Launch Goals

- Deliver payload to desired position and velocity, safely, reliably, and on time
  - Low earth orbit: \( \sim 24,000 \text{ ft/s} = \sim 7.3 \text{ km/s} \)
  - Escape: \( >36,000 \text{ ft/s} = \sim 11 \text{ km/s} \)
- Minimize launch cost and propellant use
- Minimize hazard to infrastructure and damage to environment
Launch Vehicle Systems

- Propulsion and Power
  - Main engines
  - Attitude-control thrusters
  - Retro-rockets
  - Ullage rockets
  - Turbo-pumps
  - Batteries, fuel cells
  - Pressurizing bottles
  - Escape/destroy systems

- Structure
  - Skin, frames, ribs, stringers, bulkheads
  - Propellant tanks
  - Fins, control surfaces
  - Inter-stage adapters, fairings
  - Heat shields, insulation

- Electronics
  - Guidance and control computers
  - Sensors and actuators
  - Radio transmitters and receivers
  - Radar transponders
  - Antennas

- Reusable launchers/orbiters
  - Wings, parachutes
  - Landing gear
  - Orbital maneuvering units
  - Robot arms
  - Life support systems (manned vehicle)

Vehicle Mass Components

Initial and final masses of a single-stage rocket

\[ m_i = m_{\text{payload}} + m_{\text{structure/engine}} + m_{\text{propellant}} \]

\[ m_f = m_{\text{payload}} + m_{\text{structure/engine}} \]
Launch Vehicle Configuration Design Goals

- Minimum weight -> sphere
- Minimum drag -> slender body
- Minimum axial load -> low thrust
- Minimum lateral load -> sphere
- Minimum gravity loss -> high thrust

Configuration Design Goals

- Maximum payload -> lightweight structure, high mass ratio, multiple stages, high specific impulse
- Perceived simplicity, improved range safety -> single stage
- Minimum cost -> low-cost materials, economies of scale
- Minimum environmental impact -> non-toxic propellant

# The Rocket Equation

Ideal velocity increment of a rocket stage, $\Delta V_i$ (gravity and aerodynamic effects neglected)

\[
(V_f - V_i) = \Delta V_i = I_{sp} g_o \ln \left( \frac{m_i}{m_f} \right) \equiv I_{sp} g_o \ln \mu
\]

\[m_i = m_{\text{payload}} + m_{\text{structure/engine}} + m_{\text{propellant}}\]

\[m_f = m_{\text{payload}} + m_{\text{structure/engine}}\]

\[\mu \triangleq \frac{m_i}{m_f} : \text{Mass Ratio}\]

\[
\Delta V_i = I_{sp} g_o \ln \left( \frac{m_i}{m_f} \right) = I_{sp} g_o \ln \frac{m_f + m_{\text{propellant}}}{m_f}
\]

### Ideal Velocity Increment for Single Stage with Various Specific Impulses

<table>
<thead>
<tr>
<th>Mass Ratio</th>
<th>Isp = 220 s</th>
<th>= 275 s</th>
<th>= 400 s</th>
<th>= 500 s</th>
<th>= 850 s</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1.50</td>
<td>1.90</td>
<td>2.70</td>
<td>3.40</td>
<td>5.78</td>
</tr>
<tr>
<td>3</td>
<td>2.40</td>
<td>3.00</td>
<td>4.30</td>
<td>5.30</td>
<td>9.16</td>
</tr>
<tr>
<td>4</td>
<td>3.00</td>
<td>3.80</td>
<td>5.40</td>
<td>6.80</td>
<td>11.56</td>
</tr>
<tr>
<td>5</td>
<td>3.50</td>
<td>4.30</td>
<td>6.30</td>
<td>7.90</td>
<td>13.42</td>
</tr>
</tbody>
</table>

Single stage to orbit with payload ($\Delta V_i \sim 7.3$ km/s)?

\[
\mu_{\text{required}} = e^{\Delta V_i / I_{sp} g_o}
\]
Required Mass Ratio for Various Velocity Increments

\[ \mu_{\text{required}} = e^{\Delta V_i / I_{sp} g_0} \]

