



Safety and Mission Assurance (SMA)



History of Solid Rockets

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- The first true rockets were created by accident
- In the first century, the Chinese had a form of gunpowder consisting of only saltpeter, sulfur, and charcoal dust
- They filled bamboo tubes with this gunpowder mixture and tossed them into fires to create explosions during religious festivals
- Eventually the Chinese began experimenting with these gunpowder-filled bamboo tubes
- First they attached the gunpowder-filled bamboo tubes to arrows and launched them with bows
- Then they discovered that these gunpowder-filled bamboo tubes could launch themselves just by the thrust produced from the escaping gas, which led to the creation of the first true solid-propellant rocket



- The date of the first use of the first true solid-propellant rockets was in 1232
- During the battle of Kai-Keng, the Chinese repelled the Mongol invaders with their flying fire arrows
- These flying fire arrows consisted of a tube filled with gunpowder that was capped at one end and open at the other
- The tube was attached to a long stick that acted as a simple guidance system to prevent the rocket from going off path
- This rocket design is most similar to today's fireworks



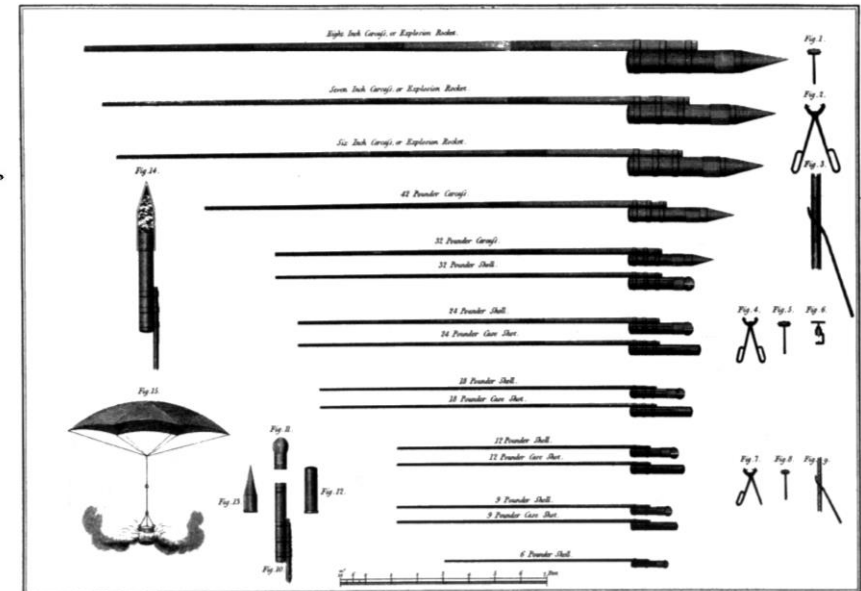
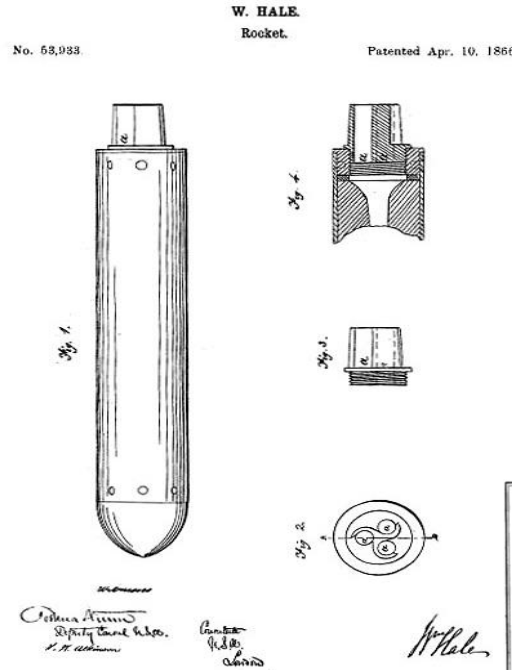
Chinese soldier launches a fire-arrow.

