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Safety in the New Exploration Age

Assessing the risks to astronauts

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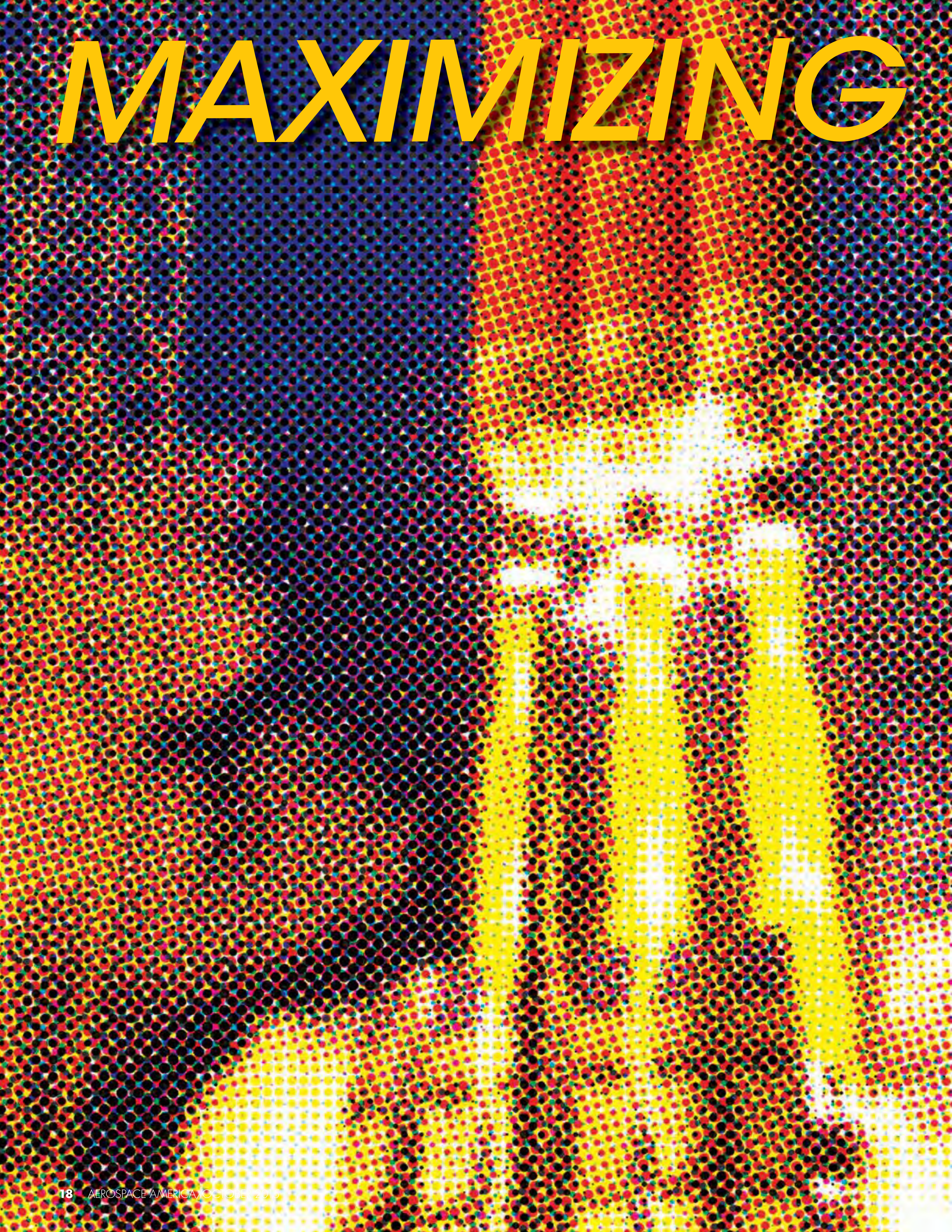
MAXIMIZING



SAFETY

Nothing is more tragic or paralyzing to space exploration than the deaths of a crew of astronauts. With the U.S. making bold plans to send humans to an asteroid and Mars, Debra Werner and Anatoly Zak set out to understand the odds of deadly accidents or illnesses — and how NASA and the industry aim to keep those risks to acceptable levels.

