SpaceX Starship

Starship is a two-stage super heavy-lift launch vehicle under development by SpaceX. As of May 2024, it is the largest and most powerful rocket ever flown.[4] Starship's primary objective is to lower launch costs significantly via economies of scale.[5] This is achieved by reusing both rocket stages, increasing payload mass to orbit, increasing launch frequency, creating a mass-manufacturing pipeline, and adapting it to a wide range of space missions.[6] Starship is the latest project in SpaceX's decades-long reusable launch system development program and ambition of colonizing Mars.

Starship has two stages: the Super Heavy booster and the Starship spacecraft. Both stages are equipped with Raptor engines, the first production full flow staged combustion cycle engines, which burn liquid methane and liquid oxygen. Their main structure is made from stainless steel. After boosting the spacecraft, the Super Heavy booster uses its engines to slow down before being caught by a pair of mechanical arms attached to the launch tower.[7] After completing its mission, the Starship spacecraft reenters the atmosphere. Following a 'belly flop' maneuver, where the spacecraft turns from a horizontal to a vertical orientation, and then slows to a hover with its engines. Lunar and depot variants do not need to reenter the atmosphere and thus do not have a thermal protection system.

As of 2024, Starship is in development with an iterative and incremental approach, involving test flights of prototype vehicles, which often end in the destruction of the test vehicle. As a successor to SpaceX's Falcon 9 and Falcon Heavy rockets, Starship will perform a wide range of space missions. For missions to further destinations, such as geosynchronous orbit, the Moon, and Mars, Starship will rely on orbital refueling from the tanker variants, a ship-to-ship propellant transfer demonstration is expected to occur in 2025 to prove out this critical capability.[8][9] Starship will deploy SpaceX's second-generation Starlink satellite constellation, and the Starship HLS variant will land astronauts on the Moon as part of the Artemis program, starting with Artemis 3 in 2026.

Starship

Starship prototype in launch configuration: Starship spacecraft sits on top of Super Heavy.

Function	General-purpose and mass-produced super-heavy lift launch vehicle
Manufacturer	SpaceX
Country of origin	United States
Project cost	At least US$5 billion[1]
Cost per launch	$100 million (expendable)[2]
Size	
Height	121.3 m (398 ft)
Diameter	9 m (30 ft)

Description

When stacked and fully fueled, Starship has a mass of approximately 5,000 t (11,000,000 lb),[c] a diameter of 9 m (30 ft)[11] and a height of 121.3 m (398 ft).[12] The rocket has been designed with the goal of being fully reusable to reduce launch costs;[13] it consists of the Super Heavy first-stage booster and the Starship spacecraft[14] which are powered by Raptor and Raptor Vacuum engines.[15] The bodies of both rocket stages are made from stainless steel[16] and are manufactured by stacking and welding stainless steel cylinders.[17] These cylinders have a diameter of 9 m (30 ft) a height of 1.8 m (5 ft 11 in), a thickness of 4 mm (0.16 in) and a mass of 1,600 kg (4,000 lb) each.[17] Domes inside the spacecraft separate the methane and oxygen tanks.[17] SpaceX has stated that Starship, in its "baseline reuseable design", will have a payload capacity of 100–150 t (220,000–331,000 lb) to low earth orbit and 27 t (60,000 lb) to geostationary transfer orbit.[18][19]

Super Heavy booster

The first-stage booster, named Super Heavy, is 71 m (233 ft) tall and 9 m (30 ft) wide.[11] It contains 33 Raptor engines arranged in three concentric rings.[20] The outermost ring of 20 engines lack gimbal actuators to save weight.[21] At full power, all engines combined produce 74,400 kN (16,700,000 lb_f) of thrust.[22]

The booster's tanks can hold 3,400 t (7,500,000 lb) of propellant, consisting of 2,650 t (5,840,000 lb) of liquid oxygen and 750 t (1,650,000 lb) of liquid methane.[d][23] In 2021, Elon Musk said that the final design will have a dry mass between 160 t (350,000 lb) and 200 t (440,000 lb), with the tanks weighing 80 t (180,000 lb) and the interstage 20 t (44,000 lb).[3]

The booster uses four electrically actuated grid fins for control, each with a mass of 3 t (6,600 lb).[3] The booster is lifted from protruding hardpoints, which are located between gridfins.[24] Above the grid fins is the vented interstage, used for hot staging;[25] in which the upper stage fires its engines during stage separation rather than after.[26]

Starship spacecraft

The Starship spacecraft is 50.3 m (165 ft) tall and 9 m (30 ft) in diameter. It uses 6 Raptor engines, three of which are optimized for use in vacuum.[11][27] The engines produce 14,700 kN (3,300,000 lb_f) of thrust.[22] The vehicle's payload bay is planned to measure 17 m (56 ft) tall and 8 m (26 ft) in diameter with an internal volume of 1,000 m^3 (35,000 cu ft); slightly larger than the

Mass	5,000 t (11,000,000 lb)
Capacity	
Payload to LEO	
Mass	Reusable: 100–150 t (220,000–331,000 lb)
Volume	1,000 m^3 (35,000 cu ft)
Associated rockets	
Derivative work	Starship HLS
Comparable	N1 Saturn V Space Shuttle Falcon Heavy Space Launch System Long March 9
Launch history	
Status	In development
Launch sites	SpaceX Starbase, OLM-A SpaceX Starbase, OLM-B (under construction) Kennedy Space Center, LC-39A (planned) Cape Canaveral Space Force Station, SLC-37 (planned)
Total launches	4
Success(es)	2 (IFT-3, IFT-4)[a]
Failure(s)	2 (IFT-1, IFT-2)
First flight	April 20, 2023
Last flight	June 6, 2024
First stage – Super Heavy	

ISS's pressurized volume.[28] Starship has a total propellant capacity of 1,200 t (2,600,000 lb)[10] across its main tanks and header tanks.[29] According to Elon Musk in 2019, the header tanks are better insulated due to their position and are reserved for use to flip and land the spacecraft following reentry.[30] A set of reaction control thrusters, which use the pressure in the fuel tank, control attitude while in space.[31]

