SpaceX 6
Starship and Super Heavy Booster

Jim Rauf

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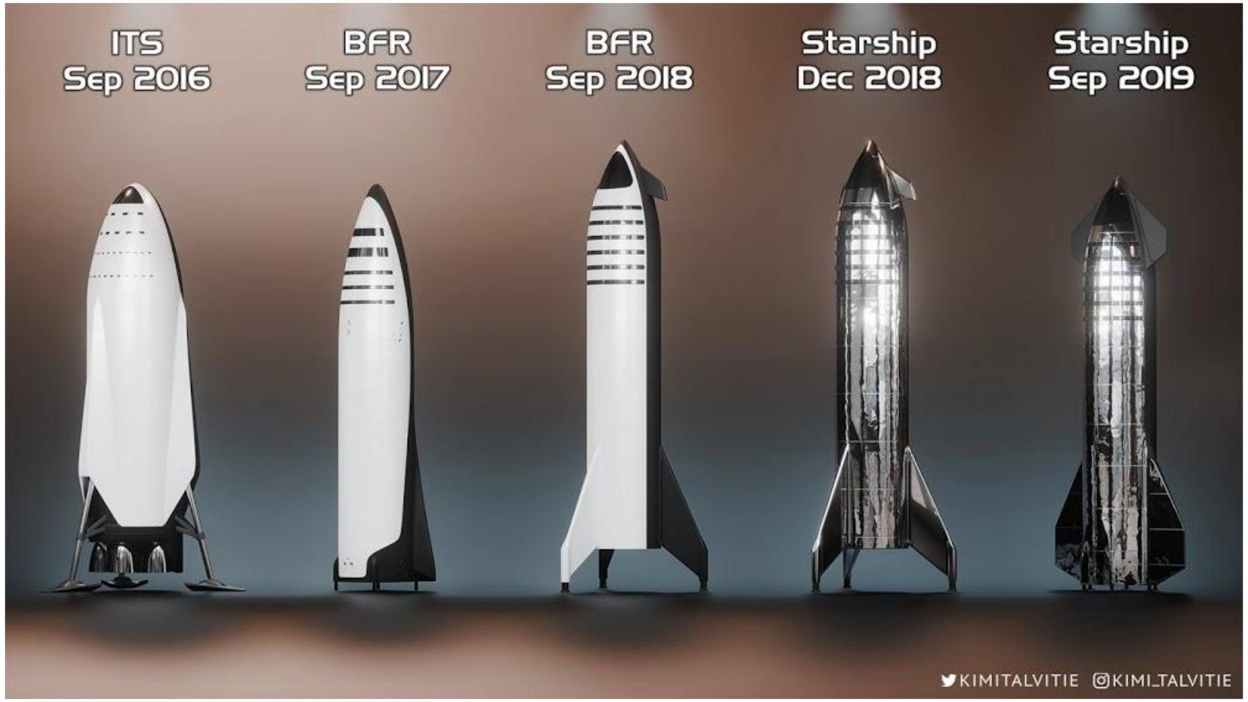
- 2002 **SpaceX** founded
- 2008 **Falcon 1** launch to **LEO**
- 2010 **First Falcon 9** launch
- 2012 First **Cargo Dragon** flight to **ISS**
- 2014 **Falcon 9** first stage was recovered
- 2018 **First Falcon Heavy** launch
- 2019 All three **Falcon Heavy** stages land
- 2020 First **Crew dragon** flight to ISS
- **SpaceX** launches to date
    - **Falcon 9s** 266
    - **Falcon Heavy** 8
- **SpaceX's** next rocket is the **Super Heavy** and **Starship**

Starship System

- 2012 preliminary **Super Heavy** and **Starship ,** previously known as the **Interplanetary Transport System (ITS)** and the **Big Falcon Rocket (BFR**)   design work began
- 2019, **SpaceX** began to refer to the **Starship / Super Heavy** combination as the **Starship System**
- **Starship system's** ultimate mission: to ferry up to 100 peoples to **Mars** on each flight!
- The vehicle is a fully reuseable system:
    - **Super Heavy** first stage
    - **Starship** spacecraft second stage
- First flight of a **Starship Test Article** , **Starhopper**, was July 25,2019
- Test articles and prototypes of **Starship** and **Super Heavy** continue to the present time