When the Space Shuttle Columbia broke up high over east Texas in 2003, killing all seven astronauts, flight safety advocates turned it into a watershed moment to push for toughened safety standards. It was the second loss of a crew in just 113 flights, including the 1986 Challenger explosion. In 2004, President George W. Bush stood at a podium at NASA headquarters and announced that the shuttle fleet would be retired in 2010, a date later shifted to 2011. NASA followed with an ambitious goal proposed by the Astronaut Office: Why not develop a successor that would bring crews home safely 999 times out of 1,000 missions?

The goal, however, was short lived, waylaid by the realities of launching spacecraft atop thousands of pounds of explosive propellant, circling Earth amid bits of spent rocket stages and exploded satellites and blazing back into the atmosphere at hypersonic speeds.

In 2010, NASA quietly accepted a lower threshold for the shuttle's successor of 1 loss of crew in 270 missions to low Earth orbit. Any greater risks and NASA would cancel the program. Then, in an unexpected twist, NASA's safety experts factored in the risks of traveling to Mars or an asteroid, as the agency plans to do in the 2030s with the Space Launch System rockets. NASA determined the loss-of-crew rate on that type of mission would be 1 in 75.

The numbers suggested that flying on SLS and Orion would be riskier than one of the last flights on the shuttle. That assessment upset the Aerospace Safety Advisory Panel, a group of experts tasked by Congress in 1968 to periodically assess safety after the Apollo 1 launch-pad fire that killed three astronauts. The technology executives

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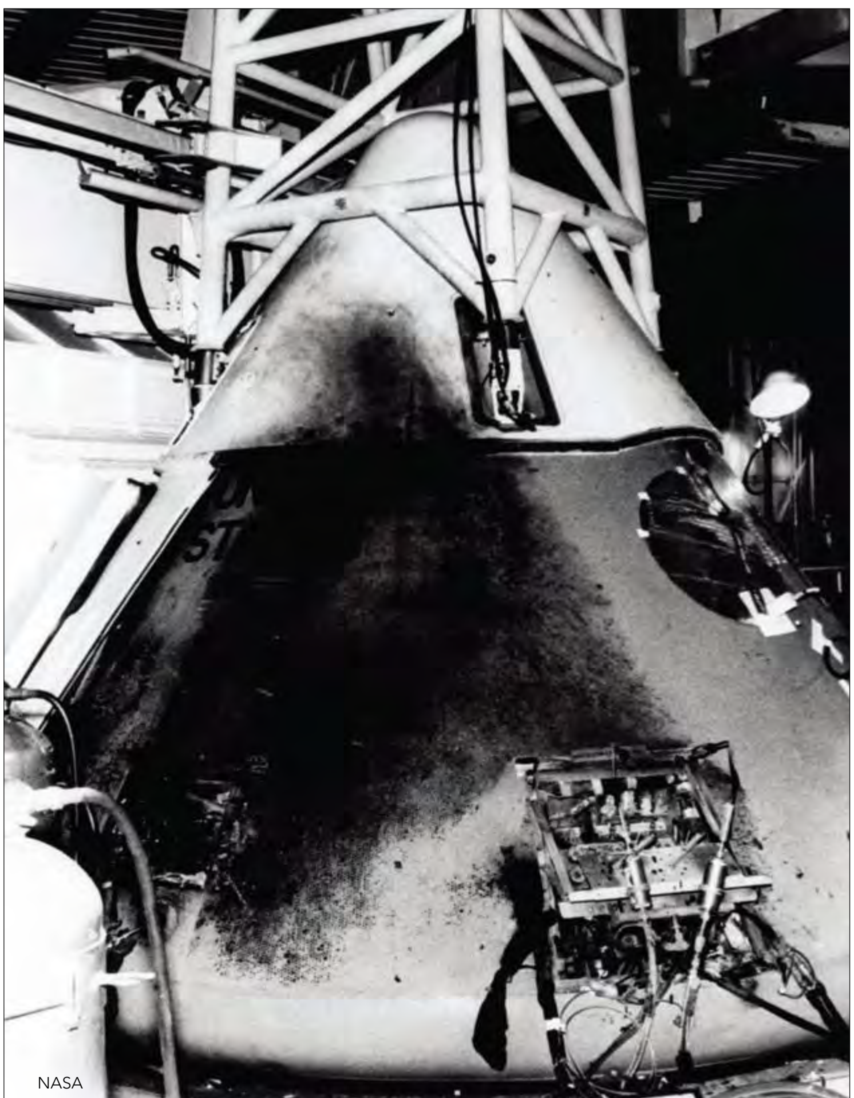
and retired military officers on the panel had pressed NASA for months to share its assessment of risk on Orion and SLS flights. Calculations that new human spaceflights would not be significantly safer than with the shuttles did not sit well.

