BY JOE PAPPALARDO / ILLUSTRATIONS BY JONATHAN BARTLETT

HOW WE'LL DIE ON MARS

Establishing a permanent human presence on the Red Planet will be risky, but researchers are finding solutions that will keep future residents alive long enough to die peacefully. Here's how it could happen.

Gathered in a common room, the mourners say goodbye to the body of their pioneering geologist, dead from a brain aneurysm. The Mars base memorial service remembers a fellow colonist, but also celebrates a milestone for humanity: On June 23, 2034, she became the first person to die of natural causes on Mars.

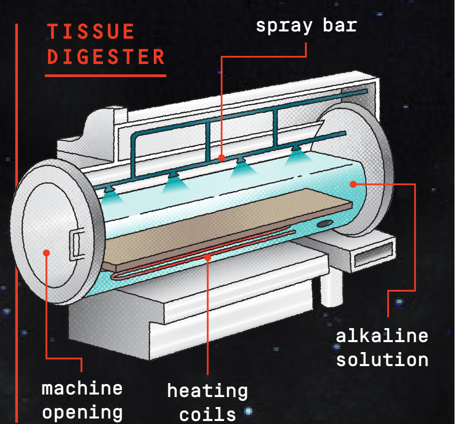
After the service, while the mourners head to the public grove that serves as a graveless cemetery, a pair of technicians undress the body and move it to a room ringed with stainless-steel pods. These are tissue digesters. The techs transfer the body into an empty pod and seal the lid. Soon it fills with water spiked with potassium hydroxide, a caustic base. Then the pod is heated to 300° Fahrenheit and pressurized to 70 psi.

After about 12 hours of pressure-cooking alkaline hydrolysis, the pod drains with an automated whoosh, leaving only the bones. The broth is piped to the colony's anaerobic digester, where microorganisms break down biodegradable waste to produce methane gas that will fuel spacecraft and other vehicles. The remaining liquid becomes fertilizer along with the bones, which are heat-dried and crushed into a nitrogen- and mineral-rich powder. Nitrogen is a key component of chlorophyll, making this a valuable addition to the fertilizer used to grow Martian crops. Any remaining solids are transferred to compost bins to eventually form building materials like walls, deck planks, and particle boards. Every molecule is reused. There are no landfills on Mars.

Dying on Mars means living on Mars, and that our species has mastered the dangers the Red Planet poses. The hazards—the journey through space, treacherous landing, and brutal realities of life on an alien planet—are formidable. And the longer people stay on Mars, the greater the challenges grow.

Undaunted, engineers today are developing solutions that could lead to Martian funerals tomorrow. And the first humans could land as soon as 2029, if SpaceX can keep its ambitious timeline to settle Mars. "This is a very hard, dangerous, and difficult thing, not for the faint of heart. There's a good chance you'll die," SpaceX founder Elon Musk told a conference in September 2020. "It's going to be tough going, but it will be pretty glorious if it works out."

Getting things to "work out" on Mars will mean designing a generation of new equipment, spacecraft, landers, and infrastructure to deliver and support permanent residents on an alien world. From the moment the spacecraft leaves Earth, each step of colonization will be defined by the engineering that is meant to let settlers live a full life on Mars.



ALYSE MARKEL (TISSUE DIGESTER)

PART ONE:

PERILOUS VOYAGE

FROM INSIDE THE *ship's recreation room, the Mars-bound geologist can see a landscape of motionless stars through a high-impact quartz glass porthole. It's just wide enough for a single person to get a glimpse, and she can't help but wonder if this narrow view of deep space was worth the cost and risk. The quartz can withstand heating and cooling without cracking, but each window represents an interruption in the structural integrity of the hull.*

Each porthole is a symbol of stubborn, human defiance and biocentrism. Why take the species this far without granting them the ability to see, with their own eyes, where they're going? It's also a sign of humans' psychological frailty. Staring at something, anything, beyond the confines of the spaceship bulkheads is a welcome relief for the mind as well as the eyes. NASA's Human Research Program rates "isolation and confinement" as one of the key threats to human health during long-duration spaceflight. Getting to Mars requires a journey of around 35 million miles, representing at least six months on a likely cramped, regimented vessel.

The days of gnawing zero-G nausea can meld together, separated only by interior lights approximating Earth's solar cycle. The passengers are kept busy with a daily routine of exercise, chores, and medical checks, all of which is meant to keep themselves, and their companions, physically and mentally fit.

