ENAE 791 Course Overview

- Context
- Course goals
- Web-based content
- Syllabus
- Policies
- Project content
- Challenges of launch and entry

Space Launch - The Physics

- Minimum orbital altitude is ~200 km

$$\frac{Potential\ Energy}{kg\ in\ orbit} = -\frac{\mu}{r_{orbit}} + \frac{\mu}{r_E} = 1.9 \times 10^6\ \frac{J}{kg}$$

- Circular orbital velocity there is 7784 m/sec

$$\frac{Kinetic\ Energy}{kg\ in\ orbit} = \frac{1}{2}\frac{\mu}{r_{orbit}^2} = 30 \times 10^6\ \frac{J}{kg}$$

- Total energy per kg in orbit

$$\frac{Total\ Energy}{kg\ in\ orbit} = KE + PE = 32 \times 10^6\ \frac{J}{kg}$$

Theoretical Cost to Orbit

- Convert to usual energy units

$$\frac{Total\ Energy}{kg\ in\ orbit} = 32 \times 10^6\ \frac{J}{kg} = 8.9\ \frac{kWhrs}{kg}$$

- Domestic energy costs are ~$0.11/kWhr

  – Theoretical cost to orbit $1/kg

Actual Cost to Orbit

- SpaceX Falcon 9
  - 22,800 kg to LEO
  - $67 M per flight
  - Lowest cost system currently flying
- $2939/kg of payload
- Factor of 2900x higher than theoretical energy costs!

What About Airplanes?

- For an aircraft in level flight,

$$\frac{\text{Weight}}{\text{Thrust}} = \frac{\text{Lift}}{\text{Drag}}, \text{ or } \frac{mg}{T} = \frac{L}{D}$$

- Energy = force x distance, so

$$\frac{\text{Total Energy}}{\text{kg}} = \frac{\text{thrust} \times \text{distance}}{\text{mass}} = \frac{Td}{m} = \frac{gd}{L/D}$$

- For an airliner (L/D=25) to equal orbital energy, d=81,000 km (2 roundtrips NY-Sydney)

Equivalent Airline Costs?

- Average economy ticket NY-Sydney round-round-trip ~$1500
- Average passenger (+ luggage) ~100 kg
- Two round trips = $30/kg
  - Factor of 30x more than electrical energy costs
  - Factor of 100x less than current launch costs
- But…

  you get to refuel at each stop!

Equivalence to Air Transport

- 81,000 km ~ twice around the world
- Voyager - one of two aircraft to ever circle the world non-stop, non-refueled - *once*!

Orbital Entry - The Physics

- 32 MJ/kg dissipated by friction with atmosphere over ~8 min = 66kW/kg
- Pure graphite (carbon) high-temperature material: cp=709 J/kg°K
- Orbital energy would cause temperature gain of 45,000°K!
- Thus proving the comment about space travel, "It's utter bilge!" (Sir Richard Wooley, Astronomer Royal of Great Britain, 1956)

The Vision

"Once you make it to low Earth orbit, you're halfway to anywhere!"

- Robert A. Heinlein

Goals of ENAE 791

- Learn the underlying physics (orbital mechanics, flight mechanics, aerothermodynamics) which constrain and define launch and entry vehicles
- Develop the tools for preliminary design synthesis, including the fundamentals of systems analysis
- Provide an introduction to engineering economics, with a focus on the parameters affecting cost of launch and entry vehicles, such as reusability
- Examine specific challenges in the underlying design disciplines, such as thermal protection and structural dynamics

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http://spacecraft.ssl.umd.edu

Web-based Course Content

- Data web site at http://spacecraft.ssl.umd.edu
  - Course information
  - Syllabus
  - Lecture notes
  - Problems and solutions
- Teams site at https://go.umd.edu/ENAE791S24access
  - Communications for team projects (forums, wiki, blogs)
  - Surveys for course feedback
  - Backup for spacecraft.ssl.umd.edu if needed

Schedule Overview (1)

- Fundamentals of Launch and Entry Design
  - Orbital mechanics
  - Basic rocket performance
- Entry flight mechanics
  - Ballistic entry
  - Lifting entry
- Aerothermodynamics
- Thermal Protection System (TPS) analysis
- Entry, Descent, and Landing (EDL) systems

Schedule Overview (2)

- Launch flight mechanics
  - Gravity turn
  - Targeted trajectories
  - Optimal trajectories
  - Airbreathing trajectories
- Launch vehicle systems
  - Propulsion systems
  - Structures and structural dynamics analysis
  - Avionics
  - Payload accommodations
  - Ground launch processing

Schedule Overview (3)

- Systems Analysis
  - Cost estimation
  - Engineering economics
  - Reliability issues
  - Safety design concerns
  - Fleet resiliency
  - Reusability
  - Multidisciplinary optimization
- Case studies
- Design project

Grading Policies

- Grade Distribution
  - 25% Problems
  - 75% Term Project
- Late Policy
  - On time: Full credit
  - Before solutions: 70% credit
  - After solutions: 20% credit

A Word about Homework Grading

- Homework is graded via a discrete filter
  - ✓ for homework problems which are essentially correct (10 pts)
  - ✓- for homework with significant problems (7 pts)
  - ✓-- for homework with major problems (4 pts)
  - ✓+ for homework demonstrating extra effort (12 pts)
  - 0 for missing homework
- A detailed solution document is posted for each problem after the due date, which you should review to ensure you understand the techniques used

