical degradation of the composite.

COPVs are stronger and lighter weight than metallic pressure vessels. While cylindrical COPVs are more common, spherical COPVs are also used. Grimes-Ledesma said there's not necessarily an ideal size, shape or thickness of a COPV based on the temperature or fluid inside the vessel. Sizes and shapes of COPVs are typically driven by packaging constraints within the spacecraft, and considerations of cost and schedule with COPV manufacturers.

A long history of using COPVs for flight has resulted in a lot of lessons learned, which have contributed to development of various standards. "There are specific standards that, if followed, should help you mitigate the risks," said Grimes-Ledesma. "Like all standards, they're subject to interpretation, which can be kind of problematic and usually requires a discussion."

STRESS RUPTURE

Various rupture failure modes of COPVs are addressed during engineering design. She said work is ongoing to address COPV risks that are still not fully understood, such as stress rupture, impact damage, and liner crack growth. "Understanding risk requires adequate visibility into how the requirements are met. Sometimes, these seemingly small details can be the big 'gotchas' with COPVs, so a lot of detailed review and significant oversight is usually necessary," said Grimes-Ledesma.

Safe, reliable use of COPVs is dependent on preventing rupture failures. A COPV rupture can be catastrophic to the surrounding spacecraft structure and components. Stress rupture is a time-dependent failure mode of the composite material that can occur at operating pressures and temperatures, resulting in rupture failure below the ultimate stress. The NESC and International Space Station (ISS) Program are conducting large test programs on composite strands and COPVs to quantify the risk of stress rupture failure in flight.

IMPACT DAMAGE

NASA and the U.S. Air Force conducted an independent study of impact damage of COPVs at White Sands Test Facility. Based on the study conducted in the late 1990s, recommendations for preventing impact damage to a COPV include developing and following a damage control plan and having damage tolerance testing and/or protective covers. Grimes-Ledesma says information is also needed from various suppliers in order to understand risk that could occur from impact damage.

Impact damage was not as big of a concern during the Apollo era because the metallic pressure vessels were less susceptible to failure due to impact. Questions regarding long-term reliability of COPVs were raised due to issues on the space shuttle orbiter, and became significant for the ISS, robotic missions and future programs. Nine pressure vessel failures or leaks occurred on space shuttle orbiter COPVs, drawing attention to impact damage, cycle life, stress rupture reliability of the Kevlar composite, and changes in fracture mechanics knowledge.

Lorie Grimes-Ledesma.

Space shuttle orbiter pressurant tank for the orbital maneuvering system.

COPV tank snug inside sounding rocket.

APOLLO LESSONS LEARNED

During Apollo development of all-metal pressure vessels, 19 failures occurred. "This lesson learned from a large number of metallic pressure vessel failures during the Apollo era was really critical and very important for COPVs because a lot of the failure modes that were observed in these all-metal pressure vessels also are very important to the liner," said Grimes-Ledesma. "Three of those failed while they were installed in the spacecraft, two during a system test, and one, of course, was Apollo 13, as everybody is probably familiar."

Others failed during acceptance or qualification tests due to:

- Stress corrosion cracking from red nitrogen tetroxide
- Weld cracks and embrittled weld repairs
- Stress corrosion cracking from water (steel motor case)
- Sustained load crack growth in water (growth of an existing crack due to exposure to water)

Fracture-based concerns were captured in a series of recommendations at the time. Johnson Space Center Materials Engineer Glenn Ecord authored "Apollo Experience Report – Pressure Vessels," which included a wish list for future pressure vessels and COPVs. Fracture mechanics was pinpointed as a key concern in pressure vessel design, whether it was a metallic pressure vessel or COPV. Recommendations in the report, released in September 1972, included:

- Evaluate material selections and compatibility for components and fluids used inside pressure vessels.
- Verify weld techniques.
- Regulate and control ground pressurization of flight pressure vessels.
- Log the number of pressurizations.
- Establish responsibility and authority for pressure vessels.
- Do not eliminate quality assurance documentation or requirements.
- Do not remove requirements or testing of pressure vessels unless sufficient oversight is provided.

COPV FAILURE MODES

- Insufficient design/strength
- Over-pressurization
- Liner buckling
- Insufficient weld strength/elongation
- Boss shear
- Composite stress rupture
- Impact damage
- Delamination (at a skirt or strut interface point)
- Liner-sustained load crack growth
- Liner fatigue crack growth
- Liner stress corrosion cracking
- Corrosion
- Material embrittlement

LABORATORY TESTING

Grimes-Ledesma said COPV lessons are not necessarily always learned from an accident or problem that occurred in service, but sometimes come through laboratory examination of the failure mode to understand whether an imagined concern is actually a large risk. She emphasized the importance of design standards that define very specific ways pressure vessels can fail; process controls; and testing as viable approaches to mitigate COPV risk.

Lorie Grimes-Ledesma's forum presentation on Mitigating the High Risk of COPVs: http://go.nasa.gov/2jmgD90

Capsule Parachute Assembly System

Parachutes are critical to safely returning the Orion spacecraft and its crew to Earth. Orion's Capsule Parachute Assembly System (CPAS) has the job of stabilizing and slowing the capsule from traveling more than 300 mph down to about 17 mph to safely splash down in the ocean. "If the parachutes don't work in any phase, that can mean loss of the vehicle or loss of crew," said CPAS Deputy Project Manager Brian Anderson. "There's no backup system."

Anderson presented a CPAS overview as part of the Human Spaceflight Knowledge Sharing Forum panel on "Using Lessons Learned to Mitigate NASA's Top Technical Risks." He focused on the Orion parachute system, but noted that the lessons are applicable to all human-rated parachute systems.

The Orion spacecraft is built to take astronauts farther into the solar system than ever before, provide emergency abort capabilities, sustain the crew during the mission and provide safe re-entry through Earth's atmosphere. CPAS is composed of 11 total parachutes that deploy in a precise sequence. Three parachutes help pull off Orion's forward bay cover, which protects the top of the crew module from the heat of reentry through Earth's atmosphere. Two drogues then deploy to slow and steady the capsule. Three pilot parachutes then pull out the three orange and white mains that Orion rides on for the final 8,000 feet of its descent. Orion's main parachutes -- each made of more than 10,000 square feet of nylon and Kevlar fabric -- are packed to the density of oak wood to fit in the top of the spacecraft, but cover almost an entire football field when fully inflated.

While there's no backup system for the parachutes, there is some built-in redundancy in that the system can function on one drogue parachute or with two of the three parachutes, if one main parachute is lost, and still meet landing requirements.

DYNAMIC DEPLOYMENT

Parachute deployment is a dynamic event. The quality of the deployment can be affected by many uncontrollable factors occurring independently or in combination, including atmospheric conditions, angle of attack, altitude, dynamic pressure, packing and routing variations, minor sequence differences, and lead/lag conditions.

"Parachutes themselves are very challenging and chaotic," said Anderson. "They're the only system that assembles itself midair."

For human spaceflight, deployment conditions vary widely due to vastly different nominal entry, pad abort and ascent abort requirements. "Because of the requirements of human spaceflight, we have to deploy under a really wide range of conditions from very low velocities up to very high velocities," he said. "And because of that wide range of operational parameters, it's very tricky and it causes a lot of risk into a system if you don't test that system out well."