"It was the ASAP's hope that the inherently safer architecture of the SLS and Orion as compared to the Space Shuttle, including full abort capability, separation of energetics from the crew module, and parachute reentry instead of aerodynamic, would greatly improve inherent safety," according to ASAP's 2014 annual report.

Against that backdrop, astronaut safety is a paramount focus from the Kennedy Space Center in Florida, where Lockheed Martin is building the next Orion capsule and Boeing will assemble its CST-100 capsules, to Hawthorne, California, where SpaceX is building Dragon-2. Even as NASA works to study the safety risks of missions aboard these spacecraft and their rockets, officials know that there is only one way to prove the safety merits of NASA's decision to launch relatively simple capsules on conventional rockets: Start the new era of human spaceflight with them.



Apollo 1's command module the day after a flash fire during a 1967 launch pad test killed astronauts Roger Chaffee, Gus Grissom and Edward White.

NASA

NASA cautions against the temptation to make misleading comparisons. Orion, the agency's flagship human spaceflight program, can't be easily compared to the space shuttle in terms of risk, because of their drastically different missions. The shuttle was intended strictly for flights in low Earth orbit, while Orion is being developed for still-undefined deep-space missions.

"The actual loss of crew value will vary depending on the mission," William C. Hill, NASA deputy associate administrator for exploration systems development, says by email. "This makes the loss-of-crew number one example where it is difficult to compare shuttle with Orion/SLS."

To evaluate safety, NASA analyzes risk for specific elements of a mission and aggregates those numbers. Launch and ascent gets a rating. In-space activity gets another. Atmospheric entry, descent and landing gets a third.

For launch and ascent, NASA will require Lockheed Martin to show that Orion poses no more than a 1-in-1,400 risk of loss of crew. Boeing must show that SLS poses no more than a 1-in-550 risk. For Orion's entry, descent and landing, the risk must be no more than 1 fatal accident in 650 missions.

But until the actual mission has been specified, it's impossible to determine the precise risks astronauts will face. Missions can vary significantly in duration and exposure to hazards including micrometeoroids, radiation and orbital debris, Hill says.

"The initial test flights will enable us to gather hard data and learn how to improve systems," Hill adds. "We expect to continue making safety enhancements as we learn more."

Radiation, meteoroids and debris

One NASA safety expert, who was not authorized to speak on behalf of the agency, says comparing Orion to shuttle "is comparing apples to kumquats. It is not that the [Orion] spacecraft is more dangerous. It is what we are asking the crew to do."

A SpaceX Crew Dragon lifts off during a pad-abort test in May. The unmanned test demonstrated how the capsule would save astronauts from a failing launch vehicle.

Low Earth orbit was the destination for the shuttle orbiters. But for Orion, it will be only the first stop. An upper stage, or space tug, must fire with more than twice as much force as the most powerful double-engine Centaur upper stage on the Atlas 5 rockets. The extra power will be necessary to escape Earth's gravity and traverse through space junk, meteoroids, the Van Allen radiation belt and the galactic cosmic radiation beyond Earth's magnetosphere.

Orion's carbon composite shell, which surrounds its titanium honeycomb crew compartment, will shield astronauts from enough radiation that long-term health effects are more of a concern than losing a crew member due to acute radiation sickness during a mission. If astronauts eventually travel in deep space for two or three years, radiation might take a toll on their central nervous, cardiovascular or immune systems that would be seen later in the mission.

"We only have hints of that, but it is enough to be concerned," says Ronald Turner, an analyst at Anser, a nonprofit research institute in Falls Church, Virginia.

