OVERVIEW OF STARSHIP

Unless referred to otherwise, Starship refers to the combination of the Super Heavy Booster and Starship upper stage.

SpaceX's Starship is a groundbreaking innovation in space transportation. Starship is an entirely reusable stainless steel rocket powered by 39—eventually 42—Raptor engines using methane and oxygen as propellants. The fully integrated rocket stands 121 meters tall and measures nine meters in diameter. Starship's payload bay internal volume is ~1,000 cubic meters, which is on par with the International Space Station. Its size and thrust capacity are designed for crewed and uncrewed missions to LEO, the Moon, and Mars.

Starship represents a significant leap forward in rocket engineering, as SpaceX aims to develop a fully and rapidly reusable orbital-class rocket that can be mass-produced. While the Saturn V rocket, known for its pivotal role in the Moon landings, was effective, its lack of affordability contributed to the discontinuation of NASA's extended Moon missions. Starship has the potential to catalyze transformative change in the space economy by substantially reducing launch costs.

- We anticipate that this unprecedented shift will expand the industry's addressable market considerably as Starship would enable novel space missions and applications to become technically and financially feasible.

STARSHIP ARCHITECTURE

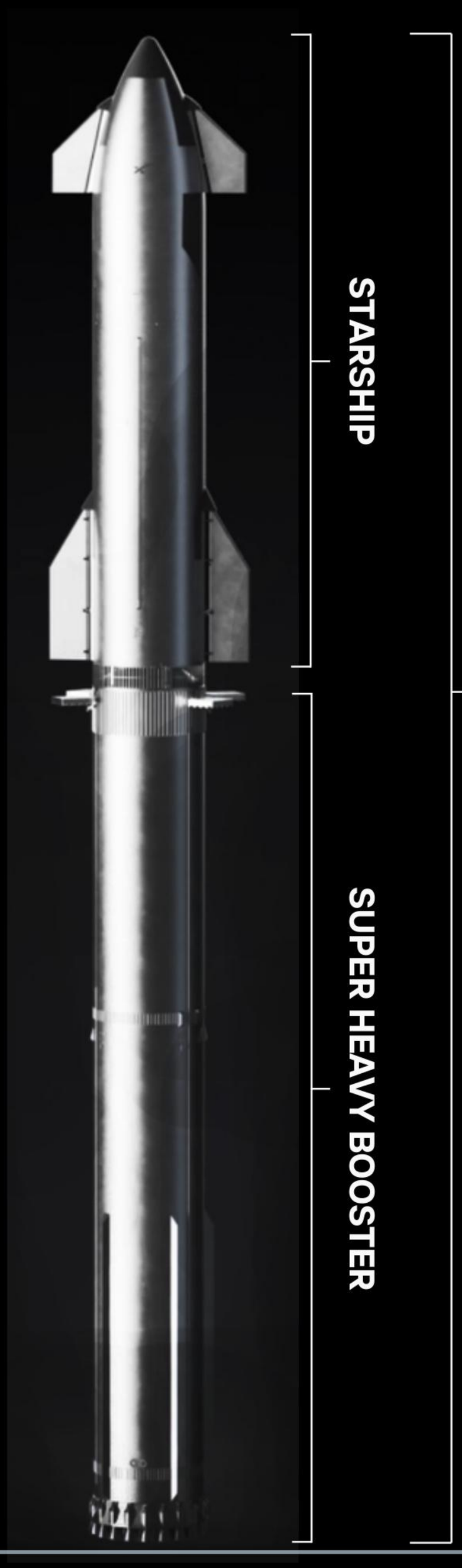
The Starship upper stage and the Super Heavy booster, collectively known as Starship (confusing, we know), are a fully reusable space transport system designed for missions to Earth orbit, the Moon, Mars, and eventually beyond. Starship holds the record as the most powerful launch vehicle ever built. It has the capability to transport up to 150 metric tons in a reusable configuration, and up to 250 metric tons when used in an expendable format.

Super Heavy Booster: The 71-meter tall Super Heavy booster is powered by 33 Raptor engines and is designed for fully reusable. The Super Heavy booster provides the necessary thrust for the 50-meter tall Starship spacecraft to achieve orbit.

- How it lands: Once the booster and Starship upper stage separate, the booster will descend back to the Mechazilla launch tower, hovering above the tower's chopstick-like arms for a midair catch.