Deployment can only be validated by repeated observation of airdrop tests with mortars and a representative parachute compartment. Anderson said verifying performance in regimes where data is not available or cannot be collected should be avoided.

Parachute modeling is almost exclusively empirical. Some predictions, such as loads, torque and terminal rate of descent, use physics-based models anchored to test reconstructions. Other aspects, such as packing and integration, deployment and inflation, are not modeled with enough confidence to verify with analysis.

PARACHUTE TESTS

The Apollo Program had 151 parachute drop tests composed of single-parachute as well as cluster-parachute tests. The Orion Program plans to conduct a total of 44 parachute drop tests that will include 25 system tests with parachute clusters in various configurations. Following completion of 36 development tests, including Exploration Flight Test 1 (EFT-1), the first of eight qualification tests was completed in September 2016.

"We don't need to go to 151 to get to the same reliability because we have learned from Apollo. But at the same time,

Brian Anderson.

A test to begin qualifying the Orion parachute system for crewed flights was conducted in September 2016, one of eight integrated, qualification drop tests planned over a three-year period.

A crane lowers a main parachute for installation on the Orion spacecraft inside the Operations and Checkout Building high bay at NASA's Kennedy Space Center in Florida.

we have significant enough differences that we do need to understand, for example, how our system interacts with the vehicle, how we pack, and how we deploy. All of those things are very important to learn," said Anderson.

Data from Space Shuttle Solid Rocket Booster parachute testing shows the failure rate begins to stabilize at 25 tests, indicating good reliability has been reached at that point. In addition to drop tests, CPAS has also completed a significant number of ground tests, including wind tunnel, mortar deployment, riser abrasion, vibration, retention system/deployment bag strip, seam and joint, riser torque, riser twist load amplification, and packing.

LESSONS LEARNED

Anderson shared three CPAS lessons learned:

Lesson Learned No. 1: Test Technique Challenges

He said the CPAS team learned that getting the test article onto the desired test point can be very challenging and should not be underestimated. Whether the test occurs out of an airplane or using balloons, he said the test technique can be as challenging as the design of the flight parachute system itself.

Lesson Learned No. 2: Computational and Subscale Test Techniques

Computational techniques are not mature enough to be primarily relied upon for human spaceflight parachute design, although they are getting close, according to Anderson. He said fluid structure interaction capabilities are improving and great work is being done by some of the parachute vendors and others using LS-DYNA multiphysics simulation software. Methods for testing subscale parachutes and test vehicles require additional detailed study and investment, but could ultimately result in cost savings or reduction in logistical complexity.

Lesson Learned No. 3: Adequate System-Level Testing

Anderson said the most important lesson learned may be that there needs to be adequate system-level testing.

"Our chief engineer always says that in order for us to have a successful design, it needs to be given the opportunity to fail with repeated demands during development testing. And in order to see that -- not necessarily a full-scale failure where you hit the desert at a very high speed, but even just small parts of the parachute system -- having sufficient instrumentation and video coverage is required to truly understand the system and to have confidence in reliability growth," he said.

Anderson gave an example of a CPAS pendulum swing issue that didn't surface until the third test with two main parachutes, and would likely have gone unnoticed and unresolved with fewer tests. He said the number of system-level tests needs to be adequate to find "hidden" failure modes.

The adequate number is design-dependent, including parachute platform, packing methods and shapes, vehicle integration, and concept of operations, and also hinges on the relationship of the current design to previous, similar designs. Anderson said CPAS has benefited greatly from Apollo, and commercial partners have benefited from CPAS experience.

Brian Anderson's forum presentation on CPAS Lessons Learned: http://go.nasa.gov/2jkdt5A

Common Threads Among Catastrophic Mishaps

Lessons noted but not heeded when precursor events and anomalies occurred have oftentimes been the culprit of historic mishaps. Lessons not learned and not effectively acted upon are to blame in deadly mishaps across the globe. In his "Common Threads Among Catastrophic Mishaps" presentation at the Human Spaceflight Knowledge Sharing Forum, Brian Hughitt, Technical Fellow, Quality Engineering within NASA's Office of Safety and Mission Assurance, examined causes of a wide range of disasters.

Brian Hughitt.

The most common thread among catastrophic mishaps studied, according to Hughitt, is lessons not learned -- and consequently not recognized for implementation of corrective actions that would have prevented future missteps. The second most common thread is material control inadequacies, where a simple material failure or inadequacy resulted in a fatal mishap.

THE BIG DIG TUNNEL COLLAPSE

Recognized as the largest, most complex and technologically challenging highway project in U.S. history, the Central Artery/Tunnel Project, unofficially known as the Big Dig, was designed to significantly reduce Boston traffic congestion.

"If you look at the metrics, they're just hard to fathom. Five miles of tunnels. 200 bridges in a densely populated urban area. But the metric I'd like everybody to take particular note of is that in addition to all these amazing things that needed to be done, the project was billions of dollars over cost and years behind schedule," said Hughitt. "Decisions were made that were very mindful of those schedule and cost pressures."

In September 1999, a construction worker noticed some of the fasteners in the tunnel ceiling had started to pull out.

Engineers performed proof testing on some of the fasteners that had pulled out, observed unexpected behavior, and called in the fastener supplier, who said the problem was with the concrete or cleaning procedures and took no corrective action. Under the direction of the project manager, heavy load testing and finite element analysis were performed to verify design assumptions and everything checked out. A design manager, structural engineer, and quality inspector all pointed out, however, that a key piece of information -- the cause of the anchor failure and how the repair would fix it -- was missing.

"It is mind-boggling to me that when the inspector noticed that previously tested fasteners had slipped out, they didn't perform 100 percent inspection. That would have been quick, easy and cheap to do," said Hughitt. "They didn't treat the failures systemically, but as a bunch of isolated cases."

In July 2006, the fastener issue caused a section of the I-90 connector tunnel ceiling to detach from the tunnel roof, sending 26 tons of concrete and suspension hardware onto a vehicle and fatally crushing a passenger. The National Transportation Safety Board (NTSB) listed the probable cause of the tunnel ceiling collapse as the contractors' use of an inappropriate epoxy formulation due to their failure to identify potential creep in the anchor adhesive, which resulted from a general lack of understanding and knowledge in the construction community about creep in adhesive anchoring systems.

Hughitt said creep was not an unknown phenomenon at that time, but that the specific individuals involved in the megaproject didn't know anything about it. He listed several contributing causal factors of the design vulnerability:

- The ceiling was held in place by rods and fasteners, but didn't need to be as most ceilings constructed at that time had continuous ceilings. Initially, lightweight, laminate ceiling panels were planned, but concrete was later approved to save money.
- Engineers recommended mechanical fastening systems, but epoxy was used instead, and the glued-in studs failed.
- Corporately, the supplier manufacturer knew all about creep, but the individuals called to the scene to investigate the issue prior to the mishap had no knowledge of it.

"The knowledge had not been captured and transferred to the right people," said Hughitt. "And no matter what they did -- all the best installation practices, all the proof testing in the world -- it wouldn't have fixed this problem, because it was the wrong solution."