Height	71 m (233 ft)
Diameter	9 m (30 ft)
Empty mass	200 t (441,000 lb)
Gross mass	3,600 t (7,937,000 lb)
Propellant mass	3,400 t (7,496,000 lb)
Powered by	33 Raptor engines
Maximum thrust	7,590 t_f (74,400 kN; 16,700,000 lb_f)
Specific impulse	327 s (3.21 km/s) (sea-level)
Propellant	Liquid oxygen / Methane
Second stage – Starship	
Height	50.3 m (165 ft)
Diameter	9 m (30 ft)
Empty mass	~100 t (220,000 lb)[3]
Gross mass	1,300 t (2,866,000 lb)[b]
Propellant mass	1,200 t (2,646,000 lb)
Powered by	3 Raptor engines 3 Raptor vacuum engines
Maximum thrust	1,250 t_f (12,300 kN; 2,760,000 lb_f)
Specific impulse	327 s (3.21 km/s) (sea-level) 380 s (3.7 km/s) (vacuum)
Propellant	Liquid oxygen / Methane

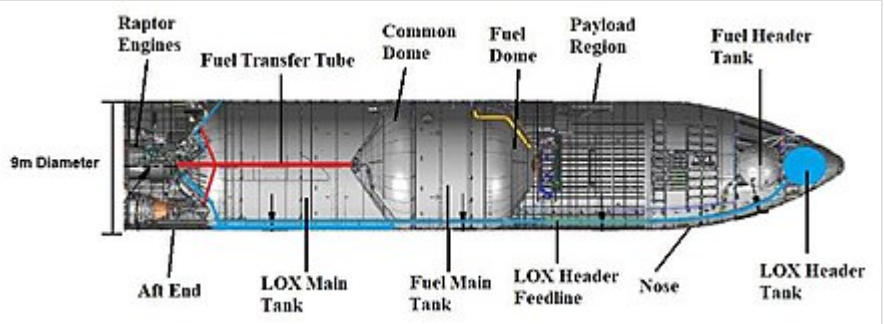


Diagram of a V1 Starship's internal structure. Not shown in this diagram are the flaps: the aft flaps are placed at the bottom (or left in this orientation), and the forward flaps are placed at the top (here, right) portion of the spaceship.

The spacecraft has four body flaps to control the spacecraft's orientation and help dissipate energy during atmospheric entry, composed of two forward flaps and two aft flaps.[32] According to SpaceX, the flaps replace the need for wings or tailplane, and reduce the fuel needed for landing.[33]:1 Under the forward flaps, hardpoints are used for lifting and catching the spacecraft via mechanical arms.[24] The flap's hinges are sealed in aero-covers because otherwise, they would be easily damaged during reentry.[3]

Starship's heat shield is composed of eighteen thousand[34][35] hexagonal black tiles that can withstand temperatures of 1,400 °C (2,600 °F).[36][37] It is designed to protect the vehicle during atmospheric entry and to be used multiple times with minimal maintenance between flights.[13] The silica-based tiles[38] are attached to Starship with pins[37] and have small gaps in between to allow for heat expansion.[3]

Starship is planned to be able to be refueled by docking with separately launched Starship propellant tanker spacecraft in orbit. Doing so could allow it to reach higher-energy targets,[e] such as geosynchronous orbit, the Moon, and Mars.[39] A propellant depot could store methane and oxygen on-orbit, and could be used by Starship HLS to replenish its fuel tanks.[40]

Variants

For satellite launch, Starship is planned to have a large cargo door that will open to release payloads, similar to NASA's Space Shuttle, and close upon reentry as an alternative to a jettisonable fairing. Instead of a cleanroom, payloads would be integrated directly into Starship's payload bay, which requires purging the payload bay with temperature-controlled ISO class 8 clean air.[18] To deploy Starlink satellites, the cargo door is to be replaced with a slot and dispenser rack, whose mechanism has been compared to a Pez candy dispenser.[41]

Starship HLS

Starship Human Landing System (HLS) is a planned crewed lunar lander variant of the Starship vehicle that would be modified for landing, operation, and takeoff from the lunar surface.[42] HLS features landing legs, a body-mounted solar array,[43] a set of thrusters mounted mid-body to assist with final landing and takeoff,[43] two airlocks,[42] and an elevator to lower crew and cargo onto the lunar surface.[44]

In 2021, Musk said that between "four and eight" launches would be required to fully fuel HLS.[45] The same year, the Government Accountability Office said that SpaceX would "require 16 launches overall",[45] and in 2023, a NASA official estimated the number of Starship launches required for one lunar

landing to be "in the high teens".[45] In 2024, SpaceX vice president of customer operations estimated that the number of launches would be "10-ish", though this number is subject to change.[46] These launches will reportedly have to be in "rapid succession" in order to manage schedule constraints and cryogenic fuel boil-off.[45] When fully fueled, Starship HLS is designed to land 100 t (220,000 lb) of payload on the Moon.[47][48][49]

Raptor engine

Sea level-optimized Raptor 1 engine, May 2020

Raptor is a family of rocket engines developed by SpaceX for use in Starship and Super Heavy vehicles. It burns liquid oxygen and methane in an efficient and complex full-flow staged combustion power cycle. The Raptor engine uses methane as fuel rather than kerosene because methane gives higher performance and prevents the build-up of deposits in the engine from coking.[50][51] Methane can also be produced from carbon dioxide and water using the Sabatier reaction.[52] The engines are designed to be reused many times with little maintenance.[53]

Raptor operates with an oxygen-to-methane mixture ratio of about 3.6:1, lower than the stoichiometric mixture ratio of 4:1 necessary for complete combustion, since operating a higher temperatures would melt the engine.[3] The propellants leave the pre-burners and get injected into the main combustion chamber as hot gases instead of liquid droplets allowing a higher power density as the propellants mix rapidly via diffusion.[50] The methane and oxygen are at high enough temperatures and pressures that they ignite on contact, eliminating the need for igniters in the main combustion chamber.[54] The engine structure itself is mostly aluminum, copper, and steel; oxidizer-side turbopumps and manifolds subject to corrosive oxygen-rich flames are made of an Inconel-like SX500 superalloy.[54] Some components are 3D printed.[55]