<table>
<thead>
<tr>
<th>Ideal Velocity Increment, km/s</th>
<th>Isp = 240 s</th>
<th>= 400 s</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>19.6</td>
<td>6.0</td>
</tr>
<tr>
<td>8</td>
<td>29.9</td>
<td>7.7</td>
</tr>
<tr>
<td>9</td>
<td>45.7</td>
<td>9.9</td>
</tr>
<tr>
<td>10</td>
<td>69.9</td>
<td>12.8</td>
</tr>
<tr>
<td>11</td>
<td>106.9</td>
<td>16.5</td>
</tr>
<tr>
<td>12</td>
<td>163.5</td>
<td>21.3</td>
</tr>
</tbody>
</table>

... and there are velocity losses due to gravity and aerodynamic drag

Ratios Characterizing a Rocket Stage

\[ \mu = \frac{m_{\text{initial}}}{m_{\text{final}}} \]
\[ \lambda = \frac{m_{\text{payload}}}{m_{\text{initial}}} \]
\[ \eta = \frac{m_{\text{structure/engine}}}{m_{\text{initial}}} \]
\[ \epsilon = \frac{m_{\text{propellant}}}{m_{\text{initial}}} = \frac{\mu - 1}{\mu} \]

\[ \lambda + \eta + \epsilon = 1 \]

Payload is what’s left after propellant and structure are subtracted
Ideal Velocity Increment for a Two-Stage Rocket

For each stage

\[ \Delta V_{I_j} = I_{sp_j} g_o \ln \frac{m_{pay_j} + m_{s/e_j} + m_{prop_j}}{m_{pay_j} + m_{s/e_j}}, \quad j = 1, 2 \]

For both stages

\[ \Delta V_I = \Delta V_{I_1} + \Delta V_{I_2} = I_{sp_1} g_o \ln \frac{m_{pay_1} + (m_{s/e_1} + m_{prop_1})}{m_{pay_1} + m_{s/e_1}} + I_{sp_2} g_o \ln \frac{m_{pay_2} + m_{s/e_2} + m_{prop_2}}{m_{pay_2} + m_{s/e_2}} \]

\[ = I_{sp_1} g_o \ln \frac{m_{init_2} + (m_{s/e_1} + m_{prop_1})}{m_{init_2} + m_{s/e_1}} + I_{sp_2} g_o \ln \left( \frac{m_{pay_2} + m_{s/e_2} + m_{prop_2}}{m_{pay_2} + m_{s/e_2}} \right) \]

\[ = g_o \left[ I_{sp_1} \ln \mu_1 + I_{sp_2} \ln \mu_2 \right] \]

Ideal Velocity Increment for a Multiple-Stage Rocket

- Ideal velocity increment of an \( n \)-stage rocket

\[ \Delta V_I = g_o \sum_{j=1}^{n} I_{sp_j} \ln \mu_j \]

- With equal specific impulses

\[ \Delta V_I = I_{sp} g_o \ln (\mu_1 \cdot \mu_2 \cdot \ldots \mu_n) = I_{sp} g_o \ln (\mu_{overall}) = I_{sp} g_o \ln \mu^n \]
Required Mass Ratios for Multiple-Stage Rockets

- Staging reduces *individual mass ratios* to achievable values
- With equal specific impulses for each stage

### Required Individual Mass Ratio

<table>
<thead>
<tr>
<th>Ideal Velocity Increment, km/s</th>
<th>Single Stage</th>
<th>Two Stages</th>
<th>Three Stages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isp = 240 s = 400 s = 850 s</td>
<td>Isp = 240 s = 400 s = 850 s</td>
<td>Isp = 240 s = 400 s = 850 s</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>19.55</td>
<td>5.95</td>
<td>2.32</td>
</tr>
<tr>
<td></td>
<td>4.42</td>
<td>2.44</td>
<td>1.52</td>
</tr>
<tr>
<td></td>
<td>1.69</td>
<td>1.81</td>
<td>1.32</td>
</tr>
<tr>
<td>8</td>
<td>29.90</td>
<td>7.68</td>
<td>2.61</td>
</tr>
<tr>
<td></td>
<td>5.47</td>
<td>2.77</td>
<td>1.62</td>
</tr>
<tr>
<td></td>
<td>3.10</td>
<td>1.97</td>
<td>1.38</td>
</tr>
<tr>
<td>9</td>
<td>45.72</td>
<td>9.91</td>
<td>2.94</td>
</tr>
<tr>
<td></td>
<td>6.76</td>
<td>3.15</td>
<td>1.72</td>
</tr>
<tr>
<td></td>
<td>3.58</td>
<td>2.15</td>
<td>1.43</td>
</tr>
<tr>
<td>10</td>
<td>69.92</td>
<td>12.79</td>
<td>3.32</td>
</tr>
<tr>
<td></td>
<td>8.36</td>
<td>3.58</td>
<td>1.82</td>
</tr>
<tr>
<td></td>
<td>4.12</td>
<td>2.34</td>
<td>1.49</td>
</tr>
<tr>
<td>11</td>
<td>106.92</td>
<td>16.50</td>
<td>3.74</td>
</tr>
<tr>
<td></td>
<td>10.34</td>
<td>4.06</td>
<td>1.93</td>
</tr>
<tr>
<td></td>
<td>4.75</td>
<td>2.55</td>
<td>1.55</td>
</tr>
<tr>
<td>12</td>
<td>163.50</td>
<td>21.29</td>
<td>4.22</td>
</tr>
<tr>
<td></td>
<td>12.79</td>
<td>4.61</td>
<td>2.05</td>
</tr>
<tr>
<td></td>
<td>5.47</td>
<td>2.77</td>
<td>1.62</td>
</tr>
</tbody>
</table>