Hughitt said that in hindsight, which is 20/20, it was inevitable that ceiling panels were eventually going to detach, but he identified cognitive dissonance as one of the explanations for why people were blinded to this preventable outcome.

*The Big Dig during construction.
Photo credit: adm*

Signs from the Big Dig construction area. Photo credit: Stephen Gore

"We have our own experiences and knowledge. And everything we see, we filter through our knowledge and experience base. And if you see something that just doesn't align with that, it doesn't compute," said Hughitt. "It's beyond your reality. You filter it out and come up with explanations that do fit your knowledge and reality base. And that's what occurred."

MCDONNELL DOUGLAS DC-10

When Turkish Airlines Flight 981 crashed into the Ermenonville Forest outside Paris in 1974, killing all 346 people on board, it was at the time the deadliest plane crash in aviation history. An improperly secured cargo door separated from the plane, causing an explosive decompression that severed cables necessary to control the aircraft. While the approximate cause was determined to be a faulty latch, Hughitt noted that multiple, interrelated causal factors were to blame. A baggage handler of normal strength had pushed the handle fully down, thinking he had secured the door, when he had, actually, only bent the internal bars and rods out of shape.

Hughitt said the door configuration, which used an outward opening hatch door design so that more paying passengers could fit inside the McDonnell Douglas DC-10, had design vulnerabilities. He noted that if proper safety design principles had been in place, the plane could not have taken off. But once the hatch door handle was down, the cockpit indicator light went off.

Hughitt pointed out that unethical behavior also occurred. McDonnell Douglas subcontractor Convair performed a failure mode effects analysis that definitively showed the deadly consequence of a cargo door latch failure, but the analysis never made it to the FAA. McDonnell Douglas attributed the incident almost entirely to human failure, but an earlier NTSB accident investigation clearly determined that design characteristics of DC-10 latch mechanisms permitted the door to appear to be closed when, in fact, they were not fully engaged and the lock pins were not in place.

"It gets almost into the realm of disbelief," said Hughitt. Significant issues with the latch mechanisms had been documented, and the NTSB had provided a report on the known design vulnerabilities. The FAA proceeded to write an Airworthiness Directive based on NTSB recommendations, which would have effectively grounded the DC-10 fleet. However, the President of McDonnell Douglas persuaded the FAA Administrator to soften the requirements. The company failed to act upon even the less stringent requirements at the time of the mishap -- measures that Hughitt noted would have prevented the accident.

In addition to factors that caused the Big Dig and McDonnell Douglas DC-10 mishaps, Hughitt listed overconfidence and failure of imagination as contributing mishap causal factors and, within the past five years, has added fraud and counterfeiting to his matrix of

“You can do as many analyses and tests as possible, but empirical evidence, demonstrated reliability -- there’s no substitute for that. Always fly like you test, and test like you fly.”

common threads among mishaps. He said NASA, the Missile Defense Agency and other organizations have lost tremendous assets in recent years due to fraud, and called it “a very real and present danger.”

USS THRESHER AND APOLLO 1

Hughitt shared observations of other mishaps, including the USS Thresher, lost at sea due to improperly fabricated silver-brazed pipe joints that resulted in the United States’ greatest single submarine disaster, and Apollo 1, where astronauts Virgil Grissom, Edward White and Roger Chaffee lost their lives when a fire broke out in the command module during a preflight test.

Hughitt recalled being astounded as a young quality engineer 35 years ago when reading through the report of the April 1963 USS Thresher submarine sinking, saying he hadn’t known at the time that such a causal chain could exist. He initially thought the compounding and overlapping of the series of events that doomed the Thresher seemed remarkably unfair and unlikely, but learned later in his career after studying other disasters that it’s not that uncommon in highly complex systems for multiple causal factors to all align.

“Both the Thresher and Apollo 1 were brand new platforms, first in their class. “Technical innovations and advancements are vitally important, but they come with risk,” said Hughitt. “When something is new, your safety senses ought to be ‘tingling.’ It’s unproven. And it’s virtually impossible to fully prove highly complex systems this new. You can do as many analyses and tests as possible, but empirical evidence, demonstrated reliability -- there’s no substitute for that. Always fly like you test, and test like you fly.”

Brian Hughitt’s forum presentation on Common Threads Among Catastrophic Mishaps: http://go.nasa.gov/2jIN3jQ

MOST COMMON THREADS AMONG CATASTROPHIC MISHAPS

- Lessons not learned
- Failure to control critical material items
- Vulnerable design
- Workmanship shortcomings
- Process control failures
- Fraud

Shared Accountability Lessons from Commercial Partnerships

"Trust, but verify" is the approach NASA and its commercial partners are adapting as part of the new shared accountability model for safe, affordable launch to low-Earth orbit. The goal of NASA's Commercial Crew Program (CCP) is to achieve safe, reliable and cost-effective access to and from the International Space Station (ISS) and low-Earth orbit through the development of a U.S. commercial crew space transportation capability. NASA and industry are investing time, money and resources to develop systems for the U.S. to launch astronauts to space from America. To accelerate the program's efforts and reduce the gap in American human spaceflight capabilities, NASA awarded more than $8.2 billion in Space Act Agreements and commercial crew contracts.

NASA will fly missions to meet its space station crew rotation and emergency return obligations once a transportation capability is certified to meet agency requirements. CCP certification activities are based on a shared accountability balance that acknowledges:

- Industry's safety obligations in owning and operating Crew Transportation System (CTS) services for both government and private sectors.
- NASA's critical obligations for assuring crew safety and mission success for NASA missions, relying on a shared assurance and risk-based strategy.

During the "Shared Accountability: Lessons from Commercial Partnerships" panel discussion at the Human Spaceflight Knowledge Sharing Forum, representatives of NASA and commercial partners Boeing and SpaceX provided an overview of the new model. "A lot of my history is on the Space Shuttle Program, so the shared accountability model is new for me, just like it is for a lot of us who are used to traditional ways that we have gone about trying to launch humans into space," said Panel Moderator Katherine Van Hooser, Chief Engineer for NASA's Marshall Space Flight Center.

Katherine Van Hooser.

ROLES AND RESPONSIBILITIES

One of the biggest departures from the traditional approach is that NASA previously would have chaired review and engineering control boards, and contractors would have attended. Under the CCP shared accountability model, NASA attends and industry partners act as the decision authority. NASA personnel are on the partners' boards, get full insight into what's going on, and advise industry partners.

NASA has a critical role in assuring crew safety and mission success for agency missions. NASA defines the requirements, approves any variances to those requirements, and ensures compliance through the evaluation and approval of industry assertion of readiness to transport crew to and from the ISS.

Ed Burns.

Launch Pad 39A at NASA's Kennedy Space Center in Florida undergoes modifications by SpaceX to adapt it to the needs of the company's Falcon 9 and Falcon Heavy rockets.

Industry responsibilities include design, development, test and evaluation (DDT&E), production of the space vehicles, and operations.