Starship Upper Stage: The Starship spacecraft represents a significant departure from traditional designs. It features ~1,000 cubic meters of payload volume and is designed to survive reentering the atmosphere for full reusability. Six Raptor engines power the spacecraft, with three optimized for sea-level operation and three for vacuum environments. Starship upper stage will eventually be powered by nine Raptor engines.

- How it lands: Once Starship's second stage completes its mission, it will re-enter the atmosphere and orient to a horizontal fall. This belly-flop maneuver will increase its surface area and help slow descent speeds. Just prior to landing, the vehicle will fire its engines and realign vertically, readying itself for capture by Mechazilla's chopstick arms.



RAPTOR ENGINES

Starship is powered by the Raptor engine, a reusable methane-oxygen engine with twice the thrust (230 tf) of Falcon 9's Merlin engine. Starship uses six Raptors: three standard for atmospheric conditions and three vacuum-optimized engines for space. The Super Heavy booster is powered by 33 Raptors, with 13 in the center for control and 20 around the perimeter for added thrust.

The Raptor is a full-flow engine (see page 13) which through gasifying both fuel and oxidizer before combustion, leads to better mixing, more complete combustion, and higher thrust efficiency. This design contributes to the engine's potential for high reusability and reliability.

Raptor 2: In late 2021, SpaceX began production on its Raptor 2 engine. The Raptor 2 engine is a slimmed-down, more powerful, and efficient version of the Raptor 1. It also comes in at half the cost. The Raptor 2 is capable of 230+ metric tons of thrust, compared to the Raptor 1's 185 metric tons.[5]

By late 2022, SpaceX had ramped up production rate to one engine a day.[6] SpaceX has built 400+ Raptor engines. The Raptor 2 will power all Starship launches until Raptor 3 is ready.

Raptor 3 on the horizon: SpaceX has begun developing and testing Raptor 3 prototypes with impressive results. Preliminary Raptor 3 tests indicate it can generate 20% more thrust than the Raptor 2 at 270+ metric tons of thrust.[7] The increased thrust could allow Starship to transport 200 tons of payload to orbit in a fully reusable configuration.

5.Elon Musk on X 6.Ars Technica 7.Elon Musk on X

KEY ADVANTAGES

Full and rapid reusability:

SpaceX is designing Starship to be the first fully reusable rocket with little to no refurbishment between flights. Full reusability would lead to substantial cost savings compared to expendable rockets, potentially transforming the landscape of the launch industry into something more akin to commercial air travel.

Assuming a 100-flight lifespan, as Musk estimates for the Falcon 9, the amortized vehicle costs could plummet by a staggering 99% compared to expendable alternatives. Consequently, SpaceX has stated that the average marginal launch costs could drop to $10M or even as low as $2M (without including fixed costs).[8,9] While this objective seems ambitious, Falcon 9's partially reusable marginal costs are around $15M,[10] with $10M attributed to the expendable second-stage booster. Hence, a sub-$10M cost for a fully reusable vehicle in the long run is not entirely far-fetched.

Payload capacity:

Starship is designed to deliver up to 150 metric tons in a reusable configuration and a staggering 250 metric tons with an expendable booster. It will accommodate a payload fairing of 8 meters in diameter and up to 22 meters in height.[11] To put this into perspective, the payload bay could comfortably fit two fully loaded semi-truck trailers with additional room and weight capacity to spare.

Mass manufacturing:

Just as SpaceX productized the Falcon 9, it has designed Starship for mass manufacturability, with the ultimate goal of deploying hundreds of Starships concurrently. Mass production at the company's Starfactory facility would enable the company to save further by improving fixed asset utilization and reap the benefits of learning curve effects.

Launch costs:

