Falcon 9

Falcon 9 is a partially reusable medium-lift launch vehicle that can carry cargo and crew into Earth orbit, designed, manufactured and launched by American aerospace company SpaceX. It can also be used as an expendable heavy-lift launch vehicle. The first Falcon 9 launch was in June 2010. The first Falcon 9 ISS commercial resupply mission to the ISS launched on 8 October 2012.[15] In 2020 it became the first commercial rocket to ever launch humans to orbit and is currently the only such vehicle capable of doing so.[16] It is the only U.S. rocket currently certified for transporting humans to the International Space Station.[17][18][19] In 2022, it became the U.S. rocket with the most launches in history and with the best safety record, having suffered just one flight failure.[20]

The rocket has two stages. The first (booster) stage carries the second stage and payload to a pre-determined altitude, after which the second stage lifts the payload to its ultimate destination. The booster is capable of landing vertically to facilitate reuse. This feat was first achieved on flight 20 in December 2015. As of 27 August 2023, SpaceX has successfully landed boosters 222 times.[A] Individual boosters have flown as many as 16 flights.[21] Both stages are powered by SpaceX Merlin engines, using cryogenic liquid oxygen and rocket-grade kerosene (RP-1) as propellants.[22][23]

The heaviest payloads flown to geostationary transfer orbit (GTO) were Intelsat 35e carrying 6,761 kg (14,905 lb), and Telstar 19V with 7,075 kg (15,598 lb). The former was launched into an advantageous super-synchronous transfer orbit,[24] while the latter went into a lower-energy GTO, with an apogee well below the geostationary altitude.[25] On 24 January 2021, Falcon 9 set a record for the most satellites launched by a single rocket, carrying 143 into orbit.[26]

Falcon 9 is human-rated for transporting NASA astronauts to the ISS. Falcon 9 is certified for the National Security Space Launch[27] program and NASA Launch Services Program as "Category 3", which can launch the most expensive, important, and complex NASA missions.[28]

The rocket evolved through several versions. V1.0 flew from 2010–2013, V1.1 flew from 2013–2016, while V1.2 Full Thrust first launched in 2015, encompassing the Block 5 variant, is in operation since May 2018.

Falcon 9

A Falcon 9 lifting off from LC-39A, carrying Demo-2

Function	Orbital launch vehicle
Manufacturer	SpaceX
Country of origin	United States
Cost per launch	US$67 million (2022)[1]
Size	
Height	**FT**: 70 m (230 ft)[2] **v1.1**: 68.4 m (224 ft)[3] **v1.0**: 54.9 m (180 ft)[4]
Diameter	3.7 m (12 ft)[2]
Mass	**FT**: 549 t (1,210,000 lb)[2] **v1.1**: 506 t (1,116,000 lb)[3] **v1.0**: 333 t (734,000 lb)[4]
Stages	2
Capacity	
Payload to Low Earth orbit (LEO)	
Orbital inclination	28.5°
Mass	**FT**: 22.8 t (50,000 lb)[1] Expended

Development history

Falcon 9 rocket family; from left to right: Falcon 9 v1.0, v1.1, Full Thrust, Block 5, and Falcon Heavy

Conception and funding

In October 2005, SpaceX announced plans to launch Falcon 9 in the first half of 2007.[29] The initial launch would not occur until 2010.[30]

While SpaceX spent its own capital to develop its previous launcher, the Falcon 1, development of the Falcon 9 was accelerated by partial NASA funding and commitments to purchase flights once specific capabilities were demonstrated. Funding started with seed money from the Commercial Orbital Transportation Services (COTS) program in 2006.[31][32] The contract was structured as a Space Act Agreement (SAA) "to develop and demonstrate commercial orbital transportation service",[32] including the purchase of three demonstration flights.[33] The overall contract award was US$278 million to provide three demonstration launches of Falcon 9 with the SpaceX Dragon cargo spacecraft. Additional milestones were added later, raising the total contract value to US$396 million.[34][35]

In 2008, SpaceX won a Commercial Resupply Services (CRS) contract in NASA's Commercial Orbital Transportation Services (COTS) program to deliver cargo to ISS using Falcon 9/Dragon.[35][36] Funds would be disbursed only after the demonstration missions were successfully and thoroughly completed. The contract totaled US$1.6 billion for a minimum of 12 missions to ferry supplies to and from ISS.[37]

In 2011, SpaceX estimated that Falcon 9 v1.0 development costs were on the order of US$300 million.[38] NASA estimated development costs of US$3.6 billion had a traditional cost-plus contract approach been used.[39] A 2011 NASA report "estimated that it would have cost the agency about US$4 billion to develop a rocket like the Falcon 9 booster based upon NASA's traditional contracting processes" while "a more commercial development" approach might have allowed the agency to pay only US$1.7 billion".[40]

In 2014, SpaceX released combined development costs for Falcon 9 and Dragon. NASA provided US$396 million, while SpaceX provided over US$450 million.[41]

Congressional testimony by SpaceX in 2017 suggested that the unusual NASA process of "setting only a high-level requirement for cargo transport to the space station [while] leaving the details to industry" had allowed SpaceX to complete the task at a substantially lower cost. "According to NASA's own independently verified numbers, SpaceX's development costs of both the Falcon 1 and Falcon 9 rockets were estimated at approximately $390 million in total."[40]

Development

SpaceX originally intended to follow its Falcon 1 launch vehicle with an intermediate capacity vehicle, Falcon 5.[42] The Falcon line of vehicles are named after the fictional starship the "Millennium Falcon" from the *Star Wars* film series.[43] In 2005, SpaceX announced that it was instead proceeding with Falcon 9, a "fully reusable heavy-lift launch vehicle", and had already secured a government customer. Falcon 9 was described as capable of launching approximately 9,500 kilograms (20,900 lb) to low Earth orbit and was projected to be priced at $27,000,000 USD per flight with a 3.7 m (12 ft) payload fairing and US$35 million with a 5.2 m (17 ft) fairing. SpaceX also announced a heavy version of Falcon 9 with a payload capacity of approximately 25,000 kilograms (55,000 lb).[44] Falcon 9 was intended to support LEO and GTO missions, as well as crew and cargo missions to ISS.[42]

Testing

The original NASA COTS contract called for the first demonstration flight in September 2008, and the completion of all three demonstration missions by September 2009.[45] In February 2008, the date slipped into the first quarter of 2009. According to Musk, complexity and Cape Canaveral regulatory requirements contributed to the delay.[46]