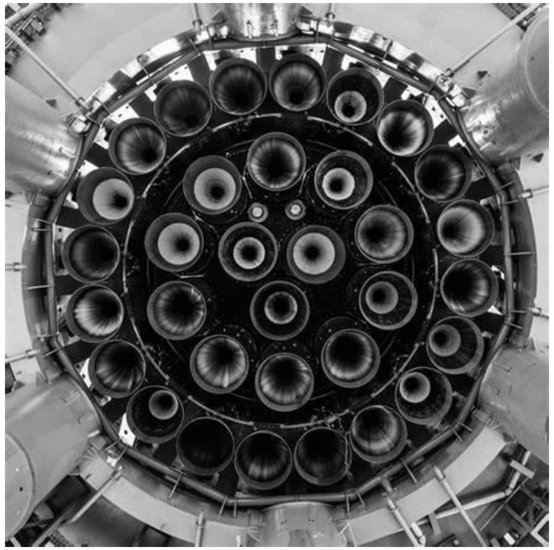


Starship System

- Both stages are made of **301 stainless steel alloy**
  - Composition: Fe, <0.15%C, 16-18%Cr, 6-8%Ni, <2%Mn, <1%Si, <0.045%P, <0.03%S
- **301 Stainless Steel** is about 67 times cheaper than carbon composites and easier to work with and is more tolerant of high temperatures
  - Temperature limit for carbon composites ~400 F
- Both stages use the **SpaceX** designed **Raptor** engines which use cryogenic **Liquid Oxygen LOX** and **Liquid Methane (CH4)**
- **Super Heavy (**first stage**)** has 33 engines generating ~16.7 million + pounds of thrust
- **Starship** (second stage) has 6 engines (3 sea level engines and 3 vacuum) generating ~3.3 million + pounds of thrust

Starship System Super Heavy

- The **Super Heavy** booster is~233 ft tall and ~30 ft in diameter
- It has thirty-three **Raptor** engines arranged in concentric rings
- The outer ring of 20 engines have their **gimbal actuators** removed to save weight and a modified injector with reduced throttle performance in exchange for greater thrust
- Maximum thrust (33 engines) is 17,100,000 lb_f
- The booster's tanks can hold 7,900,000 lb of propellant
- **Liquid oxygen (LOX) ~**6,200,000 lb
- **Liquid methane (CH4) ~**1,800,000 lb
- The final design will have a **dry mass** between ~ 350,000 lb and ~440,000 lb
- The tanks weighing ~180,000 lb
- The interstage weighing ~44,000 lb

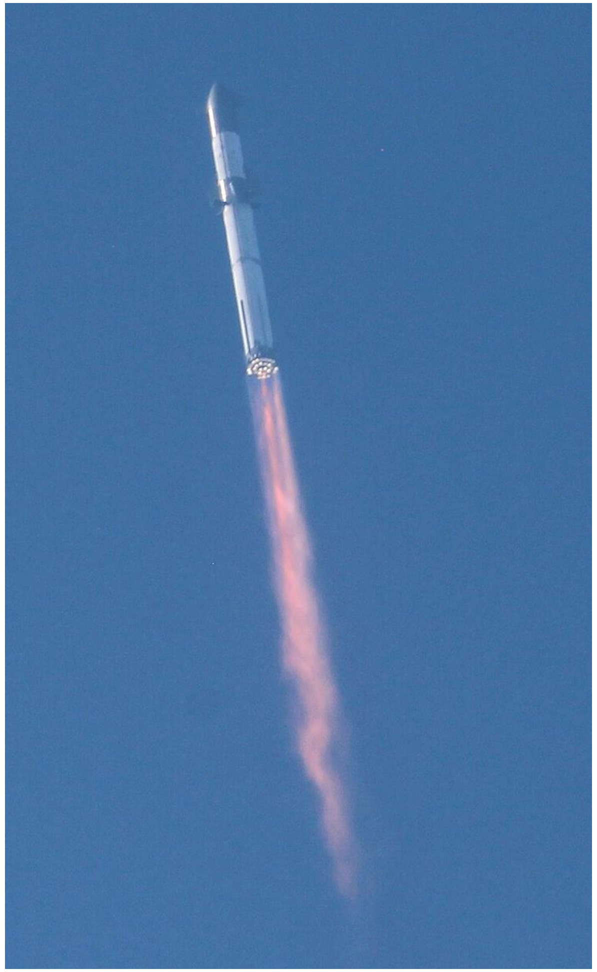


Starship System Super Heavy

- The booster is equipped with four electrically actuated **grid fins** ~ 6,600 lb each
- Adjacent pairs of grid fins are spaced sixty degrees apart
- The **grid fins** do not retract and remain extended during ascent
- The booster has can be lifted through protruding **hardpoints** located between **grid fins**
- The vented interstage is between the booster and the **Starship**
- This enables **Starship** to use **hot staging**
- The second stage separates when some of the first stages engine are still firing – allowing increased pay load
- During unpowered flight in the vacuum of space, **control authority** is provided by **cold gas thrusters** fed with residual **ullage gas**

Starship System Super Heavy Mission

- About one hour and thirty-nine minutes before flight, the super heavy booster begins **propellant load**
- At the T- 16:40 mark, engine chill begins on the booster. This is to protect the engine's turbopumps from thermal shock
- At eight seconds before launch, the thirty-three engines startup-sequence begins
- After liftoff, the engines burn for **169 seconds**
- 30 of its engines shut off, leaving the three center ones running at 50% thrust
- The **Starship** ignites its engines while still attached to the booster and separates
- The boostback burn lasts for 55 seconds
- About eight minutes into the flight, the engines reignite, and the booster is caught by a pair of mechanical arms.