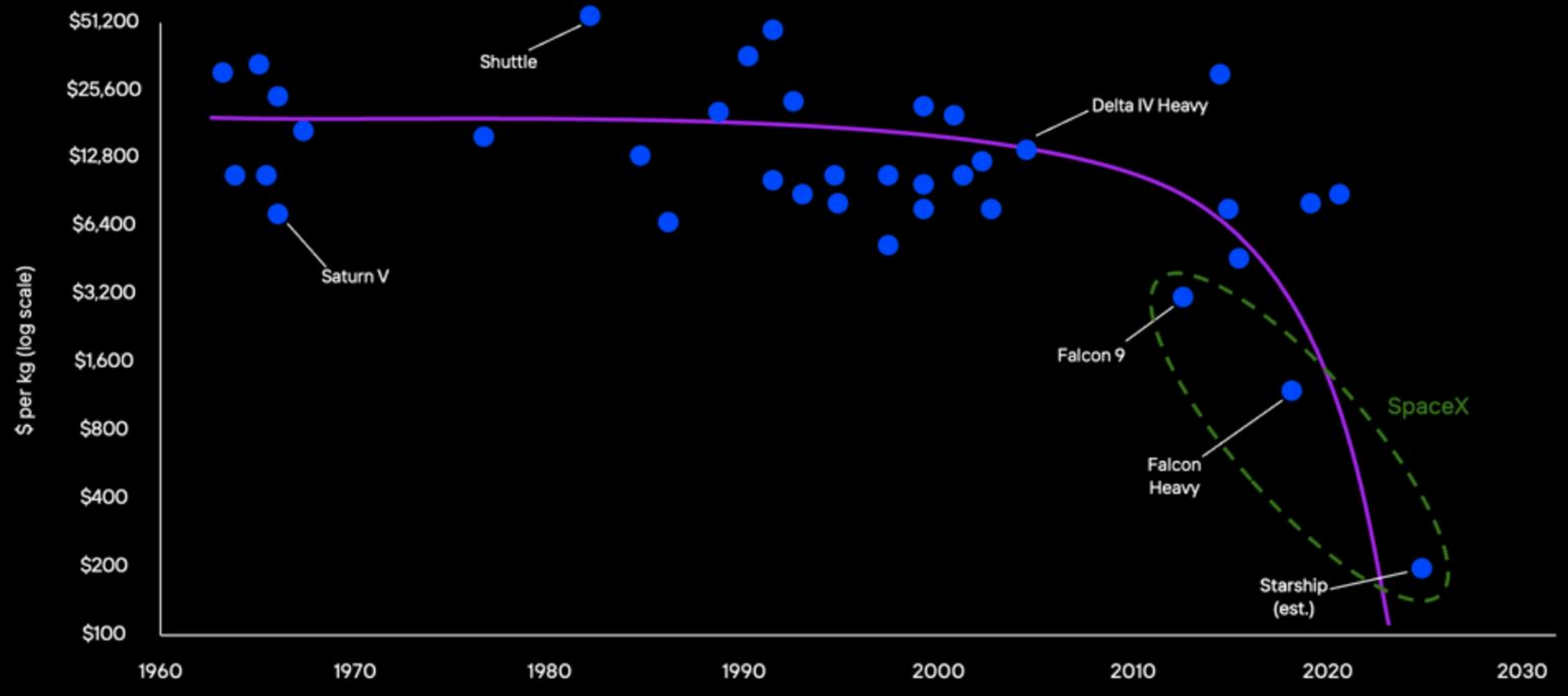
The high payload capacity and full reusability could bring the cost to orbit down by an order of magnitude. SpaceX charges ~$3,000 per kg for dedicated Falcon 9 missions, which is the most economical trip to space for satellite operators. If we apply an eventual $10M internal cost per Starship launch and a theoretical $20M price tag to the customer, the cost per kg to orbit could plummet to below $200.

However, in the near term, it's unlikely that SpaceX will reduce customer costs dramatically.

In fact, Payload estimates the cost per kg charged to the customer would likely mirror Falcon 9 (~$3,000 per kg) for the foreseeable future as SpaceX pockets the margin to pay back the heavy development costs, and since the price tag will still be the lowest in the industry.

As operations mature, SpaceX should reduce Starship prices at a rate informed by the dynamics of launch supply and demand. Although external utilization remains to be seen, it is typical for technologies to reveal new segments of the demand curve when their pricing drops significantly.

Falling Launch Costs to Orbit: Cost Per Kilogram



Source: CSIS Aerospace Security Project, PayloadResearch estimates | 2024

CRITICAL DESIGN DECISIONS

The Raptor Engine:
SpaceX has equipped Starship with 39 Raptor engines—33 on the booster and six on the upper stage. SpaceX plans to incorporate three additional Raptor engines on its upper stage, bringing the expected total future engine count to 42.[12] The Raptor is a full-flow staged combustion engine, with two turbopumps powered by fuel-rich and oxygen-rich preburners. All propellants flow through dedicated preburners and turbines before entering the main combustion chamber as hot gas. The engine offers numerous benefits, including reduced coking risk, higher efficiency, and the potential to utilize resources on Mars. The engine boasts improved thrust and efficiency compared to the Falcon 9's Merlin engine.

