ARTICLE IN PRESS

Engineering xxx (xxxx) xxx

Contents lists available at ScienceDirect

Engineering

journal homepage: www.elsevier.com/locate/eng

News & Highlights

SpaceX Starship Lands on Earth, But Manned Missions to Mars Will Require More

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Between December 2020 and March 2021, SpaceX (Hawthorne, CA, USA) launched four prototypes of its Starship, a behemoth rocket intended to one day shuttle people to Mars. Yet, after reaching an altitude of several miles and executing a controlled belly flop back toward to the ground, each one exploded in spectacular fashion during or shortly after landing [1]. On 5 May 2021, the company achieved success with a fifth Starship, dubbed SN15 (Fig. 1), which nailed the landing without blowing up [2]. As SpaceX—a relative newcomer in the rocketry business—marches forward on its mission to land people on Mars with its distinctive fail-fast, fix-fast approach, government-backed space agencies foresee using half-century-old nuclear propulsion and ion drive technology to ferry astronauts to the red planet and beyond.

"We are seeing from SpaceX a very rapid development process for a system that opens up a huge number of possibilities in space," said Casey Dreier, senior space policy adviser and chief advocate at the Planetary Society, headquartered in Pasadena, CA, USA.

SpaceX intends for the fully reusable Starship—currently 45 m-tall, shaped like a spray-paint can, and powered by three Raptor engines—to transport both crew and cargo on long-duration flights to Mars and further. SpaceX's founder, Elon Musk, who has said that humanity must colonize Mars to ensure the species' survival [3], recently set a goal of 2026 for the first manned mission to Mars [4].

Despite Musk's optimism, Dreier is less sanguine. "We have not seen them land anything on Mars yet, much less human beings, and so we need to see them work up to demonstrating that broader capability," he said. "But I definitely want to see them try."

Next up for SpaceX as it works toward Musk's goal is a test flight for a 60 m-tall version of Starship. Initially set for July 2021, the launch has since been postponed pending an environmental assessment [5]. Off in the future, possibly in late 2021 [6], is the assembly of the "full stack" version of the rocket needed for an orbital launch. This configuration stacks a Starship loaded with six Raptor engines on top of a 70 m-tall "Super Heavy" booster powered by 30 Raptor engines, packing a combined 7.1×10^7 N of thrust [5]—twice that of the most powerful launch vehicle to date, the National Aeronautics and Space Administration (NASA)'s Saturn V rocket. Eventually, Starship and its configurations are also expected to largely replace the company's Falcon Heavy rocket [7].

So far, SpaceX has conducted all test flights for Starship from its development facility in Boca Chica, TX, USA. Last year, a subsidiary of the company purchased two former deep-water oil rigs and began converting them to offshore launch pads, to which Musk plans for the orbital version of Starship to fly ahead of launches into space [8]. Once in orbit, Starship will be refueled before casting off for Mars, a trip expected to last eight to nine months [6]. Starship is powered by liquid oxygen and methane, meaning that astronauts could fly to Mars and extract more fuel from the planet's surface for the return trip or to travel further out.

Mars is not the only potential shorter-term destination for Starship, though. NASA, which has contracted with SpaceX to ferry astronauts to the International Space Station [9], awarded the company 2.9 billion USD in April 2020 to transport astronauts from lunar orbit to the surface of the moon as part of the agency's Artemis program [2]. In addition, the US Space Force plans to invest 48 million USD in SpaceX for research into making Starship capable of shipping up to 90 tonnes of supplies anywhere on earth in under one hour [10]. SpaceX itself also plans to use Starship to deliver to orbit 400 Starlink satellites at a time in its effort to build a network of 30 000 satellites to provide high-speed internet around the globe [11].

"In some ways, SpaceX are assemblers. They take existing technology, improve it, and integrate the parts. That is how they produce such robust, reliable, and reusable rockets," said Samuel Cohen, lecturer with the rank of professor of plasma physics at Princeton University in Princeton, NJ, USA and head of Princeton's Plasma Science and Technology Program. "But they are not really doing basic propulsion research."

While SpaceX has been remarkably successful scaling up existing chemical rocket technology—and sending robotic probes to Mars has become more commonplace [12]—many rocketry experts believe nuclear propulsion will be needed to power regular manned trips to Mars, though the timeline for doing so may be more than a decade after SpaceX achieves its goal of first sending people to the planet.

In April 2021, the US National Academy of Sciences, Engineering and, Medicine (NASEM) released a report [13] concluding, "Safely transporting humans to and from Mars will require advances in spacecraft propulsion. Advanced nuclear propulsion systems, including Nuclear Thermal Propulsion (NTP) and Nuclear Electric Propulsion (NEP), have the potential to substantially reduce trip time, launch mass, and space radiation exposure for astronauts compared to non-nuclear approaches."