Launch and Entry Vehicle Perspective

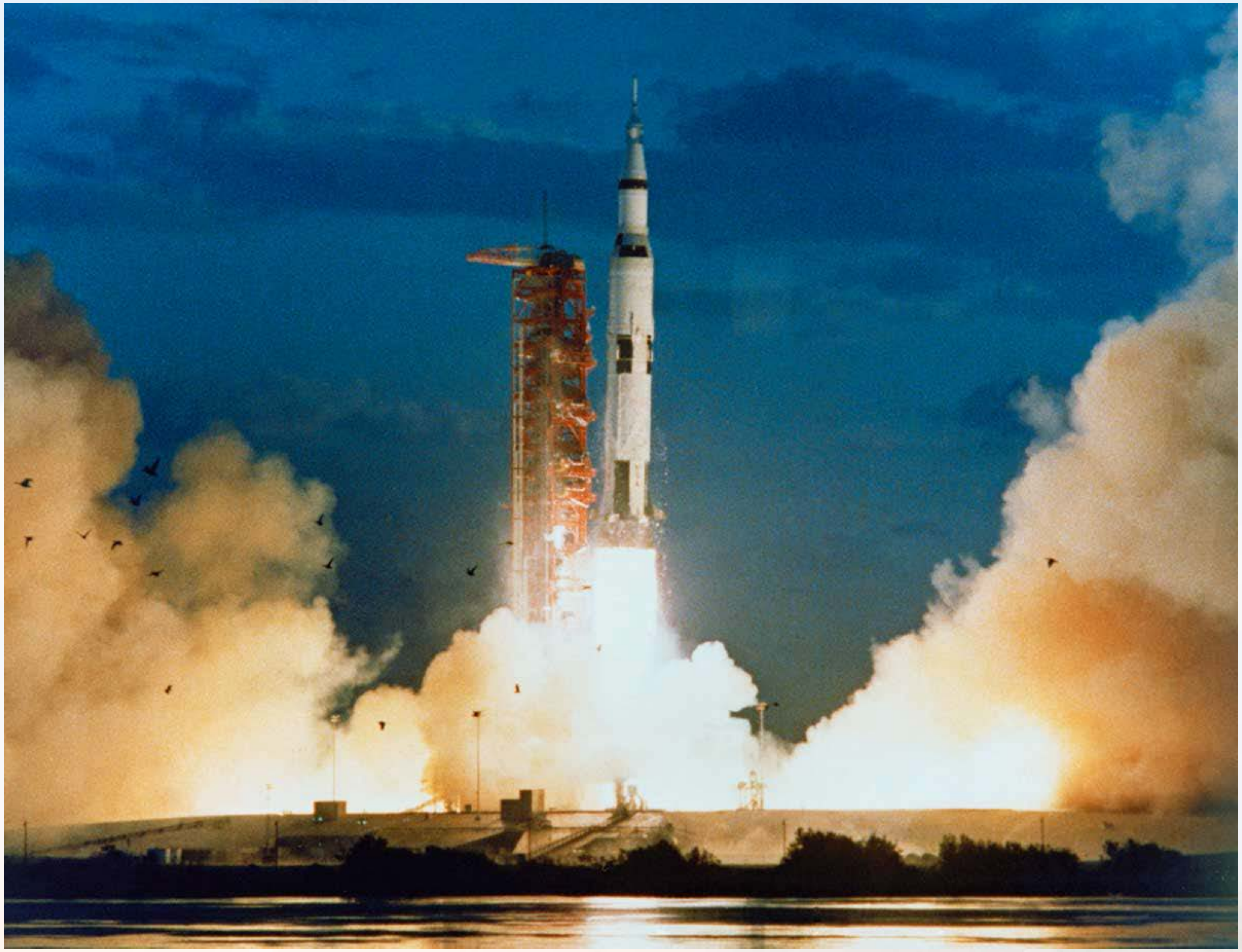
- Where did we come from?
- What's happening now?
- Where are we going?

Early U.S. Orbital Launch Vehicles

Mercury-Atlas

Gemini-Titan

Saturn V



Space Transportation System – NASA

Atlas V 401

Atlas V 551

Delta IV

Delta IV Heavy (Parker Solar Probe)

Antares Launch Vehicle – Orbital ATK

Antares Launch Vehicle – Orbital ATK

Falcon 9 – SpaceX

Falcon 9 First Stage Landing

Falcon Heavy – SpaceX (2018)

Falcon 9 Boosters Landing at Cape Canaveral

Ariane 5 (ESA)

Soyuz Launch Vehicle and Spacecraft (Russia)

Long March 5 (China)

Long March Series (China)

Electron (Rocket Labs)

Alpha (Firefly)

Space Launch System – NASA

ULA Vulcan-Centaur

Starship/Super Heavy (SpaceX)

Ariane 6 (ESA)

Blue Origin New Glenn

Neutron (Rocket Labs)

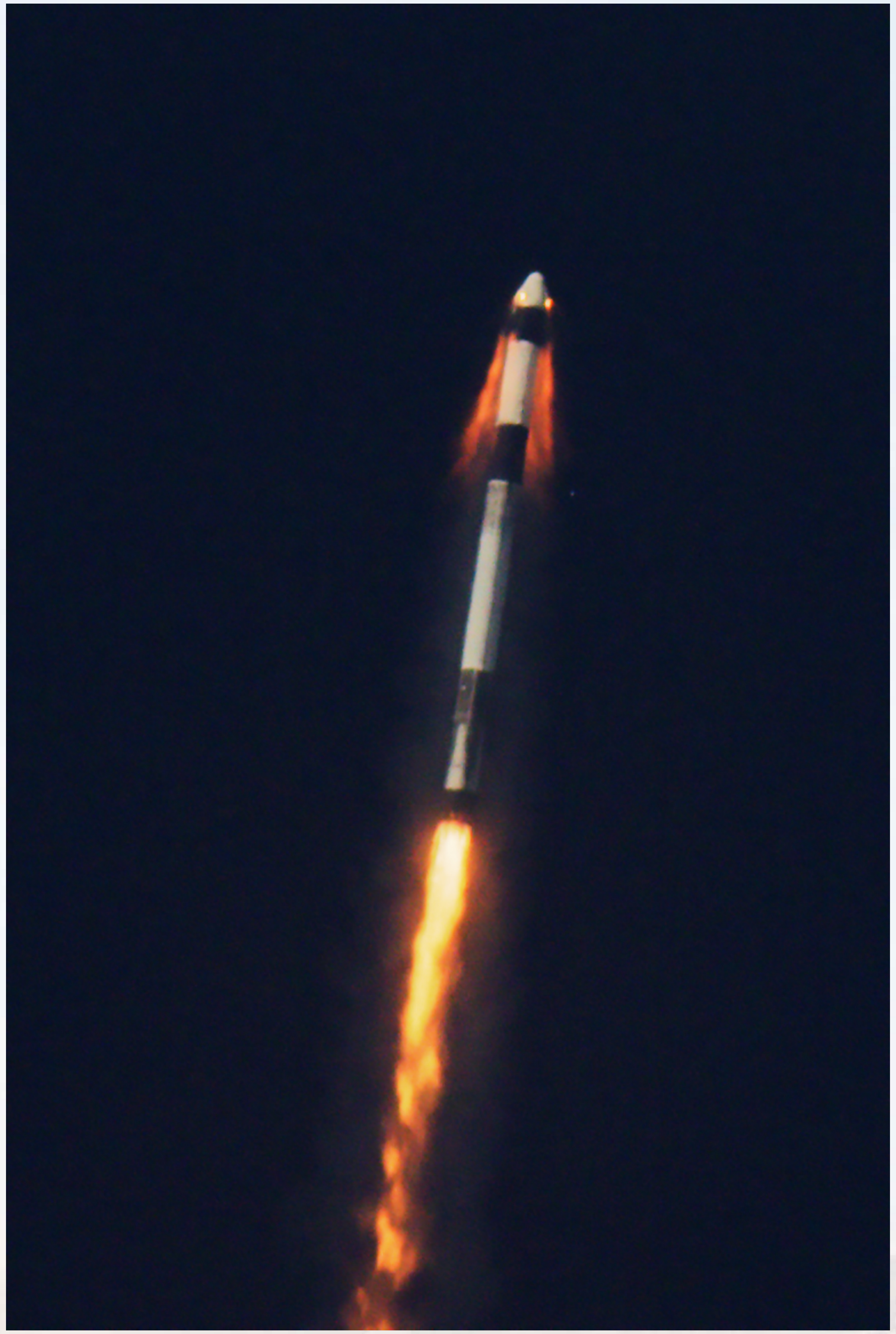
Stratolaunch Concept (Paul Allen)

