Merlin (rocket engine family)

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Merlin is a family of rocket engines developed by SpaceX for use on its Falcon 1 and Falcon 9 launch vehicles. SpaceX also plans to use Merlin engines on its Falcon Heavy. Merlin engines use RP-1 and liquid oxygen as rocket propellants in a gas-generator power cycle. The Merlin engine was originally designed for sea recovery and reuse.

The injector at the heart of Merlin is of the pintle type that was first used in the Apollo program for the lunar module landing engine (LMDE).

Propellants are fed via a single shaft, dual impeller turbopump. The turbo-pump also provides high pressure fluid for the hydraulic actuators, which then recycles into the low pressure inlet. This eliminates the need for a separate hydraulic drive system and means that thrust vectoring control failure by running out of hydraulic fluid is not possible. A third use of the turbo-pump is to provide power to pivot the turbine exhaust nozzle for roll control purposes.

Merlin 1D


Test firing at SpaceX McGregor's test stand of the Merlin 1D

Country of origin	United States
Manufacturer	SpaceX
Application	Main stage engine, Upper stage engine
Associated L/V	Falcon 9, Falcon Heavy
Liquid-fuel engine	
Propellant	LOX / RP-1 (rocket grade kerosene)
Cycle	gas-generator
Performance	
Thrust (vac.)	825 kN[1]
Thrust (SL)	756 kN[1]
Thrust-to-weight ratio	180[2]
Chamber pressure	9.7 MPa (1,410 psi)[3]
I_{sp} (vac.)	311 seconds (3.05 km/s)
I_{sp} (SL)	282 s (2.73 km/s)
Dimensions	
Dry weight	1,030 pounds (470 kg)[2]
References	
References	[4]

Contents

Variants

Three versions of the Merlin 1C engine have been produced. The Merlin engine for Falcon 1 had a movable turbo-pump exhaust assembly which was used to provide roll control by vectoring the exhaust. The Merlin 1C engine for the Falcon 9 first stage is nearly identical to the variant used for the Falcon 1 except that the turbo-pump exhaust assembly is not movable. Finally, a Merlin 1C vacuum variant is used on the Falcon 9 second stage. This engine differs from the Falcon 9 first stage variant in that it uses a larger exhaust nozzle optimized for vacuum operation and can be throttled between 60 and 100 percent.[5]

Revisions

Merlin 1A

The initial version, the **Merlin 1A**, used an inexpensive, expendable, ablatively cooled carbon-fiber-reinforced polymer composite nozzle, and produced 340 kN (77,000 lbf) of thrust. The Merlin 1A flew only twice: First on March 24, 2006, when it caught fire and failed due to a fuel leak shortly after launch,[6][7] and the second time on March 21, 2007, when it performed successfully.[8] Both times the Merlin 1A was mounted on a Falcon 1 first stage.[9][10]


SpaceX Merlin 1A

The SpaceX turbopump was an entirely new, clean sheet design contracted to Barber-Nichols, Inc. in 2002 who performed all design, engineering analysis and construction. Barber-Nichols, Inc. applied lessons learned from the RS-88 (Bantum) and NASA Fastrac engine programs for their turbopump products. The Merlin 1A turbopump uses a unique friction-welded main shaft (inconel 718 ends with an integral aluminum RP-1 impeller in the middle). The turbopump housing is constructed of investment castings (inconel at the turbine end, aluminum in the center, and 300-series stainless steel at the LOX end). The turbine is a partial-admission impulse design and turns at 20,000 rpm. Total turbopump weight was 150 lbs.

Merlin 1B

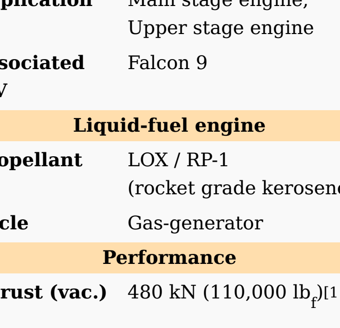
The **Merlin 1B** rocket engine was an upgraded version of the Merlin 1A engine. The turbopump upgrades were handled by Barber-Nichols, Inc. for SpaceX. It was intended for Falcon 1 launch vehicles, capable of producing 380 kN (85,000 lbf) of thrust. The Merlin 1B was enhanced over the 1A with a turbine upgrade (from 1490 kW to 1860 kW). The turbine upgrade was accomplished by adding additional nozzles (turning the previous partial-admission design to full-admission). Slightly enlarged impellers for both RP-1 and LOX were part of the upgrade. This model turned at a faster 22,000 rpm and developed higher discharge pressures. Turbopump weight was unchanged at 150 lbs.

