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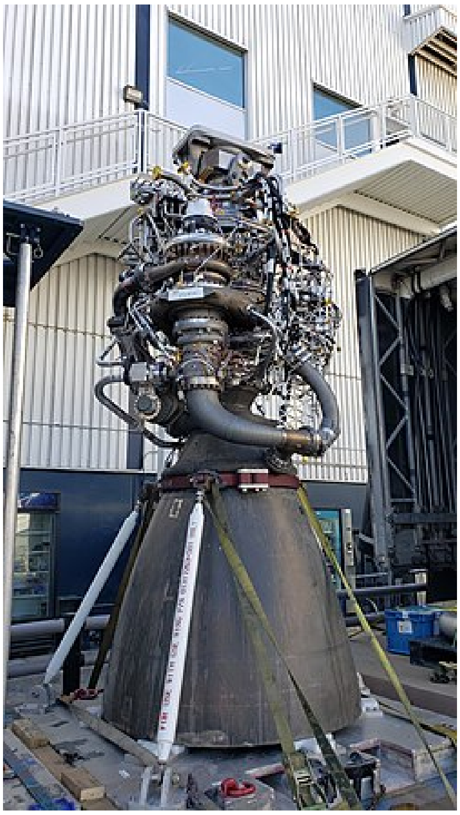
SpaceX Raptor

Raptor is a family of rocket engines developed and manufactured by SpaceX. It is the third rocket engine in history designed with a full-flow staged combustion (FFSC) fuel cycle, and the first such engine to power a vehicle in flight.[15] The engine is powered by cryogenic liquid methane and liquid oxygen, a combination known as methalox.

SpaceX's super-heavy-lift Starship uses Raptor engines in its Super Heavy booster and in the Starship second stage.[16] Starship missions include lifting payloads to Earth orbit and is also planned for missions to the Moon and Mars.[17] The engines are being designed for reuse with little maintenance.[18]

SpaceX Raptor



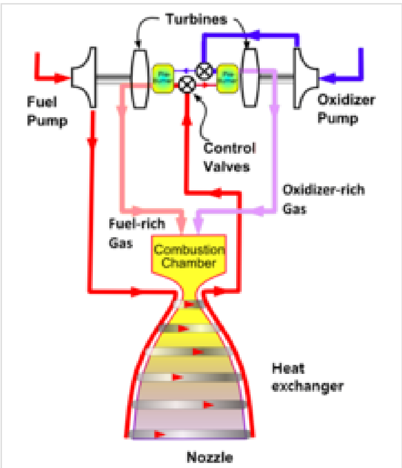
A Raptor 1 rocket engine ready for transport outside SpaceX's factory in Hawthorne, California

Country of origin	United States
Manufacturer	SpaceX
Associated LV	SpaceX Starship
Status	In production
Liquid-fuel engine	
Propellant	LOX / CH_4
Mixture ratio	3.6 (78% O_2, 22% CH_4)[1][2]
Cycle	Full-flow staged combustion
Pumps	2 turbopumps
Configuration	
Chamber	1
Nozzle ratio	34.34 (sea-level),[3] 80 (vacuum)[4]
Performance	

Design

Raptor is designed for extreme reliability, aiming to support the airline-level safety required by the point-to-point Earth transportation market.[19] Gwynne Shotwell claimed that Raptor would be able to deliver "long life... and more benign turbine environments".[20][21]

Full-flow staged combustion



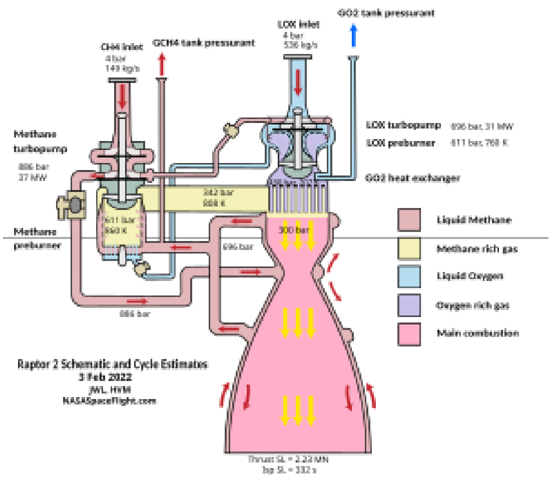
Simplified full-flow staged combustion rocket diagram

Raptor is powered by subcooled liquid methane and subcooled liquid oxygen in a full-flow staged combustion (FFSC) cycle. FFSC is a twin-shaft staged combustion cycle that uses both oxidizer-rich and fuel-rich preburners. The cycle allows for the full flow of both propellants through the turbines without dumping any unburnt propellant overboard.