SPACEX Starship System Starship Spacecraft

- The **Starship spacecraft** is ~ 160 ft tall, and ~30 ft in diameter
- It has a has six **Raptor** engines – three "vacuum" engines
- Future vehicles may have an additional 3 Raptor Vacuum engines for increased payload capacity
- The vehicle's **payload bay**, is ~ 56 ft tall by ~ 26 ft in diameter providing a volume of ~35,000 cu ft
- A larger ~ 72 ft tall payload bay can handle larger payloads
- **Starship** has a total propellant capacity of ~2,600,000 lb across its main tanks and header tanks
- The header tanks are better insulated due to their position and are reserved for use to flip and land the spacecraft following reentry
- A set of reaction control thrusters, which use the pressure in the fuel tank, control attitude while in space

Ship 25 atop the Booster 9 at Starbase on Sept. 5, 2023

Starship System Starship Spacecraft

- The spacecraft has four **body flaps,** two forward flaps and two aft flaps , to control the spacecraft's orientation and help dissipate energy during atmospheric entry
- According to **SpaceX,** the flaps replace the need for wings or tailplane, reduce the fuel needed for landing, and allow landing at destinations in the Solar System where runways don't exist **(Mars ?)**
- Under the forward flaps, **hardpoints** are used for lifting and catching the spacecraft via mechanical arms
- The flap's hinges are sealed in aero-covers because they would be easily damaged during reentry

Starship System Starship Spacecraft

- **Starship's heat shield**, composed of thousands of hexagonal black tiles that can withstand temperatures of 2,600 °F, is designed to be used many times without maintenance between flights
- The tiles are made of **silica** and are **attached with pins** rather than glued with small gaps in between to allow for thermal expansion
- Tiles **hexagonal shape** facilitate mass production and prevent hot plasma from causing severe damage to the vehicle

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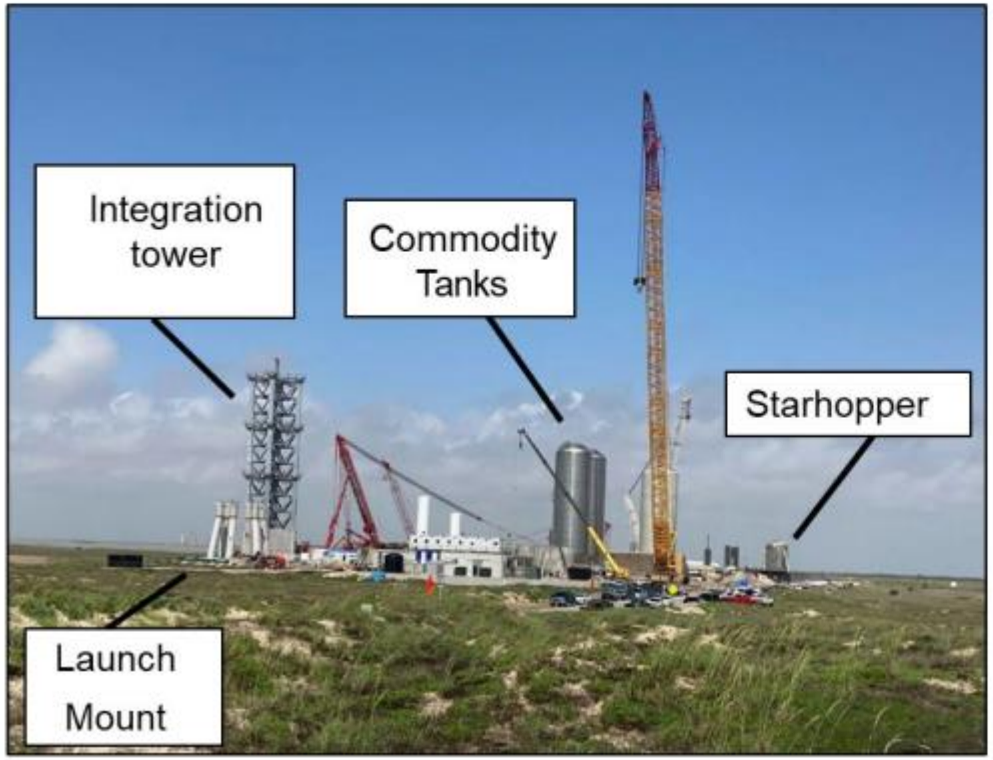
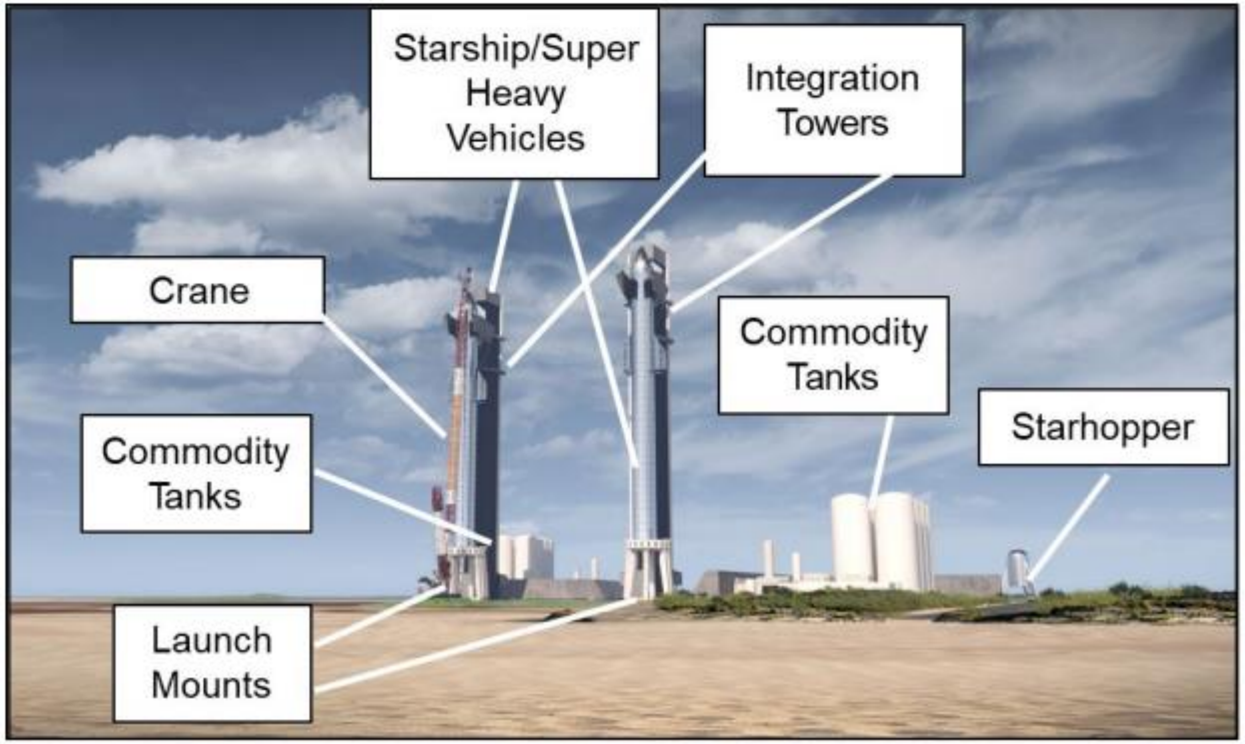
Starship System — Starship Spacecraft Variants