At sea level, the standard Raptor engine produces 2.3 MN (520,000 lbf) at a specific impulse of 327 seconds (3.21 km/s) at sea level and 350 seconds (3.4 km/s) in a vacuum.[54] Raptor Vacuum, used on the Starship upper stage, is modified with a regeneratively cooled nozzle extension made of brazed steel tubes, increasing its expansion ratio to about 90 and its specific impulse in vacuum to 380 seconds (3.7 km/s).[3] The main combustion chamber operates at a pressure of 350 bar (5,100 psi) exceeding that of any prior operational rocket engine.[50] The Raptor's gimbaling range is 15°, higher than the RS-25's 12.5° and the Merlin's 5°. SpaceX has stated they aim to achieve a per unit production cost of US$250,000 upon starting mass-production.[54]

Versions

On 4 April 2024, Elon Musk provided an update on Starship at Starbase, where two new versions of Starship were announced, Starship V2 and Starship V3.[56][57]

Specifications of each version as reported by SpaceX in April 2024

Version 1

As of 6 June 2024, Starship version 1 has been used for all 4 Integrated Flight Tests.[58][59]

Version 2

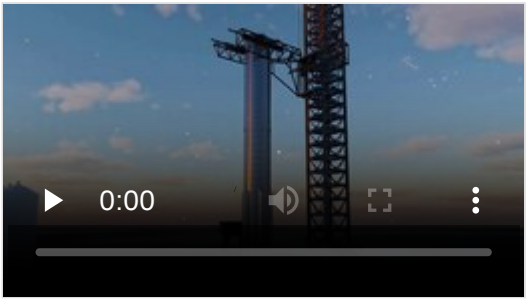
As of April 2024, exact specifications are not known for the version 2 vehicle; however, the V2 ships will feature a thinner forward flap design, a 25% increase in propellant capacity, and an increase in thrust.[60][61] The vehicle will be a total of 3.1 m (10 ft) taller than the previous V1 vehicle, and is planned to have a payload capacity of at least 100 tons to orbit when reused.[60] Additionally, the engine type will switch to Raptor 3, which removes the need for secondary engine shielding.[62]

Version 3

As of June 2024, the V3 Starship final configuration is unknown. The most recent configuration, hinted at in May 2024 by Elon Musk, was a stretched V2 vehicle, with a total height of 126 m (413 ft).[63] A previous concept in April 2024 was 150 m (490 ft) tall.[56] It is planned to have a payload capacity of at least 200 tons to orbit when reused.[64]

Planned launch and landing profile

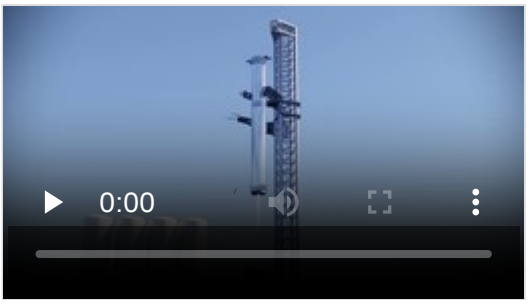
Payloads are planned to be integrated into Starship at a separate facility and then rolled out to the launch site.[23] Super Heavy and Starship are then to be stacked onto their launch mount and loaded with fuel via the ship quick disconnect (SQD) arm and booster quick disconnect (BQD).[24] The SQD and BQD retract, all thirty-three engines of Super Heavy ignite, and the rocket lifts-off.[24]



Animation of Super Heavy's integration to the launch mount, using mechanical arms.

At approximately 159 seconds after launch[65] at an altitude of roughly 64 km (40 mi), Super Heavy cuts off all but three of its center gimbaling rocket engines.[66]:58 Starship then ignites its engines while still attached to the booster, and separates.[26] During hot-staging, the booster throttles down its engines.[26] The booster then rotates, before igniting an additional ten engines for the boostback burn.[67] After the boostback burn is complete, the booster's engines shut off with Super Heavy on a trajectory for a controlled descent to the launch site using its grid fins for minor course corrections. After six minutes, shortly before landing,[68] it ignites its engines to slow sufficiently to be caught by two mechanical arms attached to the tower.[69]

Meanwhile, the Starship spacecraft continues to accelerate to orbital velocity with its six raptor engines.[70] Once in orbit, the spacecraft is planned to be able to be refueled by another Starship tanker variant.[71] Musk has estimated that 8 launches would be needed to completely refuel a Starship in low Earth orbit.[72] NASA has estimated that 16 launches in short succession (due to cryogenic propellant boil-off) would be needed to partially refuel Starship for one lunar landing.[45] To land on bodies without an atmosphere, such as the Moon, Starship will fire its engines to slow down.[73] To land on bodies with an atmosphere such as the Earth and Mars, Starship first slows by entering the atmosphere via a heat shield.[13] The spacecraft would then perform a "belly-flop" maneuver by diving back through the atmosphere body at a 60° angle to the ground,[74] controlling its fall using four flaps at the front and aft sides of the spacecraft.[31] Shortly before landing, the Raptor engines fire,[31] using fuel from the header tanks,[30] and the spacecraft resumes vertical orientation, with the Raptor engines' gimbaling helping to maneuver the craft.[31]



A short animation of Super Heavy's landing on mechanical arms. The actual landing speed is a few times slower.