The first multi-engine test (two engines firing simultaneously, connected to the first stage) was completed in January 2008.[47] Successive tests led to a 178 second (mission length), nine engine test-fire in November 2008.[48] In October 2009, the first flight-ready all-engine test fire was at its test facility in McGregor, Texas. In November, SpaceX conducted the initial second stage test firing, lasting forty seconds. In January 2010, a 329 second (mission length) orbit-insertion firing of the second stage was conducted at McGregor.[49]

The elements of the stack arrived at the launch site for integration at the beginning of February, 2010.[50] The flight stack went vertical at Space Launch Complex 40, Cape Canaveral,[51] and in March, SpaceX performed a static fire test, where the first stage was fired without launch. The test was aborted at T−2 due to a failure in the high-pressure helium pump. All systems up to the abort performed as expected, and no additional issues needed addressing. A subsequent test on 13 March fired the first-stage engines for 3.5 seconds.[52]

Production

In December 2010, the SpaceX production line manufactured a Falcon 9 (and Dragon spacecraft) every three months.[53] By September 2013, SpaceX's total manufacturing space had increased to nearly 93,000 m^2 (1,000,000 sq ft), in order to achieve a production rate of 40 rocket cores annually.[54] The factory was producing one Falcon 9 per month as of November 2013.[55]

By February 2016 the production rate for Falcon 9 cores had increased to 18 per year, and the number of first stage cores that could be assembled at one time reached six.[56]

Since 2018, SpaceX has routinely reused first stages, reducing the demand for new cores. In 2021, SpaceX performed 31 F9 launches, using only two new boosters. It successfully recovered the booster on all but one flight. The Hawthorne factory produces one (expendable) second stage for each launch.

Launch history

	17.4 t (38,000 lb)[5] when landing on ASDS **v1.1**: 13.1 t (29,000 lb)[3] **v1.0**: 10.4 t (23,000 lb)[4]
Payload to Geosynchronous transfer orbit (GTO)	
Orbital inclination	27.0°
Mass	**FT**: 8.3 t (18,000 lb) Expended 5.5 t (12,000 lb) when landing on ASDS[1] 3.5 t (7,700 lb) when RTLS[6] **v1.1**: 4.8 t (11,000 lb)[3] **v1.0**: 4.5 t (9,900 lb)[4]
Payload to Mars transfer orbit	
Mass	**FT**: 4 t (8,800 lb)[1]
Associated rockets	
Derivative work	Falcon Heavy
Launch history	
Status	**FT Block 5**: Active[7] **FT Block 4**: Retired **FT Block 3**: Retired **v1.1**: Retired **v1.0**: Retired
Launch sites	Cape Canaveral, SLC-40 Kennedy Space Center, LC-39A Vandenberg, SLC-4E Vandenberg, SLC-6 (future)
Total launches	250 (**FT**: 230 · **v1.1**: 15 · **v1.0**: 5)
Success(es)	248 (**FT**: 230 · **v1.1**: 14 · **v1.0**: 4)
Failure(s)	1 (**v1.1**: CRS-7 in-flight)
Partial failure(s)	1 (**v1.0**: CRS-1)[8]
Notable outcome(s)	1 (**FT**: AMOS-6 pre-flight destruction)
Landings	209 / 218 attempts

Rockets from the Falcon 9 family have been launched 257 times over 13 years, resulting in 255 full mission successes (99.2%), one partial success (SpaceX CRS-1 delivered its cargo to the International Space Station (ISS), but a secondary payload was stranded in a lower-than-planned orbit), and one full failure (the SpaceX CRS-7 spacecraft was lost in flight in an explosion). Additionally, one rocket and its payload AMOS-6 were destroyed before launch in preparation for an on-pad static fire test. The active version, Falcon 9 Block 5, has flown 194 missions, all full successes.

In 2022 Falcon 9 set a new record of 60 launches (all successful) by the same launch vehicle type in a calendar year. The previous record was held by Soyuz-U, which had 47 launches (45 successful) in 1979.[57]

The first rocket version Falcon 9 v1.0 was launched five times from June 2010 to March 2013, its successor Falcon 9 v1.1 15 times from September 2013 to January 2016, and the Falcon 9 Full Thrust 230 times from December 2015 to present. The latest Full Thrust variant, Block 5, was introduced in May 2018.[58] While the Block 4 boosters were only flown twice and required several months of refurbishment, Block 5 versions are designed to sustain 10 flights with just some inspections.[59]

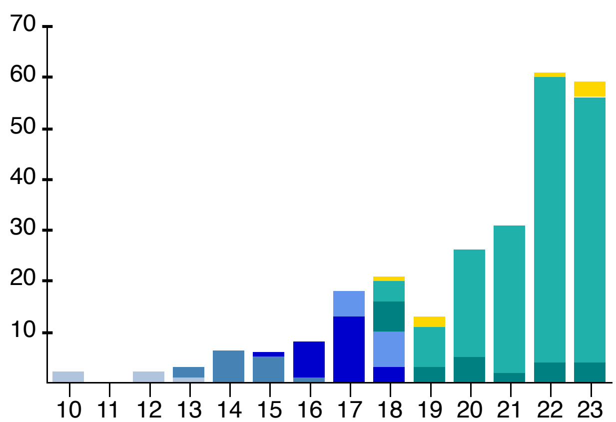
The Falcon Heavy derivative consists of a strengthened Falcon 9 first stage as its center core, with two additional Falcon 9 first stages attached and used as boosters, both of which are fitted with an aerodynamic nosecone instead of a usual Falcon 9 interstage.[60]

First flight	**FT Block 5**: 11 May 2018 (Bangabandhu Satellite-1) **FT**: 22 December 2015 (OG2 Flight 2)[9] **v1.1**: 29 September 2013 CASSIOPE[10] **v1.0**: 4 June 2010 (Dragon COTS Demo 1)[11]
Last flight	**FT Block 4**: 29 June 2018 (SpaceX CRS-15) **v1.1**: 17 January 2016 (Jason-3) **v1.0**: 1 March 2013 (SpaceX CRS-2)
First stage	
Powered by	**FT Block 5**: 9 Merlin 1D+ (maximum thrust) **FT**: 9 Merlin 1D+ **v1.1**: 9 Merlin 1D **v1.0**: 9 Merlin 1C
Maximum thrust	**FT (late 2016)**: 7.6 MN (770 t_f; 1,700,000 lbf)[12] **FT**: 6.8 MN (690 t_f; 1,500,000 lbf)[2] **v1.1**: 5.9 MN (600 t_f; 1,300,000 lbf)[3] **v1.0**: 4.9 MN (500 t_f; 1,100,000 lbf)[4]
Specific impulse	**v1.1** **Sea level**: 282 s (2.77 km/s)[13] **Vacuum**: 311 s (3.05 km/s)[13] **v1.0** **Sea level**: 275 s (2.70 km/s)[4] **Vacuum**: 304 s (2.98 km/s)[4]
Burn time	**FT**: 162 seconds[2] **v1.1**: 180 seconds[3] **v1.0**: 170 seconds
Propellant	LOX / RP-1
Second stage	