The first Orion missions are expected to last 21 days at most, which means astronauts would not have to worry too much about radiation. A bigger concern would be a collision with meteoroids or human-made debris. If an object were to pierce Orion's upper stage before it expended its propellant, the stage could be disabled or the force of the escaping gases could cause Orion and the stage to tumble violently and require immediate separation, creating risk of a collision. A similar uncontrolled tumble occurred during the 1966 Gemini-8 mission, but the crew returned home safely.

So, starting with Exploration Mission-2 in 2021, which will be the first time Orion carries a crew, the capsule will be boosted by a more powerful upper stage designed from the start for protection from impacts. This Exploration Upper Stage will give SLS power to boost additional payloads, such as a habitation module, an airlock or, if NASA changes its exploration goals, even a lunar landing module.

Debris turned out not to be a problem

Rick Stiles/NASA Columbia Accident Investigation Report

Fatal vulnerability: A chunk of foam like that on the shuttle's external tank pierced a section of reinforced-carbon-carbon material during testing at the Southwest Research Institute in Texas. Investigators concluded that foam fell from Columbia's tank during its 2003 ascent and damaged the orbiter's left wing, causing Columbia to burn up when the crew tried to return home after the mission.

on Orion's first flight, the unmanned Experimental Flight Test-1, despite the Delta 4 Heavy's less-protected Interim Cryogenic Propulsion Stage. After studying whether to add protective materials, "the team deemed that the increased risk did not really drive you to change the design," says Mike Hawes, the Orion project manager at Lockheed Martin.

Because the new Exploration Upper Stage won't be ready, the interim stage will be used on the first flight of SLS, the unmanned Exploration Mission-1 Orion mission, currently scheduled for late 2018.

On EFT-1, the NASA-Lockheed Martin team was able to mitigate the impact risk by cutting the time spent in lower orbit as Orion simulated an ejection into translunar orbit.

Getting home

Once Orion leaves Earth's orbit, an emergency return will be a lengthy and propellant-hungry affair. If a mishap occurs far enough from Earth, Orion would need to loop around the moon before heading back to Earth a la the Apollo 13 Command/Service Module and Lunar Lander.

Unlike Apollo 13, Orion won't have a lunar module to serve as a lifeboat. The Bush administration had included a lunar lander called Altair in its Constellation exploration plan, but in 2010 the Obama administration canceled Constellation and the lunar lander. While there would be no lifeboat for the crew, Hawes stresses that more advanced internal systems currently designed for the Orion would make the Apollo-13 scenario itself much less likely.

"The mission configuration is different, the mission definition is different, and, frankly, the reliability of the systems is very different," Hawes says. "Data and computing systems are all built with extra levels of redundancy and [Orion] incorporates all that the space community learned through Mercury, Gemini, Apollo, Skylab, Shuttle and space station."

Launch abort

Whether the destination is the station or deep space, the ascent phase of a mission is always among the riskiest steps.

During the shuttle program, few astronauts had faith that the escape mechanism added to the orbiters after the 1986 Challenger explosion would work. The astronauts were suppose to blow a hatch, install an escape pole, then one-by-one hook their parachute harnesses to the pole, slide down it and off the end toward the ground. Another problem was the shuttle's architecture. Attaching the orbiter to the side of the external propulsion tank meant that any material shed upstream of the orbiter during launch could potentially hit it, which is exactly what happened to Columbia. Foam insulation from the external tank broke off and struck the orbiter's left wing, fatally damaging the wing's heat shield.

Orion will ride atop its rocket to avoid the Columbia debris scenario, as will the Commercial Crew vehicles in development for transportation to and from the International Space Station. In addition, all will have abort systems requiring little or no action on the part of the crew.

In an emergency on the launch pad or before main engine cutoff, a United Launch Alliance Atlas 5 emergency detection system would direct CST-100 computers to activate four Aerojet Rocketdyne RS-88 Bantam engines to lift the crew capsule from the booster. The flight crew can also activate the same emergency system, as can flight controllers on the ground if necessary.

"If we have a horrible day, we're going to get the crew back to safety," predicts Chris Ferguson, a former space shuttle commander and Boeing's crew and mission operations director.