Initial use of the Merlin 1B was to be on the Falcon 9 launch vehicle, on whose first stage there would have been a cluster of nine of these engines. Due to experience from the Falcon 1's first flight, SpaceX moved its Merlin development to the Merlin 1C, which is regeneratively cooled. Therefore, the Merlin 1B was never used on a launch vehicle.[9][10]

Merlin 1C

The **Merlin 1C** uses a regeneratively cooled nozzle and combustion chamber. The turbopump used is a Merlin 1B model with only slight alterations. It was fired with a full mission duty firing of 170 seconds in November 2007,[11] first flew on a mission in August 2008,[13] powered the "first privately-developed liquid-fueled rocket to successfully reach orbit", Falcon 1 Flight 4, in September 2008,[13] and powered the Falcon 9 on its maiden flight in June 2010.[14]

Merlin 1C


Merlin 1C under construction at SpaceX factory

Country of origin	United States
Manufacturer	SpaceX
Application	Main stage engine, Upper stage engine
Associated L/V	Falcon 9
Liquid-fuel engine	
Propellant	LOX / RP-1 (rocket grade kerosene)
Cycle	Gas-generator
Performance	
Thrust (vac.)	480 kN (110,000 lb_f)[11]
Thrust (SL)	420 kN (94,000 lb_f)[11]
Thrust-to-weight ratio	96
Chamber pressure	6.77 MPa (982 psi)[5]
I_{sp} (vac.)	304.8 s (3.0 km/s)[5]
I_{sp} (SL)	275 s (2.6 km/s)
Dimensions	
Length	2,920 mm (115 in)[12]
Dry weight	1,380 pounds (630 kg)

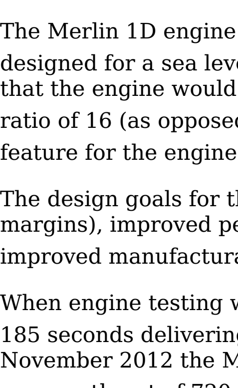
As configured for use on Falcon 1 vehicles, the Merlin 1C had a sea level thrust of 350 kN (78,000 lbf), a vacuum thrust of 400 kN (90,000 lbf) and a vacuum specific impulse of 304 seconds. In this configuration the engine consumed 140 kg (300 lb) of propellant per second. Tests have been conducted with a single Merlin 1C engine successfully running a total of 27 minutes (counting together the duration of the various tests), which equals ten complete Falcon 1 flights.[15] The Merlin 1C chamber and nozzle are cooled regeneratively by 45 kilograms (100 lb) per second of kerosene flow, and are able to absorb 10 megawatts (13,000 hp) of thermal heat energy.[16]

A Merlin 1C was first used as part of the unsuccessful third attempt to launch a Falcon 1. In discussing the failure, Elon Musk noted, "The flight of our first stage, with the new Merlin 1C engine that will be used in Falcon 9, was picture perfect."[17] The Merlin 1C was used in the successful fourth flight of Falcon 1 on September 28, 2008.[18]

On October 7, 2012 a Merlin 1C (Engine No. 1) of the CRS-1 mission experienced an anomaly at T+00:01:20 which appears on CRS-1 launch video (http://www.youtube.com/watch?v=tRTYh71D9P0) as a flash. Failure occurred just as the vehicle achieved Max-Q (maximum aerodynamic pressure). SpaceX's internal review found that the engine was shut down after a sudden pressure loss, and that only the aerodynamic shell was destroyed, generating the debris seen in the video; the engine did not explode, as SpaceX ground control continued to receive data from it throughout the flight. The primary mission was unaffected by the anomaly due to the nominal operation of the remaining eight engines and an onboard readjustment of the flight trajectory,[19] but the secondary mission payload failed to achieve orbit due to safety protocols in place to prevent collisions with the ISS.[20]

SpaceX was planning to develop a 560 kN version of Merlin 1C to be used in Falcon 9 block II and Falcon 1E boosters.[21] This engine and these booster models were dropped in favor of the more advanced Merlin 1D engine and longer Falcon 9 v1.1 booster.