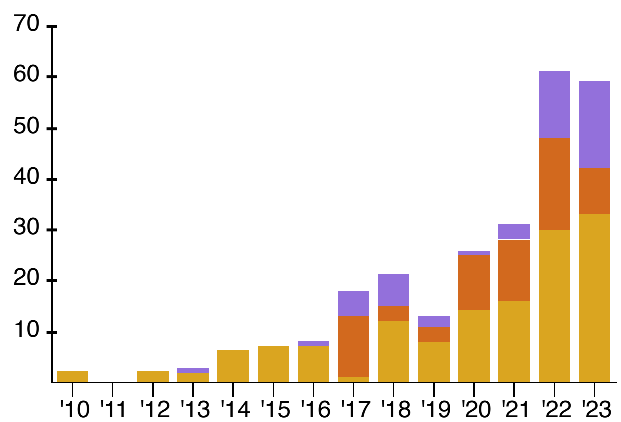
Falcon 9 first-stage boosters landed successfully in 222 of 233 attempts (95.3%), with 192 out of 197 (97.5%) for the Falcon 9 Block 5 version. A total of 197 re-flights of first stage boosters have all successfully launched their payloads.

Powered by	**FT regular**: 1 Merlin 1D Vacuum+ regular nozzle **FT short**: 1 Merlin 1D Vacuum+ short nozzle **v1.1**: 1 Merlin 1D Vacuum **v1.0**: 1 Merlin 1C Vacuum
Maximum thrust	**FT regular**: 934 kN (95.2 t_f; 210,000 lbf)[2] **FT short**: 840.6 kN (85.72 t_f; 189,000 lbf) **v1.1**: 801 kN (81.7 t_f; 180,000 lbf)[3] **v1.0**: 617 kN (62.9 t_f; 139,000 lbf)[4]
Specific impulse	**FT regular**: 348 s (3.41 km/s)[2] **FT short**: 348 s (3.41 km/s)[2] **v1.1**: 340 s (3.3 km/s)[3] **v1.0**: 342 s (3.35 km/s)[14]
Burn time	**FT regular**: 397 seconds[2] **FT short**: 397 seconds[2] **v1.1**: 375 seconds[3] **v1.0**: 345 seconds[4]
Propellant	LOX / RP-1

Rocket configurations

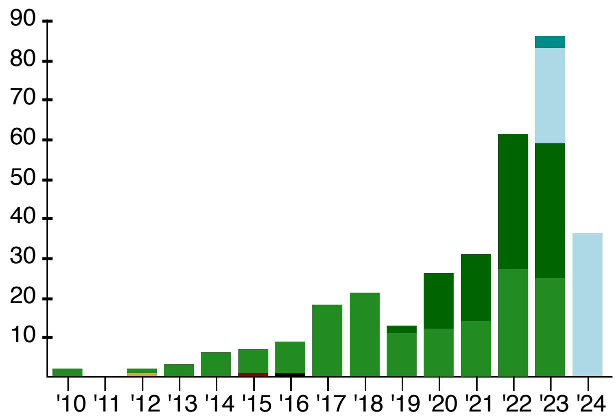


Launch sites

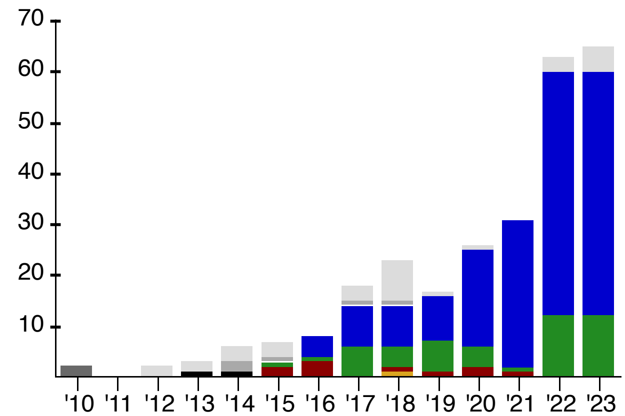


Falcon 9 v1.0
Falcon 9 v1.1
Falcon 9 Full Thrust
Falcon 9 FT (reused)
Falcon 9 Block 5 (new)
Falcon 9 Block 5 (reused)
Falcon Heavy
CCSFS, SLC-40
KSC, LC-39A
VSFB, SLC-4E

Launch outcomes



Booster landings

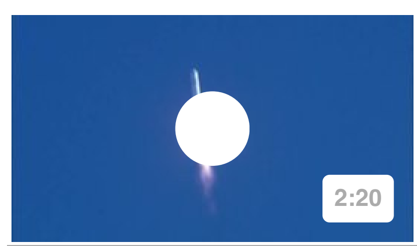


Loss before launch
Loss during flight
Partial failure
Success (commercial and government)
Success (Starlink)
Planned (commercial and government)
Planned (Starlink)

Ground-pad failure
Drone-ship failure
Ocean test failure[i]
Parachute test failure[ii]
Ground-pad success
Drone-ship success
Ocean test success[iii]
No attempt

i. Controlled descent; ocean touchdown control failed; no recovery
ii. Passive reentry failed before parachute deployment
iii. Controlled descent; soft vertical ocean touchdown; no recovery

Notable flights



SpaceX Falcon 9 launch with COTS Demo Flight 1

- Flight 1, Dragon Spacecraft Qualification Unit — June 2010, first flight of Falcon 9 and first test of Dragon,
- Flight 3, Dragon C2+ — first cargo delivery to the International Space Station,
- Flight 4, CRS-1 — first operational cargo mission to the ISS, and the first demonstration of the rocket's engine-out capability due to the failure of a first-stage Merlin engine,
- Flight 6, CASSIOPE — first v1.1 rocket, first launch from Vandenberg AFB, first attempt at propulsive return of the first stage,
- Flight 7, SES-8 — first launch to Geosynchronous transfer orbit (GTO), first non-governmental payload,
- Flight 9, CRS-3 — added landing legs, first fully controlled descent and vertical ocean touchdown,
- Flight 15, Deep Space Climate Observatory (DSCOVR) — first hyperbolic mission, injecting spacecraft into L1 point,
- Flight 19, CRS-7 — total loss of mission due to structural failure and helium overpressure in the second stage,
- Flight 20, Orbcomm OG-2 — first vertical landing of an orbital-class rocket,
- Flight 23, CRS-8 — first landing vertically achieved on an autonomous spaceport drone ship at sea,
- AMOS-6 — total vehicle and payload loss prior to static fire test (would have been Flight 29),
- Flight 30, CRS-10 — first launch from LC-39A at the Kennedy Space Center,
- Flight 32, SES-10 — first reflight of a previously flown orbital class booster (B1021, previously used for SpaceX CRS-8), first recovery of a fairing,[61][62]
- Flight 41, X-37B OTV-5 — first launch of a spaceplane,
- Flight 54 Bangabandhu-1 — the first flight of the Block 5 version,

