Onward to Mars: The Past, Present, and Future of Human Space Travel

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Cover Image: The Space Shuttle Atlantis, shown soon after it undocked from the International Space Station in 2006. The Era of the Space Shuttle is not over, and the story of human space exploration has much left to be written. A slew of private companies (with the backing of NASA) have set their eyes on the Moon, Mars, and beyond.

Source: Wikimedia Commons

Introduction

In the 20th century, humanity took to the sky. After little more than a half-century, aerospace exploration evolved from the first flight of Orville and Wilbur Wright to the Apollo 11 Moon landing. Yet even before the pace of change became so rapid, flight had been dreamed up as a concept for millennia. Glider flight, in fact, is thought to have been attempted (successfully) by the Andalusian polymath Abbas Ibn Firnas in 9th century AD. But autonomous air flight powered by an engine was a relatively new invention. And like all successful inventions, it was applied to meet the demands of a particular historical moment.

After the Wright brothers, air travel developed in leaps and bounds because aerospace research was stimulated by Two World Wars and a Cold War - and heaps of government funding. Rocketry, pioneered in the early 20th century, arrived at center stage in the 1950s: Sputnik launched in 1957, NASA was founded in 1958, the Mercury and the Apollo missions played out in the 1960s. The Shuttle program progressed throughout the 70s and 80s, and then… the Cold War suddenly stopped. On Christmas Day 1991, Soviet Premier Mikhail Gorbachev simply resigned, and the Soviet Union, for all intents and purposes, ceased to exist. Three decades of relative peace have followed. The United States and Russia even lodge together in the International Space Station.

In recent years, though, space exploration has lit up with a new intensity, and this time the competition is between private companies - the main contenders are not political figures like Reagan and Gorbachev, but private aerospace magnates: Bezos, Branson, and Musk. Regardless, there is still plenty of work for the politicians to do. As space becomes subject to more frequent and extensive exploration, international cooperation (and contest) will surely follow. The following pages tell the stories of the space race from its 20th century origins to today. Discussions about the science of space flight and the impact of space-based research, will accompany this history.

A Brief History of Human Spaceflight: From the Origins of Rocketry to the Challenger Disaster

Modern day space programs arose independently in three different countries during the early 20th century. The American father of modern rocketry is Dr. Robert Goddard. He was a physicist whose work largely contributed to the development of rocket propulsion techniques. In 1914, Goddard patented a rocket using liquid fuel; he additionally patented a two- or three-stage rocket that used solid fuel. He then began to explore the possibility of reaching extreme altitudes with rockets, and in 1920, he outlined the possibility of reaching the moon with rockets. Goddard spent the next two decades making several engineering advances in rocketry. In 1929, he created the first rocket to carry a scientific payload, a barometer, and a camera. During the 1930s, he was recruited by the American military to develop several new capabilities for rockets. In 1932, he developed techniques for the use of vanes during motor blast-off for guidance. Additionally, he developed a gyro control apparatus for rocket flight in 1932; in 1937, he was able to translate his work with gyro control into a full rocket launch. Throughout his lifetime, Goddard's work was consistently underappreciated and met with skepticism, especially his work on sending a rocket to the moon. Despite this, Dr. Goddard is known today as one of the first American scientists who not only recognized the potential of space flight but also made significant progress to making it a reality ("Dr. Robert H. Goddard," n. d.).

The Russian father of rocketry is Dr. Konstantin Tsiolkovsky. He made several significant theoretical contributions to the field of modern rocketry. After studying chemistry, mathematics, astronomy, and mechanics in university, he spent several years studying air friction and dynamics in handmade wind tunnels. He was able to develop advanced aircraft designs from his work. He then turned his attention towards the cosmos. At the end of the 19th century, he published the book Gryozy o zemle i nebe (Dreams of Earth and Sky) and an article on communication with inhabitants of other planets; in these texts, he theorized about the possibility of space travel. In 1896, he wrote his seminal paper "Exploration of Cosmic Space by Means of Reaction Devices," in which he discussed several mechanics that he believed would be critical in space exploration, including heat transfer, air friction, fuel supply maintenance, and navigation. Throughout the early 20th century, Tsiolkovsky continued to make several theoretical contributions to space flight with an emphasis on exploration of the stratosphere and interplanetary space. He was elected to the Socialist Academy of the USSR for his work in 1919 (Arlazorov, 2020).

The German father of rocketry is Dr. Hermann Oberth. His contributions mainly deal with the use of multi-stage rockets and theoretical work regarding the effect of the gravitational field on rocket launches. A student of mathematics and physics at university, Dr. Oberth taught himself rocket science and tested theories on the use of liquid rocket fuel through the early 20th century. In his work, he discovered the importance of breaking down rocket travel into multiple stages by recognizing that when a smaller rocket positioned on top of a larger one ignites while the larger rocket is in the air, their speeds will add together. Though his doctoral thesis in 1922 was rejected, Dr. Oberth continued to study rocketry and began to work on his book The Rocket into Planetary Space; the final draft, published in 1929, described how rockets might be able to break the Earth's gravitational field to reach space. He launched his first rocket in 1932 and spent the rest of his life conducting rocketry research for both Germany and the U.S. ("Hermann Oberth," n. d.)

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Forays into space would not rise to the level of manned rocketry until the early 1960s, but the seeds for U.S. space travel were sown in the 1910s, long before the onset of the Cold War and the launching of Sputnik prompted the American political establishment to focus on space. In 1911, not long after the Wright Brothers' historic flight, the American Aeronautical Association organized its first meeting, calling for the construction of a new aviation laboratory at the Smithsonian. What they got, in 1915, was the formation of a new agency with federal backing: the National Advisory Committee for Aeronautics, or NACA. Although the inception of the agency was rather modest – it was birthed out of two paragraphs in the 1915 Naval Appropriations Act and granted a measly $5,000 starting budget – the agency's budget quickly expanded as it attracted support from the U.S. military. Their first benefactors were the army, and later on, more extensive support

Figure 1: An illustration of Robert Goddard, the American father of rocketry.

Source: Wikimedia Commons

came from the Navy. Both military bodies would send formal research requests to NACA through the 1930s. This research centered largely around engine supercharging and pressure distribution, for advances in engine design would contribute mightily to a United States military that increasingly fought its battles in the air (Gorn, 2011).

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Aeronautical R&D was certainly applicable during the Second World War, and later on, in America's "forgotten" Korean War. Throughout the 1940s and 50s, new jet turbine engines and the advent of the afterburner rendered fighter craft increasingly speedy and allowed them to soar higher and traverse greater distances (Lorell and Levaux, 1998). These new innovations needed enterprising pilots to test them, giving rise to a generation of daring fighter pilots who possessed great grit. Historian Tom Wolfe coined the term "the right stuff" to describe the qualities of these pilots, many of whom he interviewed leading up to the publication of his book (the book was made into a critically-acclaimed movie in 1983, and is the subject of a new television series that premiered this October) (Wolfe, 1979). Among those he met was the former U.S. Air Force Officer Chuck Yeager. Piloting the Bell X-1, a rocket-powered aircraft, Yeager famously broke the sound barrier on October 14, 1947: a stunning demonstration of the enormous potential for rocket-based flight ("Chuck Yeager," n.d.)

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Although the vision Arnold set forth was limited to unmanned aircraft – satellites armed with ICBMs – the focus would turn to manned spacecraft by the end of the next decade (Rothstein, 2000). In 1957, the Soviet Union launched Sputnik, the first (unmanned) artificial satellite to break the bounds of Earth's atmosphere and enter space. This beach-ball sized object publicly launched the two dominant world powers, the United States and the Soviet Union, into the 'Space Race.' It might be said, however, that the race had started covertly more than a decade prior. In 1945, a team of Soviet rocket scientists infiltrated Peenemünde, the facility where Nazi scientists had developed their infamous V2 rockets. The

Soviets took as much equipment as they could carry, including the rockets themselves and any documents that the Germans had left behind (Sagdeev, 2007). But American Special Forces were not left out of this game to reap the spoils of Nazi aerospace research. CIA Operation Paper Clip brought Werner Von Braun, the lead figure in the development of the V2 rockets, and 120 of his fellow German scientists and technicians to the United States (Watkins, 2014). They would be heavily involved in NASA missions – Mercury, Gemini, and Apollo – throughout the 1950s and 60s (Wolfe, 1979).

What about NASA? NASA was created in 1958 as a product of the National Aeronautics and Space Act. The bill was borne out of an atmosphere of intense and bipartisan anxiety in political circles following the launch of Sputnik. Senate Majority leader (and later Democratic President) Lyndon Johnson chaired the 'Preparedness Investigating Subcommittee of the Senate Armed Services Committee' in late 1957 that led to the establishment of a Senate Special Services Committee on Space and Aeronautics in February 1958. Around the same time, Republican President Dwight Eisenhower asked his science advisor James Killian Jr. to convene a Presidential Science Advisory Committee on the matter of space travel. Released on March 5, 1958, a memorandum from the committee set forth a proposal to build a civilian space agency around the existing framework of NACA. Eisenhower sent draft legislation to Congress in April and the National Aeronautics and Space Act was easily passed into law on July 29th. NASA set up shop on October 1st with the following aims (direct from section 102 of the act): the "improvement of usefulness, performance, speed… of aeronautical and space vehicles," the "preservation of the role of the United States as a leader in aeronautical and space science and technology," and the "cooperation by the United States with other nations… in the peaceful application of the results thereof." Clearly, NASA's organizational objectives were crafted with Cold War imperatives in mind (Dick, 2008).

It was not just the political environment that was affected by the launching of Sputnik, but the culture of the United States at large. Historians have noted immense changes in U.S. educational policy following the Soviet launch: increased funding and support for technical development, particularly courses in science and mathematics, that would render the U.S. more globally competitive. The great fear was that the Soviet Union would churn out more science-minded students that could contribute to the Russian Space program, and that the United States would be left intellectually inferior (Steeves et al., 2009). Beyond changes to schooling, public libraries were engaged in partnership with NASA to provide space and rocket-related novels, museum-style exhibitions, and even reading clubs that would teach the public about space and its importance to national security and American identity (Spencer, 2016). Given this cultural climate, it is no surprise that the American public viewed the 'Mercury Seven' – the group of men chosen as pilots for NASA's first rocket program – as national heroes (Wolfe, 1979).

All seven astronauts were military men: Alan Shepard, Wally Schirra, John Glenn, and Scott Carpenter former members of the US Navy; Gordon Cooper and Gus Grissom of the Air Force; and Deke Slayton of the US Army Air Corps (Wolfe, 1979). Yet the pilots of the first Mercury rockets were actually not these astronauts, but primates in space suits. Unlike Laika the dog, who likely died of overheating during the orbital flight of Sputnik 2, the monkey (Sam) and two chimpanzees (Ham and Enos) made it back to earth safely in Mercury test missions during 1959 and 1960 (Sagdeev, 2007; "The Space Race," n.d.). This reassured NASA officials that it was safe to send humans to space.

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Unfortunately for the Americans, the Soviets got there first, launching Yuri Gagarin out of Earth's atmosphere aboard Vostok 1 (April 21, 1961). Gagarin was the first human to enter outer space, and NASA countered by sending up Alan Shepard as the first American into space (aboard Freedom 7 in May, 1961), and John Glenn as the first human of any country into orbit, lapping the earth three times in 1962 ("The Space Race," n.d.). However, not all Mercury flights were brilliant success stories. Gus Grissom's crash landing in the Atlantic Ocean ended with the loss of a rocket (The Liberty Bell 7), and he personally faced most of the blame from political figures and the media (it is now largely believed that a malfunction of the rocket itself, not the failures of the operator, was truly at fault) (Wolfe, 1979). The treatment of Grissom underscores the high stakes of NASA's endeavors – from both a military and an economic perspective – and the great importance that the public placed on successful flights. The American people were the ones

Figure 2: (a) The Crew of Apollo 11 (Pictured left to right: Neil Armstrong, Michael Collins, and Buzz Aldrin). (b) Astronaut Neil Armstrong, of Apollo 11, taking the first steps on the moon in 1969.