SpaceX chose a similar approach. The company's Dragon 2, an updated version of the Dragon capsules that carry supplies to the space station, is equipped with eight SuperDraco launch abort engines with a combined 120,000 pounds of thrust. After the SpaceX Falcon 9 rocket broke apart minutes following liftoff in June, Gwynne Shotwell, SpaceX president and chief operating officer, said in a NASA briefing, "The escape system slated for the second version of Dragon certainly should have taken the astronauts to a safe place after an anomaly like this. In fact, it's designed to take a far more energetic event and get the astronauts safely away."

For Orion, Lockheed Martin chose to attach a rocket assembly at the top of the capsule's aeroshell to pull it away from a failing launch vehicle and position the capsule for a safe landing under a parachute. The approach is similar to those used for Mercury, Apollo and Soyuz.

Orbital debris

NASA's plans to pay Boeing and SpaceX to keep their new commercial space taxis docked at the space station for six months to serve as emergency shelters or lifeboats will make them vulnerable to debris. By contrast, shuttle orbiters typically spent about 12 days in orbit.

"One of the most significant drivers to risk is micrometeoroid and orbital debris environment exposure time," says Phil

Technicians assess data collected during vibration tests on Orion's Launch Abort System. The inert, 16-meter-long assembly was tested in 2009 at the Orbital Sciences facility in Dulles, Virginia.

McAlister, NASA director of human spaceflight development. "There's a little bit more debris up there than there was 10, 20 or 30 years before. So the length of time you are on orbit is a significant driver to risk."

The danger is that a micrometeoroid or bit of a spent rocket body could strike an unoccupied, docked vehicle without anyone noticing.

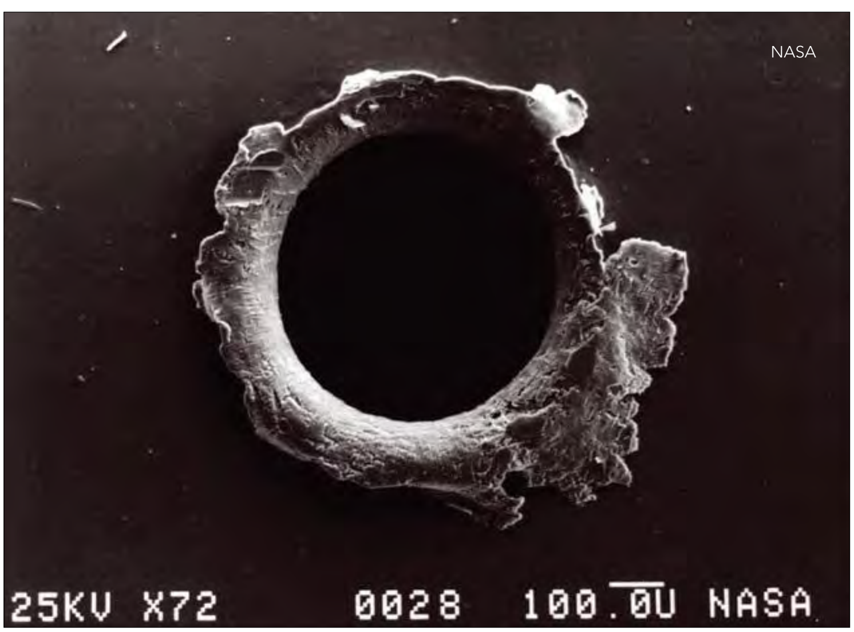
"As the space shuttle taught us, even minor damage to the thermal protection system can be catastrophic during reentry because of the extreme environment that it must withstand," says John Frost, a member of the safety panel and a former head of the Army Aviation and Missile Command's safety office.

Meteoroid or debris impacts are inevitable if a spacecraft stays up long enough, so NASA is considering technologies or strategies for inspecting the space capsules while they are docked at the space station. NASA could instruct astronauts to inspect the capsules during a spacewalk or to use one of the space station's robotic arms to survey the extent of any damage.

Boeing designed the CST-100 to deflect or absorb debris with its composite outer shell, thermal protection system and interior pressure vessel. SpaceX did not respond to requests for comments on its debris protection.