- Flight 58 Telstar 19V — heaviest communications satellite ever delivered to GEO,[63]
- Flight 69 Crew Dragon Demo-1 — first launch of the Crew Dragon (did not carry astronauts),
- Flight 72, RADARSAT Constellation — the most valuable commercial payload put into orbit,[64][65][66]
- Flight 81 — a Starlink launch, was a successful flight, but had the first recovery failure of a previously flown and recovered booster,
- Flight 83 — a successful Starlink launch, saw the first failure of a Merlin 1D first-stage engine during ascent, and the second ascent engine failure on the rocket following CRS-1 on flight 4,
- Flight 85, Crew Dragon Demo-2 — the first crewed launch of the Crew Dragon, carrying two astronauts,
- Flight 98, Crew-1 — the first crewed operational launch of the Crew Dragon, holding the record for the longest spaceflight by a U.S. crew vehicle,
- Flight 101, CRS-21 — the first launch of the Cargo Dragon 2, an uncrewed variant of the Crew Dragon,
- Flight 106, Transporter-1 — the first dedicated smallsat rideshare launch, set the record of the most satellites launched on a single launch with 143 satellites, surpassing the previous record of 108 satellites held by the November 17, 2018 launch of an Antares,
- Flight 108 — a routine Starlink launch which experienced early shut-down of a first-stage Merlin 1D engine during ascent due to damage, but still delivered the payload to the target orbit,
- Flight 126, Inspiration4 — the first orbital spaceflight of an all-private crew,
- Flight 129, DART — first planetary defenses mission against near-Earth objects,
- Flight 134, CRS-24 — the 100th successful vertical landing of an orbital-class rocket, on the sixth anniversary of the first landing in 2015,
- Flight 199 — heaviest confirmed Block 5 payload of 17,400 kg, 56 Starlink satellites.[67]
- Flight 228 — The 200th consecutive successful Falcon 9 mission.
- Flight 232 — The 200th overall successful booster landing.

Falcon 9 flight 20 historic first-stage landing at Cape Canaveral, Landing Zone 1, on 21 December 2015

Design

F9 is a two-stage, LOX/RP-1-powered launch vehicle.

Specifications

First stage

Height	41.2 m / 135.2 ft
Height (with interstage)	47.7 m / 156.5 ft
Diameter	3.7 m / 12 ft
Empty Mass	25,600 kg / 56,423 lb
Propellant Mass	395,700 kg/ 872,369 lb
Structure Type	LOX tank: monocoque
	Fuel tank: skin and stringer
Structure Material	Aluminum lithium skin; aluminum domes
Landing Legs	Number: 4
	Material: carbon fiber; aluminum honeycomb
Number Of Merlin Engines	9 sea level
Propellant	LOX / RP-1
Thrust At Sea Level	7,607 kN / 1,710,000 lbf
Thrust In Vacuum	8,227 kN / 1,849,500 lbf
Specific Impulse (sea-level)	283 sec.
Specific Impulse (vacuum Sec)	312 sec.
Burn Time	162 sec.
Ascent Attitude Control - Pitch, Yaw	Gimbaled engines
Ascent Attitude Control - Roll	Gimbaled engines
Coast/Descent Attitude Control	Nitrogen gas thrusters and grid fins

Second stage

Height	13.8 m / 45.3 ft
Diameter	3.7 m / 12.1 ft
Empty Mass	3,900 kg / 8,598 lb
Propellant Mass	92,670 kg / 204,302 lb
Structure Type	LOX tank: monocoque
	Fuel tank: skin and stringer
Structure Material	Aluminum lithium skin; aluminum domes
Number Of Merlin Engines	1 vacuum
Propellant	LOX / RP-1
Thrust	981 kN / 220,500 lbf
Specific Impulse (vacuum)	348 sec
Burn Time	397 sec
Ascent Attitude Control - Pitch, Yaw	Gimbaled engine and nitrogen gas thrusters
Ascent Attitude Control - Roll	Nitrogen gas thrusters
Coast/Descent Attitude Control	Nitrogen gas thrusters

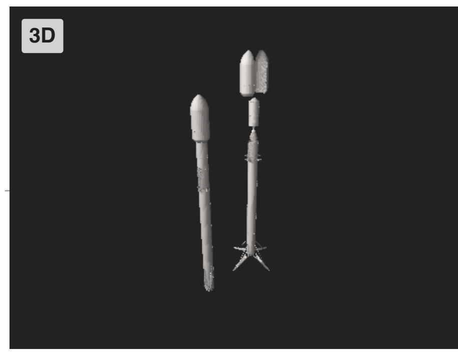
Engine

Both stages are equipped with Merlin 1D rocket engines. Every Merlin engine produces 854 kN (192,000 lb_f) of thrust.[68] They use a pyrophoric mixture of triethylaluminum-triethylborane (TEA-TEB) as an engine igniter.[69]

The booster stage has 9 engines, arranged in a conifguration that SpaceX calls Octaweb.[70] The second stage of the Falcon 9 has 1 short or regular nozzle, Merlin 1D Vacuum engine version.

Falcon 9 is capable of losing up to 2 engines and still complete the mission by burning the remaining engines longer.

Each Merlin rocket engine is controlled by three voting computers, each having 2 CPUs which constantly check the other 2 in the trio. The Merlin 1D engines can vector thrust to adjust trajectory.



Interactive 3D model of the Falcon 9, fully integrated on the left and in exploded view on the right

Tanks

The propellant tank walls and domes are made from aluminium–lithium alloy. SpaceX uses an all friction-stir welded tank, for its strength and reliability.[4] The second stage tank is a shorter version of the first stage tank. It uses most of the same tooling, material, and manufacturing techniques.[4]

The F9 interstage, which connects the upper and lower stages, is a carbon-fibre aluminium-core composite structure that holds reusable separation collets and a pneumatic pusher system. The original stage separation system had twelve attachment points, reduced to three for v1.1.[71]

Fairing

Falcon 9 uses a payload fairing (nose cone) to protect (non-Dragon) satellites during launch. The fairing is 13 m (43 ft) long, 5.2 m (17 ft) in diameter, weighs approximately 1900 kg, and is constructed of carbon fiber skin overlaid on an aluminum honeycomb core.[72] SpaceX designed and fabricates fairings in Hawthorne. Testing was completed at NASA's Plum Brook Station facility in spring 2013 where the acoustic shock and mechanical vibration of launch, plus electromagnetic static discharge conditions, were simulated on a full-size test article in a vacuum chamber.[73] Since 2019, fairings are designed to re-enter the Earth's atmosphere and are reused for future missions.