Source: www.nasa.gov

footing the bill, after all, and rocket catastrophes were a demoralizing blow to national pride.

Simultaneously, NASA built its X-Plane Program, a series of missions consisting of diverse aircrafts that started in the 1940s. On October 14thth, 1947, the X-Plane became the first rocket powered airplane to break the sound barrier. Since then, the X-Plane aircrafts pioneered the variable-sweep-wing in flight, the usage of exotic alloy metals for the primary structure of a plane, the 180-degree turn using a post-stall maneuver, the testing of boundary-layer-airflow control theories over plane wings at transonic speeds, and the intercontinental flight range (1952). These aircraft were able to reach speeds of up to 6 times the speed of sound and were the first to fly at altitudes upwards of 90,000m (NASA, 1997). Throughout the course of the ongoing X-Plane Program, aircrafts launched from various U.S. Air Force Bases, most frequently at Edwards Air Force Base, which includes the Air Force Flight Test Center and the Dryden Flight Research Center. The 20th century saw 15 major accidents and 4 fatalities during the program's testing. Due to strict safety precautions, the X-Plane program did not cause any civilian property losses or fatalities. One of the most lauded aircraft is the X-33, the product of an industry-government partnership with Lockheed Martin. Unfortunately, issues surrounding costs of rebuilding certain parts of the X-33 led to NASA defunding the project in 2001. However, many technologies from the X-33 continued to influence new rockets, especially with regard to cost control (Connor, 2016). Their legacy still holds today: most recently, X-61A Gremlins were developed in 2019 to be an unmanned air vehicle (UAV) through the Defense Advanced Research Projects Agency (DARPA) Gremlins programme for quick launching and recovery of UAVs (Cohen, 2020).

In 1965-1966, NASA created the Gemini Program, a series of ten missions. The primary goals of these missions were to prepare man's landing and understanding of the moon.. The mission's namesake alludes to the two-person capacity of the rocket ship, an improvement from the one-person Mercury vessels. These small victories gained sufficient confidence from scientists, paving the way for the Apollo lunar missions (NASA, 2011).

Perhaps the most famous quote in space history is "That's one small step for a man. One giant leap for mankind." It was coined by Neil Armstrong, the first human to set foot on the moon in 1969 during the Apollo 11 mission. The program was named Apollo after the Greek mythical god of the sun, archery, music and dance, and truth and prophecy. Each Apollo spacecraft was launched on top of a Saturn rocket; the earlier missions launched from a two-stage Saturn I B rocket and later missions used a three-stage Saturn V rocket. After the first human-testing of the command module in October 1968, Apollo 8 became the first manned mission to orbit the moon and return safely to Earth that December. Less than seven months later, Armstrong, Michael Collins, and Buzz Aldrin comprised the first crew to land on the moon on July 20th (NASA, 2019).

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Arguably one of the most famous Apollo missions is Apollo 13, in which an explosion 200,000 miles from Earth prevented the team from reaching the moon. Five years before the mission, the CM underwent renovations to increase the permissible voltage in the oxygen tanks; however, thermostatic switches in the heater weren't adapted for this change. Thus, the high temperatures degraded the Teflon insulation and the thermodynamic switches wielded shut, resulting in an explosion in tank No. 2 during its subsequent use. Signs of faulty heating went unnoticed during pre-mission testing. Despite the struggle to return the spacecraft into orbit, the small timeframe to power up the command module, the scarcity of food and water, issues with carbon-dioxide removal, and 38°F temperatures, the Apollo 13 crew luckily landed back on Earth safely (Mansfield, 2017).

The Skylab, launched in May of 1973, was the first American Space Station – a home and a laboratory in space that involved the collaboration of scientists from 28 countries. The spacecraft consisted of a multiple docking adaptor, a command and service module, a solar observatory, the Airlock Module and the Orbital Workshop (Whiting, 2018). It was crucial that the Skylab be self-sufficient in energy generation for extended periods of time and be a reliable station for communication, data collection, experimentation, living, and control systems. Skylab included four missions, the first of which was unmanned. The Skylab allowed astronauts to study the sun from new vantage points via x-ray photography and generate high quality solar and terrestrial data. The program challenged astronauts to work on in-space repairs and strengthened the relationship between on-site astronauts and ground crew. It tested man's capability to withstand the zero-gravity conditions of space and revert to gravity conditions on Earth, pushing the biological limits of the human body. In addition, the Skylab experimented with manufacturing crystals in space (George C. Marshall Space Flight Center, 1997). The Skylab was the first spacecraft to rescue another mission: a two astronaut Apollo capsule (a modified capsule of the Apollo spacecraft) collected a three-person crew, with all five members making a successful return to Earth (Whiting, 2018). As Leo Goldberg, Director of Kitt Peak National observatory, stated, Skylab "proved the value of men in space as true scientific partners in space science research" (George C. Marshall Space Flight Center, 1997).

Soon after the launch of the Skylab, the Apollo-Soyuz Test Project launched into space on July 15th, 1975; it was the first international partnership for space travel and was intended to test the compatibility of docking systems and the ability of separate spacecrafts to meet in outer space. The nine-day mission consisted of five Soviet and American astronauts (Loff, 2015). The crews launched and docked separately, with the American three-person crew flying a remodeled U.S. Apollo spacecraft and the Soviet team of two traveling on the remodeled Soyuz. Both used a jointly designed Docking module. This collaboration tested the limits of international collaboration: the Americans learned Russian, and the Soviets learned English, and the teams met several times beforehand to become comfortable with each other and the other spacecraft. Communication between the crew was in the language of the listener (e.g., Americans spoke to the Soviets in Russian). The Apollo-Soyuz Test Project was the first Russian launch that was broadcasted in the Soviet Union (Redmond, 2004). After a successful docking, the team was able to conduct experiments on board and complete 110 earth-observation tasks involving ocean currents, pollution, desert geography, erosion, vegetation patterns, and iceberg movement (Redmond, 2004). This successful mission and partnership paved the way for future international space collaborations (Loff, 2015).

The goal of NASA's Shuttle space program was to develop a reusable space shuttle that could provide "routine access to space." However, this program did not come without its struggles: at the time, there was a lack of political support as politicians were more concerned with funding programs with quick payoffs – it would take decades until the payoffs of space exploration would be felt. The U.S. government argued that after spending $24 billion dollars on lunar travel, the Shuttle should be financially self-sufficient (Launius, 1992). Ultimately, the 135 mission-program, starting with the Columbia in April 1981 and ending with the Atlantis in July 2011, cost $113.7 billion dollars. The first space shuttle was named Enterprise, though it never was used for space travel. The first shuttle to space was the Columbia, which flew on the Space Transportation System I (STS-1), deployed satellites, and served as a space laboratory. The infamous Challenger was the second shuttle created by NASA which made its first launch on April 4th, 1983. The Challenger missions included the first jetpack-powered spacewalks and the mission was the first to fix an out-of-orbit satellite. The Challenger also saw the first American woman to travel into space, Sally Ride, in 1983 (NASA, 2012).

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However, during the tenth mission of the Challenger in 1986, the crew of seven perished in an explosion. The Challenger's disaster can be traced back to numerous causes. The most famous investigation of the accident is the Roger report (officially known as the Report of the Presidential Commission on the Space Shuttle Challenger Accident), which revealed that the accident was caused by an engineering failure that had been found years prior. Other investigations cite the pressures on NASA to launch the Challenger despite caution and debates from engineers. The loss of the Challenger in January 1986 was a pivotal point for space science, with some arguing that the field was set back 38 years as a result (Launius, 1992).

With the Challenger disaster came the deterioration of the Shuttle Program: funding was lacking, and NASA was forced to take shortcuts and minimize costs for its shuttles while being incentivized to increase the number of launches. With these dangerous constraints, warning signs for malfunctions and complications were frequently ignored and the program could not retain all of its initial goals. Hundreds of experiments for the Shuttle program were indefinitely delayed and the program spent two years redesigning rocket boosters and changing its leadership structure (Launius, 1992).

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Next, NASA launched the Discovery Program in 1992 with the mission to explore our solar system. Within the Discovery Program's 13 missions, many milestones including the first spacecrafts to orbit and land on an asteroid (Near-Earth Asteroid Rendezvous, 1996), the first rover to land on another planet and on Mars (Pathfinder, 1996), and the first spacecrafts to return samples from a comet to Earth (Stardust, 1999) were completed. The Discovery Program is ongoing: The Lunar Reconnaissance Orbiter (launched in 2009) continues to orbit the moon and collect information, and the Insight (launched in 2018) studies the interior of Mars. As for the future of the Discovery Program, NASA has three missions planned: the Lucy (2021) will visit seven asteroids orbiting around Jupiter, the Psyche (2022) will study the mineral-rich asteroid 16 Psyche, and the MEGANE (2024) will investigate Phobos, the Martian moon (Harbaugh, 2020).

In 1987, Congress granted NASA funding to build the Endeavour (OV-105), a replacement for the Challenger. The name Endeavour was the winning submission name from elementary and middle schools across the US and represented British explorer James Cook's first commandant ship whose mission was to observe the movement of Venus from Tahiti, ultimately leading to the accurate calculation of the distance between the sun and the Earth. The primary mission of the Endeavor was to capture and repair INTELSAT VI, a broken communications satellite. This mission was the first to manage four spacewalks and the first to conduct a three-person spacewalk. Before landing back on Earth safely, the crew was able to conduct a Protein Crystal Growth experiment in the microgravity conditions of space (Marconi, 2013).

The Science of Spaceflight

Though the events of the Space Shuttle Challenger were widely covered in the weeks following the disaster, it was a mystery as to why the launch had failed. The country was sent into sorrow and depression; President Reagan postponed his State of the Union, schools were let out, the stock market tumbled. There are many factors that go into deciding and executing a launch, including the orientation of celestial bodies, the rotation of the Earth's orbit, the amount of fuel loaded into the engine, the type of material used to build the shuttle, and many more important considerations: any of these can go wrong.