FFSC is a departure from the more common "open-cycle" gas generator system and LOX/kerosene propellants used by its predecessor Merlin.[22] Before Raptor, no FFSC had ever been used in an actual flight and only two FFSC designs had progressed sufficiently to reach test stands: the Soviet RD-270 project in the 1960s and the Aerojet Rocketdyne Integrated Powerhead

Demonstrator in the mid-2000s.[15][23][21][24] RS-25 engines (first used on the Space Shuttle) used a simpler form of staged combustion cycle.[25] Several Russian rocket engines, including the RD-180[22] and the RD-191 did as well.[21]

FFSC has the advantage that the energy produced by the preburners, and used to power the propellant pumps, is spread among the entire fuel flow, meaning that the preburner exhaust driving the propellant turbopumps is as cool as possible, even cooler than other closed engine cycles that only preburn one propellant. This contributes to a long engine life. In contrast, an open-cycle engine in which the preburner exhaust bypasses the main combustion chamber tries to minimize the amount of propellant fed through the preburner, which is achieved by operating the turbine at its maximum survivable temperature.



Raptor 2 rocket engine cycle diagram with estimates from open-source information and analysis

An oxygen-rich turbine powers an oxygen turbopump, and a fuel-rich turbine powers a methane turbopump. Both oxidizer and fuel streams are converted completely to the gas phase before they enter the combustion chamber.[15] This speeds up mixing and combustion, reducing the size and mass of the required combustion chamber. Torch igniters are used in the preburners. Raptor 2's main combustion chamber uses an undisclosed ignition method that is allegedly less complex, lighter, cheaper, and more reliable than Merlin's. Engine ignition in Raptor Vacuum is handled by dual-redundant spark-plug lit torch igniters,[26] which eliminate the need for Merlin's dedicated, consumable igniter fluid.[21] Raptor 2 uses coaxial swirl injectors to admit propellants to the combustion chamber, rather than Merlin's pintle injectors.[27][28]

Thrust	**Raptor 1:** 185 t_f (1.81 MN; 408,000 lb_f)[5] **Raptor 2:** 230 t_f (2.26 MN; 507,000 lb_f)[6] (sea-level) 258 t_f (2.53 MN; 569,000 lb_f)[7] (vacuum) **Raptor 3:** 280 t_f (2.75 MN; 617,000 lb_f)
Throttle range	40–100%[10]
Thrust-to-weight ratio	**Raptor 1:** 88.94 **Raptor 2:** 141.1 **Raptor 3:** 183.6
Chamber pressure	350 bar (5,100 psi)
Specific impulse, vacuum	380 s (3.7 km/s)[8]
Specific impulse, sea-level	327 s (3.21 km/s)[9]
Mass flow	~650 kg/s (1,400 lb/s):[11] ~510 kg/s (1,100 lb/s), O_2[12] ~140 kg/s (310 lb/s), CH_4[12]
Burn time	Varies
Dimensions	
Length	3.1 m (10 ft)[13]
Diameter	1.3 m (4 ft 3 in)[14]
Dry mass	**Raptor 1:** 2,080 kg (4,590 lb) **Raptor 2:** 1,630 kg (3,590 lb) **Raptor 3:** 1,525 kg (3,362 lb)

Propellants

Raptor is designed for deep cryogenic propellants—fluids cooled to near their freezing points, rather than their boiling points, as is typical for cryogenic rocket engines.[29] Subcooled propellants are denser, increasing propellant mass per volume[30] as well as engine performance. Specific impulse is increased, and the risk of cavitation at inputs to the turbopumps is reduced due to the higher propellant fuel mass flow rate per unit of power generated.[21] Cavitation (bubbles) reduces fuel flow/pressure and can starve the engine, while eroding turbine blades.[31] The oxidizer to fuel ratio of the engine is approximately 3.8 to 1.[32] Methalox burns relatively cleanly, reducing carbon build-up in the engine.