Control systems

SpaceX uses multiple redundant flight computers in a fault-tolerant design. The software runs on Linux and is written in C++.[74] For flexibility, commercial off-the-shelf parts and system-wide *radiation-tolerant* design are used instead of rad-hardened parts.[74] Each stage has stage-level flight computers, in addition to the Merlin-specific engine controllers, of the same fault-tolerant triad design to handle stage control functions. Each engine microcontroller CPU runs on a PowerPC architecture.[75]

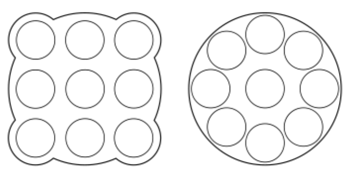
Legs/fins

Boosters that will be deliberately expended do not have legs or fins. Recoverable boosters include four extensible landing legs attached around the base.[76] To control the core's descent through the atmosphere, SpaceX uses grid fins that deploy from the vehicle[77] moments after stage separation.[78]

Versions

V1.0 flew five successful orbital launches from 2010–2013. The much larger V1.1 made its first flight in September 2013. The demonstration mission carried a small 500 kg (1,100 lb) primary payload, the CASSIOPE satellite.[71] Larger payloads followed, starting with the launch of the SES-8 GEO communications satellite.[79] Both v1.0 and v1.1 used expendable launch vehicles (ELVs). The Falcon 9 Full Thrust made its first flight in December 2015. The first stage of the Full Thrust version was reusable. The current version, known as Falcon 9 Block 5, made its first flight in May 2018.

V1.0



Falcon 9 v1.0 (left) and v1.1 (right) engine configurations

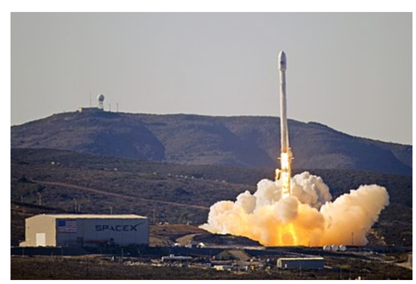
F9 v1.0 was an expendable launch vehicle developed from 2005–2010. It flew for the first time in 2010. V1.0 made five flights, after which it was retired. The first stage was powered by nine Merlin 1C engines arranged in a 3 × 3 grid. Each had a sea-level thrust of 556 kN (125,000 lb_f) for a total liftoff thrust of about 5,000 kN (1,100,000 lb_f).[4] The second stage was powered by a single Merlin 1C engine modified for vacuum operation, with an expansion ratio of 117:1 and a nominal burn time of 345 seconds. Gaseous N_2 thrusters were used on the second-stage as a reaction control system (RCS).[80]

A Falcon 9 v1.0 being launched with a Dragon spacecraft to deliver cargo to the ISS in 2012

Early attempts to add a lightweight thermal protection system to the booster stage and parachute recovery were not successful.[81]

In 2011, SpaceX began a formal development program for a reusable Falcon 9, initially focusing on the first stage.[78]

V1.1



The launch of the first Falcon 9 v1.1 from SLC-4, Vandenberg AFB (Falcon 9 Flight 6) in September 2013

V1.1 is 60% heavier with 60% more thrust than v1.0.[71] Its nine (more powerful) Merlin 1D engines were rearranged into an "octagonal" pattern[82][83] that SpaceX called *Octaweb*. This is designed to simplify and streamline manufacturing.[84][85] The fuel tanks were 60% longer, making the rocket more susceptible to bending during flight.[71]

The v1.1 first stage offered a total sea-level thrust at liftoff of 5,885 kilonewtons (1,323,000 lb_f), with the engines burning for a nominal 180 seconds, while stage thrust rises to 6,672 kN (1,500,000 lb_f) as the booster climbs out of the atmosphere.[3]

The stage separation system was redesigned to reduce the number of attachment points from twelve to three,[71] and the vehicle had upgraded avionics and software.[71]

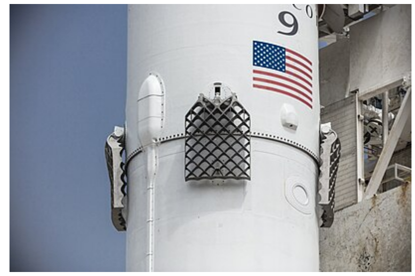
These improvements increased the payload capability from 9,000 kg (20,000 lb) to 13,150 kg (28,990 lb).[3] SpaceX president Gwynne Shotwell stated the v1.1 had about 30% more payload capacity than published on its price list, with the extra margin reserved for returning stages via powered re-entry.[86]

Development testing of the first stage was completed in July 2013.[87][88] First launch came in September 2013.

The second stage igniter propellant lines were later insulated to better support in-space restart following long coast phases for orbital trajectory maneuvers.[89] Four extensible carbon fiber/aluminum honeycomb landing legs were included on later flights where landings were attempted.[90][91][92]

SpaceX pricing and payload specifications published for v1.1 as of March 2014 included about 30% more performance than the published price list indicated; SpaceX reserved the additional performance to perform reusability testing. Many engineering changes to support reusability and recovery of the first stage were made for v1.1·

V1.2/Full thrust



A close-up of the newer titanium grid fins first flown for the second Iridium NEXT mission in June 2017

The v1.2 upgrade, also known as Full Thrust (FT),[93][94] made major changes. It added cryogenic propellant cooling to increase density allowing 17% higher thrust, improved the stage separation system, stretched the second stage to hold additional propellant, and strengthened struts for holding helium bottles believed to have been involved with the failure of flight 19.[95] It offered a reusable first stage. Plans to reuse the second-stage were abandoned as the weight of a heat shield and other equipment would reduce payload too much.[96] The reusable booster was developed using systems and software tested on the Falcon 9 prototypes.