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The commission had their own schedule of interviewing engineers and executives at NASA, its contractors, and more, but Richard Feynman was one member that never liked abiding by the rigid and, in his opinion, inefficient processes of William Rogers. Instead, Feynman conducted many of his own interviews and eventually discovered the cause of the Challenger disaster—the O-ring. In many of his interviews with engineers who had worked on the shuttle, he discovered two large issues with NASA's understanding of risk. Firstly, NASA was using what are now known as product-based risk assessments (Altabbakh et al., 2013). These types of assessments involve assigning individual risk probabilities to the components of the final product; for example, an engineer would assign a failure probability of 1 in 100,000,000 to an individual screw as well as every other part of the shuttle. This tricked engineers into thinking that they were being thorough, but, in reality, it disillusioned

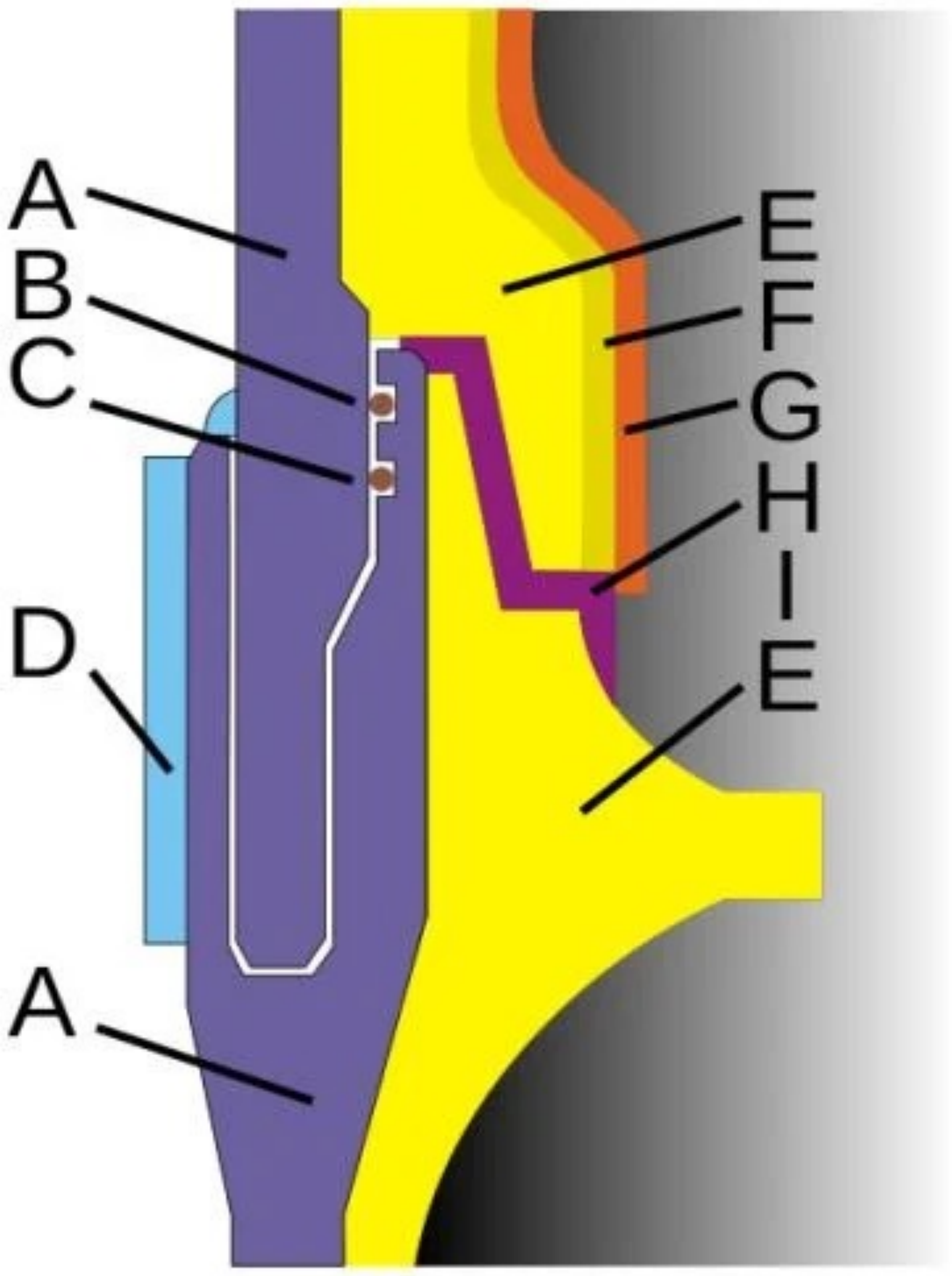

Figure 3: The above diagram depicts a cross-section of the field joints between the rocket boosters of the Challenger Space Shuttle. Letters "B" and "C" on the diagram point out the O-ring gaskets that failed on the day of the launch due to low temperatures, leading to the infamous disaster.

Source: Wikimedia Commons

them from the fact that the parts of the shuttle are interconnected. A failure in one spot can drastically increase the failure in another, so when looking at the individual failure probabilities, engineers at NASA and its contractors saw a near impossible fail rate. However, when Feynman interviewed these people individually on what they predicted the failure rate of the space shuttle actually was on a holistic basis, they responded with the 1 in 50 to 1 in 200 range (Heimann, 1993). While these might be okay odds for a raffle, they are much too high when unnecessarily risking lives.

Though the improper interpretation of risk was one major problem with the design of Space Shuttle Challenger and its launch, the root cause of the problem was NASA's failure to address a serious flaw in the design of the O-ring. The O-ring was used as a seal on the rocket booster and was vital to ensuring the structural integrity of the booster with its external fuel tank. The O-ring that was used was only cleared for temperatures above fifty degrees Fahrenheit. On the day of the launch, the temperature dropped to the thirties, which weakened the sealant on the O-ring. Subsequently, the flame from the boosters passed through the ring and reached the external tank. Perhaps the most disturbing element of this failure by NASA was the fact that Feynman was not the first one to suspect that the O-ring design was flawed ("THE SHUTTLE FINDINGS," 1986). Roger Boisjoly, one of the head engineers at Morton Thiokol, along with several other engineers, found that the O-rings had failed multiple times during their testing. In several reports to his superiors, Boisjoly recommended that the O-ring be re-designed as the current design, if left alone, could put the astronauts' lives in danger. Unfortunately, scheduled flight deadlines weighed heavily on the mins of NASA administrators in the mid 1980s, and this concern went unaddressed (Boisjoly et al., 1989). With the Soviets beating the United States in space exploration as well as Reagan's plan to announce that one of the astronauts on the Challenger was a schoolteacher during his State of the Union address, after the team was in space, NASA entrusted that the failure probability of the individual parts was so low that a disaster would be impossible. As Feynman and the Rogers Commission found, not only was this view severely mistaken but the rationale for these safety considerations was fundamentally flawed. This mistake was so severe that it led Feynman to write Appendix F in the Rogers Commission report: an over 5,000-word critique of the NASA safety protocol ("THE SHUTTLE FINDINGS," 1986).

Following the incident, stocks prices fell. This was particularly true for those companies that had contracts with NASA. On January 28, 1986, building material company Martin Marietta fell 3%, aerospace company Lockheed Corporation was down 5%, and industrial manufacturer Rockwell International lost 6% (Sutter, 2016). However, the NASA contractor that lost the most on that day was Morton Thiokol, the corporation that produced the flawed O-rings. On January 28, 1986, Thiokol stock fell 12% (Blose et al., 1996). The only reason that the stock did not fall more that day was that the trading for the stock was halted to prevent selloffs much like those during the Great Depression (later, regulators installed circuit breakers to do this automatically). NASA contracts made up over 18% of Thiokol's total sales, more than any other NASA contractor, but not far off from the 17.52% of Planning Research Corporation or 12.16% of Computer Sciences Corporation. Planning Research stock barely lost anything while Computer Sciences stock actually resulted in a gain for the day (Blose et al., 1996)! Therefore, while it can be assumed that some selloff was due to the disaster and assessment of Thiokol's dependence on NASA contracts, it is believed that some astute traders identified the company's heavy involvement in shuttle design and pinned the disaster on them, months before the Rogers Commission submitted their report to Ronald Reagan (Blose et al., 1996).

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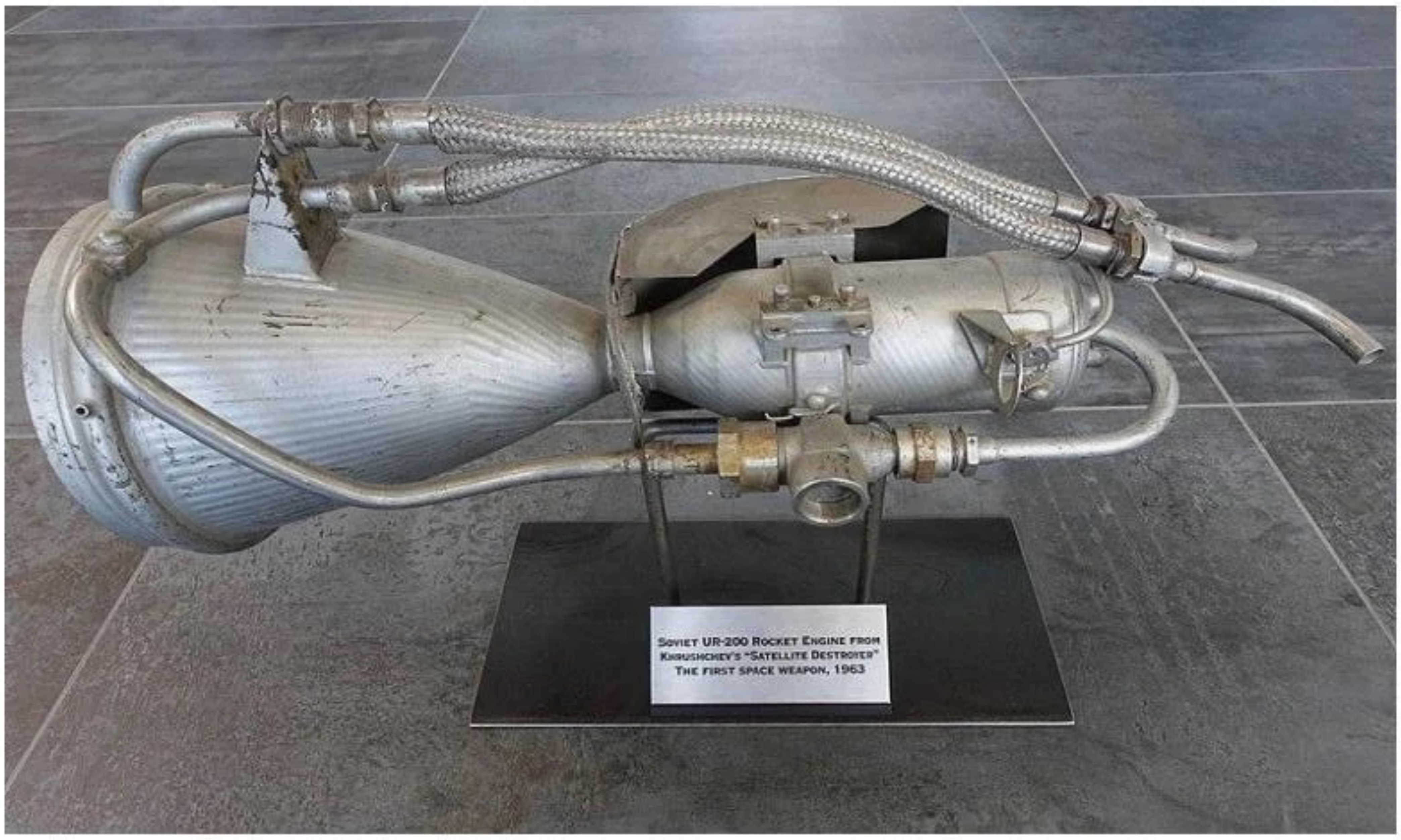

Figure 4: The image depicts a Soviet Rocket Thruster from 1963, one of the first propulsion systems of its kind that has now given rise to nuclear pulse projection, liquid-air-cycle, or nuclear-thermal rocket thrusters that are used today.

Source: Wikimedia Commons

"Aerodynamics requires calculating the physics behind virtually every point of space travel. Scientists must ensure that the shuttle is using its fuel efficiently upon liftoff, ascent, abort, and re-entry scenarios and that there is not too much stress on any one part of the shuttle."

