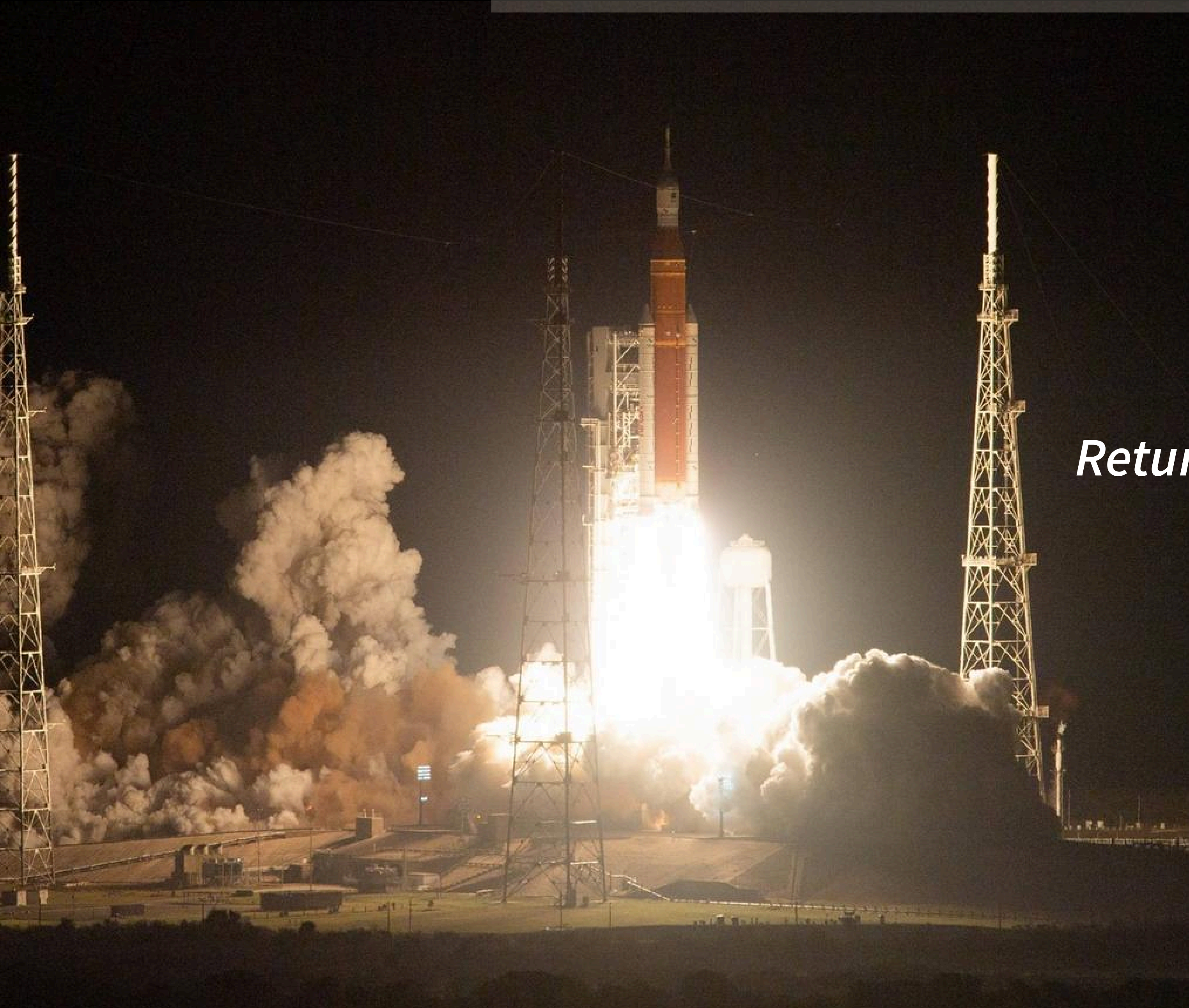


Overview of the Artemis Program

Returning to the South Pole of the Moon after 50 Years

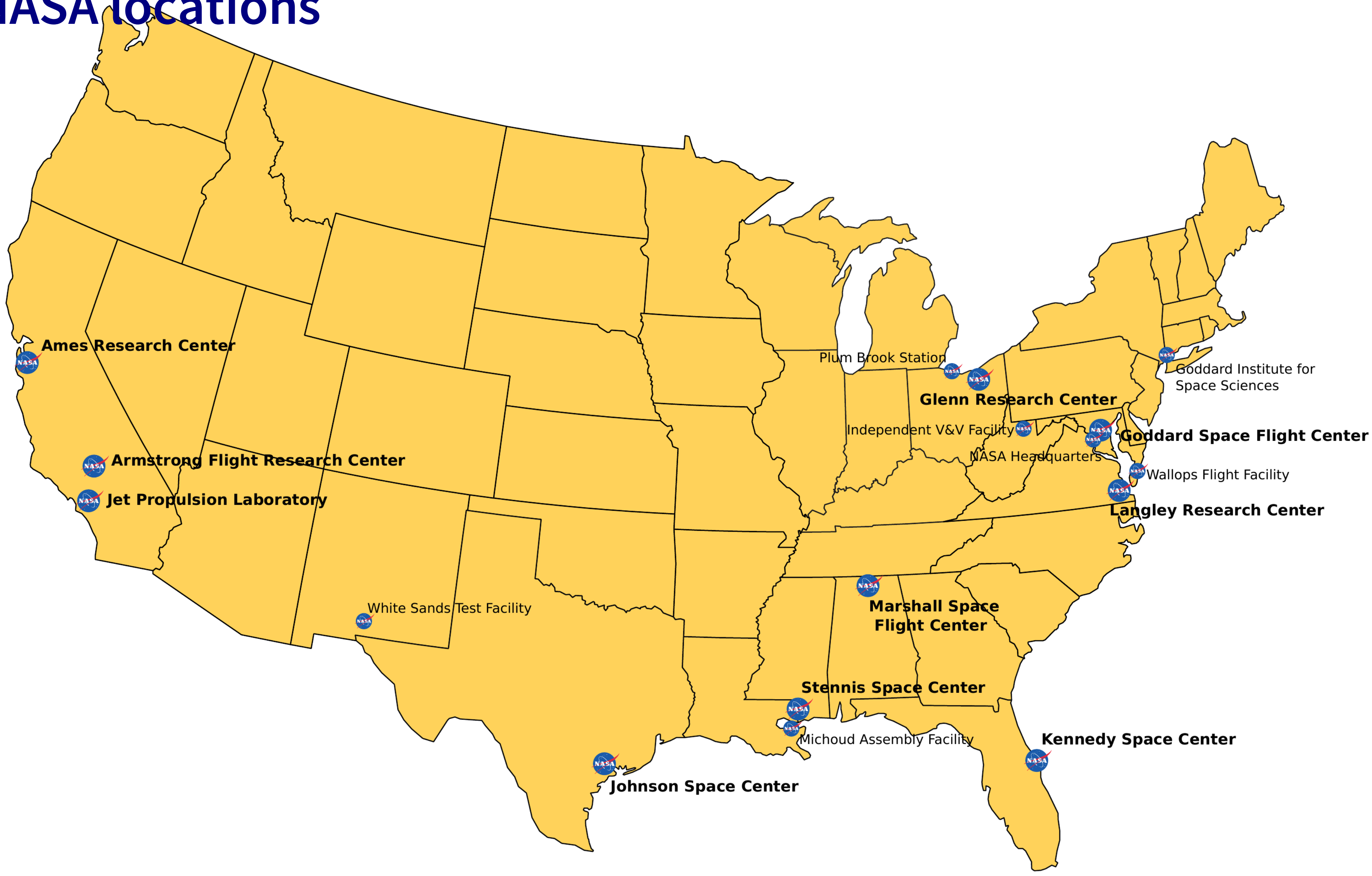
Derek J. Dalle, Ph.D.
NASA Ames Computational Aerosciences branch (ARC/TNA)