"The industry is really responsible for DDT&E, and that includes ground launch and all mission phases. Our commercial partners are accountable for asserting their readiness for certification, and we will assess their readiness for certification as we go through the process," said Ed Burns, Manager of NASA's CCP Systems Engineering and Integration Office. "It's a slightly different balance of accountability, but I think it can be successful for reaching a safe, reliable crew transportation system."

Industry partners are responsible for managing development risk, but NASA has insight into the program and will evaluate risks throughout the program life cycle. NASA conducts independent verification and validation (IV&V) of software and technical areas, reviews verification and validation evidence, and focuses on quality assurance and problem resolution.

Forum panelists representing Boeing and SpaceX said they view the CCP model as a side-by-side partnership where data is openly shared throughout the process. They described the government-industry partnership as a very positive relationship built out of mutual respect and characterized by openness and a willingness to share data.

A rocket engine static fire test was cited as an example of the way the shared accountability process works. The commercial partner held the Test Readiness Review and performed the test. NASA reviewed data from the static fire test and agreed with the partner's conclusions that the test data signaled the go-ahead for a launch pad abort test. Panelists said the process worked in a very efficient, rapid fashion, and NASA's feedback gave industry the confidence needed to do the launch pad abort test just one day after the short-duration, static fire test. Throughout testing, as in all phases of CCP, industry partners share technical issues that arise during preparation as well as risks and how they have been mitigated, and NASA offers feedback and expertise.

BENEFITS OF SHARED ACCOUNTABILITY

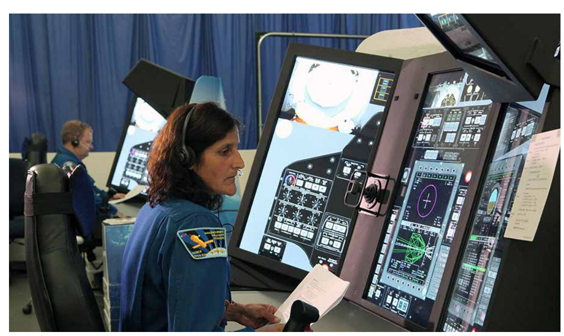
From a NASA program office perspective, Burns says one of the major benefits of the shared accountability model is a much leaner, more agile organization with fewer program office personnel and a smaller footprint than human spaceflight programs of the past, such as the Space Shuttle Program. "The balance of responsibility has changed, but the pace and the number of different issues you're going to deal with, especially having two providers working concurrently, are a lot different. So, the organization has to be lean, agile and highly adaptable," he said.

From an industry partner perspective, one of the biggest benefits has been the ability to make decisions in a timely fashion. Shared accountability has also led to increased schedule discipline and more efficient execution. Industry partners say they see themselves much more as the gatekeepers and question almost everything, every day, because of their shared accountability for mission success.

LESSONS LEARNED

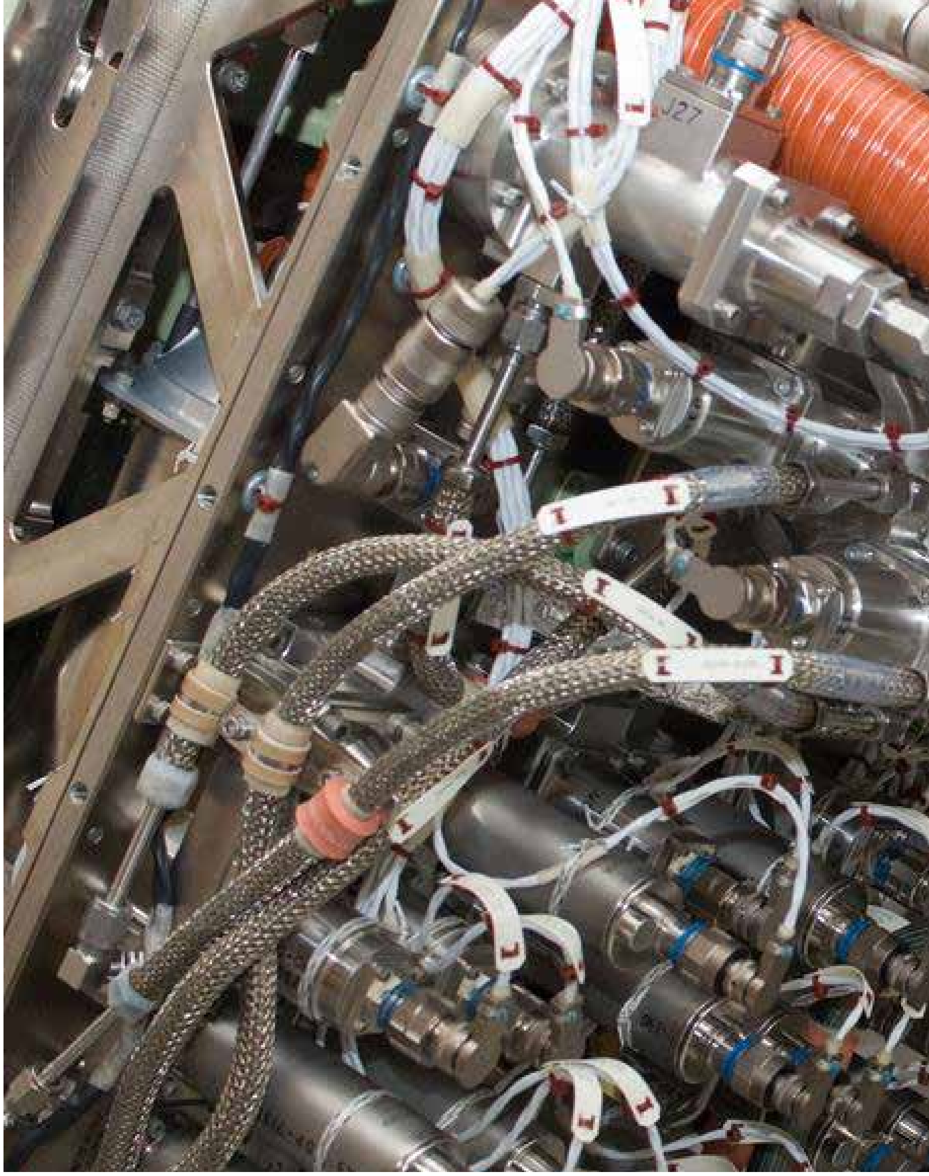
Empowering the lowest level possible from a personnel standpoint has been a boost to shared accountability as the industry partners trust, but verify, decisions that are made across the workforce. Employees who actually build the widgets share in the accountability and responsibility. From a management perspective, one of the lessons learned is that replacing or augmenting most of the traditional in-person boards -- other than risk management and change control boards -- with online decision evaluation and discussion systems has increased decision velocity. From a design perspective, industry partners say they've learned to simplify design as much as possible from the beginning, because it will get more complicated as the design evolves and internal and external stakeholders have their input.

One of NASA's major roles in CCP is establishing requirements and verifying they are met. Burns says one of the big lessons learned is that the guardians of the requirements baseline need to take that responsibility very seriously and keep nonessential requirements from shoehorning their way into the system. He says lessons learned include the importance of permitting very different approaches to meeting requirements and having requirements that don't decompose into enforcing a design or a design approach. "We've given that flexibility in design space to the providers, and they've come up with some rather innovative approaches," said Burns. "They haven't found themselves bound to traditional ways that we would do things."