The Autonomous Flight Safety System (AFSS) replaced the ground-based mission flight control personnel and equipment. AFSS offered on-board Positioning, Navigation and Timing sources and decision logic. The benefits of AFSS included increased public safety, reduced reliance on range infrastructure, reduced range spacelift cost, increased schedule predictability and availability, operational flexibility, and launch slot flexibility".[97]

FT's capacity allowed SpaceX to choose between increasing payload, decreasing launch price, or both.[98]

Its first successful landing came in December 2015[99] and the first reflight in March 2017.[100] In February 2017, CRS-10 launch was the first operational launch utilizing AFSS. All SpaceX launches after 16 March used AFSS. A 25 June mission carried the second batch of ten Iridium NEXT satellites, for which the aluminium grid fins were replaced by larger titanium versions, to improve control authority, and heat tolerance during re-entry.[101]

Block 4

In 2017, SpaceX started including incremental changes, internally dubbed Block 4.[102] Initially, only the second stage was modified to Block 4 standards, flying on top of a Block 3 first stage for three missions: NROL-76 and Inmarsat-5 F5 in May 2017, and Intelsat 35e in July 2017.[103] Block 4 was described as a transition between the Full Thrust v1.2 Block 3 and Block 5. It includes incremental engine thrust upgrades leading to Block 5.[104] The maiden flight of the full Block 4 design (first and second stages) was the SpaceX CRS-12 mission on 14 August.[105]

Block 5

In October 2016, Musk described Block 5 as coming with "a lot of minor refinements that collectively are important, but uprated thrust and improved legs are the most significant".[106] In January 2017, Musk added that Block 5 "significantly improves performance and ease of reusability".[107] The maiden flight took place on 11 May 2018,[108] with the Bangabandhu Satellite-1 satellite.[109] The Block 5 second stage included upgrades to enable it to linger in orbit and reignite its engine three or more times.[110]

Capabilities

Performance

Version	v1.0 (retired)	v1.1 (retired)	v1.2 or Full Thrust[9]	
			Block 3 and Block 4 (retired)	Block 5 (active)[111] [112]
Stage 1 engines	9 × Merlin 1C	9 × Merlin 1D	9 × Merlin 1D (upgraded)[113]	9 × Merlin 1D (upgraded)
Stage 1 mass			Dry mass 22.2 t (49,000 lb)[112]	
Stage 2 engines	1 × Merlin 1C Vacuum	1 × Merlin 1D Vacuum	1 × Merlin 1D Vacuum (upgraded)[94][113]	1 × Merlin 1D Vacuum (upgraded) (short or regular nozzle)
Stage 2 mass			Dry mass 4 t (8,800 lb)[112]	
Max. height (m)	53[114]	68.4[3]	70[2][94]	70
Diameter (m)	3.66[115]	3.66[116]	3.66[94]	3.66
Initial thrust	3.807 MN (388.2 t_f)	5.9 MN (600 t_f)[3]	6.804 MN (693.8 t_f)[2][94]	7.6 MN (770 t_f)[117]
Takeoff mass	318 t (701,000 lb)[114]	506 t (1,116,000 lb)[3]	549 t (1,210,000 lb)[2]	549 t (1,210,000 lb)
Fairing diameter (m)	—[a]	5.2	5.2	5.2
Fairing mass			3.7 t (8,200 lb)[112]	
Payload to LEO (kg) (from Cape Canaveral)	8,500–9,000[114]	13,150[3]	22,800 (expendable)[1][b]	≥ 22,800 (expendable) ≥ 17,400 (reusable)[c]
Payload to GTO (kg)	3,400[114]	4,850[3]	8,300[1] (expendable) About 5,300[119][120] (reusable)	≥ 8,300 (expendable) ≥ 5,800 (reusable)[121]
Success ratio	5 / 5[d]	14 / 15[e]	36 / 36 (1 precluded)[f]	194 / 194

a. The Falcon 9 v1.0 only launched the Dragon spacecraft; it was never launched with the clam-shell payload fairing.
b. Payload was restricted to 10,886 kg (24,000 lb) due to structural limit of the payload adapter fitting (PAF).[118]
c. Heaviest explicitly confirmed payload has been 17,400 kg[67].
d. On SpaceX CRS-1, the primary payload, Dragon, was successful. A secondary payload was placed in an incorrect orbit because of a changed flight profile due to the malfunction and shut-down of a single first-stage engine. Likely enough fuel and oxidizer remained on the second stage for orbital insertion, but not enough to be within NASA safety margins for the protection of the International Space Station.[122]
e. The only failed mission of the Falcon 9 v1.1 was SpaceX CRS-7, which was lost during its first stage operation due to an overpressure event in the second stage oxygen tank.
f. One rocket and payload were destroyed before launch, during preparation for a routine static fire test.

Reliability

As of 27 August 2023, Falcon 9 had achieved 248 out of 250 full mission successes (99.2%). SpaceX CRS-1 succeeded in its primary mission, but left a secondary payload in a wrong orbit, while SpaceX CRS-7 was destroyed in flight. In addition, AMOS-6 disintegrated on the launch pad during fueling for an engine test. Based on the Point estimation estimate of reliability, the Falcon 9 Full Thrust had become the most reliable orbital launch vehicle then in operation.[123] Block 5 has a success rate of 100% (194/194). For comparison, the industry benchmark Soyuz series has performed 1880 launches[124] with a success rate of 95.1% (the latest Soyuz-2's success rate is 94%),[125] the Russian Proton series has performed 425 launches with a success rate of 88.7% (the latest Proton-M's success rate is 90.1%), the European Ariane 5 has performed 110 launches with a success rate of 95.5%, and Chinese Long March 3B has performed 85 launches with a success rate of 95.3%.

F9's launch sequence includes a hold-down feature that allows full engine ignition and systems check before liftoff. After the first-stage engine starts, the launcher is held down and not released for flight until all propulsion and vehicle systems are confirmed to be operating normally. Similar hold-down systems have been used on launch vehicles such as Saturn V[126] and Space Shuttle. An automatic safe shutdown and unloading of propellant occur if any abnormal conditions are detected.[4] Prior to the launch date, SpaceX typically completes a test cycle, culminating in a three-and-a-half second first stage engine static firing.[127][128]

F9 has triple-redundant flight computers and inertial navigation, with a GPS overlay for additional accuracy.[4]

Engine-out capability

Like the Saturn family of rockets, multiple engines allow for mission completion even if one fails.[4][129] Detailed descriptions of destructive engine failure modes and designed-in engine-out capabilities were made public.[130]

SpaceX emphasized that the first stage is designed for "engine-out" capability.[4] CRS-1 in October 2012 was a partial success after engine no. 1 lost pressure at 79 seconds, and then shut down. To compensate for the resulting loss of acceleration, the first stage had to burn 28 seconds longer than planned, and the second stage had to burn an extra 15 seconds. That extra burn time reduced fuel reserves so that the likelihood that there was sufficient fuel to execute the mission dropped from 99% to 95%. Because NASA had purchased the launch and therefore contractually controlled several mission decision points, NASA declined SpaceX's request to restart the second stage and attempt to deliver the secondary payload into the correct orbit. As a result, the secondary payload reentered the atmosphere.[8]