October 2, 2023

About NASA

- Agency of the U.S. federal government
- 10 centers and several more locations

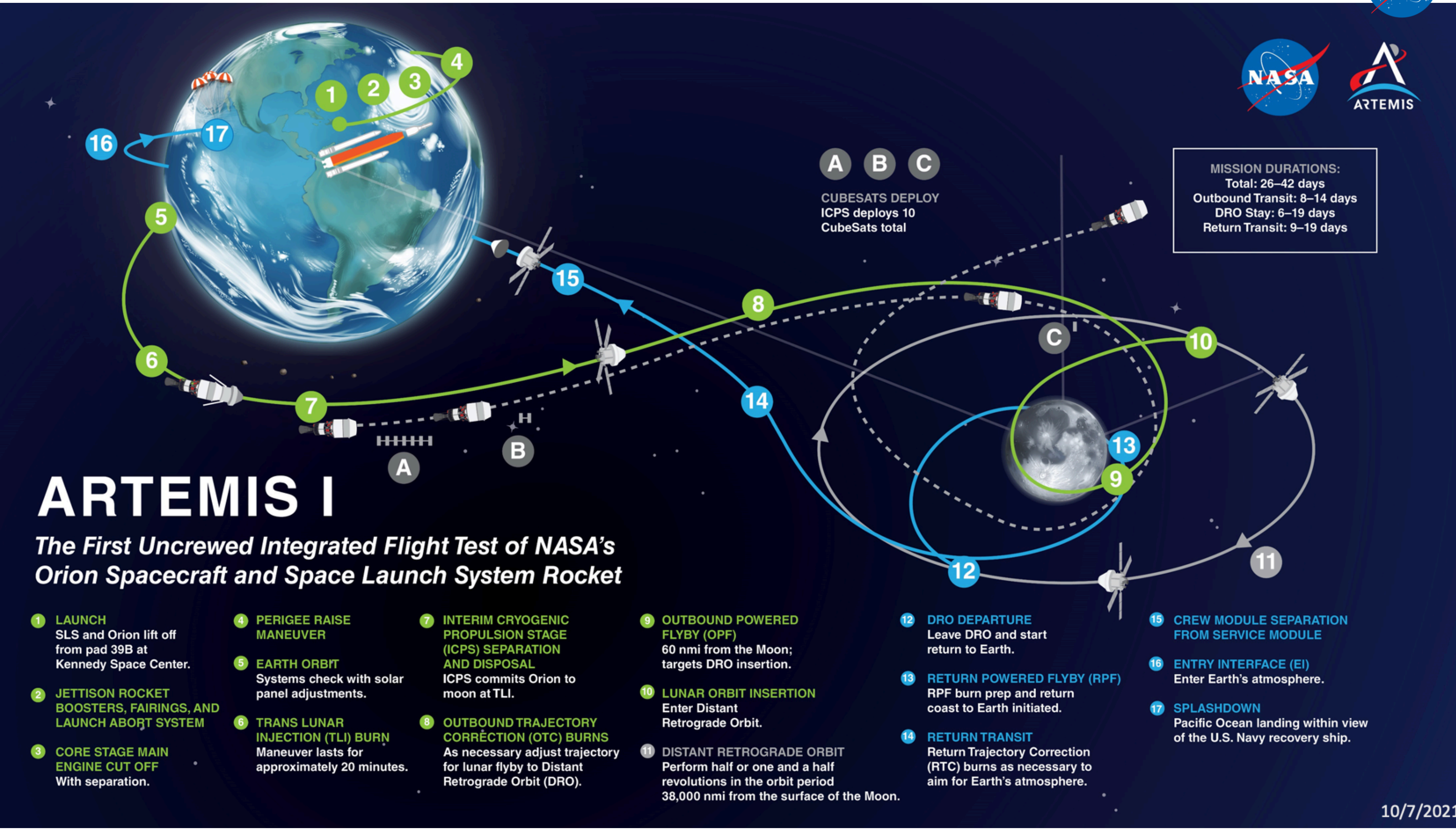
NASA locations



Artemis Missions

(*Plan*) Three missions to return the first woman, first person of color, and the next man to the South Pole of the Moon.

Create a sustainable human presence in cislunar space.


ARTEMIS I
The First Uncrewed Integrated Flight Test of NASA's Orion Spacecraft and Space Launch System Rocket
CUBESATS DEPLOY
ICPS deploys 10 CubeSats total
MISSION DURATIONS:
Total: 26–42 days
Outbound Transit: 8–14 days
DRO Stay: 6–19 days
Return Transit: 9–19 days
1 LAUNCH
SLS and Orion lift off from pad 39B at Kennedy Space Center.
2 JETTISON ROCKET BOOSTERS, FAIRINGS, AND LAUNCH ABORT SYSTEM
3 CORE STAGE MAIN ENGINE CUT OFF
With separation.
4 PERIGEE RAISE MANEUVER
5 EARTH ORBIT
Systems check with solar panel adjustments.
6 TRANS LUNAR INJECTION (TLI) BURN
Maneuver lasts for approximately 20 minutes.
7 INTERIM CRYOGENIC PROPULSION STAGE (ICPS) SEPARATION AND DISPOSAL
ICPS commits Orion to moon at TLI.
8 OUTBOUND TRAJECTORY CORRECTION (OTC) BURNS
As necessary adjust trajectory for lunar flyby to Distant Retrograde Orbit (DRO).
9 OUTBOUND POWERED FLYBY (OPF)
60 nmi from the Moon; targets DRO insertion.
10 LUNAR ORBIT INSERTION
Enter Distant Retrograde Orbit.
11 DISTANT RETROGRADE ORBIT
Perform half or one and a half revolutions in the orbit period 38,000 nmi from the surface of the Moon.
12 DRO DEPARTURE
Leave DRO and start return to Earth.
13 RETURN POWERED FLYBY (RPF)
RPF burn prep and return coast to Earth initiated.
14 RETURN TRANSIT
Return Trajectory Correction (RTC) burns as necessary to aim for Earth's atmosphere.
15 CREW MODULE SEPARATION FROM SERVICE MODULE
16 ENTRY INTERFACE (EI)
Enter Earth's atmosphere.
17 SPLASHDOWN
Pacific Ocean landing within view of the U.S. Navy recovery ship.
10/7/2021

ARTEMIS II

First Crewed Test Flight to the Moon Since Apollo

1. **LAUNCH**
Astronauts lift off from pad 39B at Kennedy Space Center.

2. **JETTISON SOLID ROCKET BOOSTERS, FAIRINGS, AND LAUNCH ABORT SYSTEM**

3. **CORE STAGE MAIN ENGINE CUT OFF**
With separation.

4. **PERIGEE RAISE MANEUVER**

5. **APOGEE RAISE BURN TO HIGH EARTH ORBIT**
Begin 23.5 hour checkout of spacecraft.

6. **ORION SEPARATION FROM INTERIM CRYOGENIC PROPULSION STAGE (ICPS) FOLLOWED BY PROX OPS DEMO**
Plus manual handling qualities assessment for up to 2 hours.

7. **ORION UPPER STAGE SEPARATION (USS) BURN**
Begins high Earth orbit checkout. Life support, exercise, and habitation equipment evaluations.

8. **PERIGEE RAISE BURN**

9. **TRANS-LUNAR INJECTION (TLI) BY ORION'S MAIN ENGINE**
Lunar free return trajectory initiated with European service module.

10. **OUTBOUND TRANSIT TO MOON**
Outbound Trajectory Correction (OTC) burns as necessary for Lunar free return trajectory; travel time approximately 4 days.

11. **LUNAR FLYBY**
6,479 miles (mean) lunar farside altitude.