Liquid methane and oxygen propellants have been adopted by many companies, such as Blue Origin with its BE-4 engine, as well as Chinese startup Space Epoch's Longyun-70.[33]

Manufacturing and materials

Many components of early Raptor prototypes were manufactured using 3D printing, including turbopumps and injectors, increasing the speed of development and testing.[29][34] The 2016 subscale development engine had 40% (by mass) of its parts manufactured by 3D printing.[21] In 2019, engine manifolds were cast from SpaceX's in-house developed SX300 Inconel superalloy, later changed to SX500.[35]

History

Conception

SpaceX's Merlin and Kestrel rocket engines use a RP-1 and liquid oxygen ("kerolox") combination. Raptor has about triple the thrust of SpaceX's Merlin 1D engine, which powers the Falcon 9 and Falcon Heavy launch vehicles.

SpaceX's Merlin engine (left) compared to a sea-level Raptor 1 engine (right)

Raptor was conceived to burn hydrogen and oxygen propellants as of 2009.[36] SpaceX had a few staff working on the Raptor upper-stage engine at a low priority in 2011.[37][38]

In October 2012, SpaceX announced concept work on an engine that would be "several times as powerful as the Merlin 1 series of engines, and won't use Merlin's RP-1 fuel".[39]

Development

In November 2012, Musk announced that SpaceX was working on methane-fueled rocket engines, that Raptor would be methane-based,[40] and that methane would fuel Mars colonization.[24] Because of the presence of underground water and carbon dioxide in Mars atmosphere, methane, a simple hydrocarbon, could be synthesized on Mars using the Sabatier reaction.[41] NASA found in-situ resource production on Mars to be viable for oxygen, water, and methane production.[42]

In early 2014 SpaceX confirmed that Raptor would be used for both first and second stages of its next rocket. This held as the design evolved from the Mars Colonial Transporter[24] to the Interplanetary Transport System,[43] the Big Falcon Rocket, and ultimately, Starship.[44]

The concept evolved from a family of Raptor-designated rocket engines (2012)[45] to focus on the full-size Raptor engine (2014).[46]

In January 2016, the US Air Force awarded a US$33.6 million development contract to SpaceX to develop a prototype Raptor for use on the upper stage of Falcon 9 and Falcon Heavy.[47][48]

The first version was intended to operate at a chamber pressure of 250 bars (25 MPa; 3,600 psi).[49] As of July 2022, chamber pressure had reached 300 bars in a test.[31] In April 2024, Musk shared the performance achieved by SpaceX with the Raptor 1 engine (sea level 185 t_f, Rvac 200 t_f) and Raptor 2 engine (sea level 230 t_f, Rvac 258 t_f) along with the target specifications for the upcoming Raptor 3 (sea level 280 t_f, Rvac 306 t_f)[50][51] and said SpaceX would aim to ultimately achieve over 330 tonnes of thrust on the sea-level booster engines.[52]

Raptor 1 and 2 engines require a heat shroud to protect pipes and wiring from the heat of high-velocity atmospheric re-entry,[31] while Raptor 3 is designed so that it does not require an external heat shield.[53]

Testing

Testing of the Raptor 's oxygen preburner at Stennis Space Center in 2015

Initial development testing[54] of Raptor components was done at NASA's Stennis Space Center,[17][55] beginning in April 2014. Testing focused on startup and shutdown procedures, as well as hardware characterization and verification.[21]

SpaceX began testing injectors in 2014 and tested an oxygen preburner in 2015. 76 hot-fire tests of the preburner, totaling some 400 seconds of test time, were executed from April-August.[54]

First test firing of a Raptor development engine on 25 September 2016 in McGregor, Texas