**https://en.wikipedia.org/wiki/Multistage_rocket**

### Mass-Ratio Effect on Final Load Factor

- Thrust-to-weight ratio = load factor
  
  \[
  \frac{\text{Thrust}}{\text{Weight}} = n \text{ (load factor)} = \frac{Thrust}{mg_o}
  \]

  \[
  n_{\text{initial}} = \frac{Thrust}{m_{\text{initial}}g_o}; \quad n_{\text{final}} = \frac{Thrust}{m_{\text{final}}g_o}
  \]

- If thrust is constant
  
  \[
  \frac{n_{\text{final}}}{n_{\text{initial}}} = \frac{m_{\text{initial}}}{m_{\text{final}}} = \mu
  \]

- If thrust is reduced, limit load factor can be enforced

<table>
<thead>
<tr>
<th>Initial Load Factor</th>
<th>Mass Ratio = 2</th>
<th>Mass Ratio = 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.3</td>
<td>2.6</td>
<td>6.5</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>10</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>15</td>
</tr>
</tbody>
</table>
Overall Payload Ratio of a Multiple-Stage Rocket

\[ \lambda_{\text{overall}} = \frac{m_{\text{payload}}}{m_{\text{initial}}} = \left( \frac{m_{\text{payload}}}{m_{\text{initial}}} \right)_n \left( \frac{m_{\text{payload}}}{m_{\text{initial}}} \right)_{n-1} \cdots \left( \frac{m_{\text{payload}}}{m_{\text{initial}}} \right)_1 = \lambda_1 \cdot \lambda_2 \cdot \ldots \lambda_n \]

Feasible design goal: Choose stage mass ratios to maximize overall payload ratio

Payload Ratios of a Two-Stage Rocket

- For equal specific impulses

\[ \Delta V = I_{sp} g_o \left[ \ln \mu_1 + \ln \mu_2 \right] = I_{sp} g_o \left[ \ln \mu_1 \mu_2 \right] = I_{sp} g_o \left[ \ln \mu_{\text{overall}} \right] \]

- Payload ratios for different structural ratios

\[ \lambda_1 = 1 - \eta_1 = \frac{1 - \mu_1 \eta_1}{\mu_1} \]
\[ \lambda_2 = \frac{1 - \mu_2 \eta_2}{\mu_2} \]
Maximum Payload Ratio of a Two-Stage Rocket

Overall payload ratio

$$\lambda_{overall} = \lambda_1 \lambda_2 = \frac{(1 - \mu_1 \eta_1)(1 - \mu_2 \eta_2)}{\mu_{overall}}$$

Condition for a maximum with respect to first stage mass ratio

$$\frac{\partial \lambda_{overall}}{\partial \mu_1} = \frac{-\eta_1 + \mu_{overall} \eta_2}{\mu_{overall}} = 0$$

Maximum Payload Ratio of a Two-Stage Rocket

Optimal stage mass ratios

$$\mu_1 = \sqrt{\frac{\mu_{overall} \eta_2}{\eta_1}}; \quad \mu_2 = \sqrt{\frac{\mu_{overall} \eta_1}{\eta_2}}$$