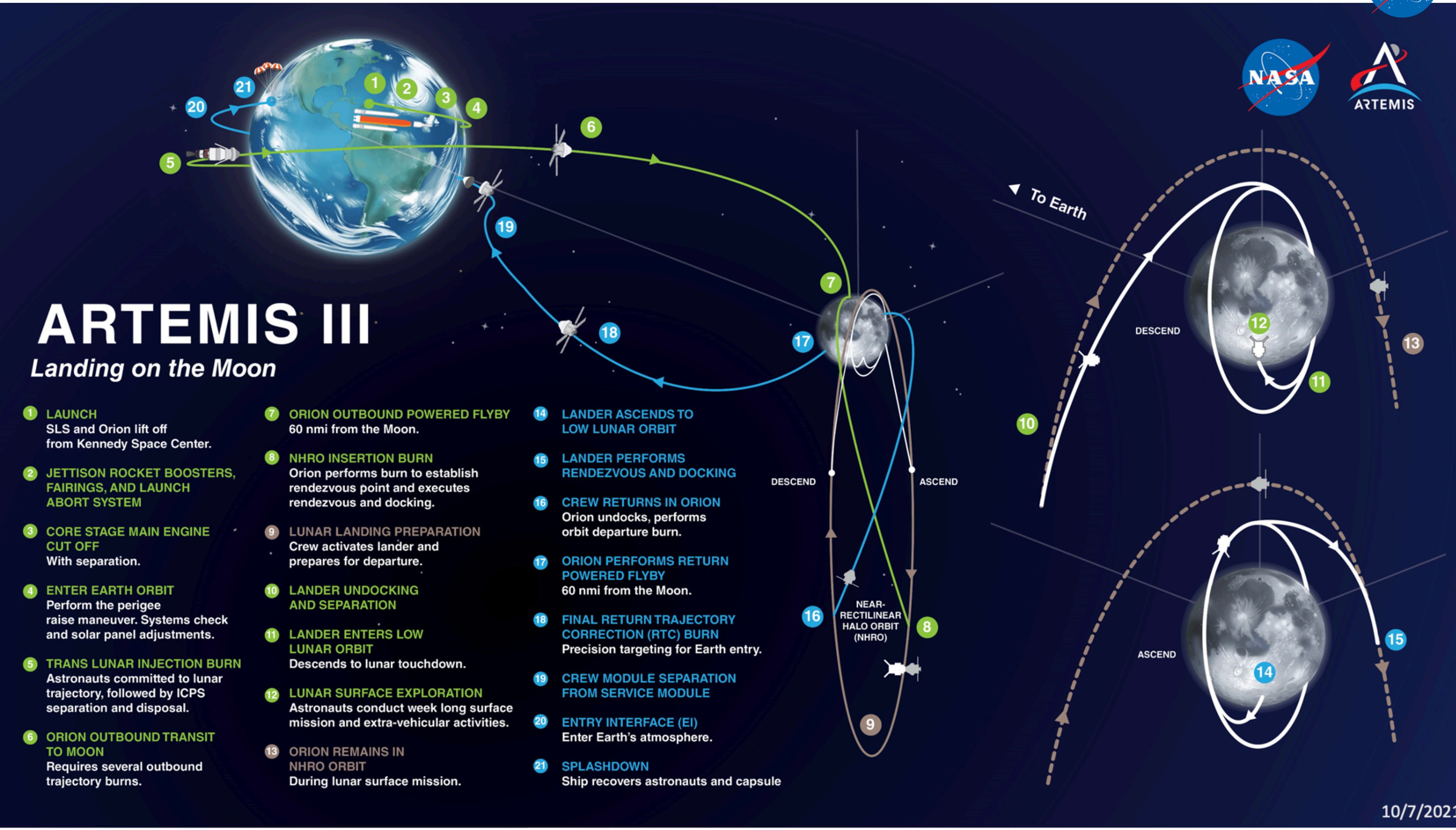
12. **TRANS-EARTH RETURN**
Return Trajectory Correction (RTC) burns as necessary to aim for Earth's atmosphere; travel time approximately 4 days.

13. **CREW MODULE SEPARATION FROM SERVICE MODULE**

14. **ENTRY INTERFACE (EI)**
Enter Earth's atmosphere.

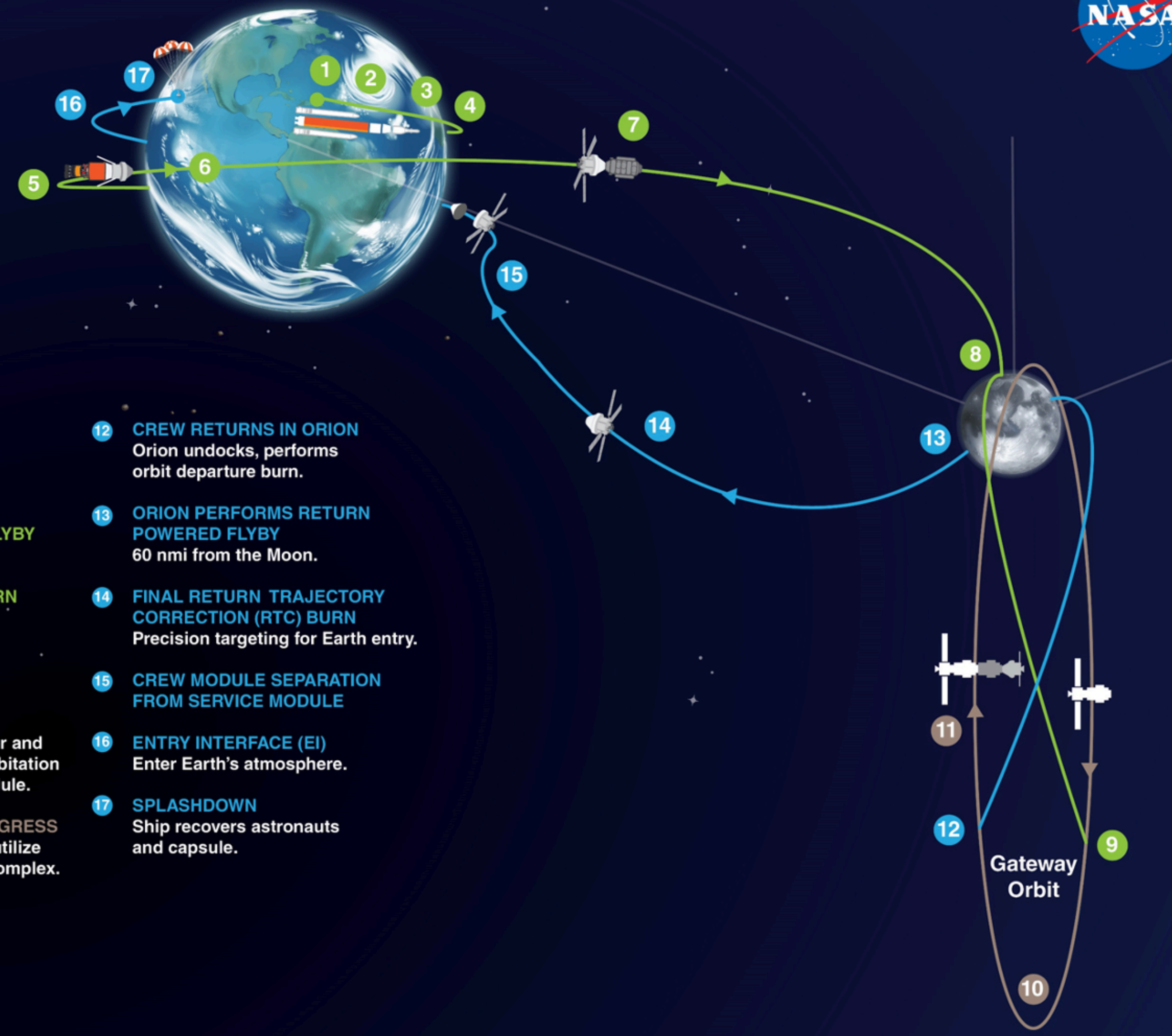
15. **SPLASHDOWN**
Ship recovers astronauts and capsule.