While Feynman's understanding of the faults of the space shuttle could be derived simply from experimentation, intuition, and interviews, actually planning, building, and testing these structures requires a much deeper knowledge of the science of spaceflight. Engineers and scientists who work at NASA, SpaceX, Virgin Galactic, Blue Origin, and other innovation hubs for space travel often undergo years of schooling and practice in the fields of mathematics, physics, aerospace engineering, and more. However, the key knowledge points that are fundamental to an aerospace engineer's work are propulsion, aerodynamics, performance, and aircraft stability (Corda, n.d.).

Studying rocket propulsion is simply understanding how to make the rocket move the spacecraft forward. Engineers must build a device that can overcome both gravity and the drag of the atmosphere. Propulsion systems began as propellers on airplanes and quickly evolved into jet engines during the Second World War. Now, many space shuttles and satellites use more than a dozen rocket engine thrusters as their propulsion systems. These propulsion systems mix fuel with oxidizers (e.g., liquid hydrogen and liquid oxygen) in order to stimulate quick combustion that propels large spacecraft forwards (mars.nasa.gov, n.d.). Engineers measure key metrics including propulsive efficiency, engine performance, and engine noise (Govinda Raju, 2009).

Aerodynamics is a field of aerospace engineering that has greatly improved with the invention of computers. Aerodynamics requires calculating the physics behind virtually every point of space travel. Scientists must ensure that the shuttle is using its fuel efficiently upon liftoff, ascent, abort, and re-entry scenarios and that there is not too much stress on any one part of the shuttle. For instance, scientists must estimate the drag acceleration and relative velocity of the shuttle upon re-entry and protect against an undershot (which can bring high temperature and high drag), an overshot (which can bring loss of control from lack of sufficient drag), and a pressure limit to the shuttle. This field has rapidly improved with computational methods that make the calculations much more precise, but scientists still must ensure that their margin of error is well within safety guidelines for the spacecraft (Bordano et al., n.d.).

Spaceflight is a delicate practice. The rocket needs to attain an absolute velocity to escape gravity, but all the required scientific instruments on space missions mean that engineers have to work with heavy loads. For example, the space shuttle on a typical mission weighs around 4.5 million pounds. The challenge is to minimize additional weight (as a greater mass translates to a higher thrust requirement) and still retain enough propellant to power the rockets to the required speeds. To tackle this, scientists employ two main strategies: using multiple phases of flight and using propellants with specific characteristics that make them ideal for spaceflight. Many rockets - such as the Pegasus XL currently used to launch satellites into space and the Saturn V that first put men on the moon - are designed to use three phases in their ascent into space. By using three phases, the rocket is able to achieve higher velocities.

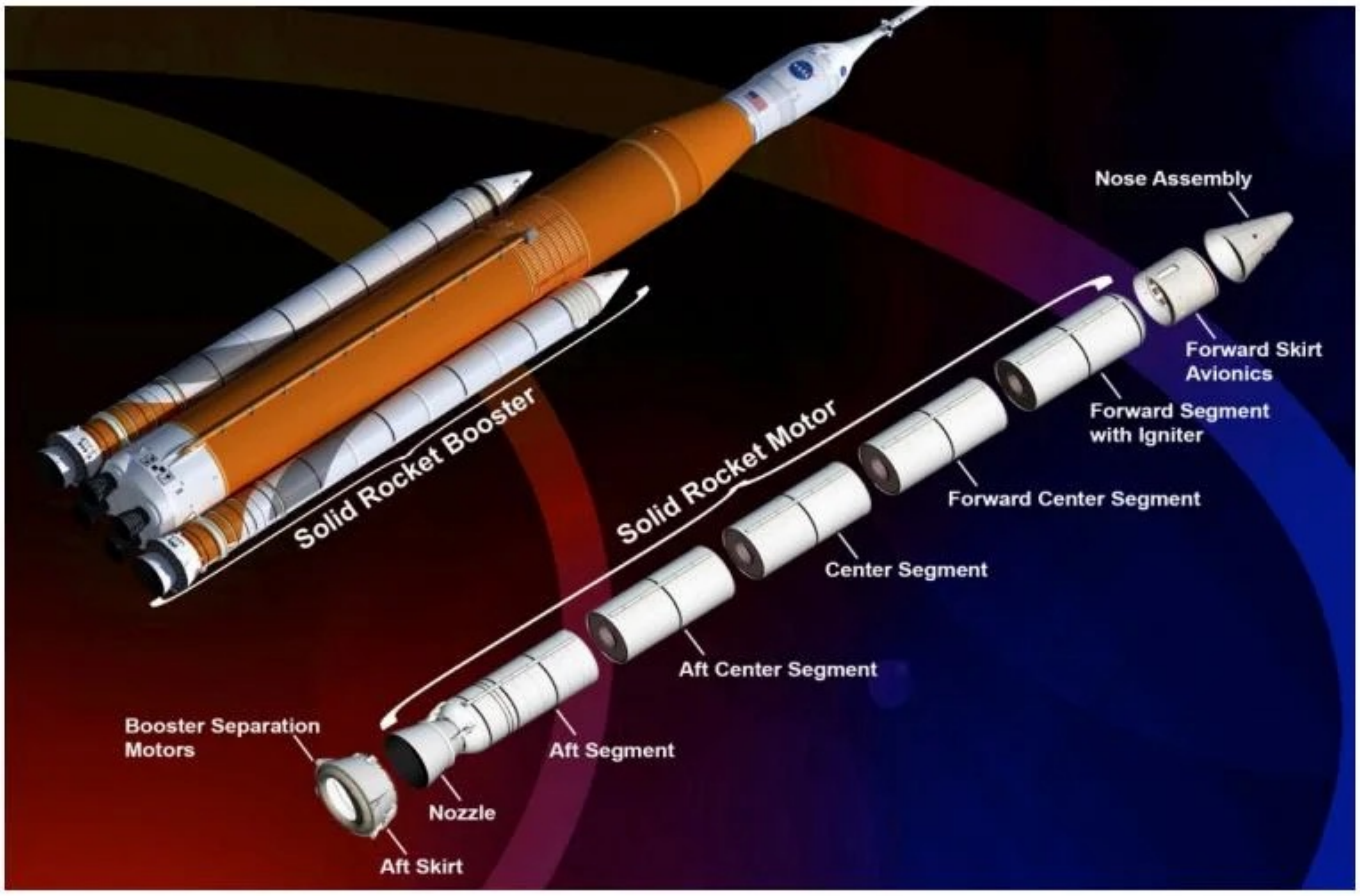

Figure 5: The image shows the attachment of Solid Rocket Boosters to a rocket. The Solid Rocket Boosters provide additional thrust during liftoff.

Source: Wikimedia Commons

The first phase of spaceflight is liftoff. Large rockets called the Solid Rocket Boosters (SRBs) are used to propel the rocket and provide the thrust needed to lift the shuttle off the launchpad. These SRBs operate in tandem with the main rocket engines for the first two minutes to give the additional thrust necessary to escape Earth's gravitational pull. The SRBs support the system's entire weight - the shuttle, the fuel tanks, the orbiter, and additional rockets - and provide an estimated 71 percent of the total thrust (Kaur et al., 2014). To achieve such amounts of thrust, the solid rocket boosters have to be powerful and therefore massive. It soon becomes necessary to drop the SRBs after all their propellant is depleted. This is done at an altitude of about 45 km. Once released, the boosters descend on parachutes, usually into the ocean, and are recovered for reuse (Kaur et al., 2014).

The next phase of spaceflight is fuel tank separation. The external tank's three main components are an oxygen tank, a hydrogen tank, and an inter-tank connecting the two propellant tanks, which houses processing equipment. When the SRBs separate, the orbiter, with the main engines still burning, carries the external tanks up to a height of around 113 km, at which point all the propellant in the tanks is fully used. The empty tanks are then jettisoned and fall in a pre-planned trajectory. Unlike the SRBs, the fuel tanks are not recovered for future reuse (Kaur et al., 2014). Once in space, the shuttle orbiter houses the astronauts for 7 to 14 days. The orbiter can be oriented with the cargo bay doors facing toward or away from the Earth, depending on the mission's objectives.

Another unique challenge presents itself during re-entry into Earth's atmosphere. The orbiter will usually be flown nose-down until a specific height. The crew will then fire up the OMS engines to slow the orbiter down. It then takes about 25 minutes to reach the edges of the atmosphere. During this time, RCS thrusters are fired to turn the orbiter so that it is moving nose-up again like it did during ascent. The leftover fuel in the forward RCS thrusters is burned as a safety precaution because this area of the orbiter experiences the highest heat in re-entry. During re-entry, the orbiter is moving at about 17,000 mph, and air friction builds up to about 1650°C (3000°F). To counter this, the orbiter is designed with a coating of ceramic insulation. At around 610 meters above the ground, the commander pulls up the nose to slow the descent rate. A parachute then helps stop the orbiter. After landing, the orbiter is powered down and taken for servicing (Kaur et al., 2014).

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Despite the enormous complexity of rocket flight, the journey of a rocket from the surface of the Earth to Earth's orbit may be grasped with a basic understanding of Newtonian mechanics. Consider a rocket on the launch pad. It remains at rest because the force of gravity acting downwards towards the center of the Earth is balanced by the normal force of the launch pad pushing up on the rocket from below. The static state of the rocket is described by Newton's first law: Every object persists in its state of rest or uniform motion in a straight line unless it is compelled to change that state by forces impressed on it.

In order to get the rocket into the air, there needs to be a strong upward force to unbalance the equilibrium of the gravitational and normal forces and accelerate the rocket upward. This upward acceleration is provided by thrust – the force produced by the ignition of fuel in the rocket's engine (Hall, 2015). Once the rocket lifts off above the ground and begins soaring into space, its behavior may be described succinctly by Newton's second law: the net force acting on the rocket is equal to its mass multiplied by its acceleration.

"The dynamics of rocket flight are complicated because a rocket is a body of changing mass; as it climbs farther and farther into space, it burns more fuel, and the consequent loss of mass is significant. The typical mass fraction of a rocket – its propellant mass divided by its total mass – is 0.8, meaning that 80% of the rocket mass is propellant."

The dynamics of rocket flight are complicated because a rocket is a body of changing mass; as it climbs farther and farther into space, it burns more fuel, and the consequent loss of mass is significant. The typical mass fraction of a rocket – its propellant mass divided by its total mass – is 0.8, meaning that 80% of the rocket mass is propellant (Man-Vehicle Laboratory MIT, 1996). This means that over time, the gravitational force (equal to mass times the gravitational acceleration constant) decreases, and the force in the upward direction further outweighs that in the downward direction. Thus, the acceleration of the rocket increases steadily as it climbs. The rapid burning of fuel is critical so that the rocket can accelerate to a high enough speed. Entering lower Earth orbit requires a speed of over 28,000 km/hour. Exiting Earth's orbit requires a much higher speed of 40,250 km/hour (Benson, 2014).

Like a rubber balloon, a rocket is a chamber enclosing gas under pressure. The difference is that while a balloon is filled with the carbon dioxide exhaled from one's breath, or on some occasions the inert gas helium, rocket combustion chambers are mixing sites for highly combustible fuels – ones that will react explosively and produce large quantities of gas. The release of this gas is what provides the rocket with thrust. Newton's third law, that for every action [in this case the release of gas from the bottom of the rocket] there is an equal and opposite reaction [the propulsion of the rocket upwards into space]" explains this phenomenon (Benson, 2014).