Optimal payload ratio

$$\lambda_{overall} = \frac{1}{\mu_{overall}} - 2 \sqrt{\frac{\eta_1 \eta_2}{\mu_{overall}}} + \eta_1 \eta_2$$

Also see

http://www.princeton.edu/~stengel/Prop.pdf
Scout Launch Vehicle
*(1961-1994)*

- Liftoff mass = 16,450 kg
- 4 solid-rocket stages
- Overall mass ratio = 34
- Overall payload ratio = 0.00425
  = 0.425% (67-kg payload)

**Typical Figures for Scout**

<table>
<thead>
<tr>
<th>Stage</th>
<th>Isp, s, vac (SL)</th>
<th>Mass Ratio</th>
<th>Payload Ratio</th>
<th>Structural Ratio</th>
<th>Impact Range, km</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (Algol)</td>
<td>284 (238)</td>
<td>2.08</td>
<td>0.358</td>
<td>0.123</td>
<td>~60</td>
</tr>
<tr>
<td>2 (Castor)</td>
<td>262 (232)</td>
<td>2.33</td>
<td>0.277</td>
<td>0.152</td>
<td>~250</td>
</tr>
<tr>
<td>3 (Antares)</td>
<td>295</td>
<td>2.53</td>
<td>0.207</td>
<td>0.189</td>
<td>~2500</td>
</tr>
<tr>
<td>4 (Altair)</td>
<td>280</td>
<td>2.77</td>
<td>0.207</td>
<td>0.154</td>
<td>Orbit</td>
</tr>
</tbody>
</table>

- High volumetric specific impulse is desirable for first stage of multi-stage rocket
- Strap-on solid rocket boosters are a cost-effective way to increase mass and payload ratios
Expendable vs. Reusable Launch Vehicles

- **Expendable Vehicle**
  - Low cost per vehicle
  - New vehicle for each launch
  - Low structural ratio
  - Continued production
  - Launch preparation
  - Upgrade in production

- **Reusable Vehicle**
  - High initial cost
  - High structural ratio
  - Maintenance and repair
  - Non-reusable parts and supplies
  - Launch preparation
  - Return to launch site
  - Upgrade
  - Replacement cost

Heavy-Lift “Big Dumb Boosters”

c. 1963

*Objective: 450,000 kg to low earth orbit*

Douglas Single-Stage-to-Orbit

- Plug nozzle
- Nozzle = Reentry Heat Shield
- Fully recoverable

General Dynamics, Martin, and Douglas Concepts

- 1-1/2 stage, fully recoverable
- Recovery at sea
- Ducted rocket
Vertical Takeoff, Horizontal Landing Vehicles

Martin Astro-Rocket

Heat shield-to-heat shield

General Dynamics Triamese

Three “identical” parallel stages

Horizontal vs. Vertical Launch

- Feasibility of “airline-like” operations?
- Use of high $I_{sp}$ air-breathing engines
- Rocket stages lifted above the sensible atmosphere
- Flexible launch parameters
Pegasus Air-Launched Rocket

- Orbital-ATK
- Three solid-rocket stages launched from an aircraft
- Aerodynamic lift used to rotate vehicle for climb

Initial mass: 18,000 to 23,000 kg
Payload mass: 440 kg

Virgin Galactic LauncherOne and Vulcan Aerospace Stratolauncher

Two mated B747-400s
Pegasus 2
Specific Energy Contributed in Boost Phase

Total Energy = Kinetic plus Potential Energy
(relative to flat earth)

\[ E = \frac{mV^2}{2} + mgh \]

Specific Total Energy = Energy per unit weight = Energy Height (km)

\[ E' = \frac{V^2}{2g} + h \]

Specific Energy Contributed in Boost Phase

Specific Energy contributed by first stage of launch vehicle
Less remaining drag loss (typical)
Plus Earth’s rotation speed (typical)