Commercial Crew Program astronauts Suni Williams, foreground, and Eric Boe practice docking operations for Boeing's CST-100 Starliner.

Innovation at NASA



Innovation often starts with stopping to look around. NASA's 2016 Human Spaceflight Knowledge Sharing Forum coincided with the agency's Innovation Day, which sparked conversations around looking for different approaches to achieve success.

"Life moves pretty fast. If you don't stop and look around once in a while, you could miss it."

\- Ferris Bueller

The infamous quote from the iconic movie "Ferris Bueller's Day Off" set the stage for Kennedy Space Center Engineering Director Pat Simpkins' presentation on innovation at NASA. "Innovation, to me, is about looking around," said Simpkins, who referenced adventures from the 1986 movie. "I'm a big fan of stopping and looking around. And I'm a big fan of looking outside your swim lane."

Simpkins shared stories from Apollo through ongoing work on Orion to demonstrate the significance of careful observation, usually beyond the focus of a launch or test.

"If you've been working in a system or a project or a program for such a long period of time, that's your swim lane," said Simpkins. "You're an expert. Absolutely. But there may be stuff going on around you that you're not noticing because you're so busy keeping your head down and coloring."

He said it's important to be open to looking at other disciplines and experimenting with approaches that aren't necessarily "how it's always been done."

Pat Simpkins.

SIMPLE SOLUTIONS

Simpkins gave an example of an unusual method used to find the source of a water leak during processing of the U.S. Laboratory for the International Space Station. All the hardware was installed, processing was almost complete, and technicians discovered water in the bottom of the Environmental Control and Life Support System bay. They couldn't figure out where the water was coming from and contemplated opening up the bay and starting over. And then someone recommended a simple, straightforward solution: lay down a brown paper bag and see where the water drips. It was a different approach to checking a leak -- not listed in the ASME Handbook -- and pointed them to the vicinity of the humidity separator where they isolated the leak, torqued the fittings, and fixed the leak.

Simpkins offered another example of an unconventional approach to problem solving. In order for the space shuttle

NASA Astronaut and Expedition 25 Commander Doug Wheelock works to install a system to extract more water out of the International Space Station atmosphere as part of the station's Environmental Control and Life Support System.

fire suppression system to remain in a ready state, NASA had a requirement to verify that the fire suppression bottles in the crew module avionics bay were filled with fire-retardant fluid. The fire suppression bottles were solid-colored with no way to visually determine how full or empty they were. After struggling to figure out how to meet the requirement, someone came up with an idea to use hot air from an off-the-shelf blow dryer. They blew hot air on the fire suppression bottles, captured a photo with an infrared camera, and verified quantity based on the shadow line in the bottle. "It was a simple way, looking outside your typical space," said Simpkins.

WRONG OR DIFFERENT

Simpkins says people have to get comfortable with the fact that there's a distinction between different and wrong. "There are some wrong ways to do things, and maybe we've got enough scars and lessons learned to say, 'Boy, we're never going to do that again.' And there's also different."

He offered the number of parachutes used for entry, descent and landing as an example. NASA has a lot of experience with three parachutes, but not with two or four. "That doesn't make four wrong. It makes it different, and it's something that we need to pay a lot of attention to, and I'm happy to say that especially the commercial crew team is asking those questions and looking at it from the point of view that there's a difference between different and wrong," he said.

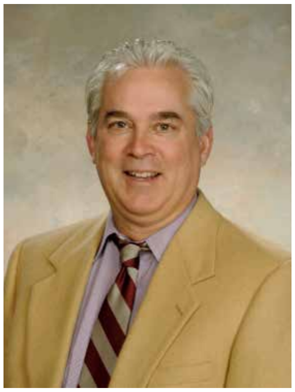
INTENSE CURIOSITY

In order to create an environment that allows innovation to flourish, Simpkins says team members need intense -- almost irritating -- curiosity. "I think you have to inspire and promote curiosity in your organization, whether it's the second-shift test engineer or the project manager," said Simpkins. "You have to reward curiosity. And then you have to ask questions, which may trigger a new thought or a new path of discovery in the program or project."

Forum panel presentation on Process for Innovation: http://go.nasa.gov/2jnw6VY

Integration Lessons

Longtime NASA Engineering Manager Chris Singer compares human spaceflight integration to marriage. Interface control documents and marriage licenses may be in place, but breakdowns will still occur if good relationships are absent. Singer, NASA's Deputy Chief Engineer for Engineering Integration prior to his retirement in 2017, says that just like a good marriage, you have to share and communicate effectively to make a human spaceflight system work.



Chris Singer.

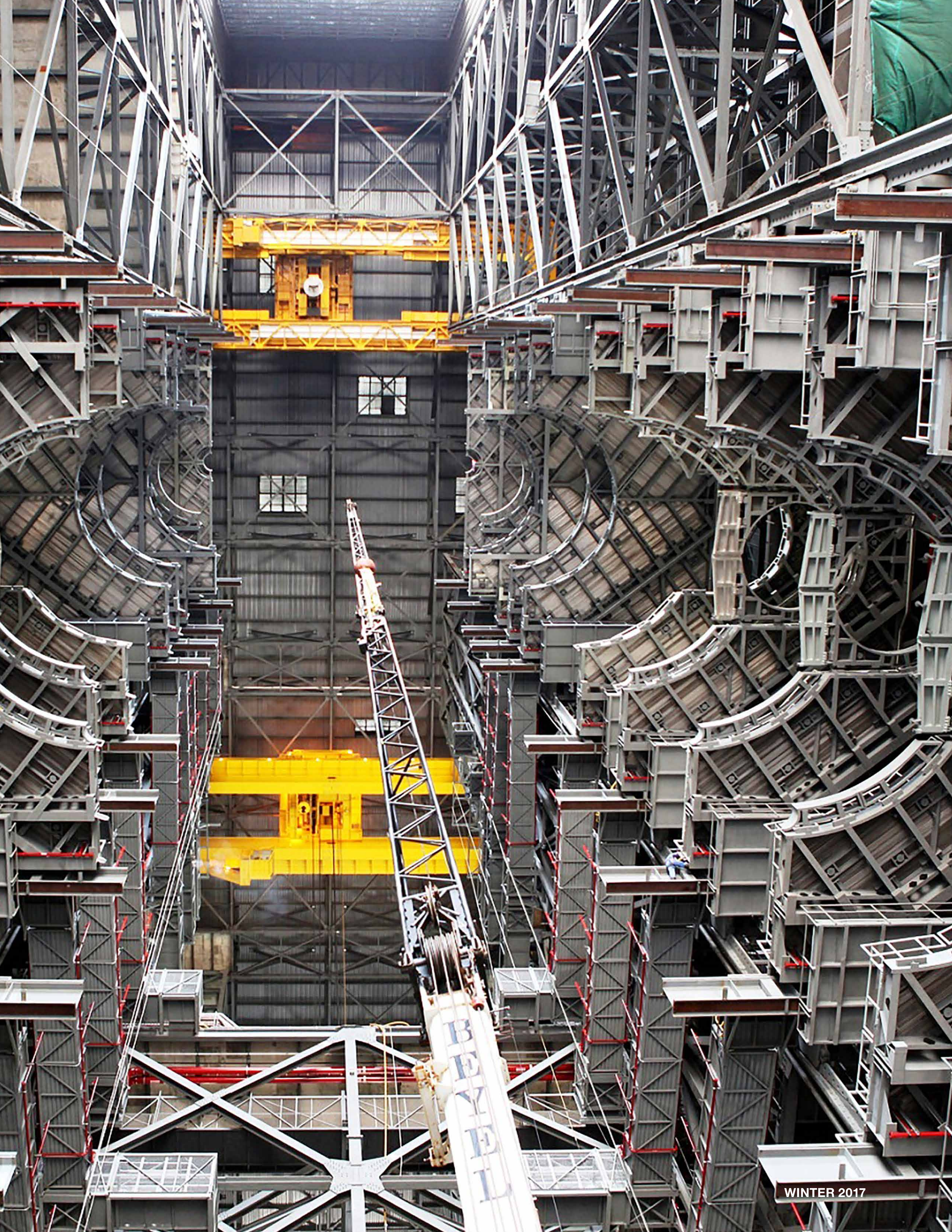
"The document doesn't make the relationship that's required to be a good system for these high-performance systems. You've got to live in each other's space. You've got to appreciate what's important to each other," said Singer. "That means you actually have to talk about what's important, and what you're worried about, and why you're worried about it, and start building that longer-term relationship."