Rocket propellant is not just fuel, but the combination of fuel and oxygen, which is necessary for the fuel to burn. Propellant comes in several varieties. It may be solid, in which case the fuel is typically a hydrocarbon. Alternatively, it may be a liquid, typically kerosene or liquid hydrogen mixed with oxygen. The components of a solid propellant are usually held together in a single loading chamber, whereas the components of a liquid propellant (liquid fuel and liquid oxygen) are held separately. In either case, the propellant is forced through a nozzle or nozzles into the combustion chamber where the fuel ignites. The resulting gas is then allowed to escape through a nozzle at the bottom of the rocket (Man-Vehicle Laboratory MIT, 1996).

There are different classifications of rocket propulsion engines depending on the gas acceleration mechanism, the energy source, and the thrust level per unit mass (Martinez-Sanchez, 2005). All of these classifications hint at the physics and chemistry behind rocket propulsion, which inform the choice of a suitable propellant. By gas acceleration mechanism, a rocket engine can be classified as either (1) thermal if it uses pressure to drive gas, (2) electrostatic if it uses electrostatic force to accelerate gas across a magnetic field, or (3) electromagnetic if it uses a combination of electric and magnetic fields across an electric conductor to create an electromagnetic force used to accelerate the gas. By the type of energy source used to drive propellant, a rocket engine can be either chemical, nuclear, or solar. A rocket engine can also either be high thrust or low thrust (Martinez-Sanchez, 2005). For any rocket system, the propellant choice will depend mainly on the type of engine being used. Propellants can be either solid, liquid, or hybrid (Braeunig, 2008).

Solid propellants are a mixture of solid compounds (fuel and oxidizer) that burn at a rapid rate, producing hot gases. These hot gases are then forced through a tight airway to produce thrust. Solid propellants can be homogeneous or composite (Martinez-Sanchez, 2005). Homogeneous propellants consist of either a single compound with oxidation and reduction capabilities (known as simple base) or a mixture of nitrocellulose and nitroglycerine (known as double base), on which plasticizer is added. Homogeneous propellants do not produce any traceable fumes, making them ideal for applications that require secrecy such military operations. Homogeneous propellants are also commonly used to perform subsidiary actions, such as jettisoning spent parts while transitioning

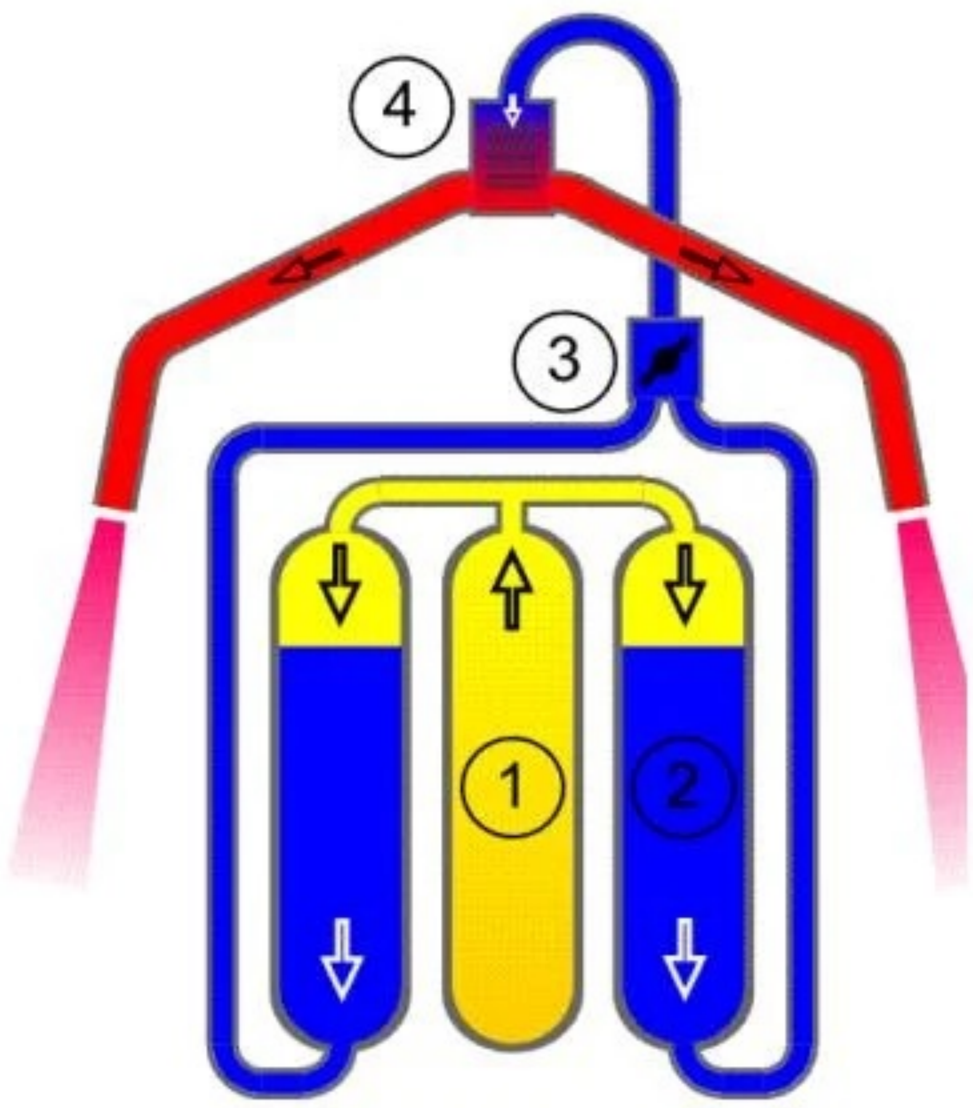

Figure 6: The image shows the compartmentalization of fuel tanks in liquid-propulsion systems. The fuel and oxidizer are stored in separate tanks due to high volatility - unlike in solid propulsion systems where the fuel and oxidizer are stored in the same chamber.

Source: Wikimedia Commons

between spaceflight phases (McCormack, n.d.). On the other hand, composite propellants use a crystallized or finely ground mineral salt as an oxidizer and an element, usually aluminum, as fuel. The oxidizer will make up about 60% to 90% of the propellant, with the fuel constituting as little as 10% of the total mass. The propellant is contained in a polymeric binder such as polyurethane, which is also consumed as fuel. Sometimes additional compounds are added as catalysts. Composite propellants are classified by the type of binder used, the most common of which are olybutadiene acrylic acid acrylonitrile (PBAN) and hydroxy-terminator polybutadiene (HTPB). (Braeunig, 2008).

For liquid propellant rockets, the different components of the propellant (fuel and oxidizer) have to be stored in separate tanks due to higher volatility. During space flight, the separate fluids are pumped into a combustion chamber, mixed, and combusted to produce thrust. This set-up leads to a significant advantage over solid-propellant engines: the controlled flow and combustion of the propellant allows liquid-propellant engines to be throttled, stopped, and even restarted. Several features specific to different liquid propellants are significant in deciding which liquid propellant to use. A suitable liquid propellant should have a high specific impulse (speed of exhaust gas ejection), high density, ability to withstand high storage temperatures, low toxicity, and low corrosion.

Liquid propellants can be either petroleum-based, cryogenic, or hypergolic. Petroleum-based propellants are obtained from crude oil and mostly consist of hydrocarbon liquids and gases. The most common petroleum-based rocket fuel is a highly refined kerosene called RP-1, which is oxidized by liquid oxygen. On the other hand, cryogenic propellants are usually made up of liquefied gases. For example, liquid hydrogen and liquid oxygen are often used as a fuel-oxidizer pair. The caveat with cryogenic propellants is that such gases only exist as liquids at extremely low temperatures. Hence, the fuel tanks must be accordingly configured, which poses both a challenge and a safety hazard in case of leakage or badly sealed storage tanks (McCormack, n.d.). Hypergolic liquid propellants consist of an oxidizer-fuel pair that reacts upon contact and does not need external combustion. Hypergolic reactions are easy to start and restart, which is ideal for spacecraft maneuvers. Furthermore, hypergolic fuels remain liquid at standard temperatures and thus do not require specially designed storage tanks or have the risks posed by cryogenic propellants (Braeunig, 2008).

Hybrid propellant engines use a mixture of solid and liquid fuel-oxidizer pairs. The fuel is usually solid. The liquid oxidizer is then pumped into the fuel storage chamber, which also acts as the reaction chamber. Hybrid propellants generally offer the combined advantages of solid and liquid propellants, such as high performance (an advantage of solid-propulsion systems) and the ability to control the combustion and reaction rates (a benefit of liquid-propulsion systems). (Braeunig, 2008).

Even with the myriad of mechanical complexities confronted during spaceflight, physiological stress on astronauts remains one of NASA's most significant concerns (Abadie et al., 2020). The first challenge to overcome is liftoff, when astronauts experience gravity forces up to twice that which a typical human can withstand without training (Lee et al., 2015). The perpendicular acceleration places particular strain on the head and neck, and blood can quickly gather near the bottom of the body. To mediate these challenges, astronauts undergo extensive training in "g-force withstanding," during which they slowly build their capacity to remain conscious—even as blood fails to reach the upper regions of the body, which often results in temporary blindness (Burton, 1988).

"Even with the myriad of mechanical complexities confronted during spaceflight, physiological stress on astronauts remains one of NASA's most significant concerns."

"Unsurprisingly, liftoff is only the beginning when it comes to the physiological challenges of space flight. Even shorter (1-3 month) visits to space take a harsh toll on the bodies of astronauts. A few of the most worrying physiological effects of space travel include muscle atrophy and losses in bone density."

Unsurprisingly, liftoff is only the beginning when it comes to the physiological challenges of space flight. Even shorter (1-3 month) visits to space take a harsh toll on the bodies of astronauts. A few of the most worrying physiological effects of space travel include muscle atrophy and losses in bone density. Weightless existence inside the spacecraft leaves astronauts lacking the day-to-day strain on the musculoskeletal system that Earth's gravity provides (Orwoll et al., 2013). Consequently, even with a strict requirement of two hours of exercise per day while in space, astronauts on 1-3 month missions usually require 2-3 years to recover the muscle mass and bone density lost during their time away from Earth (Fitts et al., 2010). Other physiological concerns include severe deficits in the quality and quantity of sleep, decreased production of red blood cells, fluid retention in the head and chest, sub-optimal nutrition, and even neurological changes that some scientists warn could lead to the early onset of neurodegenerative conditions like Alzheimer's disease (Acharya et al., 2019).

As space explorations lengthen in duration, understanding the physiological effects of prolonged periods of weightlessness has become a central focus of NASA scientists. However, these investigations survey astronauts' well-being in the best possible scenario: the vacuum-sealed and carefully monitored atmospheric conditions of a fully functioning spacecraft. Outside the craft, environmental conditions are nothing short of deadly. Spacesuits must protect their occupants from flying bits of space junk called micro-meteors, harmful ultraviolet rays, and extreme temperatures—all in addition to the vacuum conditions that can boil bodily fluids and deprive an astronaut of oxygen after only moments of exposure (Abadie et al., 2020). In the event that an astronaut did require medical attention while in space, their crewmates serve as their care providers. Astronauts undergo extensive training in first aid and emergency medical care for this purpose, and spacecraft are outfitted with medical care items ranging from liters of saline to high-quality ultrasound machines (Stewart et al., 2007). As space flight continues, NASA anticipates noteworthy advances in the quality of on-craft medical care—advancements, like ultra-high-speed telemedicine and programmable surgeons, that might be just as beneficial in under-resourced communities down on Earth as they are in the remote expanse of space.