If Starship's second stage lands on a pad, a mobile hydraulic lift will move it to a transporter vehicle. If it lands on a floating platform, it will be transported by a barge to a port and then transported by road. The recovered Starship will either be positioned on the launch mount for another launch or refurbished at a SpaceX facility.[23]:22

Development

Early design concepts (2012–2019)

In November 2005,[75] before SpaceX had launched its first rocket the Falcon 1,[76] CEO Elon Musk first mentioned a high-capacity rocket concept able to launch 100 t (220,000 lb) to low Earth orbit, dubbed the *BFR*.[75] Later in 2012, Elon Musk first publicly announced plans to develop a rocket surpassing the capabilities of their existing Falcon 9.[77] SpaceX called it the *Mars Colonial Transporter*, as the rocket was to transport humans to Mars and back.[78] In 2016, the name was changed to *Interplanetary Transport System*, as the rocket was planned to travel beyond Mars as well.[79] The design called for a carbon fiber structure,[80] a mass in excess of 10,000 t (22,000,000 lb) when fully-fueled, a payload of 300 t (660,000 lb) to low Earth orbit while being fully reusable.[80] By 2017, the concept was temporarily re-dubbed the *BFR*.[81]

In December 2018, the structural material was changed from carbon composites[82][80] to stainless steel,[83][84] marking the transition from early design concepts of the Starship.[83][74][85] Musk cited numerous reasons for the design change; low cost and ease of manufacture, increased strength of stainless steel at cryogenic temperatures, as well as its ability to withstand high heat.[86][74] In 2019, SpaceX began to refer to the entire vehicle as Starship, with the second stage being called Starship and the booster Super Heavy.[87][88][89] They also announced that Starship would use reusable heat shield tiles similar to those of the Space Shuttle.[90][91] The second-stage design had also settled on six Raptor engines by 2019; three optimized for sea-level and three optimized for vacuum.[92][93] In 2019 SpaceX announced a change to the

second stage's design, reducing the number of aft flaps from three to two in order to reduce weight.[94] In March 2020 SpaceX released a Starship Users Guide, in which they stated the payload of Starship to LEO would be in excess of 100 t (220,000 lb), with a payload to GTO of 21 t (46,000 lb).[18]

Low-altitude flight tests (2019–2021)

Starhopper to SN6

The first tests started with the construction of the first prototype in 2018, *Starhopper*, which performed several static fires and two successful low-altitude flights in 2019.[95] SpaceX began constructing the first full-size Starship Mk1 and Mk2 upper-stage prototypes before 2019, at the SpaceX facilities in Boca Chica, Texas, and Cocoa, Florida, respectively.[96] Neither prototype flew: Mk1 was destroyed in November 2019 during a pressure stress test and Mk2's Florida facility was deconstructed throughout 2020.[97][38]

Starhopper under construction, March 2019

A crane lifting Starship SN5, August 2020

After the Mk prototypes, SpaceX began naming its new Starship upper-stage prototypes with the prefix "SN", short for "serial number".[98] No prototypes between SN1 and SN4 flew either—SN1 and SN3 collapsed during pressure stress tests, and SN4 exploded after its fifth engine firing.[99]

In June 2020, SpaceX started constructing a launch pad for orbital Starship flights.[24] The first flight-capable prototype, SN5, was cylindrical as it had no flaps or nose cone: just one Raptor engine, fuel tanks, and a mass simulator.[100] On 5 August 2020, SN5 performed a 150 m (500 ft) high flight and successfully landed on a nearby pad.[101] On 3 September 2020, the similar-looking Starship SN6 repeated the hop;[102] later that month, a Raptor Vacuum engine underwent its first full duration firing at McGregor, Texas.[103]

SN8 to SN15

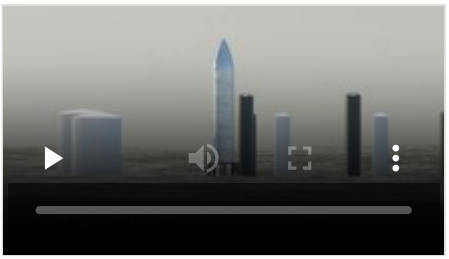
Starship SN8 was the first full-sized upper-stage prototype, though it lacked a heat shield.[104] It underwent four preliminary static fire tests between October and November 2020.[99] On 9 December 2020, SN8 flew, slowly turning off its three engines one by one, and reached an altitude of 12.5 km (7.8 mi). After SN8 dove back to the ground, its engines were hampered by low methane header tank pressure during the landing attempt, which led to a hard impact with the landing pad and subsequent explosion of the vehicle.[31]

Because SpaceX had violated its launch license and ignored warnings of worsening shock wave damage, the Federal Aviation Administration investigated the incident for two months.[105] During the SN8 launch, SpaceX ignored FAA warnings that the flight profile posed a risk of explosion.[105][106][107] FAA space

division chief Wayne Monteith said SpaceX's violation was “inconsistent with a strong safety culture", and criticized the company for proceeding with the launch "based on 'impressions' and 'assumptions,' rather than procedural checks and positive affirmations".[105]

SN8 shortly after taking off, December 2020

On 2 February 2021, Starship SN9 launched to 10 km (6.2 mi) in a flight path similar to SN8. The prototype crashed upon landing because one engine did not ignite properly.[108] A month later, on 3 March, Starship SN10 launched on the same flight path as SN9.[109] The vehicle landed hard and crushed its landing legs, leaning to one side.[110] A fire was seen at the vehicle's base and it exploded less than ten minutes later,[111] potentially due to a propellant tank rupture.[110] On 30 March, Starship SN11 flew into thick fog along the same flight path.[112] The vehicle exploded during descent,[112] possibly due to excess propellant in a Raptor's methane turbopump.[113]



Computer animation depicting a successful high-altitude flight test

In March 2021, the company disclosed a public construction plan for two sub-orbital launch pads, two orbital launch pads, two landing pads, two test stands, and a large propellant tank farm.[114] The company soon proposed developing the surrounding Boca Chica Village, Texas, into a company town named Starbase.[114] Locals raised concerns about SpaceX's authority, power, and a potential threat for eviction through eminent domain.[115]