"We stacked up things that could cause loss of crew or loss of mission," Ferguson says. "Rocks and stuff in orbit ended up being the number one thing. We take great measures to protect astronauts from small particles."

This impact mark was discovered on a component of the Solar Max scientific satellite after the space shuttle Challenger crew repaired the spacecraft in 1984. It is about the size of the period at the end of this sentence.



Closing the safety gap

No one is sure whether the commercial capsules or Orion, if used for low-Earth-orbit missions, can achieve the 1-in-270 threshold for loss of crew due to the micrometeoroid hazard. So NASA has directed Boeing and SpaceX to ensure that their vehicles can provide a one in 200 chance of loss of crew, while the space agency takes additional measures, such as inspections or shortened missions, to close the safety differential.

"We believe operational considerations will help us get to that 270 number," NASA's McAlister says. "How exactly we are going to do it, we haven't defined yet."

That 1 in 270 number, which would make Orion roughly three times as safe as the shuttle at the end of the program, "is certainly something we all hope can be achieved," says George Nield, FAA associate administrator for commercial space transportation and a member of the safety panel. "But in fairness, it's very, very difficult to predict ahead of time exactly what risks are present and exactly how and when those risks will show themselves. The intent when we started flying the shuttle was that it would be as safe as an airliner and we were going to have regular people — teachers and others — fly on it. As it turned out, it wasn't quite as safe as we hoped."

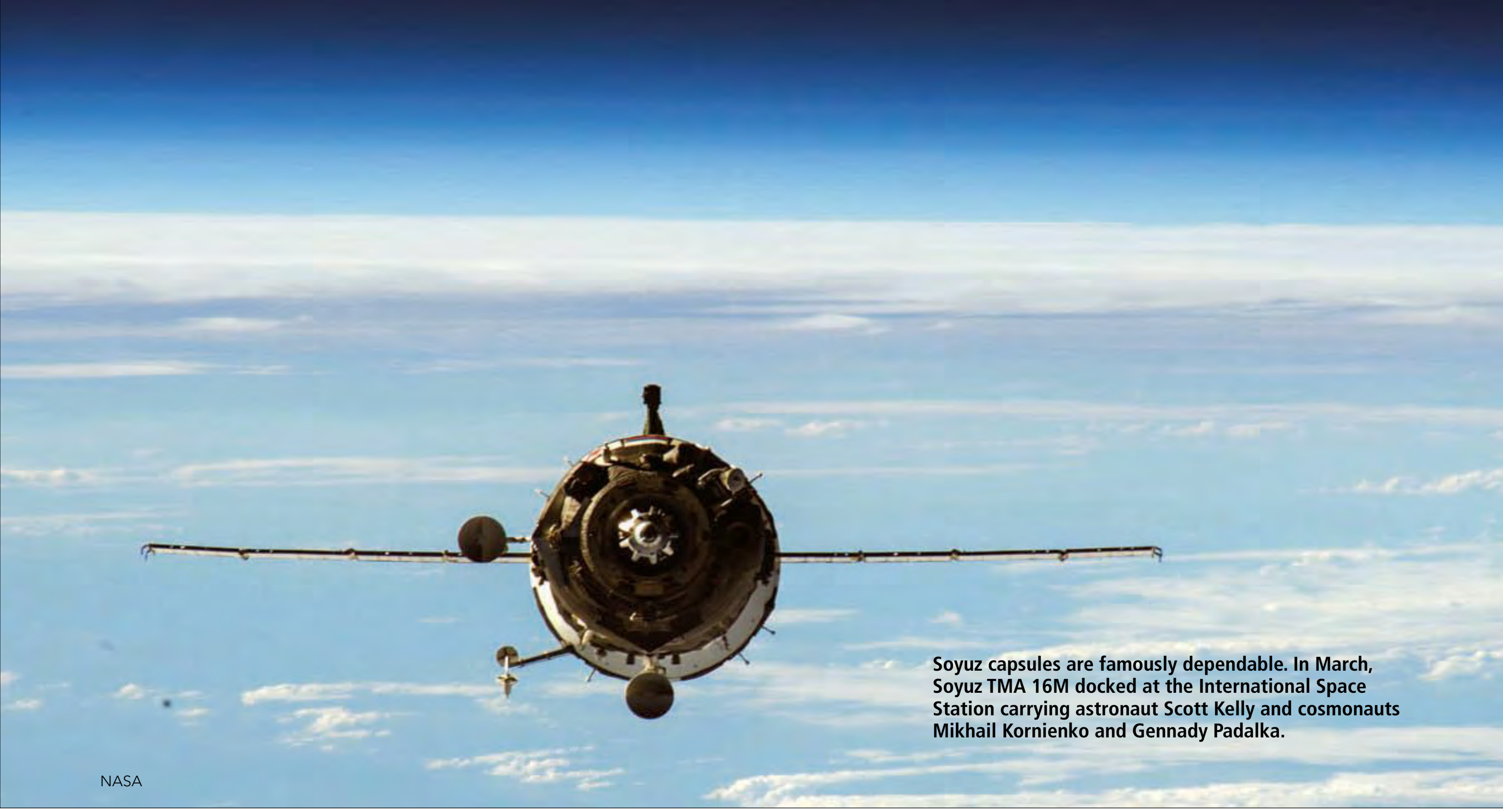
In retrospect, the loss-of-crew risk at the outset of the shuttle program was closer to 1 in 12, according to ASAP's 2011 annual report.