History Continued: The End of the Shuttle Program and the Genesis of Private Rocketry

Despite the major setback that the Challenger disaster caused the shuttle program, it was only two and a half years later on September 29, 1988 that the Discovery launched a communications satellite which replaced the one lost in Challenger. With Ronald Reagan's note that "America is back in space," this relaunched a productive era of American space travel (Norcross, 2019). In the following year, 1989 saw the deployment of the Magellan to Venus and the Galileo to Jupiter by the shuttle Atlantis, providing invaluable future data on extraplanetary function and marking the first interplanetary mission in nearly eleven years. Perhaps more invaluable was Discovery's launch of the Hubble Telescope on April 24, 1990, whose later research on background radiation led scientists to estimate the universe's age at 14 billion years and conclude dark matter to be the driver of the universe's expansion, among other discoveries (Stillman, 2020). Six years later, Columbia would be launched, carrying the largest satellite ever launched, the Chandra X-Ray Observatory, which expanded humanity's view of the physical universe (Howell, 2018).

The International Space Station was the next large step in human space exploration. What would become a symbol of international cooperation was first ordered as an American project by Ronald Reagan in 1984 to be completed within the decade (ISS National Laboratory, n.d.). However, the Space Station, which had originally been a U.S. project dubbed Freedom, was changed going into the 1990s to expand international cooperation and increase funding, notably incorporating Russian plans, but also drawing on collaboration from Japan and the European Space Agency (Harland, 2020). The 1993 invitation for Russia to join the international effort was particularly significant following the collapse of the Soviet Union just prior, as this effectively united the two main contenders in the "space race" facet of the cold war. However, it was not until November 2, 2000 that the American astronaut Bill Shepherd and two Russian cosmonauts, Yuri Gidzenko and Sergei Krikalev, became the first of a continuous, rotating crew to attend the assembled station more than a decade in the making (ISS National Laboratory np).

Although much of the important work on the ISS focuses on scientific study, a primary task of crewmembers is the simple maintenance of the facility. Indeed, following the 2003 Columbia shuttle disaster to be discussed later, the ISS reacted by reducing the crew size to two members who were mostly relegated to maintaining the station (Harland np). Construction subsequently resumed in 2006 with notable additions including the American Destiny module, which can simulate a nearly weightless environment for further study on the station (Harland 2012; Harland 2020). Since its inception, crewmembers have always remained on the station to maintain the system and perform experiments, with replacements of personnel every three months in the form of astronauts flying back on the Russian Soyuz shuttle to be sent back to the station with a new crew. Some of the more recent experiments have included research on capillary flow function aimed at improving and cutting costs of infectious disease tests (e.g., those for HIV/AIDS) (Gaskill, n.d.). Although the history of the ISS has largely been one of success, both scientifically and geopolitically, it, too, has an expiration date for government funding. American funding is set to expire in 2024, which is the same year NASA projects to land again on the moon. Notably, though, private space companies will be allowed to potentially use the station for commercial purposes (Weiterung, 2019).

In 2003, NASA experienced its first loss of life since the Challenger disaster. The seven astronauts aboard the Shuttle Columbia had completed their mission, restocking the ISS and staging a series of scientific experiments en route. They had studied the effect of space conditions on bacterial respiration (cellular utilization of oxygen and organic compounds to produce chemical energy) and assessed their own physiological conditions while riding on the shuttle. The mission made it as far as orbital reentry before the shuttle broke apart and killed everyone aboard (Cowen, 2003). It was a catastrophe of a different nature; less sudden and immediate than the Challenger explosion – the Columbia astronauts could literally feel the warmth of Earth's embrace – but no less shocking and bitter a tragedy. In the 400-page report that detailed the astronauts' plight in their final seconds, it was determined that the depressurization of the shuttle would have rendered them all incapacitated within seconds and unable to take any corrective action as the shuttle began to break apart. In reality, there was nothing the astronauts could have done even if they had regained consciousness. The report found no evidence whatsoever of crew member error ("Report: Columbia Astronauts Killed," 2008).

As was the case after the Challenger disaster, NASA put a halt to all further shuttle launches and set up a commission to investigate what went wrong. The investigation centered around a piece of insulation surrounding the fuel tank. The insulating foam had broken free during launch and punched a hole in the heat shield covering Columbia's wing. This is thought to have caused the disintegration of the shuttle upon re-entry, as it would have allowed for superheated atmospheric gas to penetrate the wing ("Report: Columbia Astronauts Killed," 2008). Columbia was the oldest existing shuttle at the time, and in the aftermath of its explosion, many suggested that NASA should have either refurbished or decommissioned Columbia long before its eventual demise (Lawler et al., 2003). Alongside this critique, the long-standing criticism of the Shuttle Program's mission – that it was far too expensive and inefficient to allow for its stated aim of frequent, regular launches – was spoken with even greater force (Logsdon, 1986; Center for the Study of Technology and Society, 2006).

On the day of the Columbia disaster, President Bush vowed that "our journey to space will go on." And so it did. In the aftermath of the disaster, there was broad bipartisan consensus that NASA ought to continue receiving public support, but with a new focus on enhanced safety standards and new technology that would make flights safer and more capable of delivering payloads or gathering scientific data (Lawler et al., 2003). In 2005, shuttle flights resumed. The official vision birthed out of the Columbia Disaster, set forth by Bush in his "Vision for Space Exploration" (2006), called for the completion of the ISS and retirement of the shuttle program by 2010. Its replacement was to be the smaller, more cost-effective Crew Exploration Vehicle (CEV) (The New Atlantis, 2006).

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Despite these intended changes, NASA's budget was increasingly strained. Its funds were spread thin to cover both the aging shuttle program and the new CEV program at once – with significant funds also going towards ISS construction (which was not completed until 2011), planetary probes (Cassini, Messenger, New Horizon) and Mars rovers (Spirit, Opportunity) (The New Atlantis, 2006). The onset of the Great Recession in 2008 further diminished prospects of a budget increase to support NASA's space-bound endeavors. Obviously, there were plenty of problems that required government funding on Earth. In 2011, the Shuttle Program came to an end, with the final flight of Atlantis in July of that year. It marked the conclusion of a three-decade-long program that supported 133 successful launches (Witze, 2011). This was not the end of American space travel, however, but the conclusion of a single chapter in a long and storied history. In fact, a new era in American Space Flight had its roots well before the last shuttle launch.

Figure 7: An image of SpaceX's Dragon spacecraft, used to carry seven passengers or cargo between Earth and its orbit.

Source: Wikimedia Commons

The New Titans of Space Travel

SpaceX

"Musk has pursued his goal of decreasing costs and increasing the reliability of spaceflight by developing reusable rockets and launch systems. At the date of writing, Falcon 9, SpaceX's reusable,

Elon Musk, widely known as the founder of Paypal and Tesla, extended his business dominance to space when he founded and became the Chief Executive Officer of Space Exploration Technologies Corporation (SpaceX) in 2002. SpaceX has the broad mission of making spaceflight more inexpensive and reliable with Musk's ultimate goal being the colonization of Mars. SpaceX's achievements are extensive; it is one of the first private companies to venture into the world of spaceflight. Some of SpaceX's most notable feats include being the first private company to successfully launch, orbit, and recover a spacecraft, send a spacecraft to the International Space Station, send a human-rated spacecraft to space, and autonomously dock a spacecraft to the International Space Station (SpaceX, n.d.). These accomplishments are all more impressive when considering that Musk never received formal training in rocket science, instead graduating with degrees in economics and physics from the University of Pennsylvania. His aerospace consultant, Jim Cantrell, claims that Musk taught himself everything he knew by reading textbooks and talking to those in the industry (Feloni, 2014).

Musk has pursued his goal of decreasing costs and increasing the reliability of spaceflight by developing reusable rockets and launch systems. At the date of writing, Falcon 9, SpaceX's reusable, two-stage rocket has had 94 total launches, 55 successful landings, and 40 re-flown rockets. The initial launching of the Falcon 9 used uses Merlin engines, one of SpaceX's engine families designed for its Falcon launch vehicles. Those Merlin engines used in the initial launch were specifically designed for a sea-level launch. Once beyond the dense atmosphere, the Merlin Vacuum Engine then propels Falcon 9 to its orbit. The first and second stages separate, and the Merlin Engines are recovered for reuse (SpaceX, n.d.). Lastly, the payload is released for its final destination. If the payload is a satellite, it is released with a protective case. If the payload is a crew or cargo, they are released in Dragon, SpaceX's spacecraft intended to carry humans and cargo from Earth to and from orbit and, in the future, beyond. Both the protective fairing and the Dragon spacecraft can be reused; the Dragon has had 23 total launches and 9 reflown missions to date (SpaceX, n.d.).

Along with Falcon 9 and Dragon, SpaceX has two newer vehicles, Falcon Heavy and Starship. Falcon Heavy is considered the world's most powerful rocket and can be used to transport almost forty-thousand pounds of payload to Mars and even greater masses for shorter destinations. The Falcon Heavy uses 27 sea level Merlin engines and has the capacity to produce more than five million pounds of thrust at liftoff, the equivalent of about eighteen 747 aircrafts at full power. The Starship rocket currently has not yet been tested, but it is expected to allow for interplanetary travel to Mars and beyond with a payload capacity even greater than that of Falcon Heavy (SpaceX, n.d.).

Unlike other space companies, SpaceX has seen much success in its operations, with about two billion dollars in revenue for 2019 (CBS News, 2018). Virtually all revenue comes from SpaceX making cargo deliveries to the International



Figure 8: The New Titans of space flight: Jeff Bezos, Elon Musk, and Richard Branson

Source: Wikimedia Commons

Space Station, but Musk recently started the "ridesharing" program for space that allows for multiple cargo delivery contracts to be filled by one spaceflight. While this is an exciting development for SpaceX, there is much more anticipation around the completion of Starship. Starship is expected to be completed in the early 2020s and replace Dragon and Falcon 9, thus becoming SpaceX's main form of transportation (SpaceX, n.d.).

Blue Origin

SpaceX's most direct competition is Blue Origin, a rapidly growing rocketry company founded and funded by Amazon CEO Jeff Bezos. Though Bezos keeps his interests in space generally quiet, he has stated before that Blue Origin is his most important work. The company was founded in 2000 in Kent, Washington, has a launch facility in West Texas, and also has a lease in Cape Canaveral ("Everything you need to know," 2019). For the first several years of its existence, the company remained largely unknown and did not make any revenue. It is entirely financed by Bezos's personal investment; in 2017, the CEO announced that he had been selling one billion dollars in Amazon stock annually to fund Blue Origin's work (Fleur, 2017). Blue Origin's goal is to give humans access to space affordably and reliably. Bezos does not believe that humans should entirely abandon Earth in favor of interstellar colonization; rather, he believes that space travel and exploration is a necessary next step in maintaining life on Earth. He envisions that humans will harvest resources from space to make sure that progress on Earth does not become stagnant and believes that through space colonization, Earth will have enough resources to support one trillion individuals ("Jeff Bezos: reusable rockets," 2017).