Artemis II Crew


ARTEMIS III
Landing on the Moon
ARTEMIS
To Earth
DESCEND
ASCEND
NEAR-RECTILINEAR HALO ORBIT (NHRO)
1 LAUNCH
SLS and Orion lift off from Kennedy Space Center.
2 JETTISON ROCKET BOOSTERS, FAIRINGS, AND LAUNCH ABORT SYSTEM
3 CORE STAGE MAIN ENGINE CUT OFF
With separation.
4 ENTER EARTH ORBIT
Perform the perigee raise maneuver. Systems check and solar panel adjustments.
5 TRANS LUNAR INJECTION BURN
Astronauts committed to lunar trajectory, followed by ICPS separation and disposal.
6 ORION OUTBOUND TRANSIT TO MOON
Requires several outbound trajectory burns.
7 ORION OUTBOUND POWERED FLYBY
60 nmi from the Moon.
8 NHRO INSERTION BURN
Orion performs burn to establish rendezvous point and executes rendezvous and docking.
9 LUNAR LANDING PREPARATION
Crew activates lander and prepares for departure.
10 LANDER UNDOCKING AND SEPARATION
11 LANDER ENTERS LOW LUNAR ORBIT
Descends to lunar touchdown.
12 LUNAR SURFACE EXPLORATION
Astronauts conduct week long surface mission and extra-vehicular activities.
13 ORION REMAINS IN NHRO ORBIT
During lunar surface mission.
14 LANDER ASCENDS TO LOW LUNAR ORBIT
15 LANDER PERFORMS RENDEZVOUS AND DOCKING
16 CREW RETURNS IN ORION
Orion undocks, performs orbit departure burn.
17 ORION PERFORMS RETURN POWERED FLYBY
60 nmi from the Moon.
18 FINAL RETURN TRAJECTORY CORRECTION (RTC) BURN
Precision targeting for Earth entry.
19 CREW MODULE SEPARATION FROM SERVICE MODULE
20 ENTRY INTERFACE (EI)
Enter Earth's atmosphere.
21 SPLASHDOWN
Ship recovers astronauts and capsule
10/7/2021

ARTEMIS IV

International Habitation Module delivery to Gateway



1. **LAUNCH**
SLS with I-HAB payload and crewed Orion lift-off from Kennedy Space Center.

2. **JETTISON ROCKET BOOSTERS, FAIRINGS, AND LAUNCH ABORT SYSTEM**

3. **CORE STAGE MAIN ENGINE CUT OFF**
With separation.

4. **ENTER EARTH ORBIT**
Exploration Upper Stage performs circularization of Low Earth Orbit. Systems check and solar panel adjustments.

5. **TRANS LUNAR INJECTION BURN**
Exploration Upper Stage commits Astronauts in Orion and I-HAB to lunar trajectory.

6. **ORION TUGS I-HAB TO MOON**
Orion separation from USA, docking with I-HAB and extraction from USA followed by Orion tug of I-HAB to NRHO and EUS disposal.

7. **ORION OUTBOUND TRANSIT TO MOON**
Requires several outbound trajectory burns.

8. **ORION OUTBOUND POWERED FLYBY**
60 nmi from the Moon.

9. **GATEWAY ORBIT INSERTION BURN**
Orion performs burn to establish rendezvous point and executes rendezvous and docking.

10. **INTERNATIONAL HABITATION MODULE ARRIVAL AT GATEWAY**
I-HAB docking with Orion to Power and Propulsion Element (PPE) and Habitation and Logistic Outpost (HALO) module.

11. **I-HAB ACTIVATION AND CREW INGRESS**
Astronauts ingress, activate and utilize I-HAB as part of larger Gateway complex.

12. **CREW RETURNS IN ORION**
Orion undocks, performs orbit departure burn.

13. **ORION PERFORMS RETURN POWERED FLYBY**
60 nmi from the Moon.

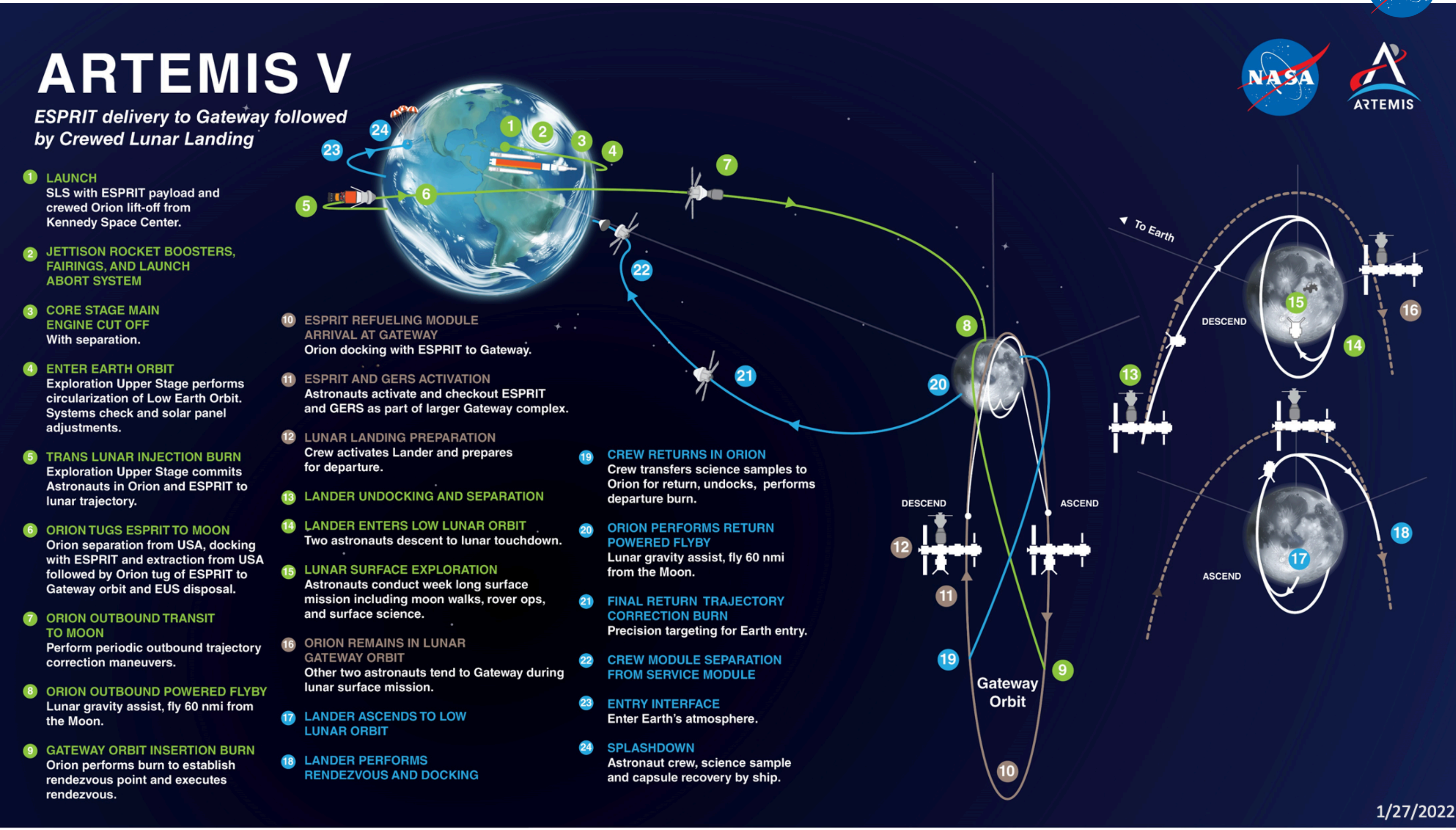
14. **FINAL RETURN TRAJECTORY CORRECTION (RTC) BURN**
Precision targeting for Earth entry.