The human body is designed around gravity. It is, essentially, a pressurized container of fluid, and gravity pulls those fluids down to our feet. But in space, that fluid freely flows into the upper body, raising arterial pressure in the skull enough to make the head swell, damage vision, and reduce cognitive ability.

Earthbound doctors combat pressure imbalances with lower-body negative pressure (LBNP) chambers that draw body fluid toward the legs. Cosmonauts strapped themselves into similar machines in the late 1970s to prepare for high-G landings, fearing blackouts when the body's fluids recalibrated under intense gravity, but they were uncomfortable and took too much time to set up.

An updated version of LBNP could soon return to space. In December 2019, Alan Hargens, PhD, a space physiologist at the University of California, San Diego, published a paper in the journal *Aerospace Medicine and Human Performance* describing his design of a mobile LBNP suit. "It works like a vacuum cleaner that sucks an object off the floor," Hargens says. "But in this case, you suck in some person's body up to their waist, and they're sealed in the chamber with sort of a kayak skirt."

RAISE THE SHIELDS!

The journey to Mars would expose travelers (and their electronic equipment) to six to nine months of cosmic radiation if they're unprotected. The average annual dose from cosmic radiation on Earth totals 0.33 millisieverts (mSv), and a medical CT machine delivers anywhere from 2 to 10 mSv of radiation per scan. The *Curiosity* rover turned on its radiation detector during the trip to Mars and measured an average of 1.8 mSv per day. Using this data, the Southwest Research Institute calculated that a trip to Mars would expose travelers to a whopping 330 mSv. One thousand mSv increases fatal cancer risk by 5 percent; NASA's limit for astronauts today is 3 percent. Any spaceship heading to the Red Planet must have robust radiation shields, and researchers are coming up with novel approaches.

1 / LIGHTWEIGHT ARMOR ▸ The main obstacle to shielding spacecraft from radiation is weight, but advances in materials science have made a physical shield more appealing. For example, a 2020 study found the seldom-used silicon polymer perhydropolysilaxane is a good absorber of x-rays, gamma radiation, and neutrons. Another 2020 NASA study found that mixing oxidized metal powder (rust) into a polymer and then incorporating it into commonly used coatings helps repel charged particles while adding minimal weight.

2 / CHARGED SPIDERWEB ▸ An elegant solution to radiation could come by unfurling a large lightweight gossamer structure that is charged to a high negative voltage to repel all inbound, positively charged ions. This electrostatic shield guards against proton storms caused by explosions from the sun called coronal mass ejections, and could be deployed only during those events while the ship relies on another system for day-to-day protection.

3 / INVISIBLE BUBBLE ▸ If a magnetic field protects Earth from space radiation, why not bring one for the trip to Mars? NASA has sponsored years of research into this technology. The most promising, a design called Magnetospheric Dipolar Torus (MDT), features an enormous superconducting ring magnet that produces a magnetic field to repel most forms of cosmic radiation. A compensation coil with an opposite-moving current deflects the field from the ship itself. Ongoing research for NASA is heading toward a small-scale MDT prototype for testing.

PART TWO:

SURVIVING THE LANDING

THE LAST MOMENTS *of the journey to Mars are the most dangerous. Strapped to her seat, the geologist tries not to picture what's happening outside: entering Mars's thin atmosphere at 16,000 mph. Each passenger was warned that the craft would "decelerate aerodynamically," but the phrase doesn't capture being pressed into their seats by more than five times Earth's gravity.*

Six miles high, the atmosphere becomes thick enough to produce lift. The spaceship rotates its tail fins to tilt the nose up until it looks like a missile soaring backward across the Martian landscape.

The engines flare to life a mile and a half above the surface, shedding enough speed to land safely. With another wiggle of its fins, the ship stands fully upright, engines aimed straight down and still roaring. It slowly settles down on the planet under a cushion of exhaust, the edges of the tail fins now doubling as legs.

LANDING PADS ON DEMAND

To the delight of 1950s pulp science fiction fans, retrorockets have become the preferred method of landing spacecraft. But on Mars, those plumes will tear deep gouges in the terrain below, exactly where the lander aims to set down, says Matt Kuhns, former chief engineer at Masten Space Systems. In partnership with NASA's Innovative Advanced Concepts office, Masten (now part of Astrobotic) developed a possible solution called an Instant Landing Pad that adds a flat surface to a crater on demand.