<table>
<thead>
<tr>
<th></th>
<th>Altitude, km</th>
<th>Mach Number</th>
<th>Earth-Relative Velocity, km/s</th>
<th>Remaining Drag Loss, km/s</th>
<th>Earth Rotation Speed, km/s</th>
<th>Specific Kinetic Energy, km</th>
<th>Total Specific Energy, km</th>
<th>Percent of Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scout 1st-Stage Burnout</td>
<td>22</td>
<td>4</td>
<td>1.2</td>
<td>0.05</td>
<td>0.4</td>
<td>123.42</td>
<td>145.42</td>
<td>3.93%</td>
</tr>
<tr>
<td>Subsonic Horizontal Launch</td>
<td>12</td>
<td>0.8</td>
<td>0.235</td>
<td>0.15</td>
<td>0.4</td>
<td>12.05</td>
<td>24.05</td>
<td>0.65%</td>
</tr>
<tr>
<td>Supersonic Horizontal Launch</td>
<td>25</td>
<td>3</td>
<td>0.93</td>
<td>0.04</td>
<td>0.4</td>
<td>85.57</td>
<td>110.57</td>
<td>2.99%</td>
</tr>
<tr>
<td>Scramjet Horizontal Launch</td>
<td>50</td>
<td>12</td>
<td>3.6</td>
<td>0</td>
<td>0.4</td>
<td>829.19</td>
<td>879.19</td>
<td>23.74%</td>
</tr>
<tr>
<td>Target Orbit</td>
<td>300</td>
<td>25</td>
<td>7.4</td>
<td>0</td>
<td>0.4</td>
<td>3403.34</td>
<td>3703.34</td>
<td></td>
</tr>
</tbody>
</table>
Trans-Atmospheric Vehicles
(Aerospace Planes)

• **Power for takeoff**
  – Turbojet/fans
  – Multi-cycle air-breathing engines/scramjets
  – Rockets

• **Single-stage-to-orbit**
  – Carrying dead weight into orbit
  – High structural ratio for wings, powerplants, and reusability
  – SSTO has very low payload ratio

---

Trans-Atmospheric Vehicle Concepts

*Various approaches to staging*

- Boeing TAV
- Rockwell TAV
- Rockwell StarRaker
- Lockheed Clipper
- Lockheed TAV
Venture Star/X-33

- Reusable, single-stage-to-orbit, proposed Space Shuttle replacement
- Advertised payload ratio = 2% (dubious)
- X-33: Sub-orbital test vehicle
- Improved thermal protection
- Linear spike nozzle rocket
- Program cancelled following tank failure in X-33 testing

ULA Atlas Evolution
ULA Delta Evolution

Orbital-ATK Minotaur and Antares

Minuteman ICBM Derivative

RD-181 Motor

10/28/2014 Failure https://www.youtube.com/watch?v=9V1_BiTkHJ4
Blue Origin New Shepard and OTS

ULA Vulcan Launcher

Successor to Delta 4 Heavy and Atlas Heavy

- 0 – 6 Orbital-ATK solid-rocket boosters
- LOX/Methane 1st stage, derived from Delta 4 (2 Blue Origin BE-4)
- LOX/LH2, Centaur or ACES 2nd stage (1 or 4 Aerojet Rocketdyne RL-10C)
Firefly Launch Vehicle and Aero-Plug Motor

PERFORMANCE
Payload / 200 kg to Sun Synchronous Orbit

PROPULSION: STAGE 1
Engine / F6E-2
Propellant / Lox / RP-1
Cycle / Pressure-fed
Configuration / Plug cluster aerospike
Thrust (SL) / 99,800 lbf
Isp (vac) / 299 sec

PROPULSION: STAGE 2
Engine / F6E-1
Propellant / Lox / RP-1
Cycle / Pressure-fed
Configuration / Conventional bell
Thrust (vac) / 6,200 lbf
Isp (vac) / 325 sec

STRUCTURES
Stage 1 Diameter / 6 ft
Stage 2 Diameter / 5 ft
Materials / Carbon composite

SpaceX Falcon 9, Heavy

- Falcon Heavy
  - Payload to Low Earth Orbit – 53,000 kg
  - Payload to Geosynchronous Orbit = 21,200 kg
  - Liftoff Mass = 1.462 x 10^6
  - 2 stages, plus 2 boosters, all LOX/RP-1
  - 27 Merlin 1D (SL) 1st stage rockets
  - 1 Merlin 1D (vac) 2nd stage rocket
Launch Vehicle Structural Loads

- **Static/quasi-static loads**
  - Gravity and thrust
  - Propellant tank internal pressure
  - Thermal effects
    - Rocket
    - Cryogenic propellant
    - Aerodynamic heating

- **Dynamic loads**
  - Bending and torsion
  - “Pogo” oscillations
  - Fuel sloshing
  - Aerodynamics and thrust vectoring

- **Acoustic and mechanical vibration loads**
  - Rocket engine
  - Aerodynamic noise
Structural Material Properties