- There is a Chinese legend where rockets were supposedly used as a means of transportation
- A Chinese official ordered the creation of a chair with two large kites with forty-seven fire arrow rockets fixed to it
- Once assembled, the Chinese official sat in the chair and ordered forty-seven rocket assistants to light the fuses
- When the smoke cleared, the Chinese official and the flying chair were both gone
- Seeing as the fire arrows were just as likely to explode as they were to fly, it is possible that the Chinese official and the chair were both blown to pieces if this event actually took place

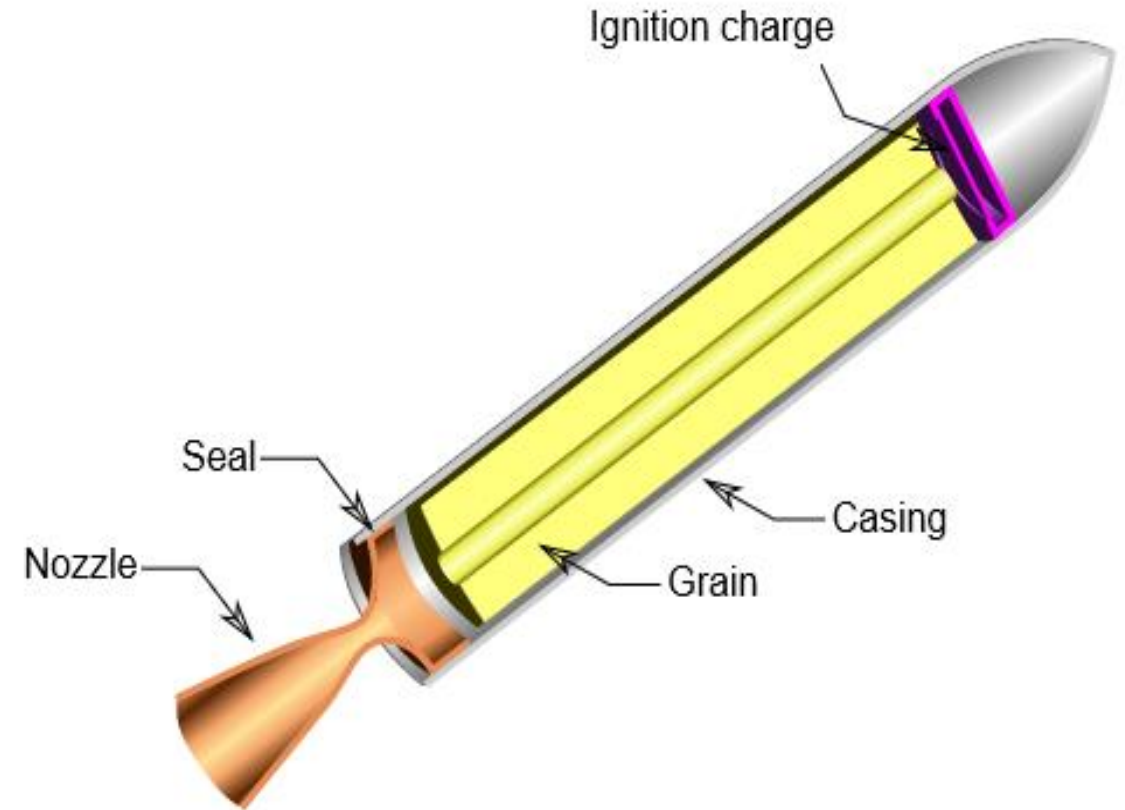


Legendary Chinese official Wan Hu braces himself for "liftoff"

- By the 16th century, rockets were mainly used in firework shows
- A German fireworks maker, Johann Schmidlap, invented the step rocket
 - A large first stage rocket carried a smaller second stage rocket
 - When the first stage rocket ran out of propellant, the second stage rocket continued to a higher altitude
- In the 17th century, Sir Isaac Newton and his three scientific laws impacted the way rockets were designed, increasing understanding of how and why rockets worked
- During the 18th and 19th centuries, British Colonel William Congreve designed several successful “Congreve” rockets which were used in the War of 1812
- In the 19th century, William Hale improved the design and stability of the Congreve rockets by removing the guide stick and instead vectoring some of the thrust through exhaust holes to provide rotation of the rocket



- All rockets used some form of solid or powdered propellant up until the 20th century, when liquid propellant was used more often
- Solid rockets are still used today due to their simplicity and reliability compared to liquid engines
- Since solid-propellant rockets can remain in storage for long periods of time and then reliably launch on short notice, they are frequently used in military applications such as missiles
- Solid propellants have different performance than liquid propellants, so they are used for different purposes
 - Liquid propellants have a higher specific impulse, but a lower total impulse than solid propellants
- Solid rockets are frequently used as boosters in order to increase payload capacity
 - Solid rockets cannot be turned on and off or easily change throttle
 - The Solid Rocket Boosters (SRBs) were used on the Space Shuttle
 - Solid rockets have been used on several recent and current space launch vehicles, including Atlas V and Vulcan