Merlin Vacuum (1C)

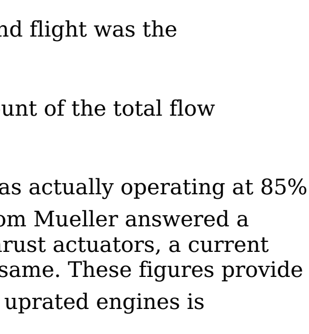

Merlin 1C Vacuum engine at Hawthorne factory in 2008

On March 10, 2009 a SpaceX press release announced successful testing of the Merlin Vacuum engine. A variant of the 1C engine, Merlin Vacuum features a larger exhaust section and a significantly larger expansion nozzle to maximize the engine's efficiency in the vacuum of space. Its combustion chamber is regeneratively cooled, while the 2.7 metres (9 ft)-long[22] niobium alloy[5] expansion nozzle is radiatively cooled. The engine delivers a vacuum thrust of 411 kN (92,500 lbf) and a vacuum specific impulse of 342 seconds.[23] The first production Merlin Vacuum engine underwent a full duration orbital insertion firing (329 seconds) of the integrated Falcon 9 second stage on January 2, 2010.[24] It was flown on the second stage for the inaugural Falcon 9 flight on June 4, 2010. At full power the Merlin Vacuum engine operates with the greatest efficiency ever for an American-made hydrocarbon rocket engine.[25]

An unplanned test of a modified Merlin Vacuum engine was made in December 2010. Shortly before the scheduled second flight of the Falcon 9, two cracks were discovered in the 2.7 metres (9 ft)-long niobium-alloy-sheet nozzle of the Merlin Vacuum engine. The engineering solution was to cut off the lower 1.2 metres (4 ft) of the nozzle, and launch two days later, as the extra performance that would have been gained from the longer nozzle was not necessary to meet the objectives of the mission. Even with the shortened nozzle, the engine placed the second-stage into an orbit of 11,000 kilometres (6,800 mi) altitude.[22]

Merlin 1D

The Merlin 1D engine was developed by SpaceX in 2011–2012, with first flight in 2013. The Merlin 1D was originally (April 2011) designed for a sea level thrust of 620 kN (140,000 lbf).[26] At the 2011 AIAA Propulsion Conference, SpaceX's Tom Mueller[27] revealed that the engine would have a vacuum thrust of 690 kN (155,000 lbf), a vacuum specific impulse (I_{sp}) of 310 s, an increased expansion ratio of 16 (as opposed to the previous 14.5 of the Merlin 1C) and chamber pressure in the "sweet spot" of 9.7 MPa (1,410 psi). A new feature for the engine is the ability to throttle from 100% to 70%.[3]


The 100th Merlin 1D engine, built at SpaceX's Hawthorne factory in 2014. The engine is already attached to its Octaweb load plate, for positioning in a Falcon 9 as one of eight outer engines.

The design goals for the new engine included increased reliability (increased fatigue life and increased chamber and nozzle thermal margins), improved performance (thrust design objective 140,000 pounds-force (620 kN) and 70-100 percent throttle capability), and improved manufacturability (lower parts count and fewer labor hours).[28]

When engine testing was completed in June 2012, SpaceX stated that the engine had completed a full mission duration test firing of 185 seconds delivering 650 kN (147,000 lbf) of thrust and also confirming the expected thrust-to-weight ratio exceeding 150.[29] As of November 2012 the Merlin section of the Falcon 9 page describes the engine as having a sea level thrust of 650 kN (147,000 lbf), a vacuum thrust of 720 kN (161,000 lbf), a sea level specific impulse (I_{sp}) of 282 s and a vacuum specific impulse (I_{sp}) of 311 s.[4] The engine has the highest specific impulse ever achieved for a gas-generator cycle kerosene rocket engine. On March 20, 2013 SpaceX announced the Merlin 1D engine has achieved flight qualification. In June 2013, the first orbital flight vehicle to use the Merlin 1D, the Falcon 9 1.1 first stage, completed development testing.[30]