By early 2016, SpaceX had constructed an engine test stand at their McGregor test site in central Texas for Raptor testing.[21][17] The first Raptor was manufactured at the SpaceX Hawthorne facility in California. By August 2016 it was shipped to McGregor for development testing.[56] The engine had 1 MN (220,000 lb_f) thrust.[57] It was the first-ever FFSC methalox engine to reach a test stand.[21]

A subscale development engine was used for design validation. It was one-third the size of the engine designs that were envisioned for flight vehicles.[21] It featured 200 bars (20 MPa; 2,900 psi) of chamber pressure, with a thrust of 1 meganewton (220,000 lb_f) and used the SpaceX-designed SX500 alloy, created to contain hot oxygen gas in the engine at up to 12,000 pounds per square inch (830 bar; 83 MPa).[35] It was tested on a ground test stand in McGregor, firing briefly.[21] To eliminate flow separation problems while testing in Earth's atmosphere, the test nozzle expansion ratio was limited to 150.[21]

By September 2017, the subscale engine had completed 1200 seconds of firings across 42 tests.[58]

SpaceX completed many static fire tests on a vehicle using Raptor 2s, including a 31 engine test (intended to be 33) on 9 February 2023,[59] and a 33 engine test on 25 August 2023.[60] During testing, more than 50 chambers melted, and more than 20 engines exploded.[31]

SpaceX completed its first integrated flight test of Starship on 20 April 2023. The rocket had 33 Raptor 2 engines, but three of those were shut down before the rocket lifted off from the launch mount. The flight test was terminated after climbing to an altitude of ~39 km over the Gulf of Mexico. Multiple engines were out before the flight termination system (FTS) destroyed the booster and ship.[61]

On the second integrated flight test all 33 booster engines remained lit until boostback burn startup, and all six Starship engines remained lit until the FTS was activated.[62][63]

On the third integrated flight test, all 33 booster engines once again remained lit until main engine cutoff (MECO), and then following hot-staging, 13 successfully relit to perform a boostback for full duration.[64] On the booster's landing burn, only 3 engines of the planned 13 lit, with 2 shutting down rapidly, the other remained lit until the booster was destroyed ~462 metres above sea level.[64] The ship successfully kept all 6 engines lit until second stage / secondary engine cutoff (SECO) without issues, however a planned in-space raptor re-light was cancelled due to rolling during coast.[64]

Starship

Original configuration

Big Falcon Rocket with its Super Heavy booster firing (artist's concept)

In November 2016, Raptor was projected to power the proposed Interplanetary Transport System (ITS), in the early 2020s.[21] Musk discussed two engines: a sea-level variant (expansion ratio 40:1) with thrust of 3,050 kN (690,000 lbf) at sea level for the first stage/booster, and a vacuum variant (expansion ratio 200:1) with thrust of 3,285 kN (738,000 lbf) in space. 42 sea-level engines were envisioned in the high-level design of the first stage.[21]

Three gimbaled sea-level Raptor engines would be used for landing the second stage. Six additional, non-gimbaled, vacuum-optimized Raptors (Raptor Vacuum) would provide primary thrust for the second stage, for a total of nine engines.[65][21] Raptor Vacuums were envisioned to contribute a specific impulse of 382 s (3,750 m/s), using a much larger nozzle.[66]

In September 2017 Musk said that a smaller Raptor engine—with slightly over half as much thrust as the previous designs—would be used on the next-generation rocket, a 9 m (30 ft)-diameter launch vehicle termed Big Falcon Rocket (BFR) and later renamed Starship.[67] The redesign was aimed at Earth-orbit and cislunar missions so that the new system might pay for itself, in part, through economic spaceflight activities in the near-Earth space zone.[68] With the much smaller launch vehicle, fewer Raptor engines would be needed. BFR was then slated to have 31 Raptors on the first stage and 6 on the second stage.[69][21]

By mid-2018, SpaceX was publicly stating that the sea-level Raptor was expected to have 1,700 kN (380,000 lbf) thrust at sea level with a specific impulse of 330 s (3,200 m/s), with a nozzle exit diameter of 1.3 m (4.3 ft). Raptor Vacuum would have specific impulse of 356 s (3,490 m/s) in vacuum[58] and was expected to exert 1,900 kN (430,000 lbf) force with a specific impulse of 375 s (3,680 m/s), using a nozzle exit diameter of 2.4 m (7.9 ft).[58]