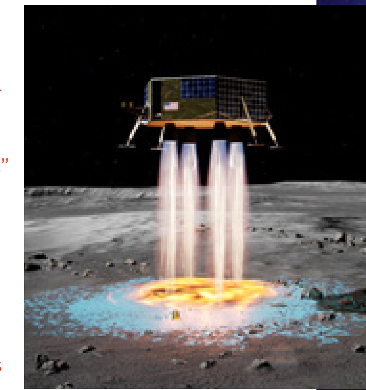
HOW IT WORKS

1 → A few hundred meters above the surface of Mars, the lander hovers.

2 → Aluminum pellets are fed into the engine exhaust nozzle, where they partially melt, and are blasted onto the surface.

3 → The pellets form a layer on the surface of the landing location, which almost immediately hardens into a shell less than an inch thick. "Once you get the first layer down, the rest of it should be able to build up pretty easily," Kuhns says.

4 → After deploying the spray for 15 seconds as many as five times, the lander sets down on the clean, stable surface under the power of its main engines.



COURTESY ASTROBOTIC (LANDING PAD)

Landing on Mars is notoriously difficult. The atmosphere is 100 times less dense than Earth's, the ground often obscured by dust, and the terrain littered with boulders, craters, and slopes. And "[Mars] has enough of an atmosphere to be really annoying and not enough of one to be quite as useful as we would like," says Matt Kuhns, who formerly worked as chief engineer at Masten Space Systems but has since joined SpaceX.

Over the years, space agencies have used a combination of protective armor, speed-shedding parachutes, last-minute sky cranes, and bouncing touchdown cocoons to deliver rovers and landers to the planet's surface. The direct, propulsive landing profiled above—most notably used by SpaceX's Starship, which is currently being built and tested in South Texas—could provide a relatively safe alternative.

Setting down with precision will be vital to building a permanent presence on Mars, since a steady cadence of delivery rockets will need to land near and not on the colony's infrastructure. Fortunately, humans have already scored impressive interplanetary bull's-eyes. On February 18, 2021, NASA's Mars rover *Perseverance* took pictures of the ground while parachuting through the atmosphere and matched what it saw to an onboard map made by the Mars Reconnaissance Orbiter. This system enabled the rover to touch down within an 82,000-square-foot-wide area—a bit bigger than a football field—making it the most precise Mars landing ever.

The spacecraft must also ensure the landing spot is free of hazards. In October 2020, Blue Origin launched a capsule carrying NASA's next-generation alien landing device, the Safe and Precise Landing–Integrated Capabilities Evolution (SPLICE). Four miles above the West Texas scrub, SPLICE shot and compared 3D images against a map, then automatically adjusted the lander to stay on target and confirm the terrain was free of obstacles.

PART THREE:

MARS IS TRYING TO KILL US

THE MARS GEOLOGIST *tries to keep her hand from trembling as she stows the final sample of volcanic rock from the slope of Olympus Mons. Collecting samples of the solar system's largest volcano by hand should fulfill any geologist's dream. Instead, she's racing a deadly, invisible solar flare.*

It's a short trip back to the rover, a ruggedized golf cart. But there's no time to drive back to the safety of the colony, and so her expedition partner has already started to unpack a pill-shaped emergency shelter for two. The fabric walls have wide pouches that hold carbon-fiber plates that block radiation, while a battery pack and oxygen tanks replenish their suits.

A solar flare makes an already-bad background radiation on the Martian surface—about 38 times that on Earth—even more dangerous.

For this reason, the first Martians will likely live in underground bunkers. "We'll need to take precautions, such as putting a meter or two of dirt on top of settlements," says Bruce Jakosky, PhD, professor of Geological Sciences at the University of Colorado and principal investigator of the Mars Atmosphere and Volatile Evolution (MAVEN) orbiter, which studies the planet's climate. "Water can also provide protection, so one could build habitats that are covered with water tanks." Of the two, using dirt makes more sense. Even though hydrogen molecules are effective blockers of radiation, in water they spread out. For this reason, it takes about 14 feet of water to reduce gamma radiation penetration to safe levels, as opposed to just a few inches of Martian soil in a bag or baked into bricks.