The first flight of the Falcon 9 with Merlin 1D engines launched the CASSIOPE satellite for the Canadian Space Agency. CASSIOPE, an 800 pounds (360 kg) weather research and communications satellite, was launched into a highly elliptical low Earth orbit (LEO). The second flight was the geosynchronous transfer orbit (GTO) launch of SES-8.[31] [32]

The basic Merlin fuel/oxidizer mixture ratio is controlled by the sizing of the propellant supply tubes to each engine, with only a small amount of the total flow trimmed out by a "servo-motor-controlled butterfly valve" to provide fine control of the mixture ratio.[33]

On November 24, 2013, during a joint teleconference of SES and SpaceX regarding the SES-8 launch, Elon Musk stated that the engine was actually operating at 85% of its potential, and they anticipated to be able to increase the sea level thrust to about 165,000 pounds-force (730 kN).[34] In June 2015 Tom Mueller answered a question about the Merlin 1D thrust/weight ratios on Quora. He specified that the Merlin 1D has a weight of 1,030 lb (470 kg) including thrust actuators, a current vacuum thrust of 162,500 pounds-force (723 kN), and an uprated vacuum thrust of 185,500 pounds-force (825 kN), which still weighs the same. These figures provide for a current thrust/weight ratio of ≈158 and an uprated thrust/weight ratio of ≈180.[2] According to SES S.A., the first Falcon 9 v1.1 with uprated engines is scheduled for mid-2015, and will carry the company's SES-9 payload.[35]

The main propellant supply tubes from the RP-1 and liquid oxygen tanks to the nine engines on Falcon 9 are 10 cm (4 in) in diameter.[33]

Merlin 1D Vacuum

A vacuum version of the Merlin 1D engine was developed for the Falcon 9 v1.1 and the Falcon Heavy second stage.[36][3]

In late 2012, Elon Musk tweeted an image of the Merlin 1D-Vac firing on the test stand and stated "Now test firing our most advanced engine, the Merlin 1D-Vac, at 80 tons of thrust." [37] Currently the official SpaceX's Falcon 9 product page lists the thrust of the Merlin Vacuum on the second stage of the launcher at 934 kN (210,000 lbf) and specific impulse of 348 seconds in vacuum conditions.[36] The increase is due to the greater expansion ratio afforded by operating in a vacuum, now 165:1 using an updated nozzle extension.[36][38]

According to a SpaceX-released Payload User's Guide, the Merlin 1D-Vac can throttle to 39% of its maximum thrust, or 360 kN (81,000 lbf).[38]

Design

Engine control

SpaceX uses a dual-redundant design in the Merlin flight computers. The system uses three computers in each processing unit, each constantly checking on the others, to instantiate a fault-tolerant design. One processing unit is part of each of the ten Merlin engines (nine on first stage, one on second stage) used on a Falcon 9 launch.[39]

Turbopump

The Merlin LOX/RP-1 turbopump used on Merlin engines 1A-1C was designed and developed by Barber-Nichols.[40] Starting with the Merlin 1D, SpaceX conducted all turbopump development and manufacturing.

Production

As of August 2011, SpaceX was producing Merlin engines at the rate of eight per month, planning eventually to raise production to about 33 engines per month (or 400 per year).[3] By September 2013, SpaceX total manufacturing space had increased to nearly 93,000 square meters (1,000,000 sq ft) and the factory had been configured to achieve a maximum production rate of up to 40 rocket cores per year, enough to use the 400 annual engines envisioned by the earlier engine plan.[41] By October 2014, SpaceX announced it had manufactured the 100th Merlin 1D engine and that engines were now being produced at a rate of 4 per week, soon to be increased to 5.[42]