Space Shuttle Solid Rocket Booster Functionality



- Ignition: The SRBs were ignited at T-0
 - Once the SRBs were lit, the rocket began moving and the range safety system was the only thing that could stop the rocket if it went out of control
- Liftoff and Ascent: Timing sequence referencing ignition was important for a successful flight
- Ascent: Accelerometers detected and reported the vehicle's flight and orientation, as flight reference computers translated navigation commands into engine and motor nozzle gimbal commands
- Separation: SRBs were jettisoned at about 146,000 ft (45 km)
- Range Safety System (RSS): The RSS opens up the case and rapidly depressurizes it leading to the extinguishing of the solid propellant; this capability reduced the risk of harm to the public
- Descent: After continuing to rise to about 220,000 feet (67 km) after separation, the SRBs began to fall back to earth and were slowed by a parachute system to prevent damage upon water impact
- Recovery: Specially fitted NASA recovery ships recovered the SRBs and descent/recovery hardware
 - Out of 270 SRB launches over the Shuttle program, all but four were recovered – those from STS-4 (due to a parachute malfunction) and STS-51-L (Challenger disaster)
 - Recovery also allowed post-flight examination of the boosters, identification of anomalies, and incremental design improvements

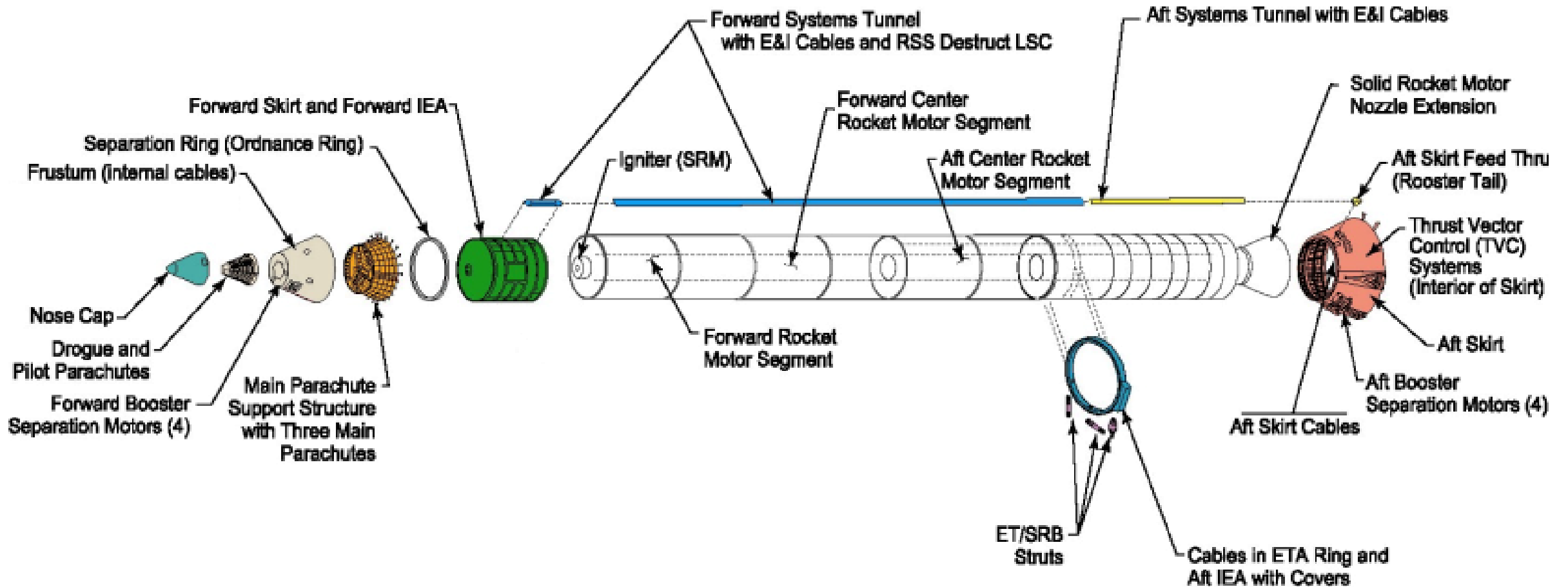


Highlights of the Space Shuttle SRB Design



- **Hold-Down Posts:** Each SRB had four hold-down posts that fit into support posts on the mobile launcher platform
- **Hydraulic Power Units (HPUs):** There were two self-contained, independent HPUs on each SRB, connected by hydraulic system to the rock and tilt servoactuators