In early April, the orbital launch pad's fuel storage tanks began mounting.[24] SN12 through SN14 were scrapped before completion; SN15 was selected to fly instead,[116] due to improved avionics, structure, and engines.[111] On 5 May 2021, SN15 launched, completed the same maneuvers as older prototypes, and landed safely.[116] SN15 had a fire in the engine area after landing but it was extinguished.[111] According to a later report by SpaceX, SN15 experienced several issues while landing, including the loss of tank pressure and an engine.[33]:2

Integrated flight tests (2023–)

First integrated flight test

In July 2021, Super Heavy BN3 conducted its first full-duration static firing and lit three engines.[117] Around this time, SpaceX changed their naming scheme from "SN" to "Ship" for Starship crafts,[118] and from "BN" to "Booster" for Super Heavy boosters.[119] A month later, using cranes, Ship 20 was stacked atop Booster 4 to form the full launch vehicle for the first time; Ship 20 was also the first craft to have a body-tall heat shield.[35] In October 2021, the catching mechanical arms, also known as "chopsticks", were installed onto the integration tower and the first tank farm's construction was completed.[24]

In June 2022, the Federal Aviation Administration determined that SpaceX must address more than 75 issues identified in the preliminary environmental assessment.[120] In July, Booster 7 tested the liquid oxygen turbopumps on all thirty-three Raptor engines, resulting in an explosion at the vehicle's base, which

destroyed a pressure pipe and caused minor damage to the launchpad.[121] By the end of November, Ship 24 had performed 2- and full 6-engine static test fires,[122]:20 while Booster 7 had performed static fires with 1, 3, 7, 14, 11 engines[123][122]:20 and finally on February 9, 2023, a static fire with 31 engines at 50% throttle.[124] In January 2023, the whole Starship stack underwent a full wet dress rehearsal.[125]

After a launch attempt aborted on 17 April 2023,[126] Booster 7 and Ship 24 lifted off on 20 April at 13:33 UTC in the first orbital flight test.[127] Three engines were disabled during the launch sequence and several more failed during the flight.[128] The spacecraft also lost thrust vectoring control of the Raptor engines later in the flight, which led to the rocket spinning out of control.[128] The vehicle reached a maximum altitude of 24 mi (39 km).[129] Approximately 3 minutes after lift-off the rocket's autonomous flight termination system was activated. The system failed to destroy the vehicle, which tumbled for another 40 seconds before disintegrating.[130][131][132] The first flight test blasted large amounts of sand and soil in the air, reaching communities within a 10-km (6-mile) radius.[133][134] A brushfire on nearby state parkland also occurred, burning 3.5 acres of state parkland.[135]

Starship during the first integrated flight attempt; notice the multiple engine failures on the first stage.

Second integrated flight test

After the first test flight, SpaceX began work on the launch mount to repair the damage it sustained during the test and to prevent future issues. The foundation of the launch tower was reinforced and a water powered flame deflector was built under the launch mount.[136] Ship 25 and Booster 9 were rolled to the suborbital and orbital launch sites in May to undergo multiple tests.[137][138]

In August, SpaceX submitted to the FAA the 63 corrective actions they had to take before another launch could take place.[139] Following SpaceX's final report, the FAA closed the investigation on September 8, 2023.[140][141] By October 31, 2023, the FAA had concluded the safety review portion of the launch license.[142]

On November 18, 2023, Booster 9 and Ship 25 lifted off the pad.[143] All 33 engines continued to function until staging, where the second stage separated by pushing itself away from the first stage using a hot-staging technique.[67] Following separation, the Super Heavy booster completed its flip maneuver and initiated the boostback burn before exploding following multiple successive engine failures.[67][144][145] Three and a half minutes into the flight at an altitude of ~90 km over the Gulf of Mexico, blockage in a liquid oxygen filter caused one of the engines to fail in a way that resulted in the destruction of the booster.[146]

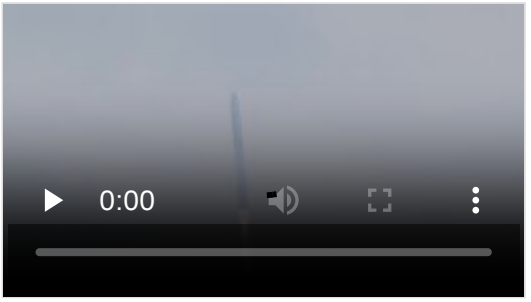
The second stage continued until it reached an altitude of ~149 kilometres (93 mi), after over eight minutes of flight; prior to engine cutoff, telemetry was lost on the second stage.[67] SpaceX said that a safe command based on flight performance data triggered the Flight Termination System and destroyed the second stage,[67] prior to achieving its planned orbit or attempting re-entry.[147] It appeared to re-enter a few hundred miles north of the Virgin Islands, according to NOAA weather radar data.[148]

Starship during the second integrated flight attempt

Third integrated flight test

Following the second flight test (which saw the loss of both stages), significant changes were implemented, including upgrading Starship's thrust vector control system to electric thrust vector control (TVC)[149] and measures to delay liquid oxygen (LOX)[149] venting until after Starship engine cutoff (SECO) has taken place.

IFT-3 launched from the SpaceX Starbase facility along the South Texas coast around 8:25 CDT on March 14, 2024, coincidentally the 22nd anniversary of its founding.[150][151] Like IFT-2, all 33 engines on the booster ignited and stage separation was successful.[152] B10 conducted a boostback burn, however, the planned landing in the Gulf of Mexico was not successful, as it exploded at 462 meters above the surface.[153]



Video of Starship during the third integrated flight attempt

The Starship spacecraft itself – after reaching space and orbital velocity – conducted several tests after engine cutoff, including initiating a propellant transfer demo and payload dispenser test.[154][155] It attempted to re-enter the atmosphere,[153][156] and at an altitude of around 65 km, all telemetry from Ship 28 stopped, indicating a loss of the vehicle.[157] This flight test demonstrated a cryogenic propellant transfer, by transferring propellant from the Ship's header tanks into its main tanks while in space, a technology which is required for Starship HLS to exit low earth orbit (LEO). The result of this test was declared successful by NASA and SpaceX. Additional data analysis is occurring on the fluid dynamics such as slosh and boil-off of the propellant.[158][159][160]