By June 2015, SpaceX was producing Merlin engines at the rate of four Merlin 1D engines per week, with a total production capacity in the factory of a maximum of five per week.[43]

In February 2016, SpaceX indicated that the company will need to build hundreds of engines a year in order to support a Falcon 9/Falcon Heavy build rate of 30 rocket cores per year by the end of 2016.[44]

Future engines and concepts

SpaceX has other main-engine development programs underway and they have also released details on future engine concepts. The concepts have included liquid hydrogen (LH2) fueled engines in addition to SpaceX's Merlin family of RP1-fueled engines currently in production. However, in November 2012, SpaceX CEO Elon Musk announced a new direction for the propulsion side of the company: developing methane/LOX rocket engines,[45] which have cost advantages and a slight I_{sp} advantage over kerosene while avoiding adverse aspects of liquid hydrogen technology.[46]

Merlin 2 concept

At the AIAA Joint Propulsion conference on July 30, 2010, SpaceX McGregor rocket development facility director Tom Markusic shared some information from the initial stages of planning for a new engine. SpaceX's Merlin 2 LOX/RP-1-fueled engine on a gas-generator cycle, capable of a projected 7,600 kN (1,700,000 lbf) of thrust at sea level and 8,500 kN (1,920,000 lbf) in a vacuum and would provide the power for conceptual super-heavy-lift launch vehicles from SpaceX, which Markusic dubbed Falcon X and Falcon XX. Such a capability, if built, would have resulted in an engine with more thrust than the F-1 engines used on the Saturn V.[47]

Conceived to be potentially used on more capable variants of the Falcon 9 Heavy, Markusic indicated that the Merlin 2 "could be qualified in three years for $1 billion".[48] By mid-August, SpaceX CEO Elon Musk clarified that while the Merlin 2 engine architecture was a key element of any effort SpaceX would make toward their objective of "super-heavy lift" launch vehicles—and that SpaceX did indeed want to "move toward super heavy lift"—the specific potential design configurations of the particular launch vehicles shown by Markusic at the propulsion conference were merely conceptual "brainstorming ideas", just a "bunch of ideas for discussion."[49]

Since the original discussion, no work on any "Merlin 2" kerolox engine has been pursued and made public. At the 2011 Joint Propulsion Conference, Elon Musk stated that SpaceX were instead working towards a potential staged cycle engine.[50] In October 2012, SpaceX publicly announced concept work on a rocket engine that would be "several times as powerful as the Merlin 1 series of engines, and won't use Merlin's RP-1 fuel".[51] They indicated that the large engine was intended for a new SpaceX rocket, using multiple of these large engines could notionally launch payload masses of the order of 150 to 200 tonnes (170 to 220 short tons) to low-Earth orbit. The forthcoming engine currently under development by SpaceX has been named "Raptor". Raptor will use liquid methane as a fuel, and was stated as having a sea-level thrust of 6,700 kilonewtons (1,500,000 lbf).[52] Since the initial announcement of Raptor, Musk has updated the specification to approximately 230 tonnes-force (2,300 kN; 510,000 lbf)—about one-third the original published figure—based on the results of optimizing for thrust-to-weight ratio.[53]

See also

- Draco (rocket engine) – SpaceX RCS thruster.
- Kestrel (rocket engine) – SpaceX small upper stage engine for Falcon 1.
- Falcon (rocket family) - SpaceX rockets exclusively using LOX/RP-1 launch vehicle engines.
- Raptor (rocket engine) - SpaceX methane/LOX engine
- Comparison of orbital rocket engines
- Rocket engine
- Pintle injector
- TR-106 - Low Cost Pintle Engine (LCPE) using LOX/LH2 developed by TRW in 2000.
- TR-107 - RP1 engine developed under SLI for future reusable launch vehicles.
- RS-27A – RP-1 engine used in the US Delta II launcher; Saturn 1B H-1 heritage.
- Rocketdyne F-1 – LOX/RP-1 main engine of the Saturn V moon rocket.
- Executor (rocket engine)

Wikimedia Commons has media related to ***Merlin (rocket engine)***.

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Notes

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External links

- Space Exploration Technologies Corporation (http://www.spacex.com)