- **Ground, Navigation, and Control (GN&C)**
 - **Thrust Vector Controls:** Each SRB had two hydraulic gimbal servoactuators to move the nozzle up/down and side-to-side
 - This provided thrust vectoring to help control the vehicle in all three axes (roll, pitch, and yaw)
 - Each SRB servoactuator consisted of four independent, two-stage servovalves that received signals from the drivers
 - Each servovalve controlled one power spool in each actuator, which positioned an actuator ram and the nozzle to control the direction of thrust
 - **Rate Gyro Assemblies (RGAs):** Each SRB contained three RGAs with each RGA containing one pitch and one yaw gyro
- **Propellant:** The rocket propellant mixture in each solid rocket motor consisted of ammonium perchlorate, atomized aluminum powder, iron oxide, PBAN, and an epoxy curing agent
 - The main fuel, aluminum, was used because it has a reasonable specific energy density with a high volumetric energy density and is difficult to ignite accidentally
 - The propellant had an 11-point star-shaped perforation in the forward motor segment and a double-truncated-cone perforation in each of the aft segments, providing high thrust at ignition with reduced thrust 50 seconds after lift-off to avoid overstressing the vehicle during maximum dynamic pressure (Max Q)
 - Each solid rocket motor contained more than 450,000 kg (1,000,000 lb) of propellant, which requires an extensive mixing and casting operation
 - Thrust of both boosters was equal to 5,300,000 lb
- **Electrical Power Distribution:** Each SRB had orbiter-supplied main DC bus power, cross-strapped to ensure power if one of three orbiter main buses failed