- For **satellite launch**, **Starship** will have a large cargo door that will open to release payloads and close upon reentry
- Instead of a cleanroom, payloads are integrated directly into Starship's payload bay, which requires purging the payload bay with temperature-controlled clean air
- To deploy **Starlink satellites**, the cargo door will be replaced with a slot and dispenser rack
- **Crewed Starship** vehicles would replace the cargo bay with a pressurized crew section and have a life support system
- For long-duration missions, such as crewed flights to **Mars**, **SpaceX** describes the interior as potentially including "private cabins, large communal areas, centralized storage, **solar storm** shelters, and a viewing gallery
- **Artemis Program Human Landing system (HLS)** will have a **NASA** docking system, solar panels and retro propulsion system and some other features to support the Moon landing

Starbase Boca Chica , TX





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Starbase Boca Chica, TX

- **Starship** and **Super Heavy** development and testing is conducted at SpaceX’s “**Starbase**” in **Boca Chica, TX**
- The site feature a launch and landing pad and a 146-meter-tall launch tower
- It is designed **to catch the returning boosters** by closing a pair of arms around the booster
- Work at the **Starbase** has resulted in protests from local residents – noise

Bing Videos

https://www.spacex.com/vehicles/starship/

Raptor Engine

- The Raptor is a cryogenic liquid methane and liquid oxygen powered engine developed by SpaceX
- It is the first **full-flow staged combustion cycle** engine to have flown.
- **Why the Raptor engine uses liquid methane and oxygen propellant**
- Rocket engines provide thrust by forcing a fuel to react with an oxidizer. The reaction between these propellants is what you call combustion.
- Methane is an unusual choice for rocket fuel
- Traditionally, RP-1 (a refined form of kerosene) or hydrogen are the fuels used for launch vehicles
- **SpaceX** chose methane as the **Raptor's fuel** for one main reason – their ambition to go to **Mars**
- **Methane** will be relatively easy to make and keep in the liquid state on **Mars**
- The methane fuel is **cryogenic** – meaning it is cooled to a liquid state
- This **increases the density** of the methane and allows more of it to be carried by the rocket.
- The **Raptor's oxidizer**, oxygen, is **also cryogenic**
- While rocket engines could theoretically use other substances as an oxidizer, liquid oxygen is the only one that has ever been used

Raptor Engine

- **The full-flow staged combustion cycle**
- While other full-flow staged combustion cycle engines have been lab tested in the past, the **Raptor** is the first to have flown
- This type of combustion cycle is particularly complex
- '**Staged combustion**' refers to some of the combustion occurring in **pre-burners** before the main combustion chamber
- These pre-burners drive turbines, which in-turn drive turbopumps
- The turbopumps provide propellant flow to the engine
- '**Full-flow**' refers to <u>all</u> of the propellant passing through a pre-burner
- One pre-burner drives a turbopump for the liquid methane and produces methane-rich gas
- The other pre-burner drives a turbopump for the liquid oxygen and produces oxygen rich gas
- These gases then combust together in the main chamber and provide thrust