15. **CREW MODULE SEPARATION FROM SERVICE MODULE**

16. **ENTRY INTERFACE (EI)**
Enter Earth's atmosphere.

17. **SPLASHDOWN**
Ship recovers astronauts and capsule.

1/27/2022


ARTEMIS V
ESPRIT delivery to Gateway followed by Crewed Lunar Landing
ARTEMIS
1 LAUNCH
SLS with ESPRIT payload and crewed Orion lift-off from Kennedy Space Center.
2 JETTISON ROCKET BOOSTERS, FAIRINGS, AND LAUNCH ABORT SYSTEM
3 CORE STAGE MAIN ENGINE CUT OFF
With separation.
4 ENTER EARTH ORBIT
Exploration Upper Stage performs circularization of Low Earth Orbit. Systems check and solar panel adjustments.
5 TRANS LUNAR INJECTION BURN
Exploration Upper Stage commits Astronauts in Orion and ESPRIT to lunar trajectory.
6 ORION TUGS ESPRIT TO MOON
Orion separation from USA, docking with ESPRIT and extraction from USA followed by Orion tug of ESPRIT to Gateway orbit and EUS disposal.
7 ORION OUTBOUND TRANSIT TO MOON
Perform periodic outbound trajectory correction maneuvers.
8 ORION OUTBOUND POWERED FLYBY
Lunar gravity assist, fly 60 nmi from the Moon.
9 GATEWAY ORBIT INSERTION BURN
Orion performs burn to establish rendezvous point and executes rendezvous.
10 ESPRIT REFUELING MODULE ARRIVAL AT GATEWAY
Orion docking with ESPRIT to Gateway.
11 ESPRIT AND GERS ACTIVATION
Astronauts activate and checkout ESPRIT and GERS as part of larger Gateway complex.
12 LUNAR LANDING PREPARATION
Crew activates Lander and prepares for departure.
13 LANDER UNDOCKING AND SEPARATION
14 LANDER ENTERS LOW LUNAR ORBIT
Two astronauts descent to lunar touchdown.
15 LUNAR SURFACE EXPLORATION
Astronauts conduct week long surface mission including moon walks, rover ops, and surface science.
16 ORION REMAINS IN LUNAR GATEWAY ORBIT
Other two astronauts tend to Gateway during lunar surface mission.
17 LANDER ASCENDS TO LOW LUNAR ORBIT
18 LANDER PERFORMS RENDEZVOUS AND DOCKING
19 CREW RETURNS IN ORION
Crew transfers science samples to Orion for return, undocks, performs departure burn.
20 ORION PERFORMS RETURN POWERED FLYBY
Lunar gravity assist, fly 60 nmi from the Moon.
21 FINAL RETURN TRAJECTORY CORRECTION BURN
Precision targeting for Earth entry.
22 CREW MODULE SEPARATION FROM SERVICE MODULE
23 ENTRY INTERFACE
Enter Earth's atmosphere.
24 SPLASHDOWN
Astronaut crew, science sample and capsule recovery by ship.
To Earth
DESCEND
ASCEND
Gateway Orbit
1/27/2022

Comparison to Apollo

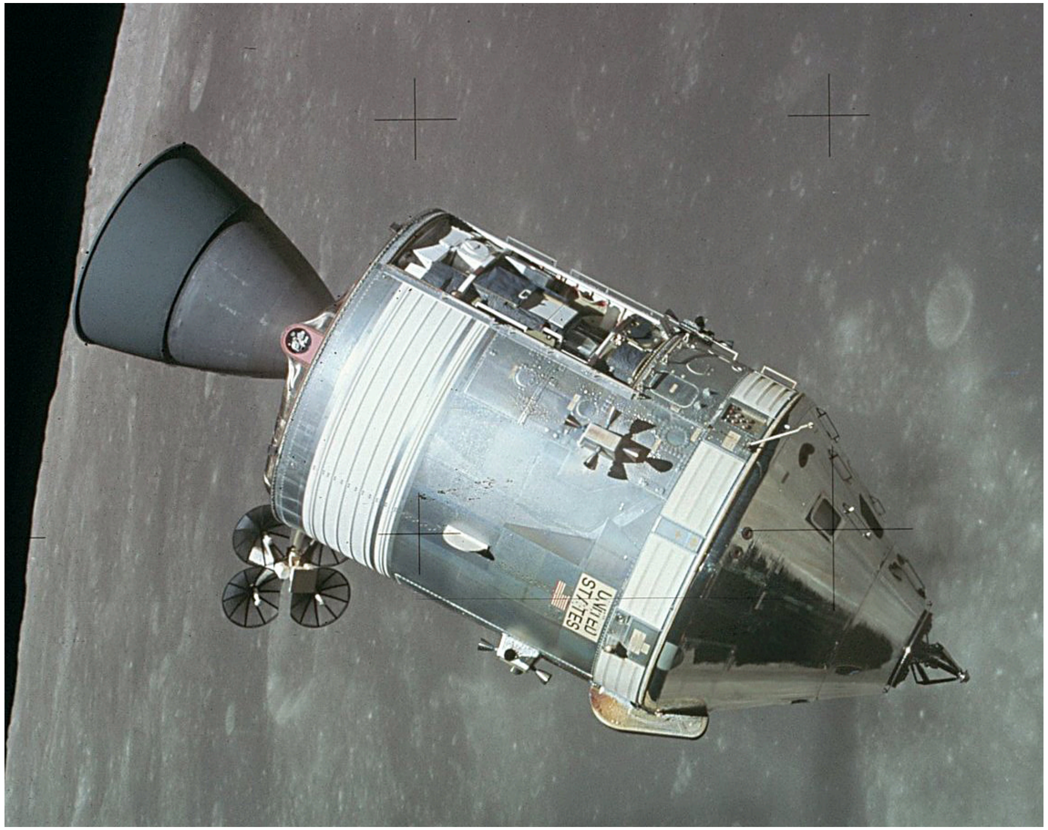
Apollo: One Saturn V Launch per Mission

- One Saturn V launch from Kennedy Space Center in Florida, USA
- Including two spacecraft: Command and Service Modules, Lunar Module
    - CSM has a large engine to enter Lunar orbit and return to Earth
    - Lunary module has two engines; one for landing and one for taking back off
- CSM stays in lunar orbit (w/ one astronaut) while LM lands on Moon (2 astronauts)
- Only CSM returns to Earth
    - Lunar ascent module discarded in Lunar orbit
    - Eventually crashes into the Moon
    - Only Command Module reenters Earth's atmosphere