In the BFR update given in September 2018, Musk showed a video of a 71-second fire test of a Raptor engine, and stated that "this is Raptor that will power BFR, both the ship and the booster; it's the same engine. [...] approximately a 200 (metric) tons engine aiming for roughly 300 bar chamber pressure. [...] If you had it at a high expansion ratio, has the potential to have a specific impulse of 380."[9] SpaceX aimed at a lifetime of 1000 flights.[70]

Proposed Falcon 9 upper stage

In January 2016, the United States Air Force (USAF) awarded a US$33.6 million development contract to SpaceX to develop a Raptor prototype for use on the upper stage of the Falcon 9 and Falcon Heavy. The contract required double-matching funding by SpaceX of at least US$67.3 million.[47][71] Engine testing was planned for NASA's Stennis Space Center in Mississippi under US Air Force supervision.[47][48] The USAF contract called for a single prototype engine and ground tests.[47]

In October 2017 USAF awarded a US$40.8 million modification contract for a Raptor prototype for the Evolved Expendable Launch Vehicle program.[72] It was to use liquid methane and liquid oxygen propellants, a full-flow staged combustion cycle, and be reusable.[48]


Starship SN20 has its tiles inspected

Production

In July 2021, SpaceX announced a second Raptor production facility, in central Texas near the existing rocket engine test facility. The facility would concentrate on serial production of Raptor 2, while the California facility would produce Raptor Vacuum and new/experimental Raptor designs. The new facility was expected to eventually produce 800 to 1000 rocket engines each year.[73][74] In 2019 the (marginal) cost of the engine was stated to be approaching US$1 million. SpaceX planned to mass-produce up to 500 Raptor engines per year, each costing less than US$250,000.[75]

Versions

Raptor has evolved significantly since it was revealed.

SpaceX rocket engines[76][77]

Version	Mass (kg)	Thrust (t)	Chamber Pressure (bar)	Specific Impulse (s)	Engine only TWR
Raptor 1	2080	185	250	350	89
Raptor 2	1630	230	300	347	141
Raptor 3	1525	280	350	350	184

Raptor Vacuum

Each version of the engine has a corresponding Raptor Vacuum (RVac) variant[78] with an extended, regeneratively-cooled nozzle for higher specific impulse in space. The vacuum-optimized Raptor targets a specific impulse of ≈380 s (3,700 m/s).[8] A full-duration test of version 1 of Raptor Vacuum was completed in September 2020 at McGregor.[78] The first in-flight ignition of a Raptor Vacuum was on S25 during the second integrated flight test.[63]

Raptor 2

Raptor 2 is a complete redesign of the Raptor 1 engine.[79] The turbomachinery, chamber, nozzle, and electronics were all redesigned. Many flanges were converted to welds, while other parts were deleted.[80] Simplifications continued after production began. On 10 February 2022, Musk showed Raptor 2 capabilities and design improvements.[80][81]

By 18 December 2021, Raptor 2 had started production.[82] By November 2022, SpaceX produced more than one Raptor a day and had created a stockpile for future launches.[83] Raptor 2s are produced at SpaceX's McGregor engine development facility.

Raptor 2s were achieving 230 t_f (510,000 lbf) of thrust consistently by February 2022. Musk indicated that production costs were approximately half that of Raptor 1.[80]

A NASA employee standing between two Raptor 2 Vacuum engines (background) and a Raptor 2 sea-level (foreground). The streamlined design is due to the reduced parts visible above the engine nozzles.