Fourth integrated flight test

The fourth integrated flight test of the full Starship configuration launched on June 6, 2024, at 7:50 AM CDT.[161] The goals for the test flight were for the Super Heavy booster to land on a 'virtual tower' in the ocean, and for the Ship to survive peak heating during atmospheric reentry.[162] The flight test was successful in both regards, with Super Heavy achieving a soft splashdown and Ship surviving atmospheric reentry and a controlled splashdown.[163]

Fifth integrated flight test

In April 2024 Musk stated one of the goals was to attempt a booster tower landing based on successful booster performance in flight 4. Vehicle testing commenced in May 2024.[164] As of May 2024, IFT-5 is expected to occur in late June.[165]

Cost and funding

SpaceX develops the Starship primarily with private funding.[166][89][1] SpaceX Chief Financial Officer Bret Johnsen disclosed in court that SpaceX has invested more than $3 billion into the Starbase facility and Starship systems from July 2014 to May 2023.[1] Elon Musk stated in April 2023 that SpaceX expected to spend about $2 billion on Starship development in 2023.[167][168]

Musk has theorized that a Starship orbital launch might eventually cost SpaceX only $1 million to launch.[169] Eurospace's director of research Pierre Lionnet stated in 2022 that Starship's launch price to customers would likely be higher because of the rocket's development cost.[39]

As part of the development of the Human Landing System for the Artemis program, SpaceX was awarded in April 2021 a $2.89 billion fixed-price contract from NASA to develop the Starship lunar lander for Artemis III.[170][171] Blue Origin, a bidding competitor to SpaceX, disputed the decision and began a legal case against NASA and SpaceX in August 2021, causing NASA to suspend the contract for three months until the case was dismissed in the Court of Federal Claims.[172][173][174] Two years later Blue Origin was awarded a $3.4 billion fixed-price contract for their lunar lander.[175]

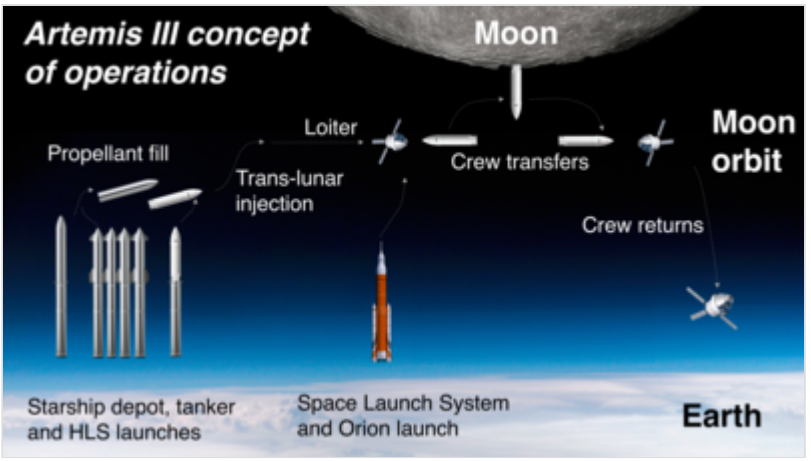
In 2022, NASA awarded SpaceX a $1.15 billion fixed-price contract for a second lunar lander for Artemis 4.[171] The same year, SpaceX was awarded a $102 million five-year contract to develop the Rocket Cargo program for the United States Space Force.[176]

Potential uses

Particular missions

SpaceX plans to use Starship to launch the second generation of satellites for SpaceX's Starlink system, which currently delivers high-speed internet to over 70 countries.[177] An analyst at financial services company Morgan Stanley stated development of Starship and Starlink are intertwined, with Starship's planned launch capacity enabling cheaper Starlink launches, and Starlink's profits financing Starship's development costs.[178] In deficit from its inception until the end of 2022,[179] Starlink was first reported to be cash flow positive in the first quarter of 2023,[180][181] though Elon Musk said that Starlink had only reached "break-even cashflow" in 2023.[182] In December 2023, the FCC issued a final denial of a $885M Starlink subsidy because of Starlink's "continuing inability to successfully launch on the Starship rocket".[183]

Starship HLS was initially chosen by NASA as the sole lunar Human Landing System for the planned Artemis 3 and Artemis 4 crewed missions, as part of the Artemis program.[42][184] Starship HLS is to be launched into a low Earth orbit, and refueled by multiple Starship tanker spacecraft.[40]:4,5 Once fueled, it would perform a trans lunar injection burn and enter a near-rectilinear halo orbit[185] around the Moon, with a perilune of 1500 km occurring over the north pole and an apolune of 70,000 km occurring over the south pole.[185][40]:4,5 The Orion spacecraft would then dock with Starship HLS and two of its four crew would transfer into Starship HLS.[186][40]:4,5 Starship HLS would then use its engines to make a powered descent and land near the lunar south pole.[40]:4,5 After the crew performs the surface portion of their mission, the HLS would ascend with the crew.[40]:4,5 The crew would then transfer into the Orion spacecraft and return to Earth.[40]:4,5



Artemis 3 launch profile of a human landing on the Moon, involving Starship HLS, Starship tanker variants, and Orion spacecraft

One future payload is the Superbird-9 communication satellite, which was Starship's first contract for externally made commercial satellites.[187] Another planned payload is the Starlab space station, which Starship will launch in a single piece.[188]

In the future, the spacecraft's crewed version could be used for space tourism—for example, for the third flight of the Polaris program.[189] Musk stated that SpaceX would complete hundreds of cargo flights before launching with human passengers.[190]

General use cases

Opinions differ on how Starship's planned low launch cost could affect the cost of space science. According to Waleed Abdalati, former NASA Chief Scientist, the planned low launch cost could reduce the cost of satellite replacement and enable more ambitious missions for budget-limited programs due to the higher percentage of the total budget taken up by launch costs for lower budget missions.[191] According to Lionnet, low launch cost might not reduce the overall cost of a science mission significantly: of the *Rosetta* space probe and *Philae* lander's mission cost of $1.7 billion, the cost of launch (by the expendable Ariane 5) only made up ten percent.[191] Similarly the Juno mission had a total budget of $1.13 billion,[192] with launch cost of $190 million[193] making up only seventeen percent of the budget.