He considers integration the most important part. "Dealing with highly complex, high-reliability systems requires a lot of effective communications," said Singer, who moderated the Integration Lessons panel at the Human Spaceflight Knowledge Sharing Forum. The panel, composed of the following individuals, shared integration challenges and lessons learned during NASA's ongoing Journey to Mars.

- Jim Geffre, NASA Orion Program
- Johnny Heflin, NASA Space Launch System (SLS) Program
- Jessica Parsons, NASA Ground Systems Development and Operations (GSDO) Program
- Jennifer Read, NASA Exploration Systems Development (ESD) Division

ESD's approach pushes the integration function to lower levels closer to the hardware owners and relies on the Orion, SLS and GSDO programs to self-integrate. Management models used by the programs could leave open the possibility of gaps in coverage, so a strong Cross-Program Integration Team (CPIT) with Integrated Task Teams (ITT) was established. The teams use resources largely owned by the programs, but report and respond to the ESD CPIT.

High up in the Vehicle Assembly Building at NASA's Kennedy Space Center in Florida, an overhead crane lowers the final work platform, A north, into place for installation in High Bay 3 In January 2017. Installation of the final topmost level completed the 10 levels of work platforms that will surround NASA's SLS rocket and the Orion spacecraft and allow access during GSDO processing for missions.



ORION INTEGRATION MODELS

The Orion Program uses a streamlined oversight model to maximize the amount of inline work, maintaining a minimum level of oversight. “Our philosophy is the best oversight comes from being part of the day-to-day work, working through the challenges with our engineers,” said Jim Geffre, Orion Vehicle System Performance and Analysis Office Lead. “Meanwhile, we maintain a strong system manager/subsystem manager function to preserve that traditional oversight role.”

Since its inception in 2005, Orion has used multiple integration models. Geffre shared lessons learned and common themes throughout the use of different integration models:

- Integration needs to occur at all levels throughout the organization.
- Emphasize communication in all directions.
- Multiple integration models can be applied successfully depending on the situation, and demand a nimble, adaptable organization.
- Don’t confuse oversight with integration; integration is most successful when participatory.

Orion and SLS are geographically distributed across NASA centers, contractors and international partners. Geffre said one of the most interesting integration challenges on Orion is the European-built service module, an essential part of the spacecraft that will power, propel and cool Orion in deep space as well as provide air and water for crew members. The European Space Agency (ESA) has engaged 13 European countries in development of the service module.

“This kind of geographic separation introduces some new integration challenges,” said Geffre. “You’re dealing with a six-to-eight-hour time difference every day, which limits how much communication can be done via telecon or phone call. We’ve had to adapt our integration model to working with ESA.”

The Orion Program created a dedicated European integration office to negotiate agreements and manage the integration function. Geffre said they rely more heavily on integration through documentation due to limited opportunities for day-to-day integration and interaction. He said one of the biggest challenges in working with the European partners is getting the documentation right so that the end product meets overall mission needs.

SLS HARDWARE INTEGRATION

The process of integrating proven engines into a new vehicle is front and center for SLS. “Legacy hardware. Legacy engines. 135 successful flights. Very robust, proven design.

“That’s what integration is all about – people. And it’s about those touch points. It’s about having people in the right positions with clear lines of responsibility, roles and responsibilities defined, and clear lines of communication.”

But it’s a new vehicle. New operating conditions. New environments. Different avionics protocols. So, we have to do some work to adapt those engines to that vehicle,” said Johnny Heflin, SLS Liquid Engine Office Deputy Manager. “We’re in the process of testing those engines at Stennis now to prove that the engine meets SLS environments and capability along with certifying the new engine controller that we’ve developed in order to interface with the new vehicle avionics.”

Jim Geffre.

SLS will be the most powerful rocket NASA has ever built. When completed, the rocket will enable astronauts to begin their journey to explore destinations far into the solar system. Heflin provided an SLS overview and a description of the systems engineering and integration (SE&I) function from an organizational point of view. “That’s what integration is all about – people. And it’s about those touch points,” he said. “It’s about having people in the right positions with clear lines of responsibility, roles and responsibilities defined, and clear lines of communication.”

Heflin added that clearly defined roles, responsibilities and communication paths are essential not only for integration, but for programs to remain lean in an era of affordability.

Johnny Heflin.

GSDO CROSS-PROGRAM INTEGRATION

GSDO is responsible for upgrading KSC infrastructure and developing ground systems to build, process, launch and recover SLS and Orion on time and on budget. GSDO relies on the CPIT model, which depends on multiple ITTs and proactive involvement of program SE&I leads who identify and address high-risk integration items.

Jessica Parsons.

Jennifer Read.

GSDO also uses Integration Engineers as technical representatives to SLS and Orion, providing program-to-program technical integration during development, integrated testing and operations.

Jessica Parsons, GSDO SLS Integration Lead, said using the CPIT model instead of an independent Level 2 Integration Office allows GSDO, SLS and Orion to work together more closely than during the Constellation Program, where issues were elevated to Level 2 for them to work the problem. "We don't wait for somebody else to solve that problem," said Parsons. "We will call our sister program and try to figure out how can we resolve that problem. What is the best solution that we can come up with for the enterprise?"

Parsons said each of the programs participates in major life cycle reviews, and she thinks this has been essential to help identify technical issues and disconnects early in the process.

"I think this integration model allows for quick decision velocity," said Parsons. Joint Integration Control Boards convene three times per week and the three program Chief Engineers make technical decisions. If they can't come to resolution on an issue, it is elevated to the Program Managers the following week to expedite decision making.

The biggest challenge from Parsons' perspective is that each program has an agile software development process. She said it's really hard to integrate the software, but they have been successful in identifying what each program needs and when the information is needed.