- The Raptor uses **regenerative cooling**
- This involves sending the **cryogenic methane** around the outside of the main combustion chamber to keep it cool
- The warmed liquid methane then flows to the pre-burner to continue the cycle
- **Reusability** has been a big consideration in the Raptor's design
- **SpaceX** aims to reuse each engine 1000 times
- As most other rocket engines have had little to no reusability, the cost per flight of the **Raptor** will be comparatively low
- This will make space travel more economical and accessible in the future

Raptor Engine

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- Traditionally, RP-1 (a refined form of kerosene) or hydrogen are the fuels used for launch vehicles
- SpaceX chose methane as the Raptor's fuel for one main reason – their ambition to go to Mars
- Unlike RP-1 and hydrogen, methane will be relatively easy to make and keep in the liquid state on Mars
- This makes missions to Mars possible without the need to bring extra fuel for the return trip

- The methane fuel is cryogenic – meaning it is cooled to a liquid state
- This increases the density of the methane and allows more of it to be carried by the rocket.
- The **Raptor'**s oxidizer, **oxygen**, is also **cryogenic**

Propellant	Boiling Temp		Density	Energy/liter
CH_4	-259 F	(-162 C)	0.46 kg/l	22.0 Mj/l
O_2	-297 F	(-183 C)	1.14 kg/l	----
H_2	-423 F	(-253 C)	0.07 kg/l	10.0 Mj/l

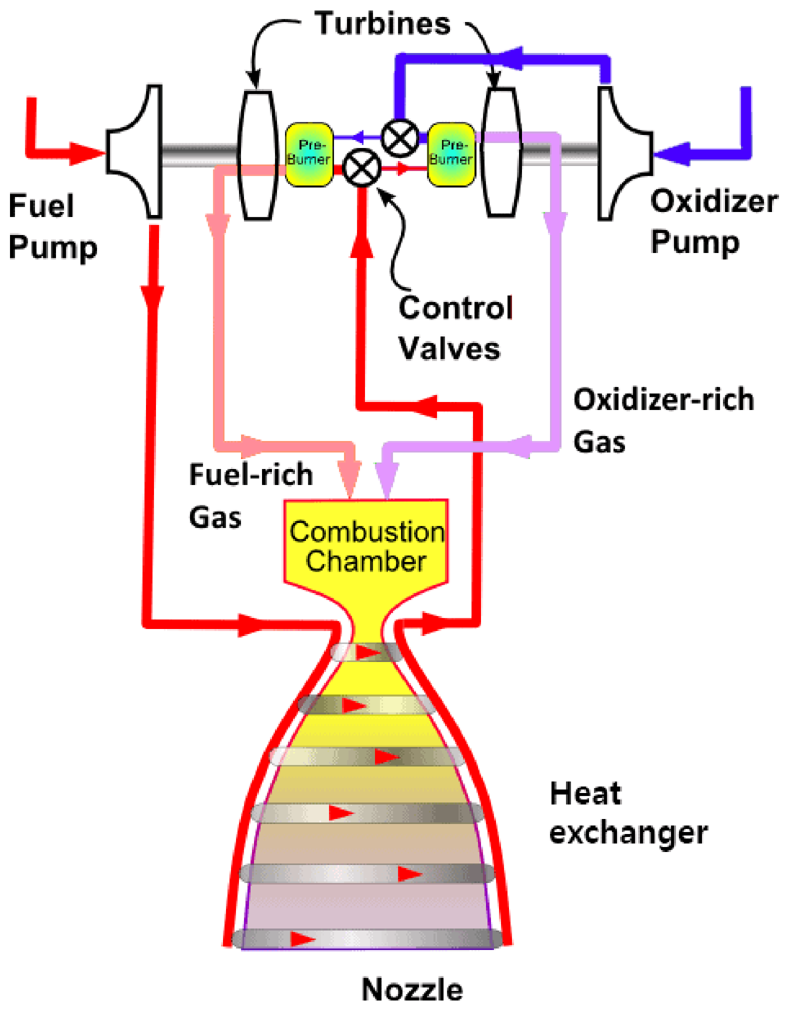
Specific Impulse generated by modern examples of rocket engines (liquid oxygen oxidizer) running on each fuel type:

1. Liquid Hydrogen: 366 – 452 seconds *(Space Shuttle/SLS RS-25 engine)*
2. Liquid Methane: 330 – 350 seconds *(SpaceX Raptor engine)*
3. RP-1 Propellant: 282 – 311 seconds *(SpaceX Merlin engine)*