Apollo Launch Vehicle: Saturn V

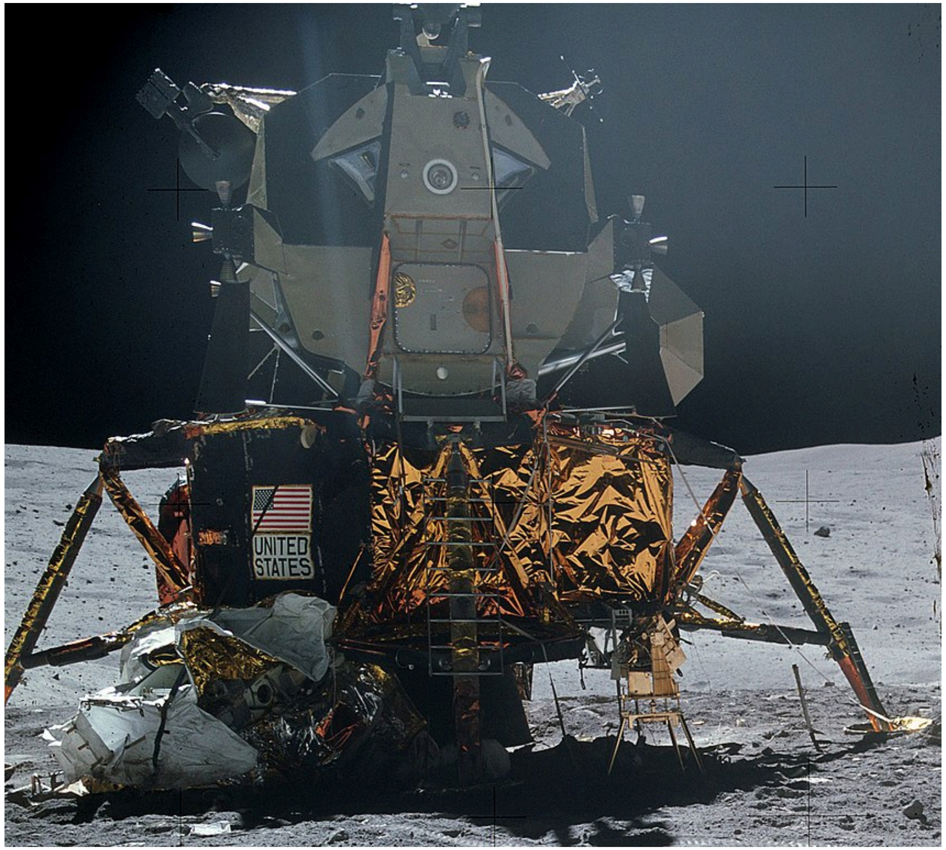
- 3 stages + 2 spacecraft
- First stage (S-IC): 5 x F-1 engines: kerosene + liquid oxygen
- Second stage (S-II): 5 x J-2 engines: liquid hydrogen + LOX
- Third stage (S-IVB): 1 x J-2 engine, used twice during mission

Apollo Spacecraft: Command and Service Module



Apollo 15 CSM in lunar orbit (photo taken from Lunar Module)

Apollo Spacecraft: Lunar Module



Apollo 16 LM on surface of the Moon

Artemis Spacecraft

- NASA vehicles (with ESA support) get the crew to Lunar orbit
- Commercially provided vehicles (SpaceX, Blue Origin, and others) provide landers and laboratory for lunar orbit