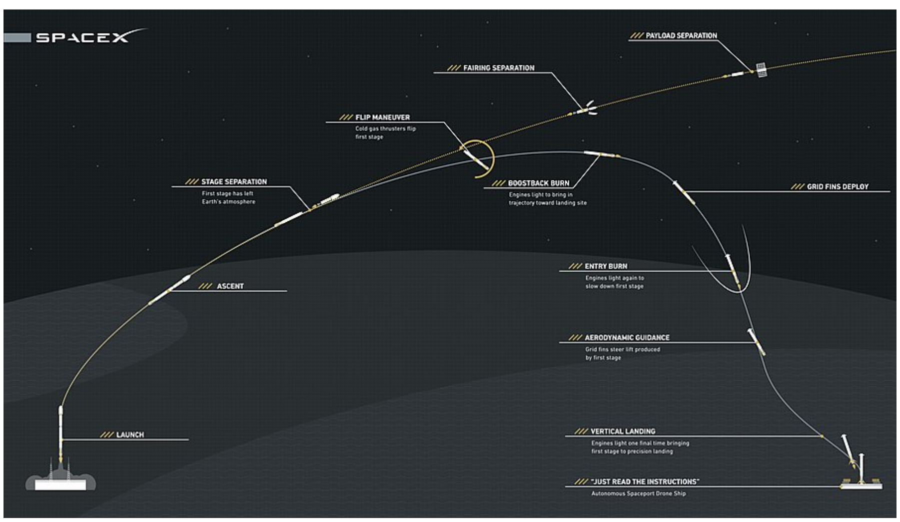
Merlin 1D engines have suffered two premature shutdowns on ascent. Neither has affected the primary mission, but both landing attempts failed. On an 18 March 2020 Starlink mission, one of the first stage engines failed 3 seconds before cut-off due to the ignition of some isopropyl alcohol that was not properly purged after cleaning.[131] On another Starlink mission on 15 February 2021, hot exhaust gasses entered an engine due to a fatigue-related hole in its cover.[132] SpaceX stated the failed cover had the "highest... number of flights that this particular boot [cover] design had seen."[133]

Reusability

SpaceX planned from the beginning to make both stages reusable.[134] The first stages of early Falcon flights were equipped with parachutes and were covered with a layer of ablative cork to allow them to survive atmospheric re-entry. These were defeated by the accompanying aerodynamic stress and heating.[81] The stages were salt-water corrosion-resistant.[134]

In late 2011, SpaceX eliminated parachutes in favor of powered descent.[135][136] The design was complete by February 2012.[78]

Powered landings were first flight-tested with the suborbital Grasshopper rocket.[137] Between 2012 and 2013, this low-altitude, low-speed demonstration test vehicle made eight vertical landings, including a 79-second round-trip flight to an altitude of 744 m (2,441 ft). In March 2013, SpaceX announced that as of the first v1.1 flight, every booster would be equipped for powered descent.[91]



Explanatory graphic of Falcon 9's first stage barge landing

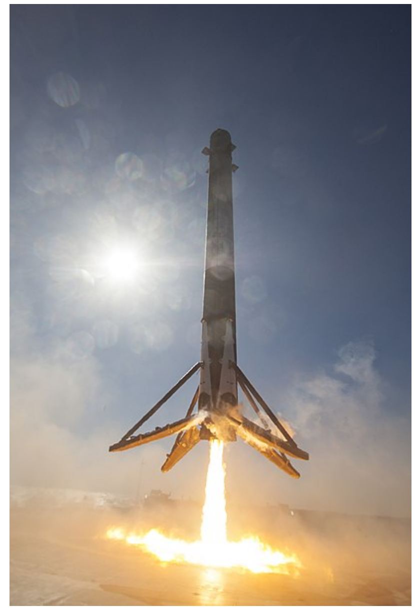
Post-mission flight tests and landing attempts

For Flight 6 in September 2013, after stage separation, the flight plan called for the first stage to conduct a burn to reduce its reentry velocity, and then a second burn just before reaching the water. Although not a complete success, the stage was able to change direction and make a controlled entry into the atmosphere.[138] During the final landing burn, the RCS thrusters could not overcome an aerodynamically induced spin. The centrifugal force deprived the engine of fuel, leading to early engine shutdown and a hard splashdown.[138]

After four more ocean landing tests, the CRS-5 booster attempted a landing on the ASDS floating platform in January 2015. The rocket incorporated (for the first time in an orbital mission) grid fin aerodynamic control surfaces, and successfully guided itself to the ship, before running out of hydraulic fluid and crashing into the platform.[139] A second attempt occurred in April 2015, on CRS-6. After the launch, the bipropellant valve became stuck, preventing the control system from reacting rapidly enough for a successful landing.[140]

The first attempt to land a booster on a ground pad near the launch site occurred on flight 20, in December 2015. The landing was successful and the booster was recovered.[141][142] This was the first time in history that after launching an orbital mission, a first stage achieved a controlled vertical landing. The first successful booster landing on an ASDS occurred in April 2016 on the drone ship *Of Course I Still Love You* during CRS-8.

Sixteen test flights were conducted from 2013 to 2016, six of which achieved a soft landing and booster recovery. Since January 2017, with the exceptions of the centre core from the Falcon Heavy test flight, Falcon Heavy USAF STP-2 mission, the Falcon 9 CRS-16 resupply mission and the Starlink-4 and 5 missions, every landing attempt has been successful. The only post-landing loss of a first stage occurred on Falcon Heavy Arabsat-6A after the centre core fell overboard during rough seas on the voyage to land.



Falcon 9's first stage successfully landing on an ASDS for the first time, following the launch of SpaceX CRS-8 to the ISS

Relaunch

The first operational relaunch of a previously flown booster was accomplished in March 2017[143] with B1021 on the SES-10 mission after CRS-8 in April 2016.[144] After landing a second time it was retired.[145] In June 2017, booster B1029 helped carry BulgariaSat-1 towards GTO after an Iridium NEXT LEO mission in January 2017, again achieving reuse and landing of a recovered booster.[146] The third reuse flight came in November 2018 on the SSO-A mission. The core for the mission, Falcon 9 B1046, was the first Block 5 booster produced, and had flown initially on the Bangabandhu Satellite-1 mission.[147]

In May 2021 the first booster reached 10 missions. Musk indicated that SpaceX intends to fly boosters until they see a failure in Starlink missions.[148][149] As of December 2022, the record is 15 flights by the same booster.