Raptor Engine

The Full-flow Staged Combustion Cycle

- ‘**Staged combustion**’ refers to some of the combustion occurring in **pre-burners** before the main combustion chamber
- The pre-burners drive **turbines**, which drive **turbopumps**
- The **turbopumps** provide **propellant flow** to the engine
- ‘**Full-flow**’ refers to all of the propellant passing through a pre-burner
- One pre-burner produces **methane-rich gas** and drives a turbopump for the **liquid methane**
- **The other pre-burner produces oxygen-rich gas** and drives a turbopump for **liquid oxygen**
- The two gases combust together in the main chamber and provide thrust



Raptor Engine

The Full-flow Staged Combustion Cycle

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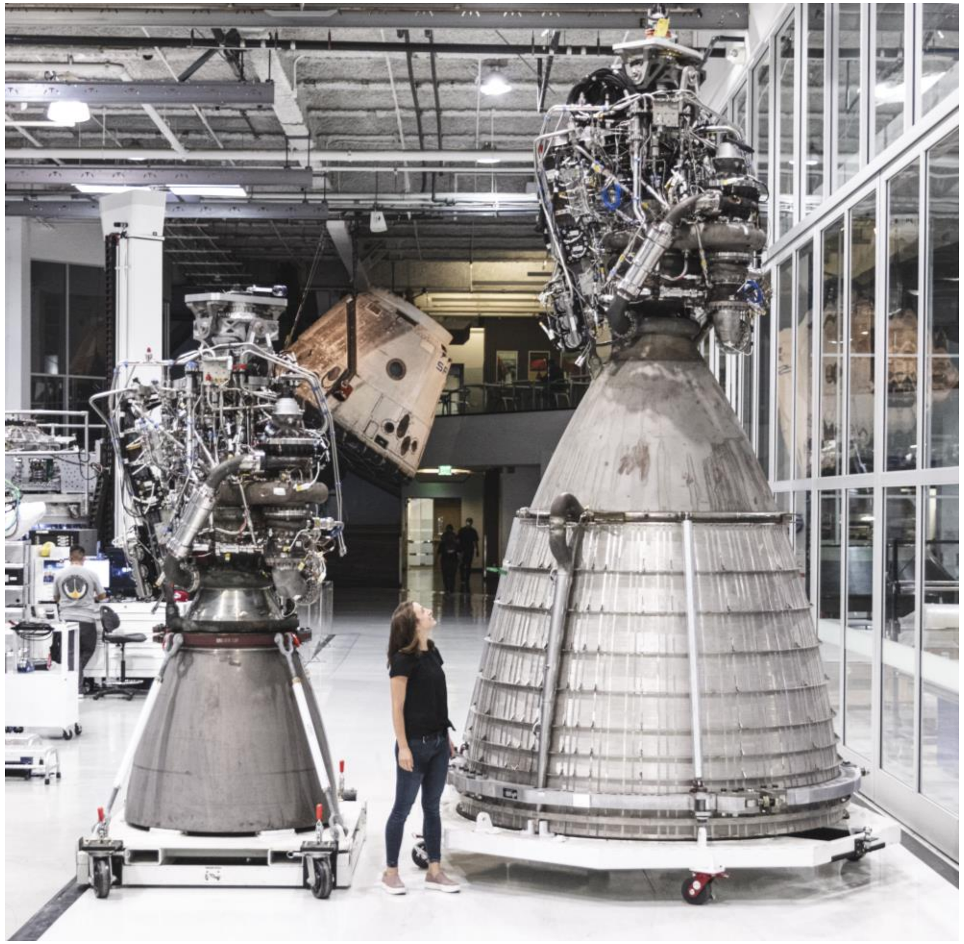
Raptor Engine

The Full-flow Staged Combustion Cycle

- **Raptor** engines are optimized for **atmospheric** operation and **vacuum** operation
- The vacuum optimized engines have larger exhaust exit areas to expand the exhaust gas int the vacuum of space
- **SpaceX** continues to develop the **Raptor** engines
- **Raptor 1** engines thrust
  - 410,000 lb
- **Raptor 2** engines thrust/pressure/Temperature:
  - 510,000 lb sea level /4,400psi/~6,500 F
  - 570,000 lb vacuum
- **Raptor 3** engines:
  - 590,000 lb sea level/5,100 psi/~6,500 F
- Both the **Super Heavy** and the **Starship** have both sea level and vacuum engine



Raptor Engine

Compressible Area Ratio

A = Area　　p_t = Total Pressure　　R = Gas Constant

M = Mach　　T_t = Total Temperature　　γ = Specific Heat Ratio

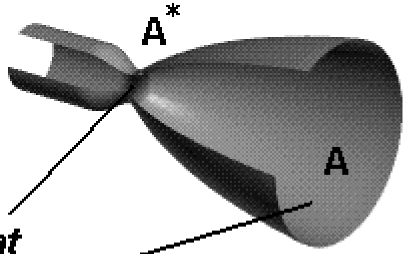
For an ideal compressible gas :

$$\dot{m} = \frac{A\, p_t}{\sqrt{T_t}} \sqrt{\frac{\gamma}{R}}\, M \left(1 + \frac{\gamma - 1}{2} M^2\right)^{-\frac{\gamma+1}{2(\gamma-1)}}$$

Sonic conditions produce maximum mass flow rate.