Detailed Space Shuttle SRB Diagram

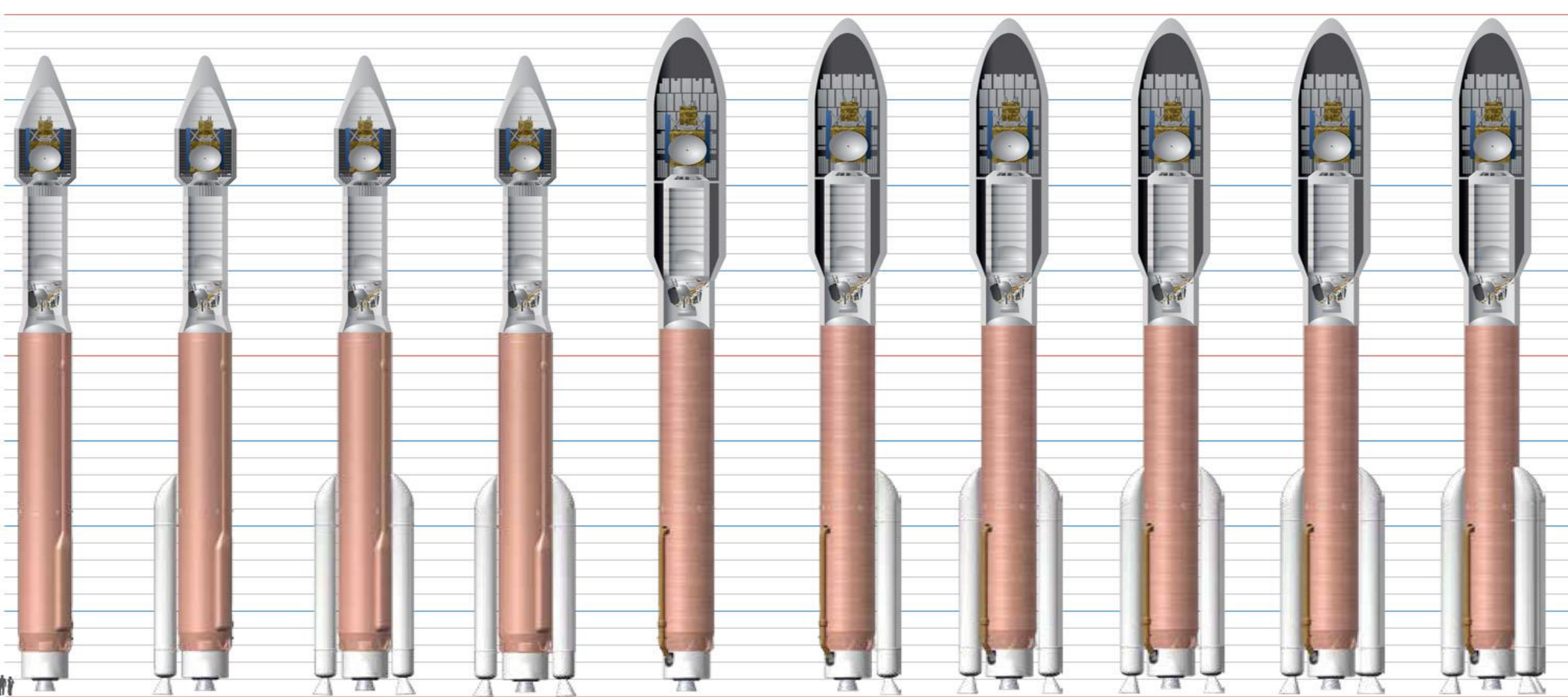




Atlas V



- The United Launch Alliance (ULA) Atlas V uses AJ-60A solid rocket boosters produced by Aerojet Rocketdyne
- Each AJ-60A is 669 inches tall, 62 inches in diameter, weighs 102,949 pounds, and produces 379,600 pounds of thrust
- The Atlas V is an expandable launch system
- Depending on the configuration, anywhere from 0 to 5 AJ-60A solid rocket boosters are used
- Each Atlas V booster configuration has a three-digit designation that indicates the features of that configuration
 - The first digit shows the diameter in meters of the payload fairing, which is always either a 4 or 5
 - The second digit indicates the number of solid rocket boosters attached to the base of the rocket, and can range from 0 to 3 with the 4-meter fairing and from 0 to 5 with the 5-meter fairing
 - All layouts of solid rocket boosters are asymmetrical
 - The third digit represents the number of engines on the Centaur stage, either 1 or 2



Atlas V 401 Atlas V 411 Atlas V 421 Atlas V 431 Atlas V 501 Atlas V 511 Atlas V 521 Atlas V 531 Atlas V 541 11 Atlas V 551