History is on the minds of NASA officials as they look to the future. By the time of the shuttle's inaugural launch in 1981, the Apollo-1 fire that killed astronauts Roger Chaffee, Gus Grissom and Edward White was a distant memory. Fresher were the memories of the Apollo moon landings and the Apollo 13 rescue.

"We were pretty much bullet-proof," a NASA official remembers. "We could do no wrong!"

That sentiment evaporated with the shuttle disasters, after which NASA's culture grew more risk-averse.

Under the latest safety criteria, Lock-



Soyuz capsules are famously dependable. In March, Soyuz TMA 16M docked at the International Space Station carrying astronaut Scott Kelly and cosmonauts Mikhail Kornienko and Gennady Padalka.

NASA

heed Martin engineers are evaluating 23 different safety parameters for Orion missions, including health risks to the crew, meteoroids, heat shield problems and parachute failures. As a result, each discipline has to bring its own risk assessment, which then ends up in the melting pot of an overall estimate.

"Sometimes these numbers are driven by many, many factors that I, a little sarcastically, refer to as a car's equivalent of a check-engine light," Hawes says. Lockheed Martin has to consider human health factors ranging from disease to radiation and all of the life support functions of the spacecraft, and then put those risks together into a single number.

Kidney stones are more likely in space than on Earth, for instance, because zero gravity causes bones to atrophy, which causes kidneys to absorb more calcium.

"You can look at those issues differently when you are in low Earth orbit on the space station than when you are going to the moon and you are several days away from home, or if you are going to Mars, where you are several months away from home," Hawes says. "We need to have better understanding and better processes to handle these kind of problems."

Safe as Soyuz

NASA and its contractors hope Orion, CST-100 and Dragon 2 will eventually prove themselves to be as safe or even safer than Soyuz, which has carried U.S. astronauts to the space station since the shuttle stopped flying in 2011. The new capsules have more meteoroid protection than Soyuz and improved heat shields. Key will be operational experience. CST-100 and Dragon 2 have not yet flown and Orion has made only one unmanned test flight. Then again, Soyuz missions in the mid-1960s were plagued with potentially fatal problems whereas an early version of Orion splashed down just as planned in the program's first flight last December.

Looking to the future, space safety experts in the U.S. and elsewhere hope to someday achieve the 1-in-1,000 loss-of-crew goal once envisioned for the shuttle fleet, but they say it will be difficult.

"If we had the possibility of building more reliable rockets, we would already have done this because no one has an interest in losing rockets," says Tommaso Sgobba, executive director of the International Association for the Advancement of Space Safety and former head of the European Space Agency's flight safety office. "There is no magic formula."

The only way to improve reliability is to fly the same rocket and space capsule repeatedly. Sgobba points to the Soyuz booster, which has flown more than one thousand missions and has not experienced a fatal accident since 1971.