Soyuz Spacecraft

Dragon Cargo Spacecraft – SpaceX

Dragon Cargo and Crew Vehicles at ISS

Dragon 2 Pad and In-flight Abort Tests



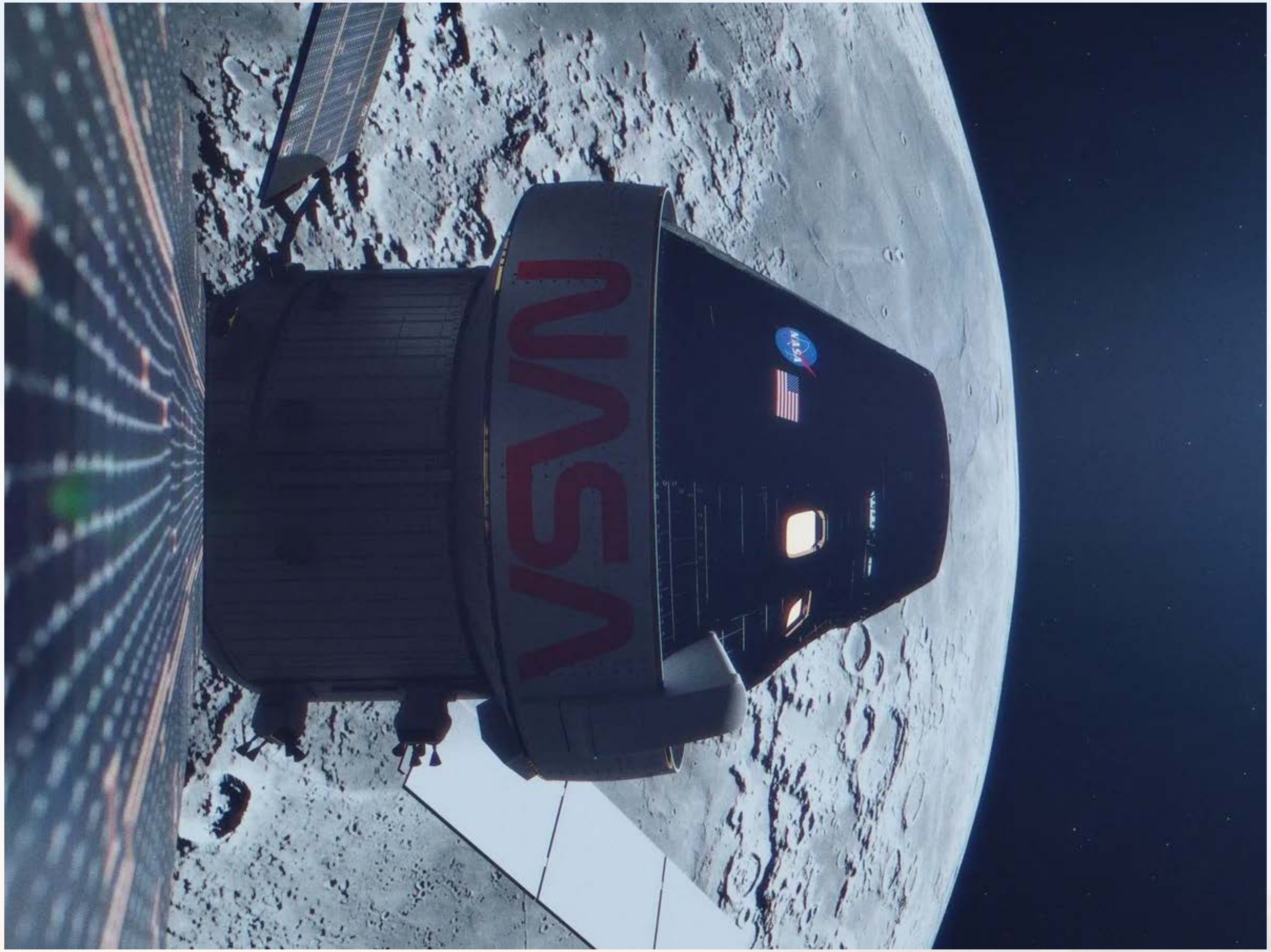
CST100/Starliner – Boeing

Boeing Starliner on Atlas V (2020)