Vulcan

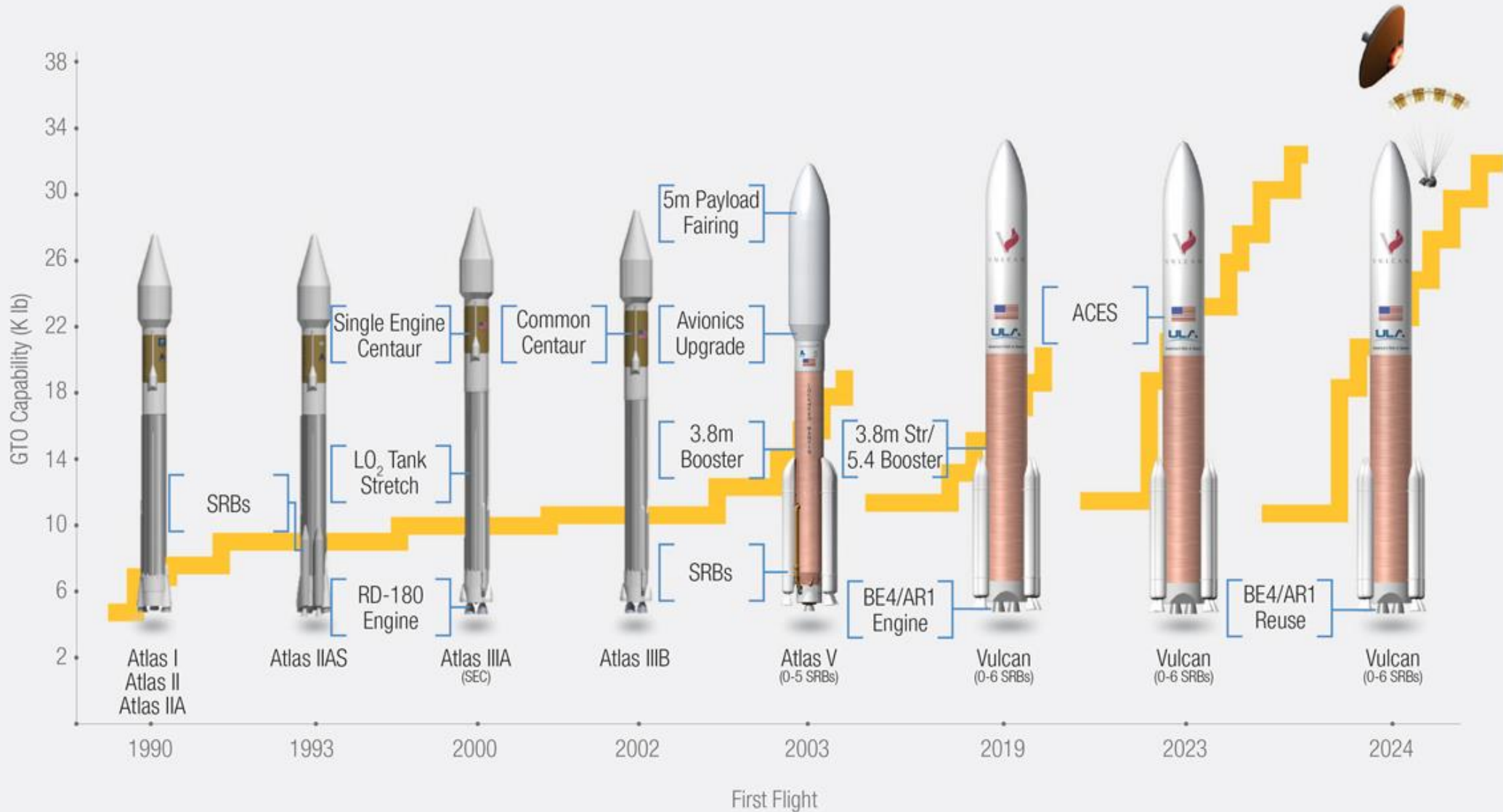


- The ULA Vulcan is a heavy-payload launch vehicle that is expected to launch in 2019
- Several aspects of the Vulcan are derived from other space launch vehicles such as the Delta IV and Atlas V
- Vulcan will initially use the same Centaur upper stage as on Atlas V, and it will be updated later to a more powerful upper stage
- It will also use a variable number of optional solid rocket boosters, called the Graphite-Epoxy Motor (GEM) 63XL, derived from the new solid rocket boosters planned for Atlas V
 - Up to four solid rocket boosters can be used on the 4-meter configuration
 - Up to six solid rocket boosters can be added to the 5-meter configuration



America's Ride to Space

Atlas - Vulcan Evolution





Common Failure Modes (Page 1 of 2)



- Case Breach: Localized burn-through of the case of the rocket that could result in loss of control
- Case Burst: Nozzle blockage or bore choking that results in overpressure in a combustion chamber
- Structural Failure: Large-scale buckling in the case or first to second stage coupling could result in a non-linear vehicle causing aerodynamic drag
 - Small-scale buckling could alter stress/strain levels in the case
- Bore Choking: Occurs when the propellant deforms radially inward and disrupts the exhaust flow, causing a choked flow condition inside the motor
 - Bore choking has the potential of causing booster overpressure and catastrophic failure
- Combustion Instabilities: Instabilities of combustion in the system
- GN&C Failure: An unexpected response or no response to given commands
- Ignition Failure: Failure of ignition in the system