NTP systems heat rocket propellant with the thermal energy produced by a nuclear reactor to create thrust, while NEP systems

https://doi.org/10.1016/j.eng.2021.08.005

Please cite this article as: C. Palmer, SpaceX Starship Lands on Earth, But Manned Missions to Mars Will Require More, Engineering, https://doi.org/10.1016/j.eng.2021.08.005

Fig. 1. SpaceX's Starship SN15 lifts off on 5 May 2021, from its launch pad near Boca Chica, TX, USA, ahead of a successful sub-orbital test flight in which the rocket landed without exploding like the previous four prototypes. Credit: Steve Jurvetson (CC BY 2.0).

use thrusters powered by electricity created from the thermal energy of the nuclear reactor. Both technologies, though, provide too little thrust to escape Earth's gravity and atmosphere, so spacecraft propelled by either would need to first be placed into orbit by a chemical rocket. The NASEM report suggests aggressive development of these systems, which were first prototyped in the 1960s, could result in a vehicle capable of manned Mars missions by 2039 [13].

Nuclear propulsion can produce twice the thrust per mass of propellant than chemical rockets, which could allow nuclear-powered ships to make the trip to Mars in just three months, less than half the time of a conventionally propelled Starship. "Everything becomes more complex and difficult the longer you are out in space," Dreier said. "The more you can reduce your travel time, the easier other challenges of getting humans to Mars—engineering, supplies, logistics—become."

And nuclear-powered trips beyond Mars would be even shorter, relatively. "To get to Mars, it is kind of a toss-up between chemical rockets and nuclear rockets," said Cohen, who leads a team researching a nuclear fusion drive for space missions. "But beyond Mars, nuclear rockets would be the clear winner."

In July 2021, NASA and the US Department of Energy collaboratively awarded 5 million USD each to three groups of companies to design nuclear thermal rockets [14]. And in April 2021, another US agency, the Defense Advanced Research Projects Agency (DARPA), selected three contractors—General Atomics (San Diego, CA, USA), Blue Origin (Kent, WA, USA), and Lockheed Martin (Bethesda, MD, USA)—to demonstrate by 2025 the first phase of a nuclear thermal rocket that would eventually fly to the moon through its Demonstration Rocket for Agile Cislunar Operations (DRACO) program [15]. Currently, however, the US has no explicit missions planned to send humans to Mars aboard nuclear-powered rockets [14].

Russia is also banking on nuclear power for interplanetary travel. The country's space agency, Roscosmos, announced plans in December 2020 to develop, build, and launch in 2030 a 500 kW nuclear reactor-powered transport and energy module called "Zeus" on a 50-month mission into deep space to slingshot around the moon to visit Venus and later Jupiter [16]. In addition, Russia is planning a nuclear-powered space station [16]. Though firm timelines for Zeus and the space station have not been announced, Dreier expressed skepticism. "Russia has a lot of ambitions in space, but their workforce, reliability, and capability have degraded seriously over the last two decades," he said. "I see a long pathway between what they want to do and what they are able to do right now."

China, which landed its Tianwen-1 lander on Mars in May 2021 [12], is also eyeing manned trips to Mars, beginning in 2033 [17]. However, the China National Space Administration wants to take a different approach, utilizing ion drives, another decades-old technology. These devices, first conceived by American physicist Edwin Hall in the 1930s [18], use electricity to accelerate ions as a form of propulsion.

Ion drives powered by solar-derived electricity have already been used on numerous small spacecraft and on China's Tiangong space station core module that welcomed four astronauts in June 2021, making it the first crewed vessel propelled by the technology [18]. However, ion drives have generally failed to compete against chemical rockets for transporting large payloads through space, and, like nuclear propulsion, ion drives do not produce enough thrust to launch spacecraft into space. The charged particles ion drives create can degrade engine components, reducing the integrity of spacecraft over time and endangering the lives of astronauts. In addition, the thrust they produce is relatively small, though theoretical improvements could put the technology on par with nuclear propulsion in terms of travel time to Mars [19].

Researchers with the Chinese Academy of Sciences, however, say they have found a solution to greatly improve the thrust of ion drives [18]. Their new design, used to power the core module of the Tiangong space station, places a powerful magnetic field within the engine's inner wall to repel damaging particles, thereby protecting the engine from erosion. The drive is composed of a unique ceramic material designed to withstand severe heat and radiation for extended periods and the researchers claim to have continuously burned a prototype for more than 11 months without problems.

Whether chemical, nuclear, or ion drive technology proves to be the best solution, "building the rockets, in a sense, is the easy part of getting people to Mars," said Dreier. "The harder stuff is your closed-loop life support, the reliability of components that you cannot replace in transit, the psychological health of astronauts, and communicating effectively with ground control. Whoever wants to be successful will have to master those things, too."

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