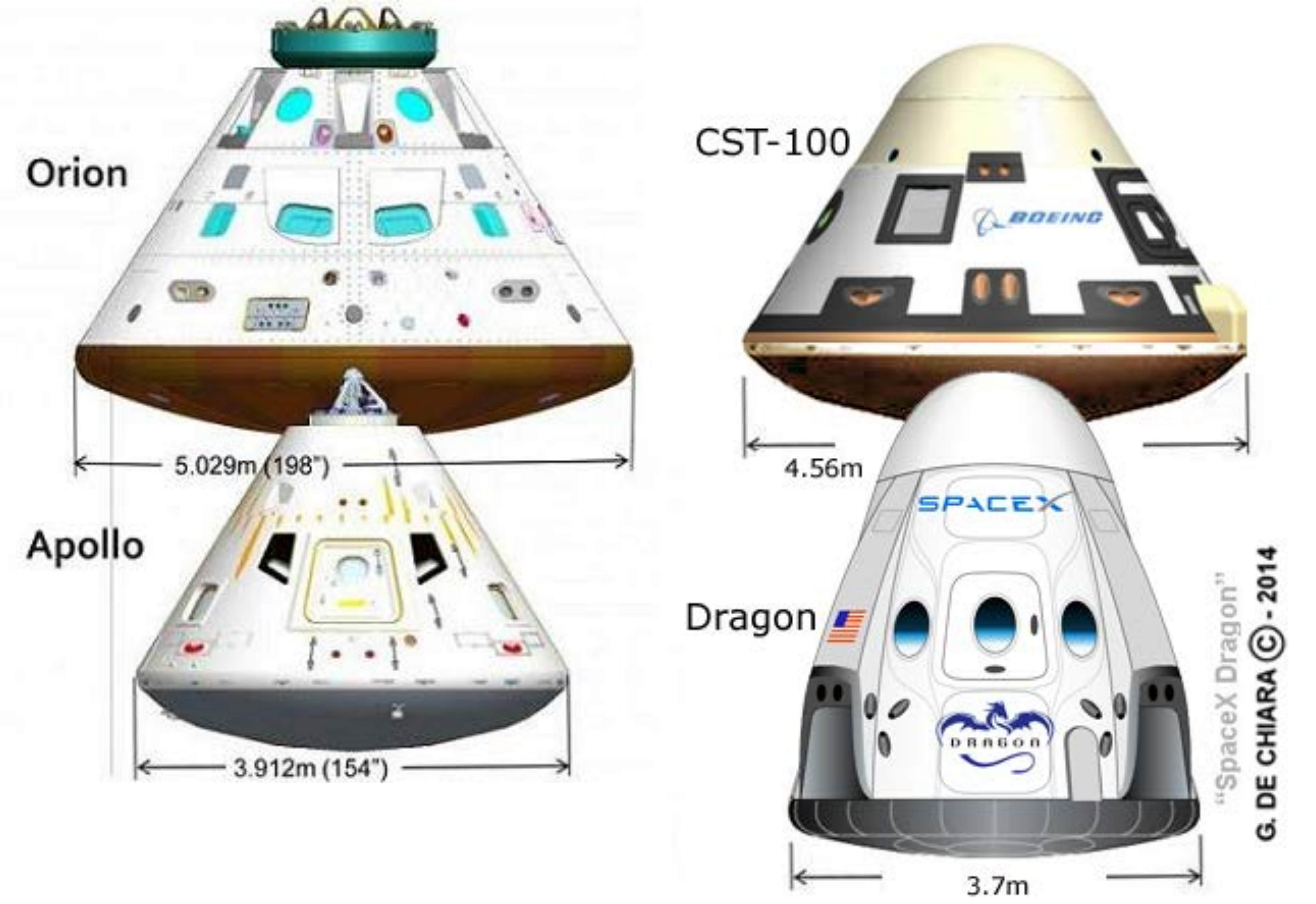
Atlas V N22 (Starliner)

Orion Spacecraft – NASA

Orion Spacecraft – Artemis 1 Mission



Commercial Crew Size Comparison



Dream Chaser – Sierra Nevada Corp.

Dream Chaser Cargo Version

Blue Origins Biconic Spacecraft

New Shepard (Blue Origin)

New Shepard Landing (Blue Origin)

Spaceship Two - Virgin Galactic

Shuttle in Gliding Landing

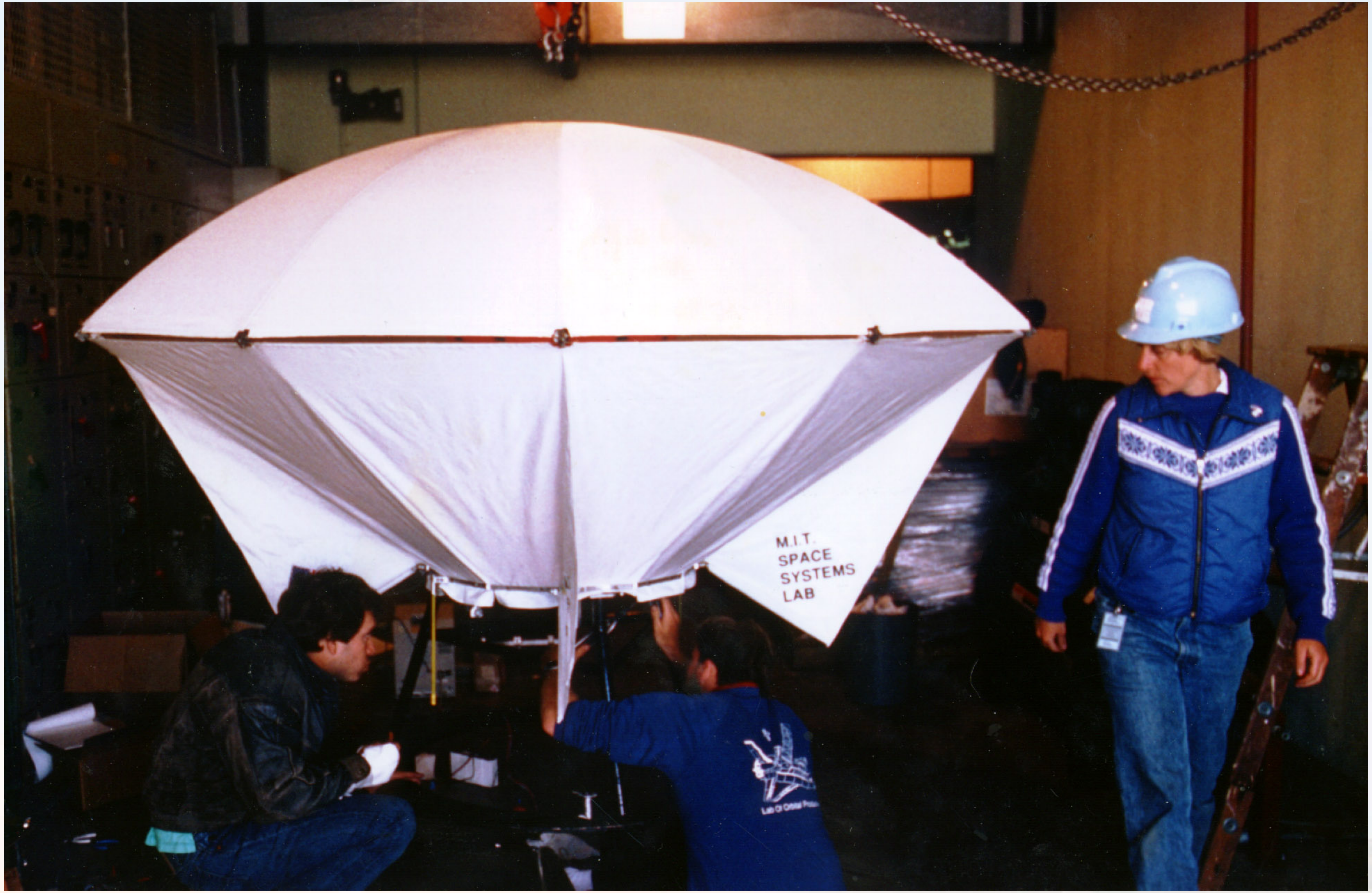
NASA Commercial Lunar Payload Services (CLPS)