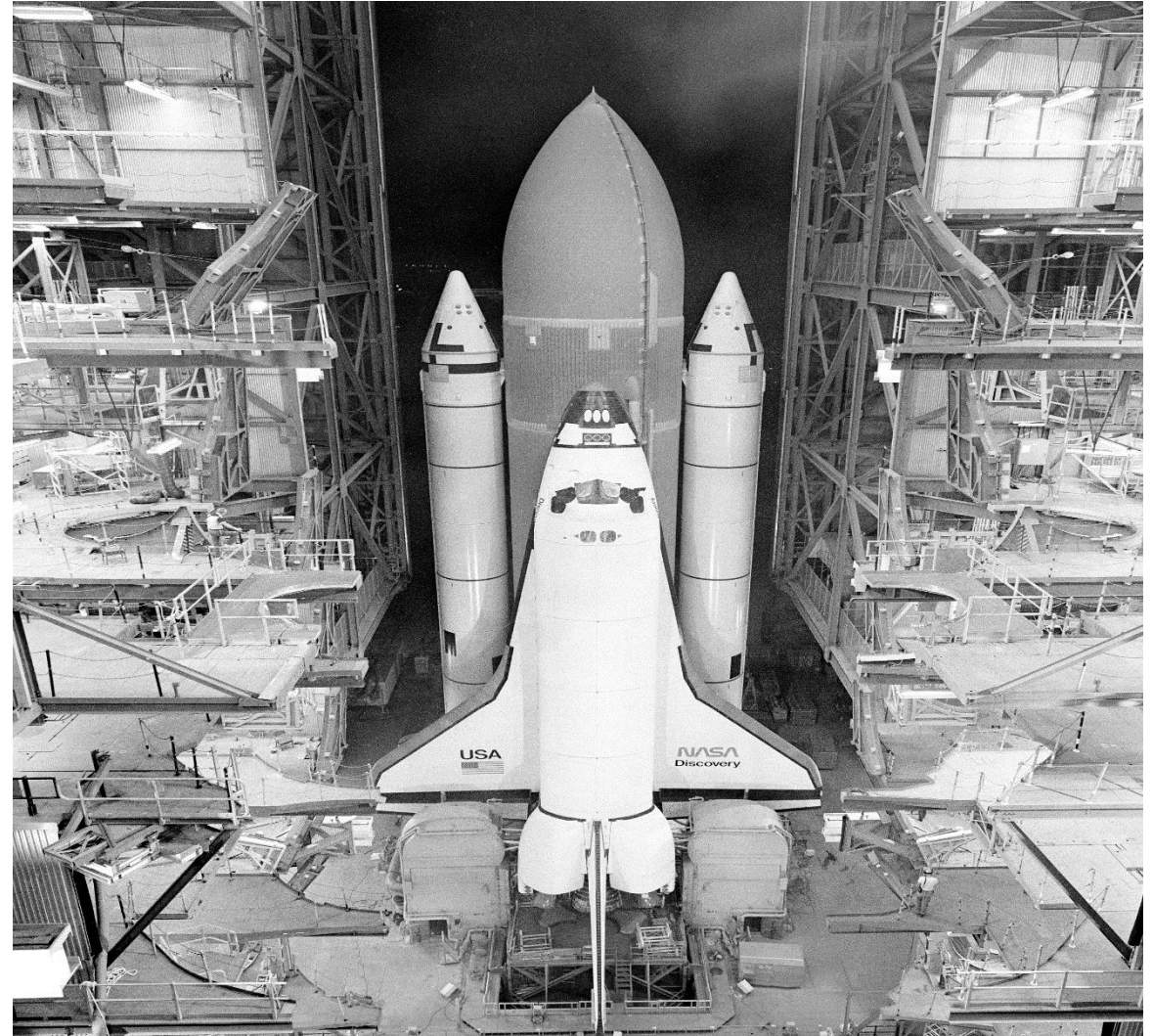


Common Failure Modes (Page 2 of 2)



- **Nozzle Failure:** Deformations of the nozzle that can affect the amount of thrust being generated
 - Breaking off of large pieces of the propellant can temporarily block the nozzle throat
 - A non-uniform failure of the nozzle could result in a non-axial component of thrust
 - A nozzle failure could also result in the plume moving closer to the aft skirt, causing increased heating and possibly affecting the TVC system
- **Debonding:** Potentially large portions of the propellant debond from the liner and become loose
 - The loose propellant can bend and stick inside the bore, possibly leading to bore choking
- **Propellant Structural Failure:** Critical defects such as cracks and voids in the solid propellant and slots of booster joint segments
 - These defects can stimulate the increase of local burn rate due to increased burning surface area
 - A large piece of propellant could also cause choking of the minimum cross section of the nozzle, causing a sharp catastrophic jump of the thrust and possible overpressure in the chamber
- **Propellant/Liner/Insulation (PLI) Bond-Line Failure:** Material properties degradation or contamination

- Solid rockets were created by accident and their design and uses have evolved over time
- Solid rockets are more simple and reliable than liquid rockets, but they have reduced performance capability
- All solid rockets have a similar set of failure modes





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