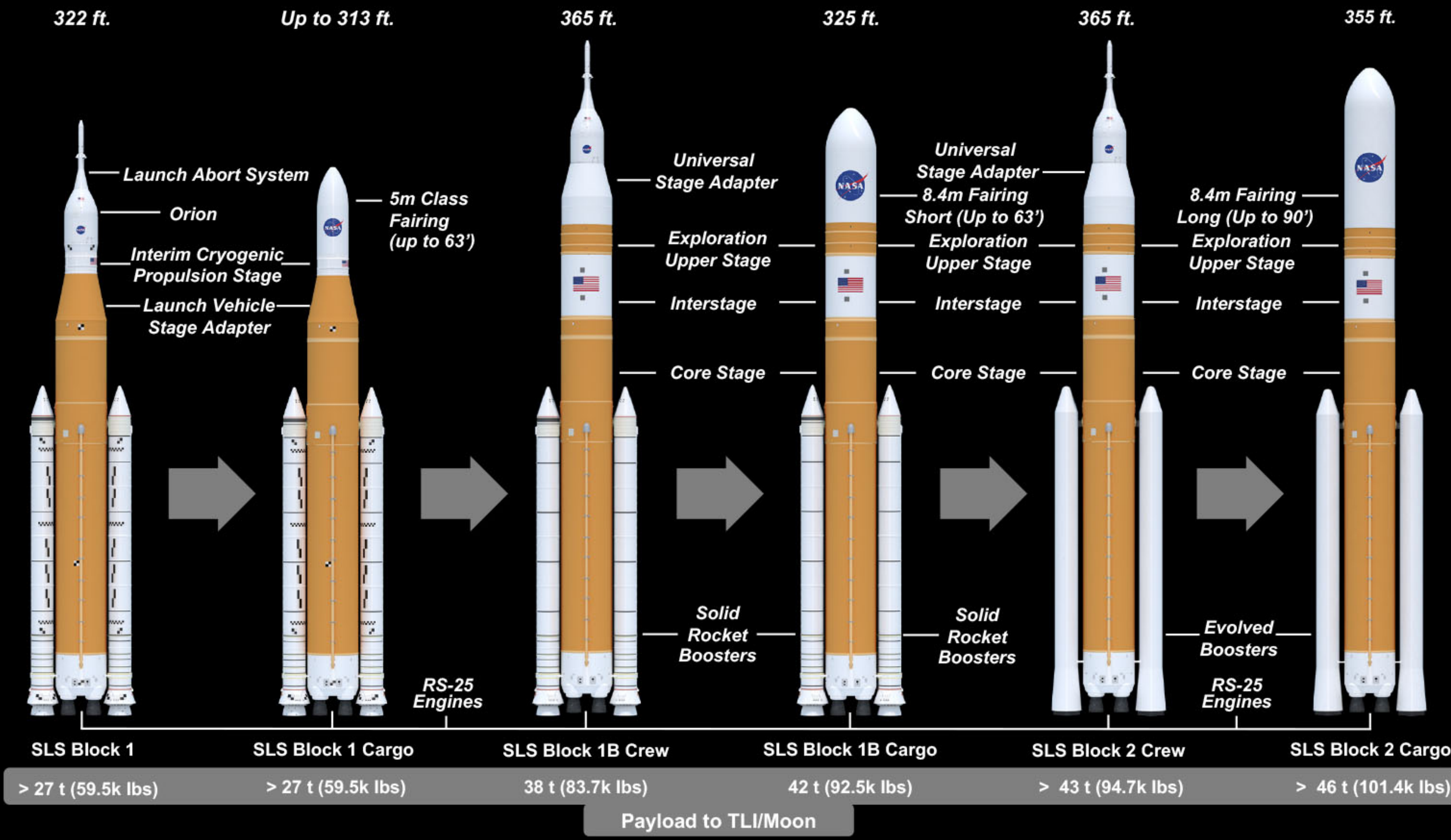
Artemis Launch Vehicle: SLS

Legacy Space Shuttle hardware includes RS-25 engines and Solid Rocket Boosters

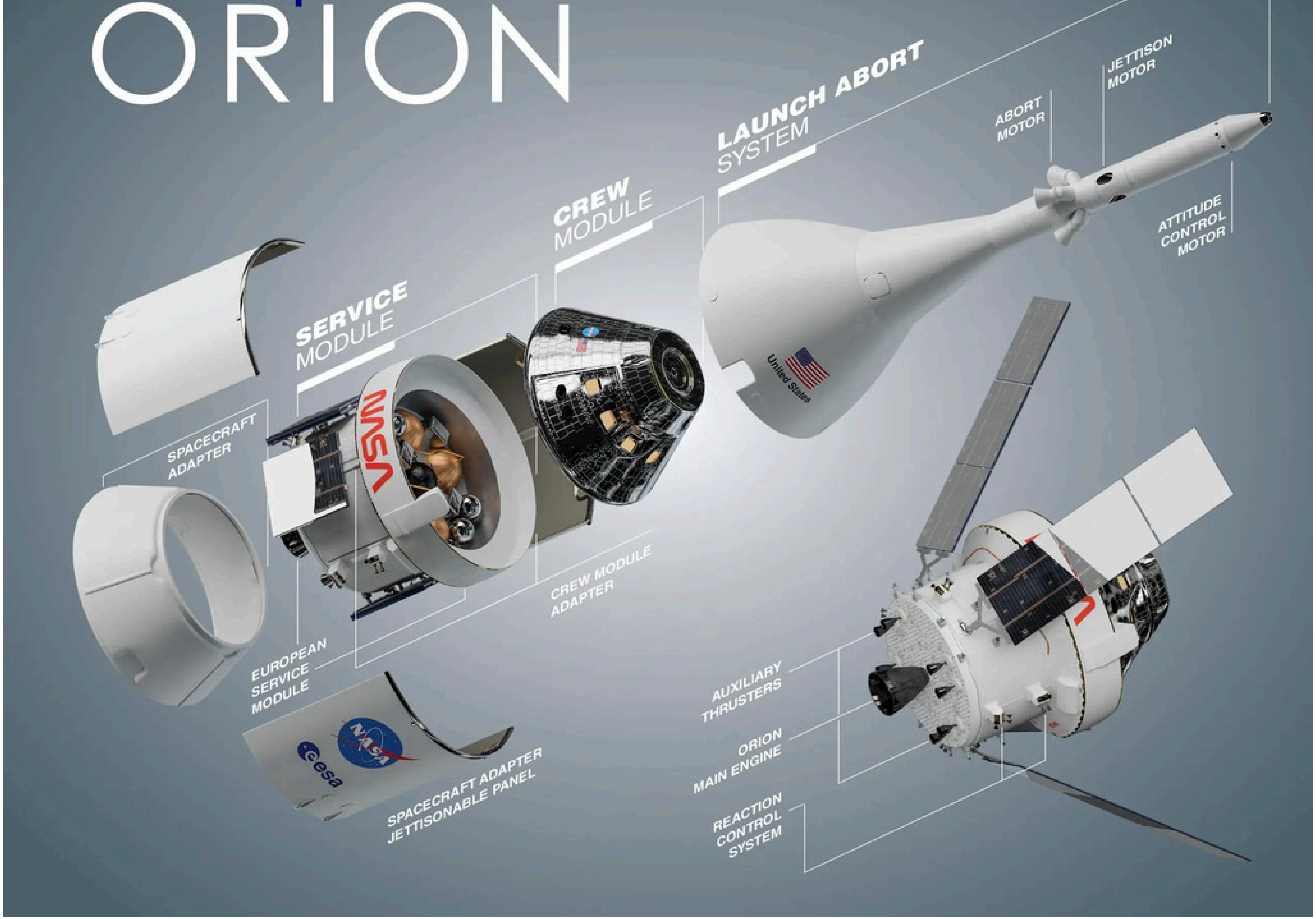
Apollo-like mission using Space Shuttle hardware