Astronomers have called to consider Starship's larger mass to orbit and wider cargo bay for proposed space telescopes such as LUVOIR, and to develop larger telescopes to take advantage of these capabilities.[194][195] Starship's 9 meters fairing width could hold an 8 meters-wide large space telescope mirror in a single piece,[194] alleviating the need for complex unfolding such as that of the JWST's 6.5m mirror which added cost and delays.[195] The low launch cost could also allow probes to use heavier, more common, cheaper materials, such as glass instead of beryllium for large telescope mirrors.[195][39] With a 5 t

(11,000 lb) mirror built using similar methods to the Hubble Space Telescope's mirror, the JWST would represent only 10% of the mass deliverable by a (refueled) Starship to the Sun-Earth L2 point, and therefore minimizing the weight of the telescope would not have been a dominant design consideration.[195]

A fully refueled Starship could launch 100 t (220,000 lb) observatories to the Moon and the Sun-Earth L2 Lagrange point.[195] A fully refueled Starship might also be capable of launching probes to Neptune, Jupiter's moon Io, or large sample-return missions.[71] Astrophysicists have noted Starship could deploy multiple antennae up to 30 meters in length, opening up radio astronomy to frequencies below 30 MHz and wavelengths greater than 10m.[195] This would give the ability to study the Universe's Dark Ages, unfeasible on Earth due to the atmosphere and human radio background.[195]

One possible future use of Starship that SpaceX has proposed is point-to-point flights (called "Earth to Earth" flights by SpaceX), traveling anywhere on Earth in under an hour.[196] In January 2022, SpaceX was awarded a $102 million five-year contract to develop the Rocket Cargo program for the United States Space Force.[176] The five-year contract is intended to "determine exactly what a rocket can achieve when used for cargo transport",[197] and will see the Air Force Research Laboratory collect data during commercial launches of Starship.[197] The contract includes an eventual demonstration mission with the launch and landing of a cargo-laden Starship in a point-to-point flight.[197]

Space colonization

According to SpaceX, Starship is intended to be able to land crews on Mars,[198]:120 though SpaceX has not published technical plans or designs about Starship's life support systems, radiation protection, docking system, or in-orbit refueling system for Mars.[199][200] The spacecraft would be launched to low Earth orbit and refueled in orbit before heading to Mars.[201] After landing on Mars, the Sabatier reaction could be used to synthesize liquid methane and liquid oxygen, Starship's fuel, in a power-to-gas plant.[202] The plant's raw resources would be Martian water and Martian carbon dioxide.[52] On Earth, similar technologies could be used to make carbon-neutral propellant for the rocket.[203] To date, there has been one proof of concept experiment (MOXIE) demonstrating the extraction of oxygen from Martian carbon dioxide, with George Dvorsky writing for Gizmodo commenting that we are not "remotely close" to turning this "into something practical".[43]

Facilities

Testing and manufacturing

Starbase consists of a manufacturing facility and launch site,[204] and is located at Boca Chica, Texas. Both facilities operate twenty-four hours a day.[17] A maximum of 450 full-time employees may be onsite.[23]:28 The site is planned to consist of two launch sites, one payload processing facility, one seven-acre solar farm, and other facilities.[23]:34–36 The company leases Starbase's land for the STARGATE research facility, owned by the University of Texas Rio Grande Valley. It uses part of it for Starship development.[205]

Raptor engines are tested at the Rocket Development facility in McGregor, Texas. The facility has two main test stands: one horizontal stand for both engine types and one vertical stand for sea-level-optimized rocket engines.[206] In the future, a nearby factory, which as of September 2021 was under construction, will make the new generation of sea-level Raptors while SpaceX's headquarters in California will continue building the Raptor Vacuum and test new designs.[206]

At Florida, a facility at Cocoa purifies silica for Starship heat-shield tiles, producing a slurry that is then shipped to a facility at Cape Canaveral. In the past, workers constructed the Starship Mk2 prototype in competition with Starbase's crews.[38] The Kennedy Space Center, also in Florida, is planned to host other Starship facilities, such as a Starship launch site at Launch Complex 39A and a production facility at Roberts Road. This production facility is being expanded from "Hangar X", the Falcon rocket boosters' storage and maintenance facility. It will include a 30,000 m^2 (320,000 sq ft) building, loading dock, and a place for constructing integration tower sections.[207] Adjacent to the Kennedy Space Center will be an additional launch site at Cape Canaveral Space Launch Complex 37, likely to service missions for the complex owner, the United States Space Force.

Ship 27, Ship 26 and Booster 10 forward section under construction in Starbase build site, March 2023

Launch sites

Starbase

Starbase is planned to host two launch sites, named Pad A and Pad B.[23]:34 A launch site at Starbase has large facilities, such as a tank farm, an orbital launch mount, and an integration tower.[23] Smaller facilities are present at the launch site: tanks surrounding the area containing methane, oxygen, nitrogen, helium, hydraulic fluid, etc.;[23]:161 subcoolers near the tank farm cool propellant using liquid nitrogen; and various pipes are installed at large facilities.[24] Each tank farm consists of eight tanks, enough to support one orbital launch.[24] The current launch mount on Pad A has a water-powered flame diverter, twenty clamps holding the booster, and a quick disconnect mount providing liquid fuel and electricity to the Super Heavy booster before it lifts off.[24]