Detecting incoming solar storms is as critical to saving lives as a tornado warning system on Earth. A large ejection could bring a radiation dose that can kill within minutes, and the accumulation of radiation from many small storms can cause long-term health problems, including cancer. Local Martian space weather forecasts require their own satellites and ground stations working together, one measuring the particles striking the planet and the other detecting how many reach the surface and how fast they're traveling. The higher the velocity, the more the damage. During a bad storm, Martians could retreat to underground chambers protected by thick layers of dirt or water, Jakosky says. Those caught on the surface must shelter in place.

The atmosphere is an unbreathable 95 percent carbon dioxide. Temperatures skew colder, between 70° and –200° Fahrenheit, compared to Earth's 116° to –114° Fahrenheit. Luckily, colonists will enjoy hot showers since steam is ubiquitous at a nuclear-powered base. Unlike on Earth, there's no debate over energy policy here: NASA, SpaceX, and the China National Space Administration recognize that only nuclear power is reliable and efficient enough for a budding Martian colony.

The difference in temperatures across the planet—hot at the equator and cold at the poles—causes enormous low-pressure systems and polar fronts, resulting in seasonal windstorms. Mars's thin atmosphere deprives the wind of actual force, even at hurricane speeds. But the fine surface particles that swirl in those gusts create dust storms that can envelop much of the planet. This dust is dangerous, and not just because it obscures views and clogs machinery. Rovers and satellites have detected concentrations of toxic perchlorates—a salt so reactive that it's used on Earth to make rocket propellant—on the Martian surface that would be swept up in the wind. "These are also a human health hazard because they block the uptake of iodine by your thyroid if ingested," says Tanya Harrison, PhD, a science team collaborator on several NASA Mars rovers and manager of science programs at Planet Federal in Washington, D.C. "And we don't know the global distribution and concentration of perchlorates [on Mars]."

By the time people reach Mars, the weather will be less mysterious. NASA's newest Mars rover, *Perseverance,* arrived in 2021 carrying a suite of weather sensors called Mars Environmental Dynamics Analyzer (MEDA) to record the changes in dust levels, wind speed, atmospheric pressure, relative humidity, air temperature, ground temperature, and radiation.

"We'll actually have *InSight, Perseverance,* and *Curiosity* operating at the same time on Mars," says Cornell University's Don Banfield, PhD, a principal research scientist for several MEDA sensors. "While they are all quite distant from one another on Mars, comparing the results from all of them will be similar to how one can learn from looking at the weather in Miami, New York, and Tokyo." (NASA's Insight lander has since shut down due to dust accumulation.)

Despite the fleet of intrepid NASA probes, there's little equivalent information available to judge the risk of another alien quirk: Gravity on Mars is about 38 percent that on Earth. "We haven't spent much time on fractional gravity," says Alan Hargens, the UCSD space physiologist. "We've only done it on the Moon, which is one sixth of our gravity, and only for a few days. We really don't know how well we'll adapt."

Studies have found that microgravity can alter the shape of the brain, muscles, intestines, and individual heart cells. An even stranger effect may be lurking, as researchers in 2020 found patterns of changes in the genomes of nematode worms that had gone to space. These genetic changes included a decrease in the thickness of muscular thick filaments, which may help explain why astronauts lose muscle mass in space. The worms' cytoskeletal layouts also evolved to be shorter and fatter than worms that had not traveled to space.

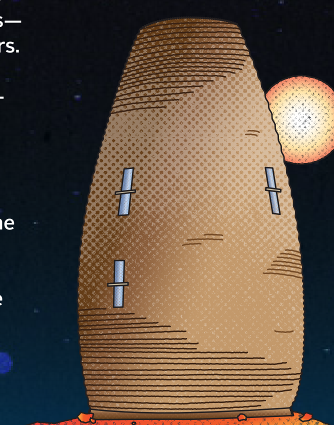
HOME SWEET HOME

Within years of their arrival, the underground structures in which the Martians first lived have been replaced by freestanding habitats that look like they were built by giant wasps.

Robotic arms 3D-print the ruddy-brown Martian dwellings by applying wet construction material—a mixture of reinforced basalt fibers and polylactic acid sourced from the waste-fueled bioreactors—in quickly hardening layers.

Cylinders are an ideal shape for a pressure vessel because their curved surfaces can withstand higher pressures. They also afford the most interior space. Each of the buildings, shielded from the elements and interconnected by subsurface tunnels, are divided into floors with comfortably sized rooms.