For M = 1.0:

$$\dot{m} = \frac{A^*\, p_t}{\sqrt{T_t}} \sqrt{\frac{\gamma}{R}} \left(\frac{\gamma + 1}{2}\right)^{-\frac{\gamma+1}{2(\gamma-1)}}$$



Mass flow rate set by choked conditions at nozzle throat

For constant mass flow rate, at any other location:

$$\frac{A}{A^*} = \left(\frac{\gamma + 1}{2}\right)^{-\frac{\gamma+1}{2(\gamma-1)}} \frac{\left(1 + \frac{\gamma - 1}{2} M^2\right)^{\frac{\gamma+1}{2(\gamma-1)}}}{M}$$

Engines optimized for vacuum operation have larger nozzle exit areas than those optimized for sea level or atmospheric operation

Raptor A/A*

Sea Level	~40
Vacuum	~200

Raptor Engine Testing

SpaceX Raptor Engine

Sea Level

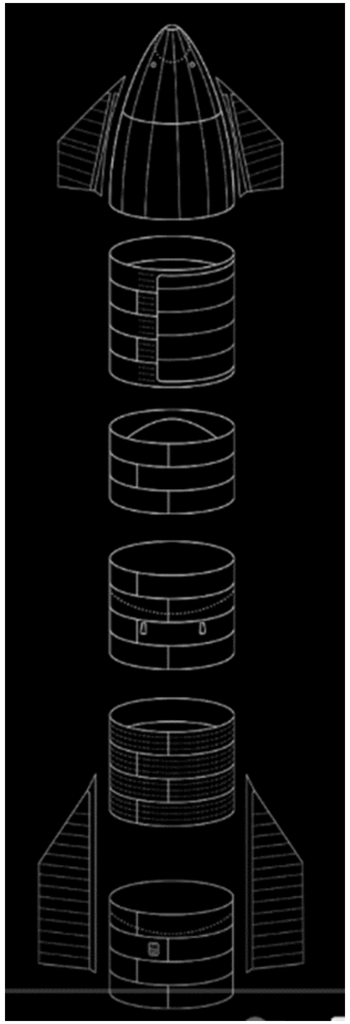
Designation	Raptor Sea-Level
Type	Full-Flow Staged Combustion
Propellant Feed	Multi-Stage Turbopump
Oxidizer	Sub-Cooled Liquid Oxygen
Fuel	Sub-Cooled Liquid Methane
Thrust (Sea Level)	3,050 Kilonewtons
Thrust (Vacuum)	3,297 Kilonewtons
Specific Impulse (SL)	334 Seconds
Specific Impulse (Vac)	361 Seconds
Chamber Pressure	300 bar
Throttle Range	20 – 100%
Ignition	Spark Igniter
Re-Start Capability	Yes
Area Ratio	40
Mixture Ratio	3.8
Flow Rate (Calc.)	931.2kg/sec
LOX Flow Rate	737.2kg/sec
LCH4 Flow Rate	194kg/sec

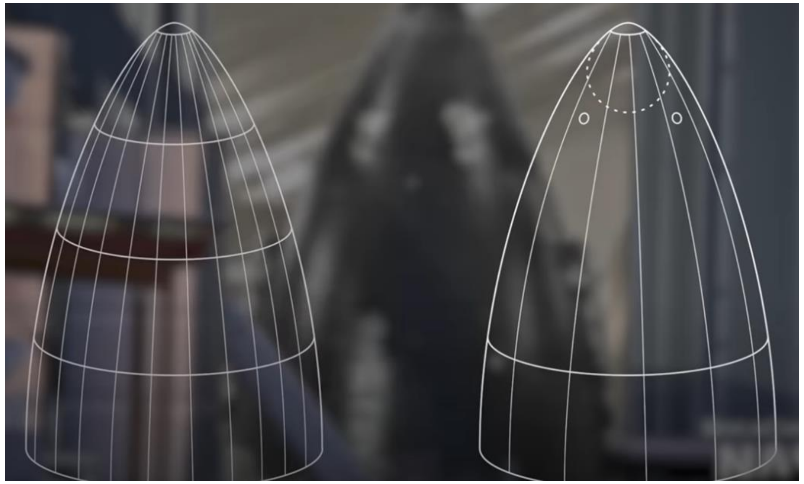
Vacuum

Designation	Raptor Vacuum
Type	Full-Flow Staged Combustion
Propellant Feed	Multi-Stage Turbopump
Oxidizer	Sub-Cooled Liquid Oxygen
Fuel	Sub-Cooled Liquid Methane
Thrust (Vacuum)	3,500 Kilonewtons
Specific Impulse (Vac)	382 Seconds
Chamber Pressure	300 bar
Throttle Range	20 – 100%
Ignition	Spark
Re-Start Capability	Yes
Area Ratio	200
Mixture Ratio	3.8
Flow Rate (Calc.)	931.2kg/sec
LOX Flow Rate	737.2kg/sec
LCH4 Flow Rate	194kg/sec