Full-Flow:
While the full-flow staged combustion engine provides the highest rocket performance among any engine type, they are also the most difficult to build. Historically, only three full-flow staged combustion cycle engines have ever been built:

- Soviet Energomash RD-270 project in the 1960s, the US government-funded
- Aerojet Rocketdyne Integrated powerhead demonstration project in the mid-2000s
- Raptor engine in 2019[13]

Of the three, only Raptor has ever launched; the immense complexity of full-flow engines ended the other two programs.

Stainless Steel Structure:
Starship's unique stainless steel structure provides significant advantages:

- **Affordability:** Stainless steel is more cost-effective than other aerospace materials, such as carbon composites. The 300-series of stainless steel costs ~$5/kg, or 95% less than carbon composites (assuming 30%+ scrap).
- **Heat management:** Stainless steel has a high melting point and high heat resistance, which are vital properties when dealing with extreme temperatures during atmospheric reentry.
- **Durability:** Stainless steel is resistant to corrosion and wear, ensuring Starship's structural integrity over multiple flights. The durability contributes to the vehicle's reusability and lowers maintenance costs.
- **Ease of manufacturing:** Stainless steel is a well-understood and widely available material, which can be easily shaped, welded, and machined. This facilitates a more efficient and accelerated manufacturing process for Starship.
- **Cryogenic compatibility:** Stainless steel maintains its strength at extremely low temperatures, making it suitable for a vehicle that uses cryogenic propellants.

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12. Elon Musk on X 13. CNBC

STARSHIP HISTORY

Musk's goal of creating a human colony on Mars was the inspiration behind Starship.

In order to colonize Mars, humanity will need to send a constant flow of vehicles containing passengers, infrastructure, and essential cargo to support the community. To achieve this at a commercially viable cost, a fully reusable mega-rocket is required.

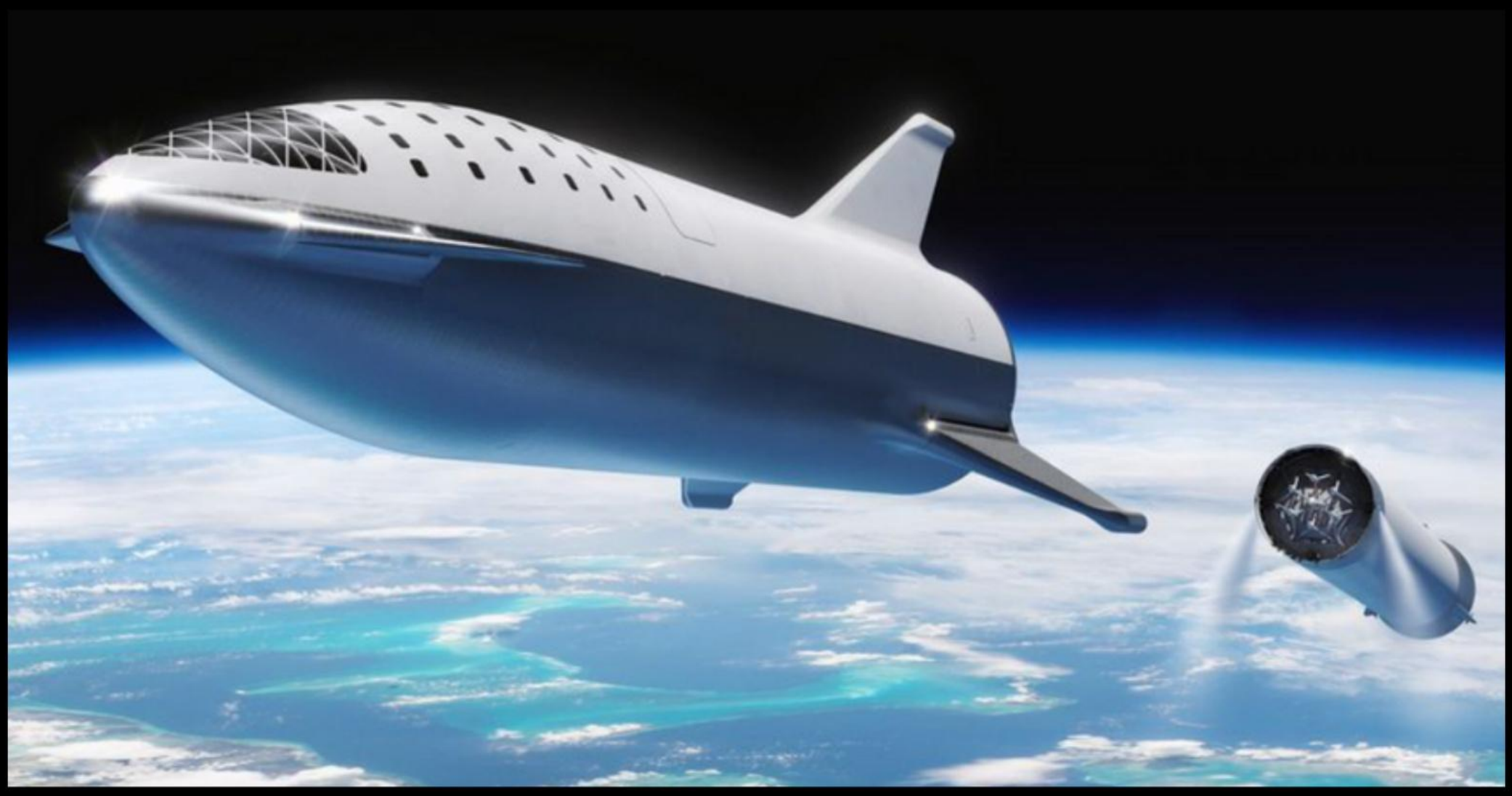
Preliminary Design & Development (2012-2016)