The first reflight of a Falcon 9, in March 2017

Recovery of second stages and fairings

Despite public statements that they would endeavor to make the second-stage reusable as well, by late 2014, SpaceX determined that the mass needed for a heat shield, landing engines, and other equipment to support recovery of the second stage was prohibitive, and abandoned second-stage reusability efforts.[96][150]

SpaceX developed payload fairings equipped with a steerable parachute as well as RCS thrusters that can be recovered and reused. A payload fairing half was recovered following a soft-landing in the ocean for the first time in March 2017, following SES-10.[62] Subsequently, development began on a ship-based system involving a massive net, in order to catch returning fairings. Two dedicated ships were outfitted for this role, making their first catches in 2019.[151] However, following mixed success, SpaceX returned to water landings and wet recovery.[152]

Launch sites

By early 2018, F9 was regularly launching from three orbital launch sites: Launch Complex 39A of the Kennedy Space Center,[153] Space Launch Complex 4E of Vandenberg Air Force Base,[154][138] and Space Launch Complex 40 at Cape Canaveral Air Force Station. The latter was damaged in the AMOS-6 accident in September 2016, but was operational again by December 2017.[155][156]

On April 21, 2023 the United States Space Force, Space Launch Delta 30 granted SpaceX permission to lease Vandenberg Space Launch Complex 6 for Falcon 9 and Falcon Heavy launches.[157] SLC-6 is likely to become the fourth launch site for Falcon 9.

SpaceX's Falcon 9 rocket delivered the ABS-3A and Eutelsat 115 West B satellites to a supersynchronous transfer orbit, launching from Space Launch Complex 40 at Cape Canaveral Air Force Station, Florida in March 2015

Pricing

At the time of F9's 2010 maiden flight, the price of a v1.0 launch was listed from US$49.9–56 million.[4] The list price increased thereafter, to US$54–59.5 million (2012).[158] 56.5 million (v1.1, August 2013),[159] US$61.2 million (June 2014),[160] US$62 million (Full Thrust, May 2016),[161] to US$67 million (2022).[1] Dragon cargo missions to the ISS have an average cost of 133 million under a fixed-price contract with NASA, including the cost of the spacecraft.[162] The 2013 DSCOVR mission, launched with Falcon 9 for National Oceanic and Atmospheric Administration (NOAA), cost US$97 million.[163]

In 2004, Elon Musk stated, "Ultimately, I believe 500 per pound (1100/kg) [of payload delivered to orbit] or less is very achievable".[164] At its 2016 launch price with a full LEO payload, Full Thrust launch costs reached US$1,200/lb ($2,600/kg).

In 2011, Musk estimated that fuel and oxidizer for v1.0 cost about 200,000.[165] The first stage uses 245,620 L (54,030 imp gal; 64,890 US gal) of liquid oxygen and 146,020 L (32,120 imp gal; 38,570 US gal) of RP-1 fuel,[166] while the second stage uses 28,000 L (6,200 imp gal; 7,400 US gal) of liquid oxygen and 17,000 L (3,700 imp gal; 4,500 US gal) of RP-1.[1]

By 2018, F9's decreased launch costs drew competitors. Arianespace began working on Ariane 6, United Launch Alliance (ULA) on Vulcan Centaur, and International Launch Services (ILS) on Proton Medium.[167]

On 26 June 2019, Jonathan Hofeller (SpaceX vice president of commercial sales) said that price discounts given to early customers on mission with reused boosters had become the standard price.[168] In October 2019, Falcon 9's "base price" of US$62 million per launch was lowered to US$52 million for flights scheduled in 2021 and beyond.[169]

On 10 April 2020, Roscosmos administrator Dmitry Rogozin, said that his outfit was cutting prices by 30%, alleging that SpaceX was price dumping by charging commercial customers US$60 million per flight while charging NASA between 1.5 and 4x as much for the same flight.[170] Musk denied the claim and replied that the price difference reflected that the F9s were 80% reusable, while Russian rockets were single use.[171] ULA CEO Tory Bruno stated "Our estimate remains around 10 flights as a fleet average to achieve a consistent breakeven point ... and that no one has come anywhere close".[172] However, Elon Musk responded "Payload reduction due to reusability of booster and fairing is <40% for Falcon 9 and recovery and refurb is <10%, so you're roughly even with 2 flights, definitely ahead with 3".[173] CNBC reported in April 2020 that the United States Air Force's launches were costing US$95 million due to needed extra security. SpaceX executive Christopher Couluris stated that reusing rockets could bring prices even lower, that it "costs 28 million to launch it, that's with everything".[173]

Secondary payloads

F9 payload services include secondary and tertiary payloads mounted via an EELV Secondary Payload Adapter (ESPA) ring, the same interstage adapter first used for launching secondary payloads on US DoD missions that use the Evolved Expendable Launch Vehicles (EELV) Atlas V and Delta IV. This enables secondary and even tertiary missions with minimal impact to the original mission. In 2011, SpaceX announced pricing for ESPA-compatible payloads.[174]

Historical artifacts and museum Falcon 9s

SpaceX first put a Falcon 9 (B1019) on public display at their headquarters in Hawthorne, California, in 2016.[175]

In 2019, SpaceX donated a Falcon 9 (B1035) to Space Center Houston, in Houston, Texas. It was a booster that flew two missions, "the 11th and 13th supply missions to the International Space Station [and was] the first Falcon 9 rocket NASA agreed to fly a second time".[176][177]

In 2021, SpaceX donated a Falcon Heavy side booster (B1023) to the Kennedy Space Center Visitor Complex.[178]

Notable payloads

- AMOS-17
- Bangabandhu Satellite-1
- Beresheet lunar lander
- Boeing X-37
- Crew and Cargo Dragon
- CRS-7
- Double Asteroid Redirection Test (DART)
- EchoStar 23
- GPS IIIA launches
- Iridium NEXT constellation
- Launches for the US National Reconnaissance Office, NROL
- Orbcomm OG2
- RADARSAT Constellation
- SES-10
- Sirius XM launches
- SpaceX Starlink
- Transiting Exoplanet Survey Satellite (TESS)

- Zuma

See also

Spaceflight portal

- Comparison of orbital launch systems
- List of Falcon 9 first-stage boosters
- SpaceX launch vehicles

Notes

A. Landing success details at List of Falcon 9 and Falcon Heavy launches

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External links

- Falcon 9 official page (https://www.spacex.com/vehicles/falcon-9/)
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- Test firing of two Merlin 1C engines connected to Falcon 9 first stage, Movie 1 (http://mfile.akamai.com/22165/wmv/spacex.download.akamai.com/22165/PR35-1.asx), Movie 2 (http://mfile.akamai.com/22165/wmv/spacex.download.akamai.com/22165/PR35-2.asx) (18 January 2008)
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