Blue Origin has two famous rockets. The first is New Shepard, which is being developed as a sub-orbital rocket meant for tourism and research. Though it can be piloted remotely, it is meant to carry passengers up to around 100 kilometers into the air. Early stages of development began in 2006, and its first flight was in April of 2015. This test was deemed a partial success by the company - the flight itself was successful, as it reached 93.5 kilometers in altitude. Additionally, the developers were able to recover the capsule. However, the propulsion module was unable to be recovered after the flight due to a failure in the hydraulic system, so the vertical landing of the shuttle was compromised ("Blue Origin's New Shepard," 2015). In November of 2015, Blue Origin launched a second version of New Shepard. This flight was a complete success. Not only was the rocket able to reach an altitude of over 100 kilometers, but both the capsule and the booster system worked, allowing the rocket to successfully perform a vertical landing. The flight was a historic one - it was one of the first rockets to perform this kind of landing successfully ("New Shepard: Bezos Claims Success," 2015). Just 61 days later, the rocket was able to be launched again. Ultimately, this second version of New Shepard launched and successfully landed for relaunch 5 times before it was retired ("Blue Origin successfully tests New Shepard abort system," 2016). New Shepard 3 was given several modifications to increase thermal protections and reusability; it was meant only to ship cargo and was not intended for any kind of passenger or commercial use. New Shepard 3 was flown from 2017 to 2019 and has flown a total of four times ("Blue Origin Delays Next New Shepard," 2018). The fourth version of New Shepard is currently under development - it is the version that Blue Origin intends to be its commercial rocket, and the first flight is expected to occur in 2021.

"Blue Origin has two famous rockets. The first is New Shepard, which is being developed as a sub-orbital rocket meant for tourism and research. Though it can be piloted remotely, it is meant to carry passengers up to around 100 kilometers into the air."

Figure 9: WhiteKnightTwo is a twin mast aircraft used by Virgin Galactic to carry SpaceShipTwo through the atmosphere. SpaceShipTwo is positioned on top of the middle wing, and the combined structure flies from horizontal takeoff to space.

Source: Wikimedia Commons

"The technology most similar to that of Blue Origin is Virgin Galactic's. Also focusing on sending customers into suborbital space, Virgin Galactic was founded in 2004 by Sir Richard Branson, the founder of Virgin Atlantic airlines and the Virgin Group."

Blue Origin's second main rocket is New Glenn. The company started to design New Glenn in 2012 and originally intended for its maiden flight to be in 2020. In 2018, they announced that they would be pushing back the first flight to 2021. Like New Shepard, New Glenn is meant to have a reusable first stage booster. This booster is meant to push the astronauts to suborbital space, where there would be stage separation. An upper stage booster would then take the company's Space Vehicle capsule, which would carry astronauts and cargo goods, into orbit,. Both the first stage and upper stage booster would return to Earth to be refueled and reused. ("Blue Origin - About Blue," n.d.).

Blue Origin still has a ways to go before it catches up to SpaceX. However, as it rapidly approaches several critical deadlines in the upcoming years, it will be able to directly compete with Musk and his rockets and propel the modern Space Race into a new age.

Virgin Galactic

The technology most similar to that of Blue Origin is Virgin Galactic's. Also focusing on sending customers into suborbital space, Virgin Galactic was founded in 2004 by Sir Richard Branson, the founder of Virgin Atlantic airlines and the Virgin Group. Branson started Virgin Galactic to materialize his interest in space, and set out to not just control the process of sending customers to space but also the process of building the rockets to do so. In 2005, he, along with Burt Rutan, founded The Spaceship Company, which designs and manufactures airships for space travel. The Spaceship Company was eventually established as a subsidiary under Virgin Galactic (Encyclopedia Britannica, 2020).

Virgin Galactic's main assets include the main spaceship, SpaceShipTwo; the carrier aircraft that will carry SpaceShipTwo, WhiteKnightTwo; and the location that will train and launch customers into space, Spaceport America. After launch, a WhiteKnightTwo aircraft is used to carry SpaceShipTwo through the high density atmosphere. Using the larger WhiteKnightTwo for its 4 turbofan engines that each supply 6,900 pounds of force at launch, Virgin Galactic can reduce the total energy needed for launch. This reduced energy allows the aircraft to launch more smoothly and horizontally, like an airplane, instead of vertically like traditional spacecrafts and their direct competitor Blue Origin (Virgin Galactic Holdings, Inc., 2020).

But Branson's long history in the aviation industry has led his words to carry more believability than they should. In 2007, an explosion during rocket testing of SpaceShipTwo was expected to severely set back the timeline of space flight (David, 2007). However, Branson claimed in July of 2008 that the maiden voyage would occur by the end of 2009. Then, in October 2009, Branson promised that flights would start within two years. In December of 2009, Branson claimed that flights would begin in 2011, and in April 2011, Branson announced that flights would start 18 months later (Garside, 2014). The promises have continued; Branson currently projects that flights will be ready by the summer of next year at the latest, and even critics have to admit that he might actually be right this time. By 2019, WhiteKnightTwo had already undertaken over 250 test flights, over 50 of which were with SpaceShipTwo. At the end of 2020, Virgin Galactic expects to complete two manned tests of SpaceShipTwo and receive its license from the Federal Aviation Administration (Virgin Galactic Holdings, Inc., 2020). So, while Branson has been known to over-promise and under-deliver, that dynamic could very well flip soon.

One of the most unique defining features of Virgin Galactic that sets it apart from other space companies is that it is a public company, meaning that anyone can invest in the company's stock. It all started in 2017 when Social Capital Hedosophia was listed as a publicly traded Special Purpose Acquisition Company (SPAC). A SPAC is an individual or a group of individuals that decides to become publicly traded, with anyone allowed to invest, but does not actually have a product to sell. It may sound foolish for people to invest in a company without a product, but SPACs like Social Capital Hedosophia enter public trading in order to secure funding to then acquire a private company that takes its place in the public sector, meaning the shareholders now own part of the new public company and could profit if the SPAC acquires a successful company.

One important detail to understand how Virgin Galactic became a publicly traded company is that they are currently losing significant amounts of money. The company's main expected service, spaceflight, is not ready, but they have to keep funding research and development to make their plans a reality. In 2019, the company realized that they had to start earning revenue or else they would quickly run out of money. As a result, they started providing engineering services in addition to their core spaceflight development operations, but they were only able to generate about $4 million in revenue in 2019 and currently no revenue in recent quarters. Compared to the over $210 million they lost from their operations in the same year, $4 million is extremely small. With a little over $450 million left in the bank even after becoming publicly traded, Virgin Galactic has only about two to three years of funds left until they run out (Virgin Galactic Holdings, Inc., 2020).

This pattern of losing money started at and has continued since its founding. Branson never expected to take so long until spaceflight, so when Social Capital Hedosophia approached him with the offer to buy his company and take it public, Branson accepted at the end of 2019. This acquisition infused the company with much needed cash and created the first publicly traded spaceflight company (Renaissance Capital, 2019). With the company being publicly traded, many space enthusiasts, including many on Wall Street, have flocked to the stock and pushed the price upwards. In September 2020, when the stock was trading at about $16, analysts at Bank of America, a major banking firm, and Susquehanna, a leading global quantitative trading company, both rated Virgin Galactic stock as a 'buy'. Bank of America actually set a hefty price target of $35. These ratings, along with buy ratings from almost all other Wall Street firms that cover the stock (Morgan Stanley, Vertical Research Partners, Cowen, UBS, Credit Suisse, and Alembic Global Advisors), have dramatically increased the price (Sheetz, 2020). However, these high price targets are mainly driven by the high price of a seat on a Virgin Galactic: $250,000. The belief is that once Virgin Galactic develops the technology, they only need a few sales to return a huge profit. The company also already has a couple hundred reservations for seats, making shareholders optimistic. However, there are many risks. Primarily, there is risk that the technology will never be developed. Even if it is developed, the company can suffer from increased regulation, fierce competition, and a loss of public favor if one of the launches fails. These concerns led Goldman Sachs analysts to recommend a hold on the stock, resulting in the only non-buy rating from Wall Street firms. So, while some Wall Street firms can price the stock at prices 100% over its current value, it essentially comes down to one question: do you believe what Branson is promising?

"One of the most unique defining features of Virgin Galactic that sets it apart from other space companies is that it is a public company, meaning that anyone can invest in the company's stock."

Launching Advancements in Science and Technology Down on Earth

Technological Advancements Born in Space

Though space exploration's advancements led to well-known innovations in healthcare and the environment, potentially the most widely-known and underappreciated inventions have come from the technology field. The most well-known advancement from research and development in space programs is modern communication with satellites. Because of space exploration, NASA and other government organizations around the world launched satellites into space and decided to allow

Figure 10: The image depicts the MS-50 headset, the lightweight headset developed by Courtney Graham and Keith Larkin for pilots of United Airlines. Graham and Larkin soon after worked with NASA to incorporate this technology into the astronaut helmet, creating the first wireless headset.

Source: Wikimedia Commons

companies and other government organizations to use the satellite bandwidth to facilitate cell, Internet, GPS, and other types of communications (Garner, 2017). Without these introductions, we certainly would not be as advanced as we are today. In fact, the enthusiasm behind satellite usage in Earth Internet has given rise to NASA starting its development of a "Space Internet." The goal is to use Laser Communications Relay Demonstration to facilitate faster communications between shuttles and Earth; the technology builds upon the past Lunar Laser Communications Demonstration that was effective at large distances and widely successful in demonstrating beyond low-Earth orbit high-data-rate laser communications. However, the most interesting advancements stemming from space travel and NASA in particular are those that are unknown to most individuals who use them every day (Garner, 2017).

"Above all, potentially the most underappreciated technological advancement arising from space exploration efforts is the cell phone camera. The Jet Propulsion Laboratory (JPL), a laboratory owned by NASA to house its cutting-edge rocketry research, was actually the initial site for the technology of photosensors and light signals that would then be developed into the digital camera built by Eastman Kodak in 1975."

One advancement in technology spurring from space exploration is modern water purification systems. While this technological advancement goes unappreciated, many of the water purification systems in developing nations use technology originally developed for NASA (Marconi, 2004). It started in the 1960s and 1970s when NASA wanted to purify drinking water for the Space Shuttle, and turned to the small Myrtle Creek business, Umpqua Research Company. The company developed an electrolytic silver iodizer called the Microbial Check Valve (MCV) cartridge. The company later developed the Regenerable Biocide Delivery Unit that extended the durability of the cartridge so that it could be used more than 100 times before replacing. The technology was so successful in serving astronauts that it has since been used on every Shuttle flight, and, in 1993, Umpqua Research was selected as the recipient of NASA's Government and Commercial Invention of the Year awards (Marconi, 2004).

Another invention that directly resulted from space travel collaboration was wireless headsets. In 1961, the United Airlines was experimenting with alternatives to the bulky and uncomfortable headsets that were usually worn by pilots (Center, 2006). Courtney Graham and Keith Larkin developed the MS-50 headset that used an acoustic tube as the headband and transducers commonly used in hearing aids as the microphone and receivable. The result was a lightweight effective headset that the Federal Aviation Administration readily accepted in 1962. Graham and Larkin also found that astronauts were suffering from similar problems. Later that

year, the two and their new company, Pacific Plantronics, worked with NASA to develop a working microphone, noise cancellation, and more into an astronaut helmet that became the first-used wireless headset (Center, 2006).

Above all, potentially the most underappreciated technological advancement arising from space exploration efforts is the cell phone camera. The Jet Propulsion Laboratory (JPL), a laboratory owned by NASA to house its cutting-edge rocketry research, was actually the initial site for the technology of photosensors and light signals that would then be developed into the digital camera built by Eastman Kodak in 1975. However, the jump to the miniaturization of this camera was also founded in the JPL by Eric Fossum (NASA - A Picture of Innovation, 2012). The development of the complementary metal-oxide semiconductor (CMOS) image sensors was the key, and Fossum acted on the opportunity by inventing the CMOS active-pixel sensor (CMOS-APS). Though the technology was intended for low power imaging in space when resources were limited, Fossum realized that it could be used for Earth applications. In 1995, he founded Photobit, licensed the CMOS-APS technology, and started to commercialize CMOS image sensors. Photobit went on to sell the technology in a variety of applications, including Web cameras, dental radiography, automotive applications, and most notably the phone camera (NASA - A Picture of Innovation, 2012).