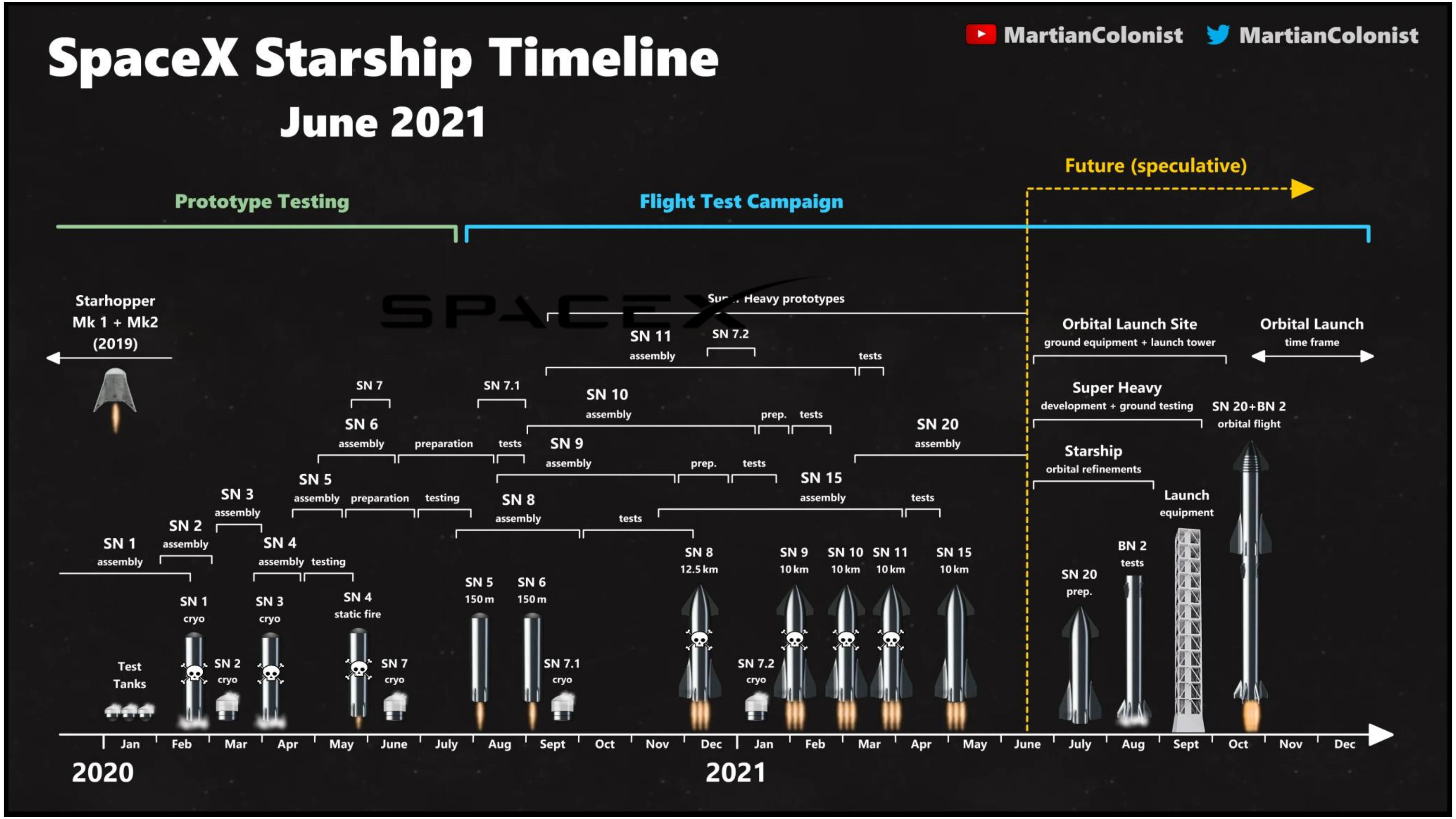
Super Heavy Booster and Starship Construction

- The stainless steel rings that make up the **Starship system's** structure are welded together using **laser welding** or **TIP-TIG welding**
  - **Friction-stir welding** is used on the aluminum material in the **Falcon 9**
- Shapes of **SS** nose one panels has changed on recent prototypes as have configuration of **SS** rings
- The grid fins do not retract and remain extended during ascent
- During unpowered flight in the vacuum of space, **control authority** is provided by cold gas thrusters fed with residual **ullage gas**
  - Space between the top of the propellant load and the top of the tank is known as "**ullage space**"
- The interstage also has protruding **hardpoints**, located between grid fins, allowing the booster to be lifted or caught by the launch tower
- All boosters now have an additional 2m tall vented interstage added, as well as a protective dome





Evolution of Starship System



Integrated Flight Test

April 20, 2023, SpaceX launched the first **Integrated Flight Test** of its **Starship** rocket
The prototype vehicle was destroyed less than four minutes after lifting off from the **SpaceX Starbase** in Boca Chica, Texas.

https://www.youtube.com/watch?v=bl7IqyEyqhY

Next Integrated Flight Test

SpaceX:
Test is ready to go
Awaiting OK from **FAA**

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