ESD LESSONS LEARNED

Jennifer Read, Integration Scientist and Lessons Learned Coordinator with KBRwyle supporting the ESD Division of NASA's Human Exploration and Operations Mission Directorate, said CPIT is a new model resulting from lessons learned from the Constellation Program. CPIT leverages the programs to lead and develop the integrated products.

"One of the great things about what we do with the CPIT model is it can grow, or it can retract as we move through our development cycle," said Read. "The ad hoc teams are short lived. They may not be product-specific, but sometimes actually an ad hoc team can turn into an integrated task team."

She said schedule is a challenge as the three programs work independently, but also collaboratively. Read noted that the importance of communication in integration is a recurring theme, and that the CPIT leads talk with each other every morning and have weekly tag-ups and a technical forum where they status technical topics and action resolution.

Orion's Geffre added that daily communication between the organizations was established as a regular business rhythm. "Sometimes you need to force that communication at the start, and then it just kind of grows organically," said Geffre. "Probably the biggest lesson learned is the benefit of early communication."

Forum session on Integration Lessons: http://go.nasa.gov/2jlLDWH

BRINGING IT ALL TOGETHER

In October 2015 SLS became the first human-rated rocket in almost 40 years to complete a Critical Design Review (CDR), clearing the way for full-scale fabrication. Orion, the world's only human-rated deep space vehicle, and the Ground Systems Development and Operations Program that will provide the facilities and ground support at NASA's Kennedy Space Center to prepare SLS and Orion for the journey to Mars, completed a joint CDR in March 2016. NASA's ESD Division manages the technical integration of the Deep Space programs designed to push human exploration farther than ever before.

Future of Space Communications

Conceptual image of Laser Communications Relay Demonstration.

Future space communications will be more flexible, scalable and affordable, thanks in part to an integrated architecture. NASA networks span the globe and cover the solar system. NASA's current space communications architecture includes the Deep Space Network, Near Earth Network and Space Network with 20 ground stations or facilities across all seven continents. The networks provide service to over 100 missions every day, continuous coverage of the Deep Space environment, and coverage from pole to pole via nine tracking and data relay satellites. The networks are a combination of NASA and commercially owned and operated assets and services.

Different services and processes are offered between each of the current space communications networks, and an effort is underway to standardize and optimize communications for future missions. NASA Space Communications and Navigation (SCaN) Chief Architect James Schier says enough progress has been made on future space communications architecture to define a vision.

"We're starting to outline a path on how we're going to get there," Schier said during his "Future of Space Communications" presentation at the Human Spaceflight Knowledge Sharing Forum. "We've identified projections for the mission needs for both science and exploration for 25 years, so we have a good idea of how much traffic we're going to have to provide for, in terms of capacity. But we're also defining the architecture so that it is scalable to meet unanticipated growth."

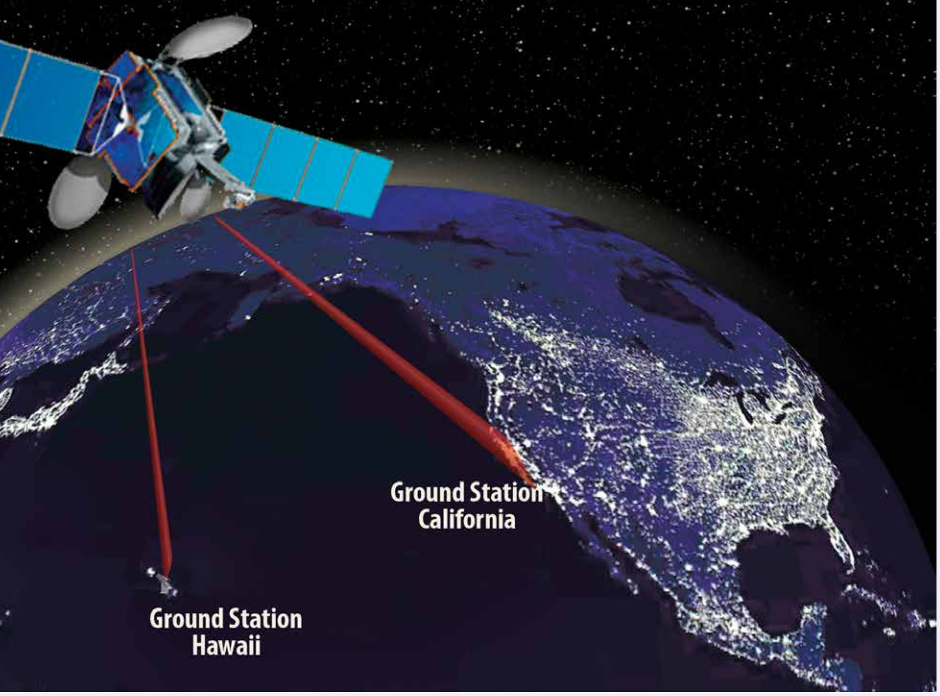
VISION FOR NEXT GENERATION ARCHITECTURE

The new NASA SCaN integrated network architecture responds to challenging mission and programmatic requirements and the call for new, enhanced communications capabilities. Schier said adopting a common architecture for lunar, Earth and Mars networks will reduce technology and development costs and allow reuse of hardware and software. He outlined the vision for the next generation architecture:

- **"Shrink" the solar system** by connecting the principal investigator (PI) more closely to the instrument or experiment, the mission controller to the spacecraft, and the astronaut to the public audience.
- **Improve the mission's experience and reduce mission burden** in terms of the effort and cost required to design and operate spacecraft to receive services from the SCaN Network.
- **Reduce network burden,** including the effort and cost required to design, operate and sustain the SCaN Network as it provides services to missions with the collateral benefit of increasing funding for communications and navigation technology.
- Apply new and enhanced capabilities of terrestrial telecommunications and navigation to space by **leveraging other organizations' investments.**
- **Enable growth of the domestic commercial space market** to provide -- and NASA to use -- commercial services currently dominated by government capabilities.
- **Enable greater international collaboration** and lower costs in space by establishing an open architecture with interoperable services that foster commercial competition and can be adopted by international agencies as well as NASA.

Schier says part of the strategy for implementing the vision is to offer incentives for NASA missions to adopt the new approach, offering lower mission burden in terms of size, weight and power (SWaP) and cost parameters. "We want to make it more appealing for the users in the future to adopt new services and go with new capabilities than to stick with the good old legacy stuff that they're more familiar and comfortable with. At the same time, we want to improve the mission experience," said Schier, referring to efforts to streamline how missions design their communications subsystems and Mission Operations Centers (MOC) as well as how they negotiate support from the SCaN Network.

James Schier.



incorporate Ka-band capability on all new 34-meter Deep Space Network antennas also includes investing in user terminals to bring cost down and overcome user community reluctance to adopt Ka-band.

5. Current: Link Layer Services ➔ Future: Network Layer Services

Link layer services don't guarantee data delivery forcing MOCs to develop software to process data for errors, resend data, and issue commands to delete data from memory. As part of reducing mission burden, the Next Gen approach includes space internetworking -- the Solar System Internet (SSI) -- that guarantees delivery and reduces burden on ground and flight segments, enables a Service-Oriented Architecture (SOA) providing access to additional applications, and offers the ability to move data directly from MOCs to PIs or directly from spacecraft to PIs.