- Stress, $\sigma$: Force per unit area
- Strain, $\varepsilon$: Elongation per unit length

$$\sigma = E \varepsilon$$

Proportionality factor, $E$: Modulus of elasticity, or Young’s Modulus

Strain deformation is reversible below the elastic limit

Elastic limit = yield strength

Proportional limit ill-defined for many materials

![Graph showing stress-strain relationship with elastic limit and proportional limit]

Material Properties (Wikipedia)

<table>
<thead>
<tr>
<th>Material</th>
<th>Young’s Modulus, GPa</th>
<th>Elastic Limit, MPa</th>
<th>Density, g/cm³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum Alloy</td>
<td>69</td>
<td>400</td>
<td>2.7</td>
</tr>
<tr>
<td>Carbon-Fiber Composite</td>
<td>530</td>
<td>-</td>
<td>1.8</td>
</tr>
<tr>
<td>Fiber-Glass Composite</td>
<td>125-150</td>
<td>-</td>
<td>2.5</td>
</tr>
<tr>
<td>Magnesium</td>
<td>45</td>
<td>100</td>
<td>1.7</td>
</tr>
<tr>
<td>Steel</td>
<td>200</td>
<td>250-700</td>
<td>7.8</td>
</tr>
<tr>
<td>Titanium</td>
<td>105-120</td>
<td>830</td>
<td>4.5</td>
</tr>
</tbody>
</table>
Structural Stiffness

- Geometric stiffness of a structure that bends about its $x$ axis is portrayed by its **area moment of inertia**

$$I_x = \int_{z_{\min}}^{z_{\max}} x(z)z^2 \, dz$$

**Area moment of inertia for simple cross-sectional shapes**

- **Solid rectangle of height**, $h$, and **width**, $w$:
  $$I_x = \frac{wh^3}{12}$$

- **Solid circle of radius**, $r$:
  $$I_x = \frac{\pi r^4}{4}$$

- **Circular cylindrical tube with inner radius**, $r_i$, and outer radius, $r_o$:
  $$I_x = \frac{\pi (r_o^4 - r_i^4)}{4}$$

---

Structural Stiffeners

- Axial stiffeners provide high $I_x$ per unit of cross-sectional area
- Circular stiffeners increase resistance to buckling
- Honeycomb and waffled surfaces remove weight while retaining $I_x$
Propellant Tank Configurations for Launch Vehicles

Serial tanks with common bulkhead
Separate serial tanks
Parallel tanks

Mercury-Redstone Structure

Semi-monocoque structure (load-bearing skin stiffened by internal components)
External skin, internal tanks separated by longerons and circular stiffeners
Aerodynamic and exhaust vanes for thrust vectoring
Saturn IB First Stage

Parallel tanks, external bracing

Saturn V First Stage

Separate serial tanks within semi-monocoque structure
Saturn V Second Stage

Integral serial tanks, with common bulkhead

Saturn IB Second Stage /
Saturn V Third Stage

Serial tanks, with common bulkhead
Ares I Crew Launch Vehicle

- ~25-mT payload capacity
- 2-Mlb gross lift off weight
- 309 ft in length

**First Stage**
- Derived from Current Shuttle Reusable Solid Rocket Motor/Booster (RSRM/B)
- Five Segments/Polybutadiene Acrylonitrile (PBAN) Propellant
- Recoverable
- New Forward Adapter

**Upper Stage**
- 280-klb Liquid Oxygen/Liquid Hydrogen (LOX/LH₂) Stage
- 5.5-m Diameter
- Aluminum-Lithium (Al-Li) Structures
- Instrument Unit and Interstage
- RCS / Roll Control for First Stage flight
- CLV Avionics System

**Upper Stage Engine**
- Saturn J-2 Derived Engine (J-2X)
- Expendable

Ares V Cargo Launch Vehicle

- ~130-mT payload capacity
- 7.4-Mlb gross lift off weight
- 358 ft in length

**Composite Shroud**

**Earth Departure Stage**
- LOx/LH₂
- One J2X+ Engine
- Al-Li Tanks/Structures

**Upper Stage Engine**
- Saturn J-2 Derived Engine (J-2X)
- Expendable

**Core Stage**
- LOx/LH₂
- Five RS68 Engines
- Al-Li Tanks/Structures

**Interstage**

**Five Segment RSRBs**
Next Time:
Spacecraft Structures