Advancements Born in Space: Healthcare and the Environment

The technological advancements that have emerged from space exploration are plentiful, but these developments do not come close to encompassing the broad range of innovations

Figure 11. The International Space Station, Courtesy of NASA, 2020;

Source: Wikimedia Commons

stemming from our extraterrestrial endeavors. In particular, space exploration has brought a number of improvements in two critical areas of science: healthcare and the environment. As for healthcare, space-related findings have contributed significantly to fields ranging from pharmaceutics to bioimaging. In many cases, even non-healthcare-related research endeavors have led to noteworthy advancements. Two of the most prominent examples include the development of Magnetic Resonance Imaging (MRI) and the Left Ventricular Assist Device (LVAD). Both technologies are critical to medical care, and it is likely that neither would have emerged when they did in the absence of NASA-led space exploration ("Left Ventricular Assist Device," n.d.).

In 1977, NASA's Jet Propulsion Laboratory developed advanced processing mechanisms for the digital images that their craft had obtained from the moon. In addition to aiding scientists as they charted craters and crevices on the moon's surface, this imaging technology would become the basis of MRI for clinical use in years to come ("Did NASA Invent MRI," n.d.). Likewise, NASA researchers did not set out to develop an artificial heart pump when they created technology that would eventually give rise to the LVAD, a critical piece of medical equipment that keeps patients healthy as they wait for heart transplants. However, when a team of engineers at the Johnson Space Center in Houston set out to build a medical device with the capacity to pump life into a half-beating heart, they referred back to the pioneering design of space shuttle fuel pump (NASA, 2002).

More recently, NASA-related research endeavors have played a role in developing a light-based treatment for cancer patients who are experiencing the painful side effects of chemotherapy. The treatment, developed from luminescent technology initially applied to the growth of plants in space, would help reduce the pain associated with bone marrow or stem cell transplants. Pain-reducing UV-light treatment j a vast array of NASA-facilitated medical innovations—a list too extensive to describe here, though replete with critical everyday medical devices such as ear thermometers, automatic insulin pumps, and even implantable heart defibrillators (Rainey, 2017).

In addition to advancements in the medical field, space-originating findings have also contributed greatly to environmental causes in the U.S. and globally. One area of focus for environmentally impactful research in space is the health of Earth's atmosphere. The Clean Air Act of 1970 designated six pollutants—nitrogen dioxide (NO2), ground-level ozone, carbon monoxide, particulate matter (microscopic

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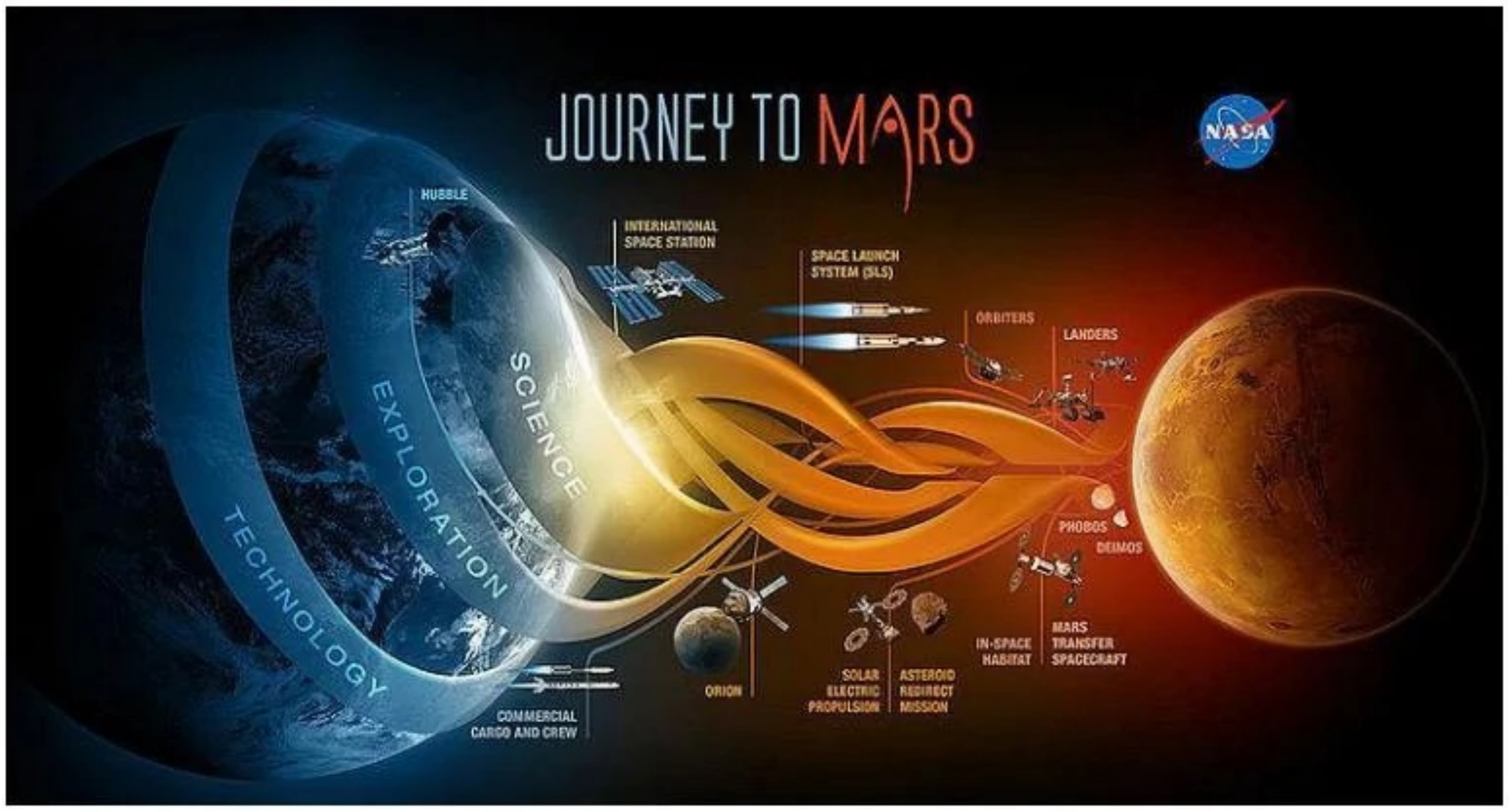

Figure 12: With eyes on the future – NASA engineers and private entrepreneurs alike are gearing up for the first human journey to Mars. If the ambitions of Elon Musk and others come to fruition, the future may hold Martian colonization, and see the rise of humanity as a multi-planet species.

Source: Wikimedia Commons

specks of solid or liquid material in the air), sulfur dioxide, and lead—as atmospheric pollutants that warrant continuous monitoring to track and maintain our atmospheric quality (EPA, 2017). Unsurprisingly, space-borne satellites have emerged as some of the most effective instruments for these monitoring efforts. NASA's Health and Air Quality applications program manages the data-collecting devices, analyzes their findings, and disseminates the research globally to aid in worldwide environmental protectionism. Most recently, the Health and Air Quality applications program has contributed to a fascinating global finding: China's large-scale response to the COVID-19 pandemic, which included limitations on industrial activities and travel, appears to have resulted in a significant decrease in atmospheric levels of nitrogen dioxide (NO2) (Myllyvirta, 2020). A NASA imaging craft named Aura partnered with the European Space Agency's Sentinel-5 satellites to provide the underlying data, just one example of the numerous advancements in environmental understanding that have originated from space exploration.

Finally, perhaps the most elusive class of space-borne advancements must be noted: global cooperation. Neither the medical innovations nor the environmental discoveries that have come as a result of space exploration could have been achieved without notable collaboration between many different agencies, scientists, foundations, and governments. International collaboration is at an all-time high—both literally and figuratively—in the International Space Station, where astronauts from the United States join colleagues from Russia, Europe, Japan, and Canada on board a space station with about as much internal volume as a Boeing 747 ("International Cooperation," n.d.). The ISS and the international collaboration that takes place inside both serve as marks of the remarkable global cooperation that space exploration requires; the station is governed and maintained via five international treaties and five sets of principles on space-related activities, each facilitated by the United Nations' Committee on the Peaceful Uses of Outer Space ("Space Law Treaties and Principles," n.d.). Undoubtedly, whether space-borne advancements come in the form of new medical devices, enhanced environmental protection, or unprecedented global cooperation, the benefits of space exploration surround us here on Earth.

"Finally, perhaps the most elusive class of space-borne advancements must be noted: global cooperation. Neither the medical innovations nor the environmental discoveries that have come as a result of space exploration could have been achieved without notable collaboration between many different agencies, scientists, foundations, and governments."

Conclusion

It is the destiny of humanity to carve out a home amongst the stars. That is the vision, at least, which today's space-flight leaders are edging towards. The notion that humanity ought to expand into space has actually been around for quite a long time. The real estate magnate John Jacob Astor IV wrote a fictional book in 1894 titled 'Journey in Other Worlds: A Romance of the Future'. In it he depicts life on Jupiter and Saturn in the year 2000. We haven't quite met the mark, but life on Mars at least is not far outside the realm of possibility from the perspective of the present day. Setting forth a more concrete vision, American physicist and space activist Gerard described in his book 'The High Frontier' (1977) the idea that industrial activity ought to be transplanted from Earth to the moon – both to lessen the burden on Earth's environment and to establish the moon as a waystation for further extra-terrestrial exploration (Simberg, 2018).

While O'Neill's plans were labeled by one Congressman (WI senator William Proxmire) as a "nutty fantasy" in the 1970s, the world may not be that far off from a more extensive and popular exploration of space (Simberg, 2018). Even NASA, whose space program had waned in the late 2000s/early 2010s, has gone back into the business of preparing to send astronauts to space. The Artemis program in particular plans to put the first woman on the moon by the year 2024 (Drake, n.d.). Artemis objectives are being supported by private contracts geared towards the construction of a lunar lander (both Blue Origin and Space X are involved), and the construction of Orion– a large spacecraft developed by Lockheed Martin that is considered to be safer and more reliable than the space shuttles ever were ("Orion Overview," n.d.). NASA has ambitious plans for human travel to Mars as well – although the Institute for Defense Analysis, in a 2019 report, has labeled these plans a bit too far-fetched. In their estimation, without significant budget increases and further government investment in Space R&D, 2037 is the earliest possible date for a feasible human launch to Mars (Linck et al., 2019)

The private space pioneers are not so limited by budget considerations, though. And if nothing else they have very high aspirations. Virgin Galactic is working on a craft that would inaugurate the space tourism industry – offering a joyride for paying customers that would provide six-minutes of weightlessness. Branson and the other private space magnates are interested in space colonization as well. Musk is perhaps best known for his focus on the planet Mars. Branson and Bezos have expressed similar intentions – musing about colonization of other planets, or even the construction of vessels that could support life within space itself (Simberg, 2018). All of these endeavors, if they do come to fruition, will necessitate legislative action. Regulations would be needed to govern space-flight patterns for example, and ensure that collisions with satellites or other space-faring craft are avoided (just as there are regulations of the same type for planes traveling within earth's atmosphere). International laws will need to be devised that address the utilization of planetary resources, and the demarcation of territory on the moon, Mars, and beyond. It will be a long road, yet the technology necessary to inaugurate this new era of human space travel, and the ambition to carry it out, are both increasing in supply.

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