PARADIGM SHIFTS

Schier said implementation of the flexible, scalable and affordable architecture will require six key paradigm shifts.

1. Current: RF ➔ Future: RF + Optical

Optical communications technology promises high data rates with low SWaP and cost for users. The optical terminal requires extremely precise pointing but has built-in vibration isolation that avoids imposing extremely high stability on the spacecraft bus, thus eliminating the need for a gimbaled antenna. The Laser Communications Relay Demo (LCRD) is set to launch in 2019 and become the first operational optical asset in 2021.

2. Current: Single Access ➔ Future: Multiple Access

Multiple access enables one network antenna to talk to multiple users simultaneously in the same overall system bandwidth, a significant improvement over single access, which points one network antenna to one user antenna and commits both for the duration of an event. The Next Gen approach introduces demand access service where the user requests access when needed and gets the necessary bandwidth.

3. Current: Scheduled Access ➔ Future: Unscheduled Access

Unscheduled access will enable further system automation and operations cost reduction, while eliminating scheduling for most missions. The current, scheduled access process is labor-intensive and requires missions to schedule events days or weeks in advance. The Next Gen approach introduces demand access services, and shifts from the unreliable link layer to guaranteed network layer service using Disruption Tolerant Networking (DTN).

4. Current: Ku-band ➔ Future: Ka-band

Ka-band can provide higher data rates at higher frequencies with lower spacecraft SWaP. The Next Gen approach to eliminate Ku-band from Next Gen Earth Relays and

6. Current: Different Near-Earth and Deep Space Architectures ➔ Future: Common Architecture

Instead of distinct networks, a common architecture will integrate space- and ground-based assets used to provide service to everything from within the near-Earth domain to Deep Space. A common architecture would help simplify mission concept definition and implementation when moving from Earth into the lunar environment, Mars and beyond. The Next Gen approach builds in resiliency that has not existed previously in space communications assets.

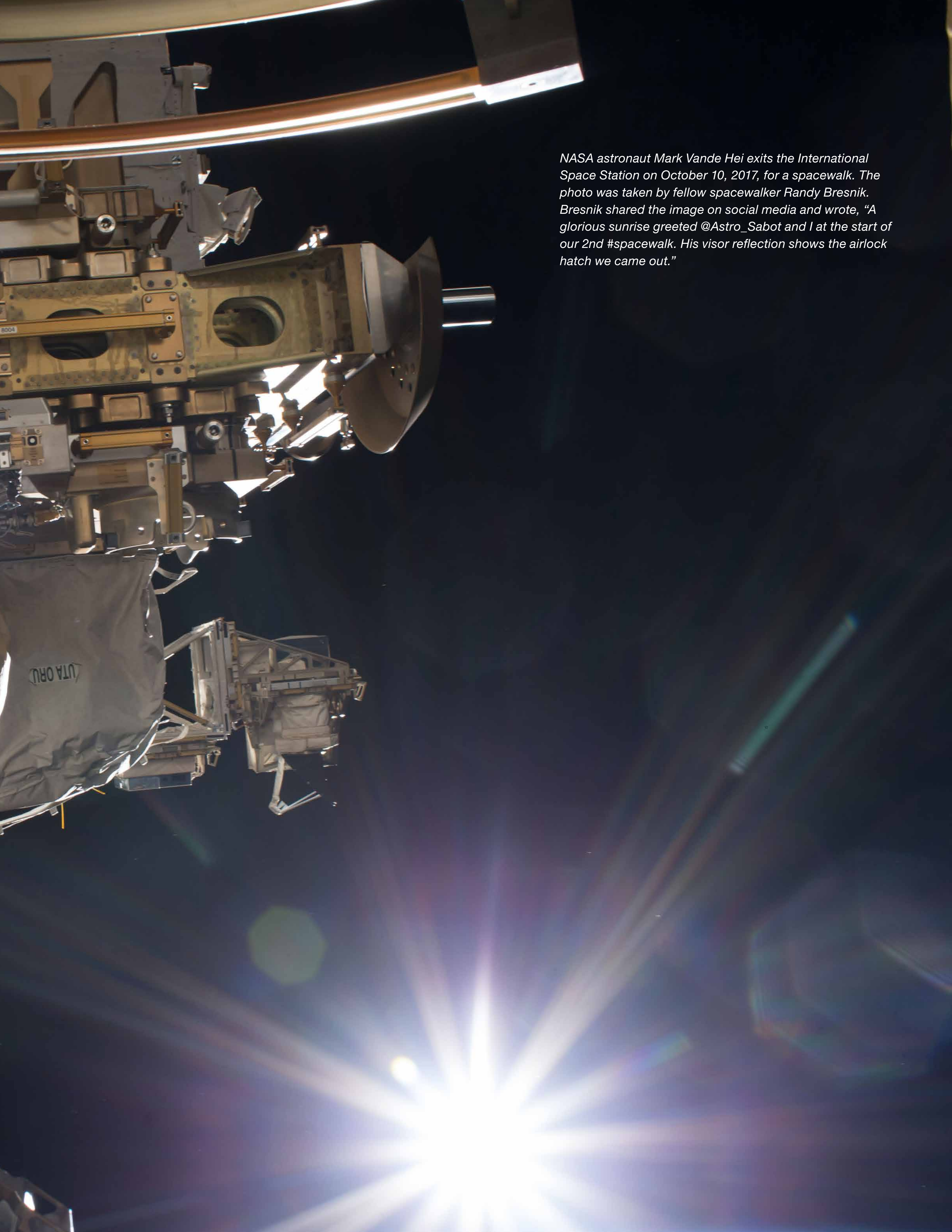
ADVANCING COMMUNICATIONS TECHNOLOGY

Schier said NASA wants to take advantage of advances in space communications technology. "The equation has changed. Right? We're no longer just the leader in technologies. We need to be the adapter of commercially available technologies," he said. "We want to make sure that we're working with industry to stimulate their adoption of new technologies and use that to help increase the rate of expansion of commercial space development."

Universal collaboration is part of the vision for future space communications. "We want to continue to work with our international partners and, in fact, expand that so that our future architecture is -- like the internet -- adopted by everybody in the universe, which will help make it more reliable, more prevalent, and increase the capability of service while reducing the cost of acquisition and operation," said Schier.

The Next Gen Architecture Concept Review is planned in late 2018.

Jim Schier's SCAN Overview forum presentation: http://go.nasa.gov/2jl10yk



NASA astronaut Mark Vande Hei exits the International Space Station on October 10, 2017, for a spacewalk. The photo was taken by fellow spacewalker Randy Bresnik. Bresnik shared the image on social media and wrote, “A glorious sunrise greeted @Astro_Sabot and I at the start of our 2nd #spacewalk. His visor reflection shows the airlock hatch we came out.”

View of city lights, clouds, stars and sunlight as seen by the International Space Station Expedition 47 crew above southern Europe in May 2016.

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NP-2017-11-2494-HQ