NASA Human Landing System (HLS) Proposals

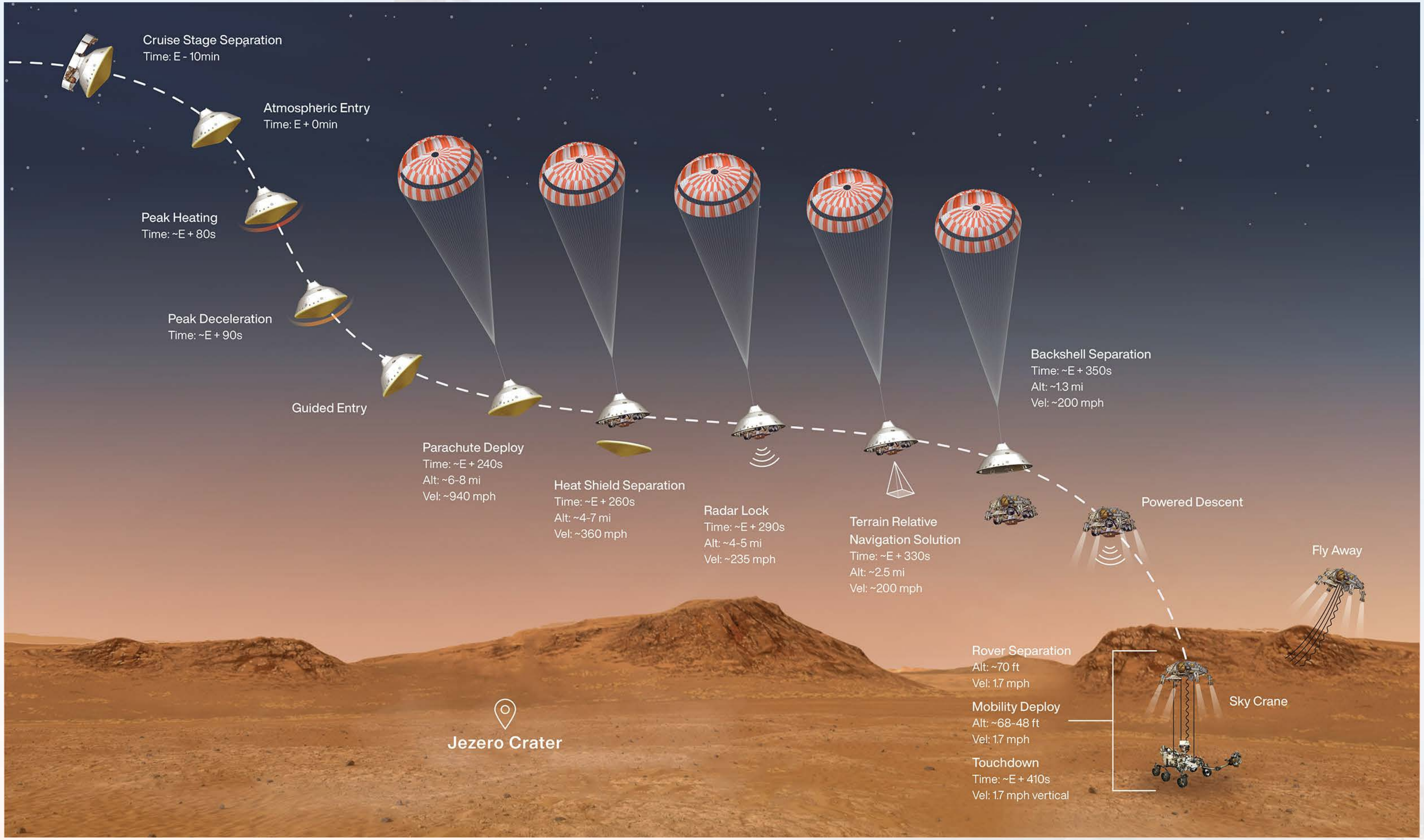
SpaceX Propulsive Landing Tests

Low-Density Supersonic Decelerator

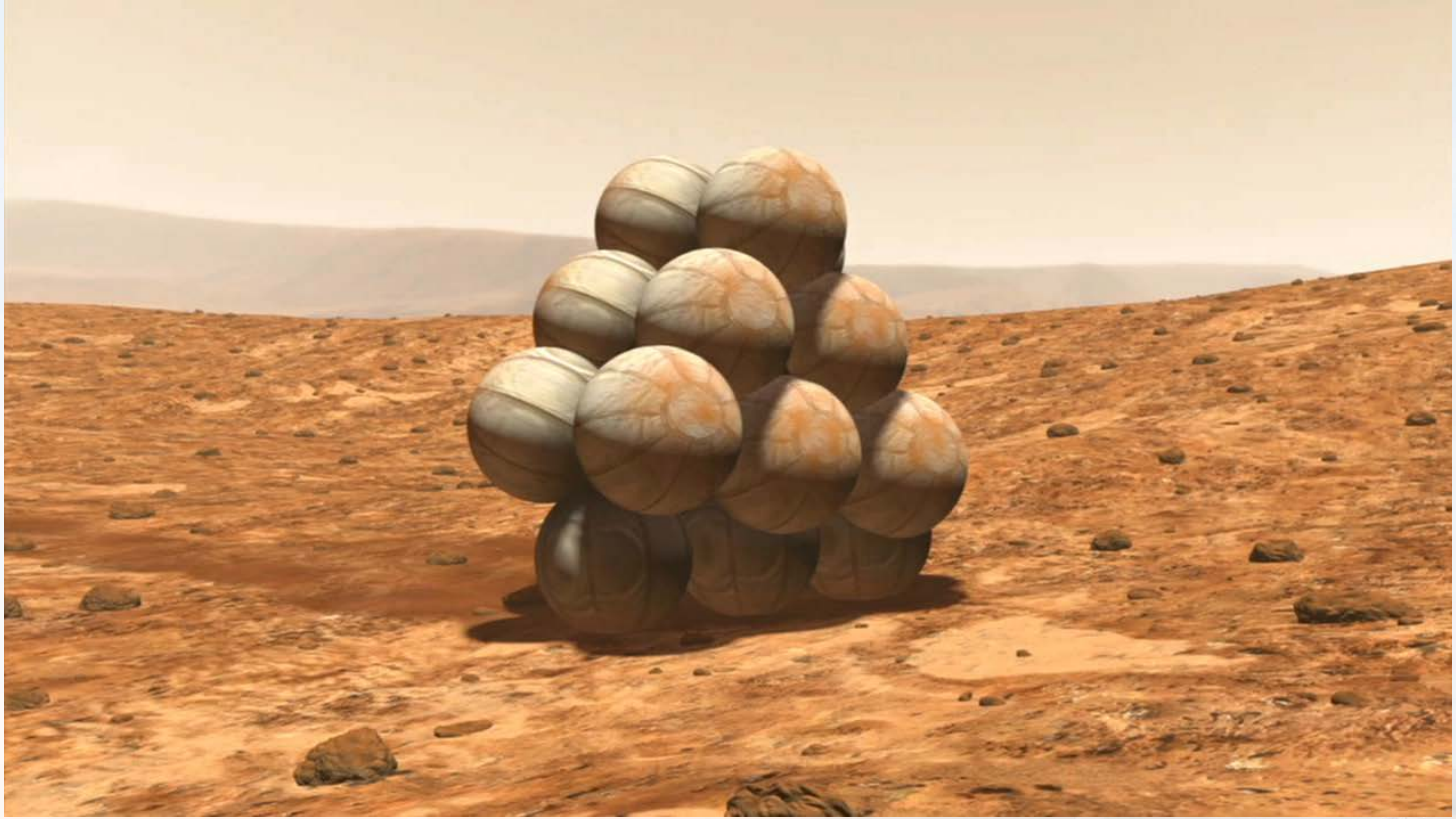
ParaShield Entry Vehicle



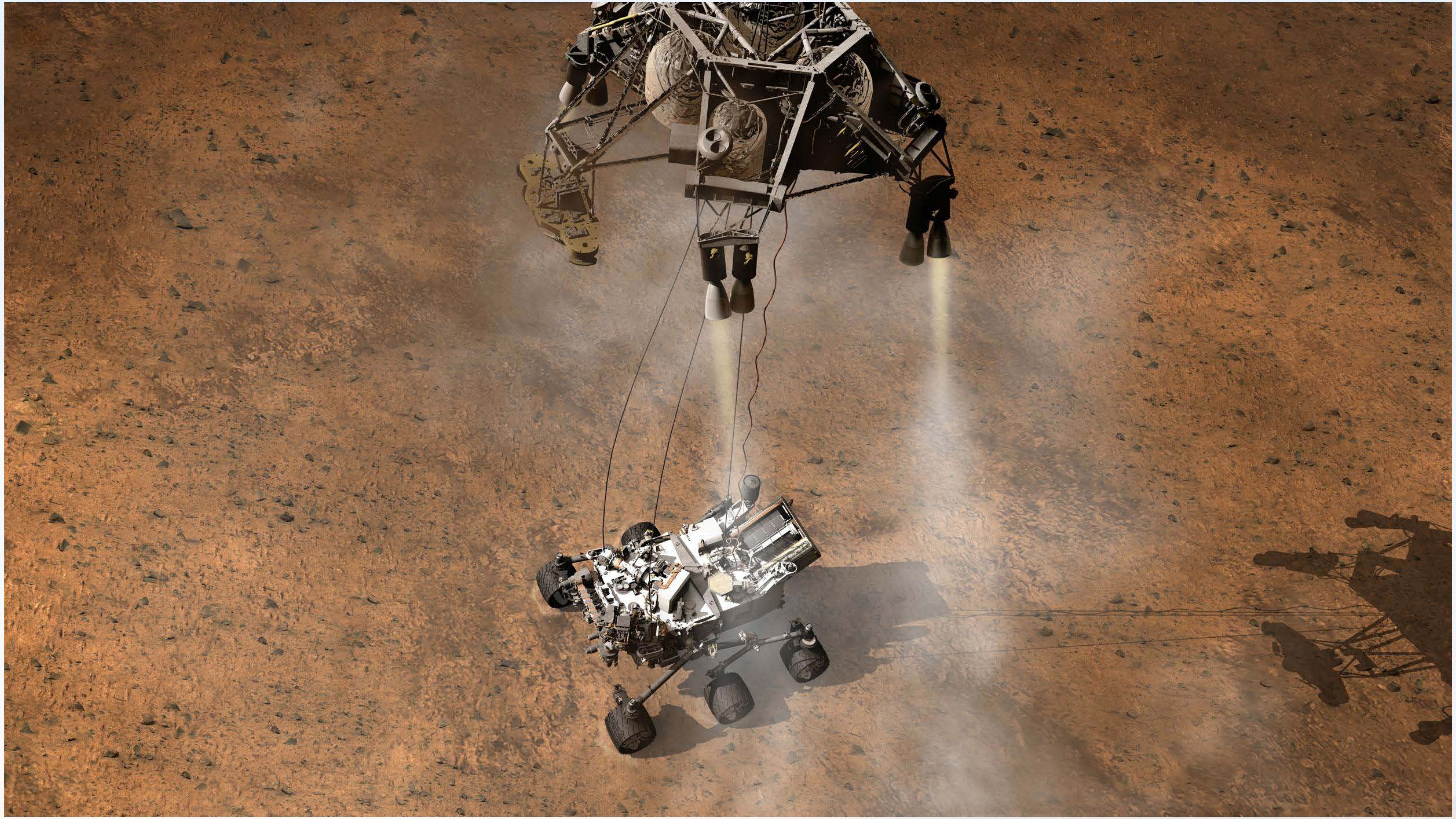
EDL – Perseverance Landing Sequence



Mars Exploration Rovers Landing Bags

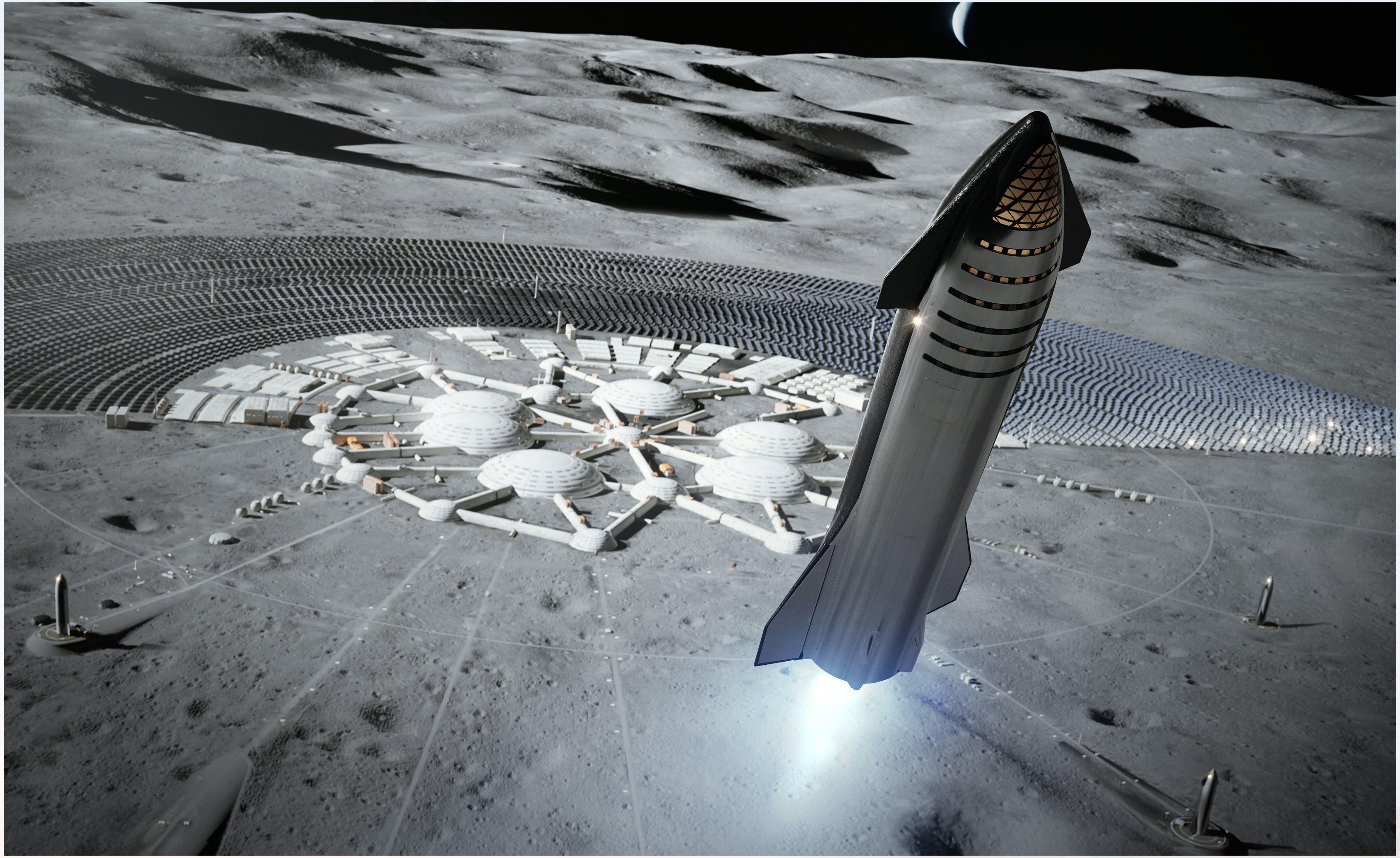