The orbital launch mount under construction in Starbase, August 2021

The integration tower or launch tower consists of steel truss sections, a lightning rod on top,[208] and a pair of mechanical arms that can lift, catch and recover the booster.[24] The decision to catch the booster with the arms rather than landing with landing legs was made to enable flights and reduce the rocket's mass and part count.[33]:2 The mechanical arms are attached to a carriage and controlled by a pulley at the top of the tower.[24] The pulley is linked to a winch and spool at the base of the tower using a cable.[24] Using the winch and the carriage, the mechanical arms can move vertically, with support from bearings attached at the sides of the carriage.[24] A linear hydraulic actuator moves the arms horizontally. Tracks are mounted on top of arms, which are used to position the booster or spacecraft.[24] The tower is mounted with a quick disconnect arm extending to and contracting from the Starship spacecraft; its functions are similar to the quick disconnect mount that powers the booster.[24]

Florida

Since 2021,[209] the company is constructing a second Starship launch pad in Cape Canaveral, Florida, in Kennedy Space Center's Launch Complex 39A,[207] which is currently used to launch Crew Dragon capsules to the International Space Station.[209] SpaceX had plans to make a separate pad at 39A's north in 2022, named Launch Complex 49.[207][210] Because of Launch Complex 39A's Crew Dragon launches, the company is studying how to strengthen the pad against the possibility of a Starship explosion and proposed to retrofit Cape Canaveral Space Launch Complex 40 instead.[209] The towers and mechanical arms at the Florida launch sites should be similar to the one at Starbase, with improvements gained from the experience at Boca Chica.[207] In 2024, the FAA initiated a second environmental review in order to assess new launch infrastructure and a higher launch cadence of up to 44 annually at LC-39A.[211]

After the retirement of Delta IV Heavy, the Cape Canaveral Space Launch Complex 37 became vacant and the site of an Environmental Impact Statement by the United States Space Force for possible Starship launch operations.[210] As of April 2024, the assessment is in progress.[212]

Responses to Starship development

In order to compete with SpaceX and close their technological gap with the company, the China Aerospace Science and Tech Corp and other aerospace actors in China have reportedly been working on their own equivalent of Starship – the Long March 9 super-heavy lift rocket,[213] which is also designed to eventually be fully reusable.[214] In 2021, the China Academy of Launch Vehicle Technology (CALT) showed a rendered video of a rocket noted to be "strikingly" similar to Starship in appearance and function.[215] In a 2022 event organized by the International Astronautical Federation and the Chinese Society of Astronautics, the CALT communicated performing research on a crewed launch vehicle powered by LOX-methane propellant, with a second stage that was very similar to Starship's.[216]

SpaceNews noted that the Chinese start-up *Space Epoch* and engine maker Jiuzhou Yunjian were developing a smaller Starship-like rocket with a methane-LOX engine similar to Raptor, stainless steel tanks and an iterative design.[217] Starship's reusability and stainless-steel construction might also have inspired Project Jarvis, a reusable upper stage for Blue Origin's New Glenn super heavy-lift launch vehicle intended to replace New Glenn's expendable upper stage in the future.[218]

In 2021, members of Congress voiced concerns about the FAA's response to SpaceX's launch license violations following the explosion of SN8, calling on the FAA to "resist any potential undue influence on launch safety decision-making".[107] In 2023, prior to Starship's second orbital test flight, SpaceX's vice president and ex-NASA engineer Bill Gerstenmaier made statements at the U.S. Senate on the importance of innovation in light of "strategic competition from state actors like China".[219][220][221] He said SpaceX was under a contract with NASA to use Starship to land American astronauts on the moon before China does,[222][219] and that the Starship test flights campaign was being held up by "regulatory headwinds and unnecessary bureaucracy" unrelated to public safety.[220][223]

Following the second integrated flight test of Starship, the Government Accountability Office (GAO) made recommendations to the FAA to "improve its mishap investigation process", finding that historically they have allowed the launch operator to conduct their own investigation with the FAA supervising.[224]

Several environmental groups have filed lawsuits against the FAA and SpaceX, claiming that environmental reviews were bypassed due to Musk's political and financial influence.[225]

SpaceX and Musk have stated their goal of colonizing Mars to ensure the long-term survival of humanity,[39][226] with an ambition of having sent one million people to Mars by 2050.[227] In March 2022, he estimated that the first crewed Mars landing could occur in 2029.[228] This timeline has been criticized as unrealistic by Kevin Olsen, a physicist at the University of Oxford who has said that "colony needs to become a factory" to produce air, fuel and water as it is "fundamentally impossible to create a completely closed environment in space", and that the technology to do so is "far, far behind the technology of space flight and habitation construction".[229] Serkan Saydam, a mining engineering professor from the University of New South Wales stated that we currently lack the technology to establish a Martian colony, and will likely lack the capacity to establish a Martian city with one million people by 2050.[229]

In 2024, the NASA-ESA Mars Sample Return project, one of NASA's highest priority flagship projects, suffered a setback when an independent review board assigned to assess the feasibility of the project came to the conclusion that the project would not be able to completed under the then mission profile. In April 2024, the Administrator of NASA then announced that a new mission profile would be needed for the project and that NASA would turn to industry for proposals, with responses due in Fall 2024, and high emphasis on lower total cost and lower risk.[230] Starship has been widely seen as a leading candidate to serve as a central component of the new mission profile architecture.[231][232][233]

Notes

a. While the upper stage burned up during reentry, IFT-3 was a successful suborbital launch
b. Gross mass is the total of the propellant mass (1,200 tonnes) and approximate empty mass (100 tonnes).
c. Super Heavy dry mass: 200 t (440,000 lb); Starship dry mass: 100 t (220,000 lb); Super Heavy propellant mass: 3,400 t (7,500,000 lb);[3] Starship propellant mass: 1,200 t (2,600,000 lb).[10] The total of these masses is about 5,000 t (11,000,000 lb).
d. 78% of 3,400 t (7,500,000 lb)[3] is 2,650 t (5,840,000 lb) of liquid oxygen.
e. Synonymous with increasing the delta-*v* budget of the spacecraft

See also

- Comparison of orbital launch systems
- Comparison of orbital launcher families
- SpaceX reusable launch system development program

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