Raptor 3

Raptor 3 is aimed to ultimately achieve 300 t_f (2.9 MN) of thrust in the booster/sea-level configuration.[51][84] As of August 2024, it had reached 280 t_f. It weighs 1525 kg. Chamber pressure reached 350 bar.[85]

Another goal is to eliminate protective engine shrouds.[52] Raptor 3 moves much of the plumbing and sensors into the housing wall,[50] where integral cooling and integral secondary flow circuits run through various sections of the engine, obviating the need for a separate heat shield. On 2 August 2024, Raptor 3 SN1 was revealed.[86] The reduction in externally visible components was so extreme that the CEO of United Launch Alliance, Tory Bruno, falsely accused SpaceX of revealing a "partially assembled" engine while comparing it to fully assembled engines.[87][88]

Many bolted joints in Raptor 2 have been eliminated/replaced by single parts. However, servicing is more difficult, as some parts lie beneath welded joints.[89]:42:19–45:50

LEET

In October 2021, SpaceX initiated an effort to develop a conceptual design for a new rocket engine with the goal of keeping cost below US$1,000 per ton of thrust. The project was called the 1337 engine, to be pronounced "LEET" (after a coding meme).[83]

Although the initial design effort was halted in late 2021, the project helped define an ideal engine, and likely generated ideas that were incorporated into Raptor 3. Musk stated then that "We can't make life multiplanetary with Raptor, as it is way too expensive, but Raptor is needed to tide us over until 1337 is ready."[83]

In June 2024, the LEET concept was clarified as a total tearup of the Raptor 3 design, although Musk stated that SpaceX will "probably do that at some point. ... [Raptor 3] looks like a LEET engine, but its way more expensive because it still has printed parts, for example."[89]

Comparison to other engines

Engine	Rockets	Thrust	Specific impulse, vacuum	Thrust-to-weight ratio	Propellant	Cycle
Raptor 3 sea-level	Super Heavy, Starship	2,750 kN (620,000 lbf)[77]	350 s (3,400 m/s)[77]	200	LCH_4 / LOX (subcooled)	Full-flow staged combustion
Raptor 3 vacuum	Starship	2,980 kN (670,000 lbf)[77]	380 s (3,700 m/s)[8]	120 (at maximum)		
Merlin 1D sea-level	Falcon booster stage	914 kN (205,000 lbf)	311 s (3,050 m/s)[90]	176[91]	RP-1 / LOX (subcooled)	Gas generator
Merlin 1D vacuum	Falcon upper stage	934 kN (210,000 lbf)[92]	348 s (3,410 m/s)[92]	180[91]		
Blue Origin BE-4	New Glenn, Vulcan	2,400 kN (550,000 lbf)[93]	339 s (3,320 m/s)[94]		LCH_4 / LOX	Oxidizer-rich staged combustion
Energomash RD-170/171M	Energia, Zenit, Soyuz-5	7,904 kN (1,777,000 lbf)[95]	337.2 s (3,307 m/s)[95]	79.57[95]	RP-1 / LOX	
Energomash RD-180	Atlas III, Atlas V	4,152 kN (933,000 lbf)[96]	338 s (3,310 m/s)[96]	78.44[96]		
Energomash RD-191/181	Angara, Antares	2,090 kN (470,000 lbf)[97]	337.5 s (3,310 m/s)[97]	89[97]		
Kuznetsov NK-33	N1, Soyuz-2-1v	1,638 kN (368,000 lbf)[98]	331 s (3,250 m/s)[98]	136.66[98]		
Energomash RD-275M	Proton-M	1,832 kN (412,000 lbf)	315.8 s (3,097 m/s)	174.5	N_2O_4 / UDMH	
Rocketdyne RS-25	Space Shuttle, SLS	2,280 kN (510,000 lbf)	453 s (4,440 m/s)[99]	73[100]	LH_2 / LOX	Fuel-rich staged combustion
Aerojet Rocketdyne RS-68A	Delta IV	3,560 kN (800,000 lbf)	414 s (4,060 m/s)	51[101]	LH_2 / LOX	Gas generator
Rocketdyne F-1	Saturn V	7,740 kN (1,740,000 lbf)	304 s (2,980 m/s)[102]	83	RP-1 / LOX	Gas generator

See also

- Comparison of orbital rocket engines
- SpaceX Mars program
- SpaceX rocket engines
- SpaceX Starship (spacecraft)
- SpaceX Super Heavy
- Starship HLS

- SpaceX Starbase

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- unofficial Raptor engine log infographic (https://www.twitter.com/artzius/status/1371479013798084609)