SpaceX 6
Starship and Super Heavy Booster
Jim Rauf
1 Introduction: topics, some basics and rocket pioneers
2 SpaceX founding, Musk’s vision, facilities, organization, personnel
3 SpaceX and NASA commercial funding
4 Falcon rockets and engines, Falcon 1, Falcon 9 and Falcon Heavy
5 Dragon spacecraft, Cargo Dragon and Crew Dragon
6 Super Heavy booster and engines and Starship Spacecraft
7 Starship Artemis Moon Human Landing System and Starlink
8 Musk’s Mars vision, plans, challenges and SpaceX summary
• 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 reusable 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

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OLLI Fall 2023
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
• **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

• 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
• 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
• 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.
The **Starship spacecraft** is ~160 ft tall, and ~30 ft in diameter.

It 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.
• 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'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
• 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
Starbase Boca Chica, TX

- **Starship** and **Super Heavy** development and testing is conducted at SpaceX’s “Starbase” in Boca Chica, TX

- The site features 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/
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 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
- 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.
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 all 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
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. 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.

<table>
<thead>
<tr>
<th>Propellant</th>
<th>Boiling Temp</th>
<th>Density</th>
<th>Energy/liter</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH4</td>
<td>-259°F (-162°C)</td>
<td>0.46 kg/l</td>
<td>22.0 Mj/l</td>
</tr>
<tr>
<td>O2</td>
<td>-297°F (-183°C)</td>
<td>1.14 kg/l</td>
<td>----</td>
</tr>
<tr>
<td>H2</td>
<td>-423°F (-253°C)</td>
<td>0.07 kg/l</td>
<td>10.0 Mj/l</td>
</tr>
</tbody>
</table>

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

2. Liquid Methane: 330 – 350 seconds *(SpaceX Raptor engine)*
3. RP-1 Propellant: 282 – 311 seconds *(SpaceX Merlin engine)*
Raptor Engine

- ‘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

• 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
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 into 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 / 4,400 psi / ~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
Engines optimized for vacuum operation have larger nozzle exit areas than those optimized for sea level or atmospheric operation.

### Raptor A/A*

<table>
<thead>
<tr>
<th>Condition</th>
<th>Mass Flow Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sea Level</td>
<td>~40</td>
</tr>
<tr>
<td>Vacuum</td>
<td>~200</td>
</tr>
</tbody>
</table>

**Compressible Area Ratio**

\[
A = \text{Area} \quad p_t = \text{Total Pressure} \quad R = \text{Gas Constant} \\
M = \text{Mach} \quad T_t = \text{Total Temperature} \quad \gamma = \text{Specific Heat Ratio}
\]

For an ideal compressible gas:

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

Sonic conditions produce maximum mass flow rate.

For \(M = 1.0\):

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

Mass flow rate set by choked conditions at nozzle throat.

For constant mass flow rate, at any other location:

\[
\frac{A}{A^*} = \left( \frac{\gamma + 1}{2} \right)^{-\frac{\gamma + 1}{2(\gamma-1)}} \left( 1 + \frac{\gamma - 1}{2} M^2 \right)^{-\frac{\gamma + 1}{2(\gamma-1)}}
\]
Raptor Engine Testing
## SpaceX Raptor Engine

### Sea Level

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

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<tr>
<td>Thrust (Vacuum)</td>
<td>3,500 Kilonewtons</td>
</tr>
<tr>
<td>Specific Impulse (Vac)</td>
<td>382 Seconds</td>
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<td>Chamber Pressure</td>
<td>300 bar</td>
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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
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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