The idea for a Starship-like rocket began in 2012 when Musk began discussing the Mars Colonial Transporter (MCT). MCT was a concept design for a fully reusable vehicle to ferry large groups of adventurous humans and their cargo to the Red Planet.

Interplanetary Transport System (2016)

The MCT concept evolved into the Interplanetary Transport System (ITS), which was announced at the International[14] Astronautical Congress in September 2016. The ITS represented a colossal undertaking, encompassing a massive booster rocket and upper stage spacecraft. This ambitious design featured a booster 122 meters tall and 12 meters in diameter. The spacecraft, intended to carry up to 100 passengers and cargo, would be propelled by dozens of Raptor engines.[15]

The ITS was designed as the epitome of reusability, with its booster returning to Earth after each launch. The spacecraft would then venture to its destination, refuel using locally produced propellants (Mars, we're looking at you), and head back home to Earth. This resourceful process is key to cutting costs and making the dream of Mars colonization a reality.



Transition to BFR and Starship (2017-Present)

In September 2017, Musk revealed a slightly scaled-down and more refined version of the ITS at the International Astronautical Congress. This new design, referred to as the Big Falcon Rocket (BFR), was a more practical and cost-effective approach to space exploration and colonization. The BFR was designed to be 100+ meters tall, with a 9-meter diameter. The revised design maintained the core principles of reusability and affordability while addressing technical and financial challenges associated with the original ITS concept.

In November 2018, Musk announced that BFR would be officially named Starship, while the booster would be called Super Heavy.

Starship Prototypes & Initial Test Flights (2019-2021)

Starhopper (2019):
The Starhopper was the first prototype of the Starship spacecraft, built to test the Raptor engine's performance and validate its basic design principles. Constructed at SpaceX's Boca Chica, Texas facility, Starhopper featured a stainless-steel structure and a single Raptor engine. It completed a low-altitude hop test in August 2019, reaching a height of 150 meters. This test demonstrated the Raptor engine's capabilities and provided valuable data for developing subsequent prototypes.

SN5 and SN6 (2020):
Following the success of Starhopper, SpaceX developed the SN5 and SN6 prototypes to test the vehicle's control systems and landing capabilities. Both prototypes featured a more refined design, with a stainless-steel structure and a single Raptor engine. In August and September 2020, SN5 and SN6 each successfully completed 150-meter hop tests. These tests demonstrated the effectiveness of the vehicle's control systems, landing legs, and thrust vectoring, which are critical for the safe landing of the spacecraft.

Starhopper reached 150 meters

SN5's successful 150-meter hop

High-Altitude Tests (2020-2021):
SpaceX then progressed to high-altitude flight tests, starting with the SN8 prototype.

- SN8 reached a height of 12.5 km but experienced a hard landing due to a loss of pressure in the fuel header tank, causing it to explode upon impact.
- SN9 followed in February 2021, reaching a height of 10 km. However, it also experienced a hard landing due to a failed engine relight, resulting in a similar explosion.
- SN10, tested in March 2021, reached the same altitude as SN9 but managed to land successfully. Unfortunately, a post-landing fire and a subsequent explosion caused by a landing leg failure destroyed the vehicle.
- SN11, launched in March 2021, reached a height of 10 km but experienced an engine issue during its descent, causing it to explode before landing.

In May 2021, SN15 completed a high-altitude flight test, reaching 10 km and landing without incident, marking a significant milestone in the Starship development process.