MSL Skycrane Mars Landing System

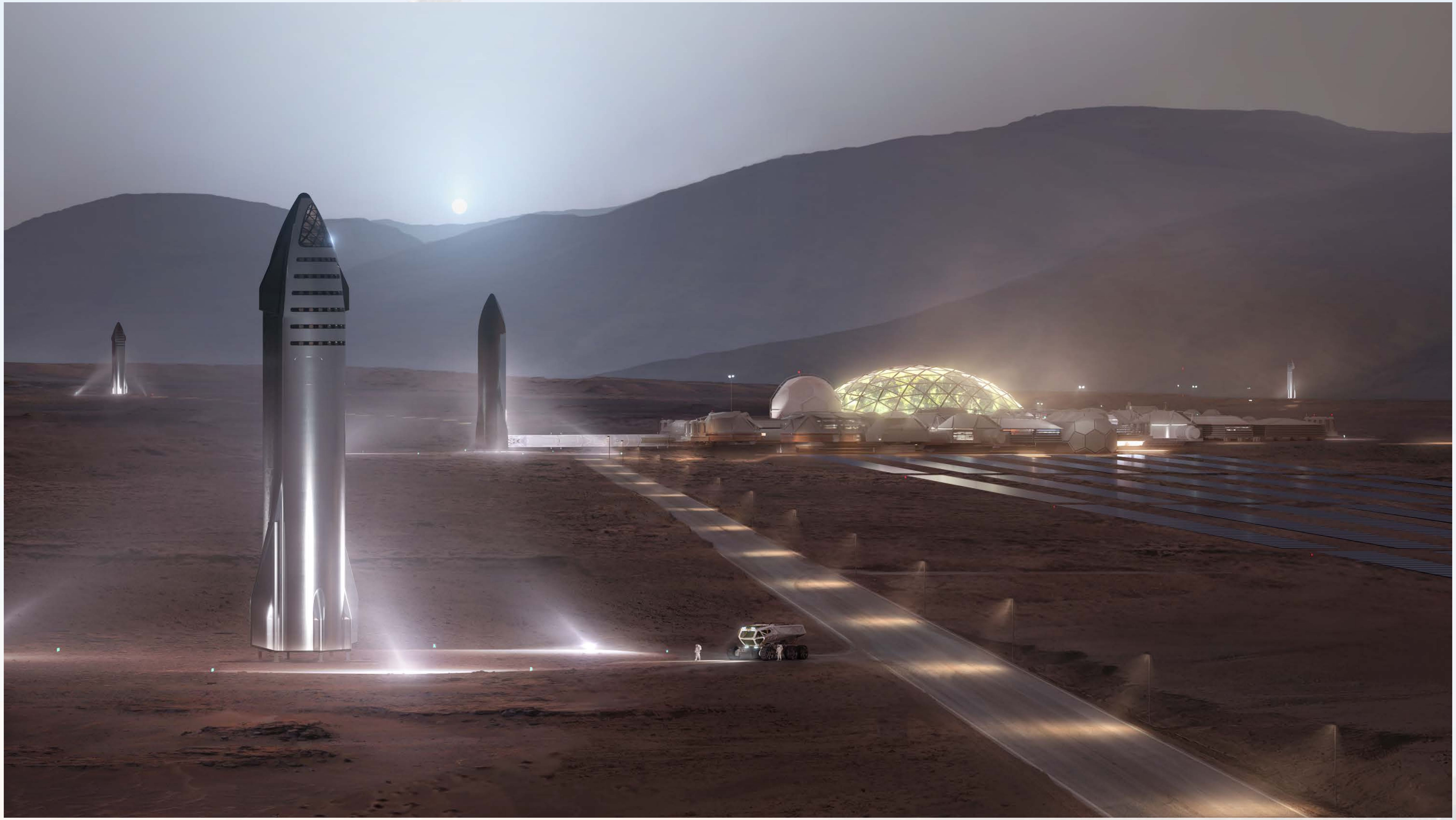


Mars Colonial Transport – SpaceX

Starship Landing at Moon Base

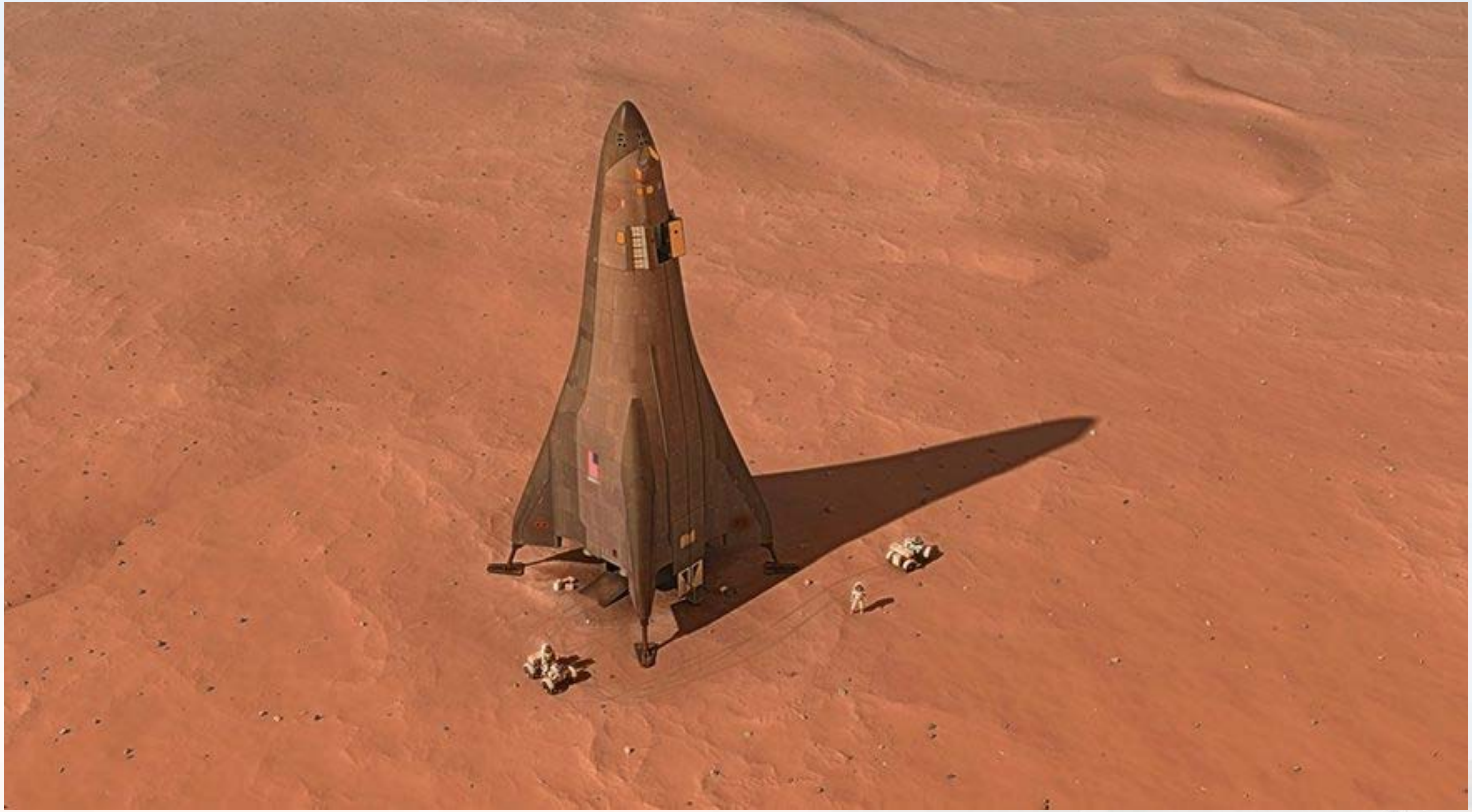


Starships at Mars Base



Lockheed Proposed Human Mars Architecture

Lockheed Mars Lander Concept



Term Project - A Fully Reusable Launch System

- A fully reusable launch system is the "holy grail" of space transportation
- SpaceX has reused the Falcon 9 first stage up to 19 times, but upper stages are expendable
- Blue Origin planned for New Glenn to be fully reusable, but recently announced the upper stage will be expendable
- SpaceX is considering starting Starship operations with expendable upper stage
- Upper stage entry from orbital velocities is hard!

Term Project

- Do this individually or in pairs (your choice)
- Perform analytical trade studies to determine optimum configuration (e.g., number of stages, propellants, size)
- All vehicles will be conceptually designed from scratch (no "catalog engineering"!)
- Design process should proceed throughout the term
- Progress reports will be due throughout the term
- Formal design presentations at end of term