Each structure is double-hulled with thermoplastic material. The space between the inner and outer walls serves as a light well, bringing natural rays from the structure's tip to other floors through inner-wall windows. A clear, water-filled roof bathes an exercise room with soft sunlight. The goal is not to build a utilitarian submarine on the Mars surface, but a comfortable home.



ALYSE MARKEL (HOME)

PART FOUR:

LIVING TO DIE A COLONIST

WHEN THE CHOICE CAME, *it was no choice at all. The geologist decided she would stay on Mars as a permanent resident. When large-scale mining production of oxygen and water from Martian ice began, she knew it was only a matter of time before the base would evolve into a colony.*

Now, decades after her arrival, there's a growing army of riding-mower-sized robots scouring the eastern crater rim of the Hellas glacier for chunks of ice they'll bring to solar-powered factories for purification. Some facilities turn the ice to water; other facilities split the ice into oxygen and hydrogen for life-support systems and rocket engines. The geologist has never seen the robots in person—the crater walls are steep and the automated machines are hazardous—but she knows they're out there, keeping the self-sustaining base alive.

The vanguard of an automated Martian workforce is already taking shape today. NASA has held an annual Robotic Mining Competition at Kennedy Space Center for a decade, leading to a plethora of possible schemes. In the past, development focused on single, ultracapable autonomous mining robots. The current leading concept is a fleet of small robots, each designed to travel on treaded wheels and fetch small portions of ice. The benefit of a swarm is that some can break down, and the life-giving mining will continue.

Masten Space Systems at one point proposed a higher-volume approach, which would capture the icy ejecta from rocket blasts in a small dome. "We could harvest hundreds of tons of water ice in a very short amount of time," says Matt Kuhns, who once worked for Masten but now works for SpaceX. "The small dome basically builds up the pressure so you can get the deep excavation, and then also captures any volatiles."

With air and water accounted for, the next step is to grow food in hydroponic setups similar to those on Earth. The water would need to be sanitized before use, and the soil requires "remediation for known impurities, like salts and perchlorates," says Stephen Hoffman, PhD, a systems engineer with the Aerospace Corporation who's working at Johnson Space Center with NASA's Mars Architecture Team. Martian farmers would also need to add nutrients to the soil.

Research performed by the Center for the Utilization of Biological Engineering in Space (CUBE), a NASA collaboration with multiple universities to create the underlying tech to create a self-sustaining, zero-waste human settlement on Mars, reveals the true scope of the challenge. CUBE researchers are studying microbes that can produce nutrients from toxic land, using nanotechnology to enhance the production of complex molecules within living cells, and designing greenhouses optimized for cramped, restricted spaces.

Technicians could clone animal cells to make lab-grown meat to supplement a mostly vegan diet. An Israeli food technology startup, Aleph Farms, cultivated meat in space for the first time during a 2020 experiment on the International Space Station (ISS). Eating meat during holidays could become a Martian tradition.

And if for any reason rockets slow or stop deliveries, the colonists will need to make their own medicine, clothing, tools, vitamins, and rocket fuel. Additive manufacturing, which uses common materials to build a nearly infinite number of products with a single machine, could help. It's common for high-end factories and hobbyist garages alike to have 3D printers; there are two NASA-funded 3D printers on the ISS that have been churning out parts since 2014 and 2016. A space doctor could manufacture specific medicines on demand from an inventory of base ingredients.

The scale of this *in situ* production will be staggering if the colony is truly to be considered self-sufficient. Elon Musk has said that reaching full sustainability requires sending around 1 million people to live on the planet. That's more than a colony or even a city; at that point, Mars will become its own political entity.

At this phase of its development, the concept of technological risk changes. The machinery that has kept humanity alive has been perfected but could introduce societal threats. "A small number of specific humans will control the fundamental elements of life: air, water, light, hydroponic systems," wrote Dr. Bleddyn Bowen, a professor of international relations at the University of Leicester, on the Spacewatch Global blog in October 2020. "The citizens of space habitats…will need to subordinate their individual freedoms to the pure needs of the technology's ability to sustain life."

When the geologist decided to finish her life on Mars, she accepted these personal sacrifices, just as she resigned herself to the tissue digester. Her remains would never find a permanent resting place here, but her role as a scientist-pioneer will never be forgotten. Maybe those left comfortable on Earth wouldn't fully understand, but for her, Mars became more than a mission. It was a new life, and not just for herself. PM