SLS EVOLVABILITY

FOUNDATION FOR A GENERATION OF DEEP SPACE EXPLORATION

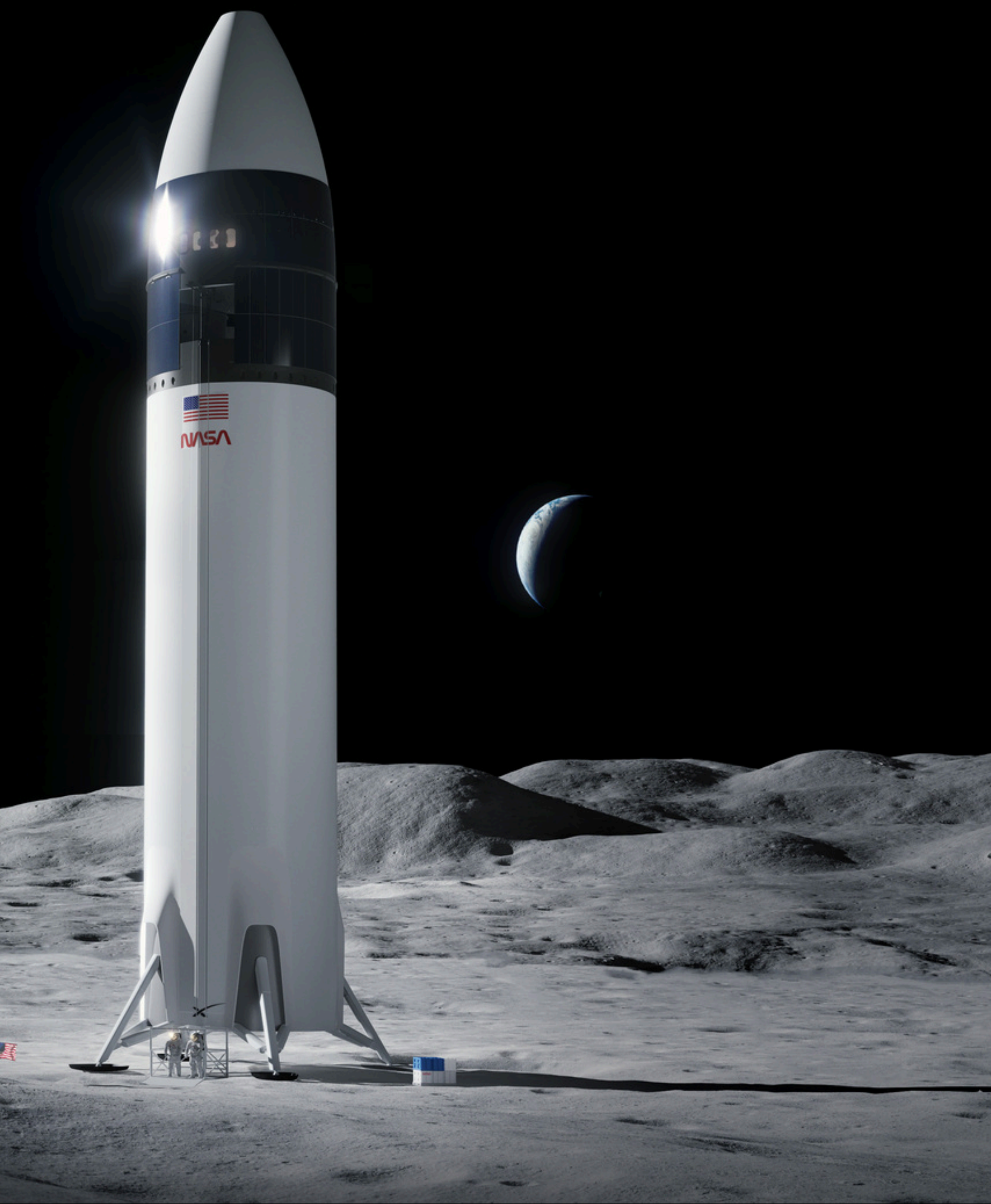


Artemis Crew Spacecraft: Orion



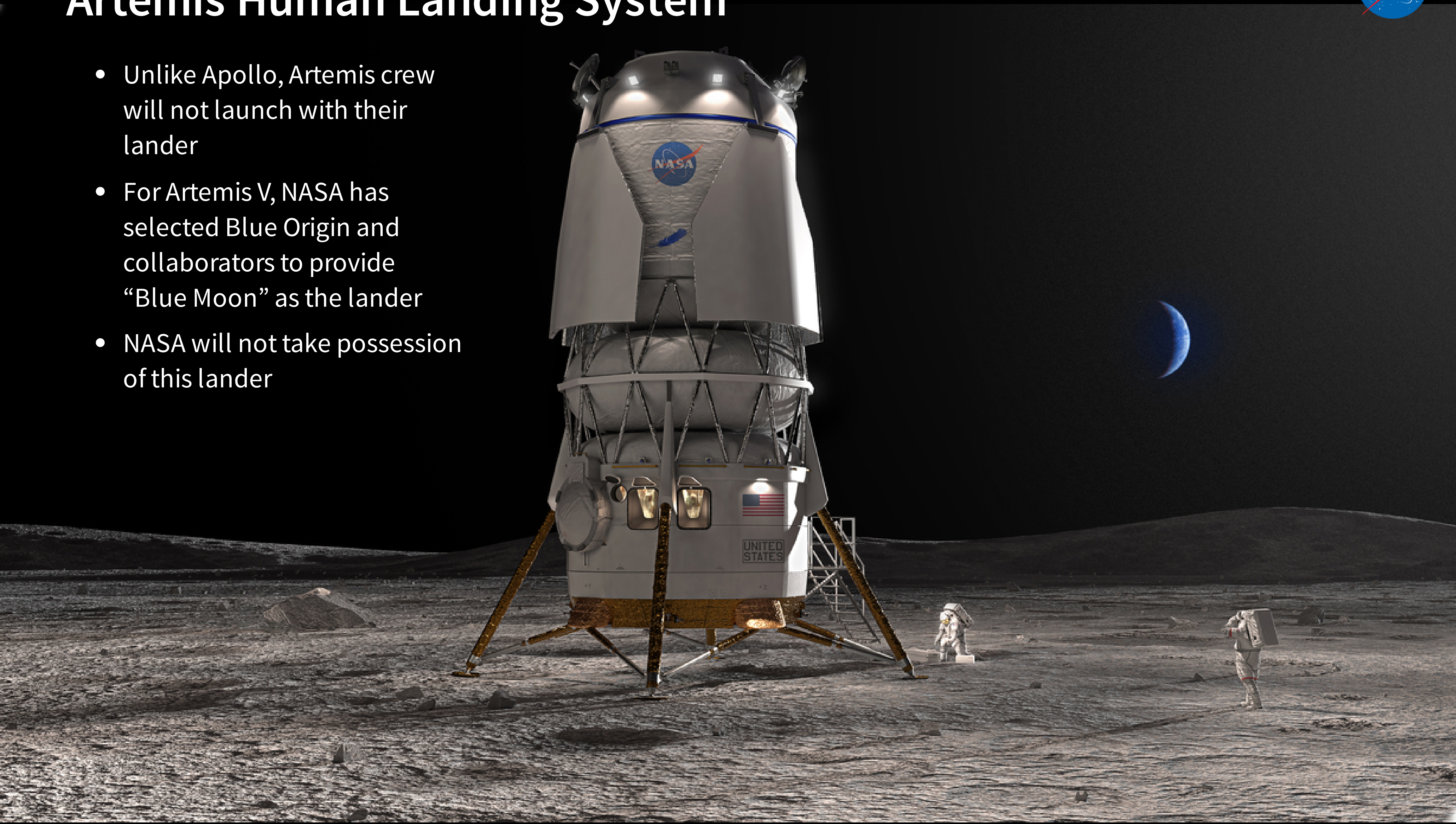
Artemis Human Landing System

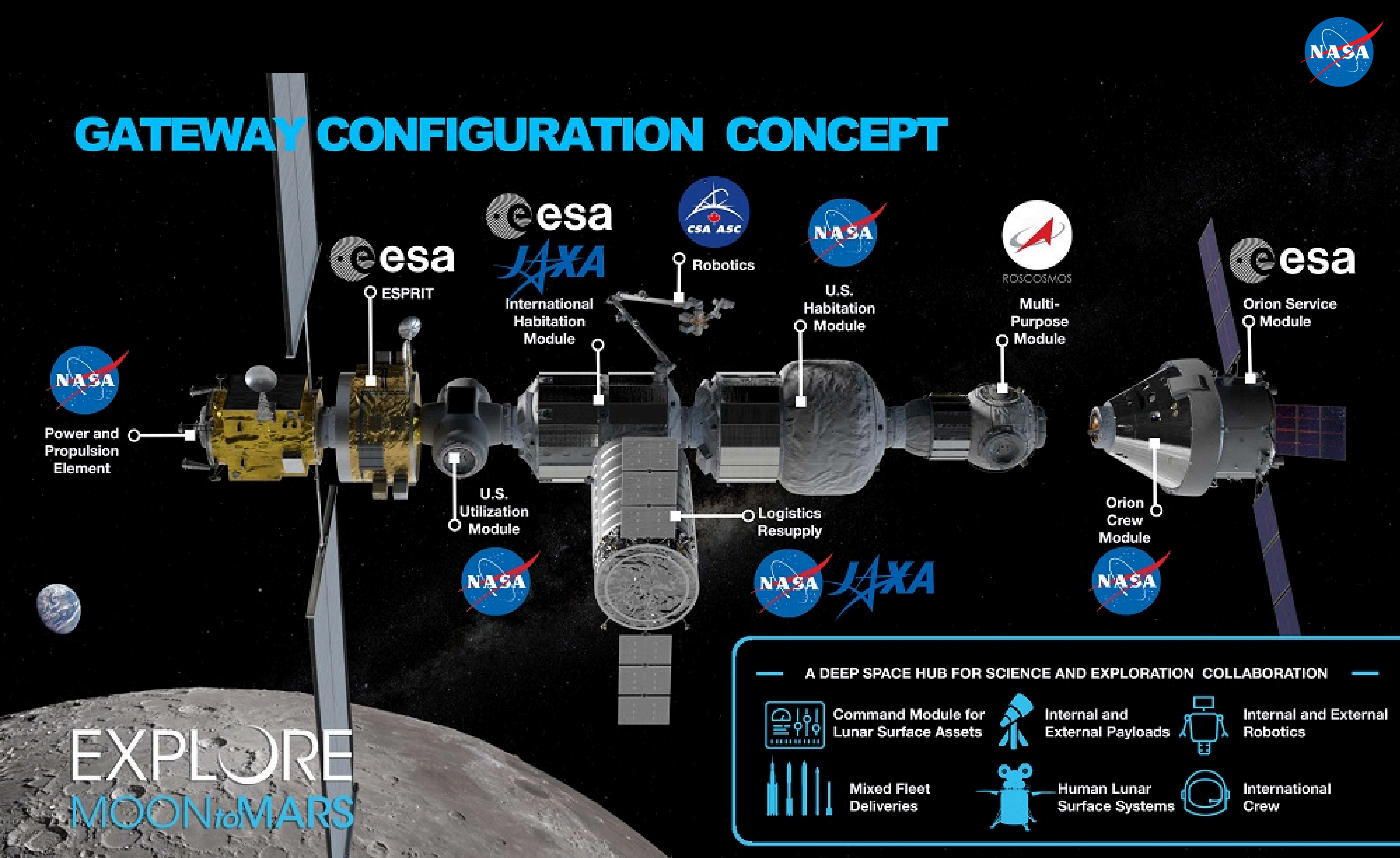
- Unlike Apollo, Artemis crew will not launch with their lander
- For Artemis III and IV, NASA has selected SpaceX
- to provide “Starship HLS” as the lander
- NASA will not take possession of these landers



Artemis Human Landing System

- Unlike Apollo, Artemis crew will not launch with their lander
- For Artemis V, NASA has selected Blue Origin and collaborators to provide “Blue Moon” as the lander
- NASA will not take possession of this lander




GATEWAY CONFIGURATION CONCEPT
NASA
esa
ESPRIT
esa
JAXA
International Habitation Module
CSA ASC
Robotics
NASA
U.S. Habitation Module
ROSCOSMOS
Multi-Purpose Module
esa
Orion Service Module
NASA
Power and Propulsion Element
U.S. Utilization Module
NASA
Logistics Resupply
NASA
JAXA
Orion Crew Module
NASA
EXPLORE
MOON to MARS
A DEEP SPACE HUB FOR SCIENCE AND EXPLORATION COLLABORATION
Command Module for Lunar Surface Assets
Internal and External Payloads
Internal and External Robotics
Mixed Fleet Deliveries
Human Lunar Surface Systems
International Crew

More about Artemis

Historical Context: Constellation Program

2008 launch of Ares I-X, prototype of Ares I crew launch vehicle

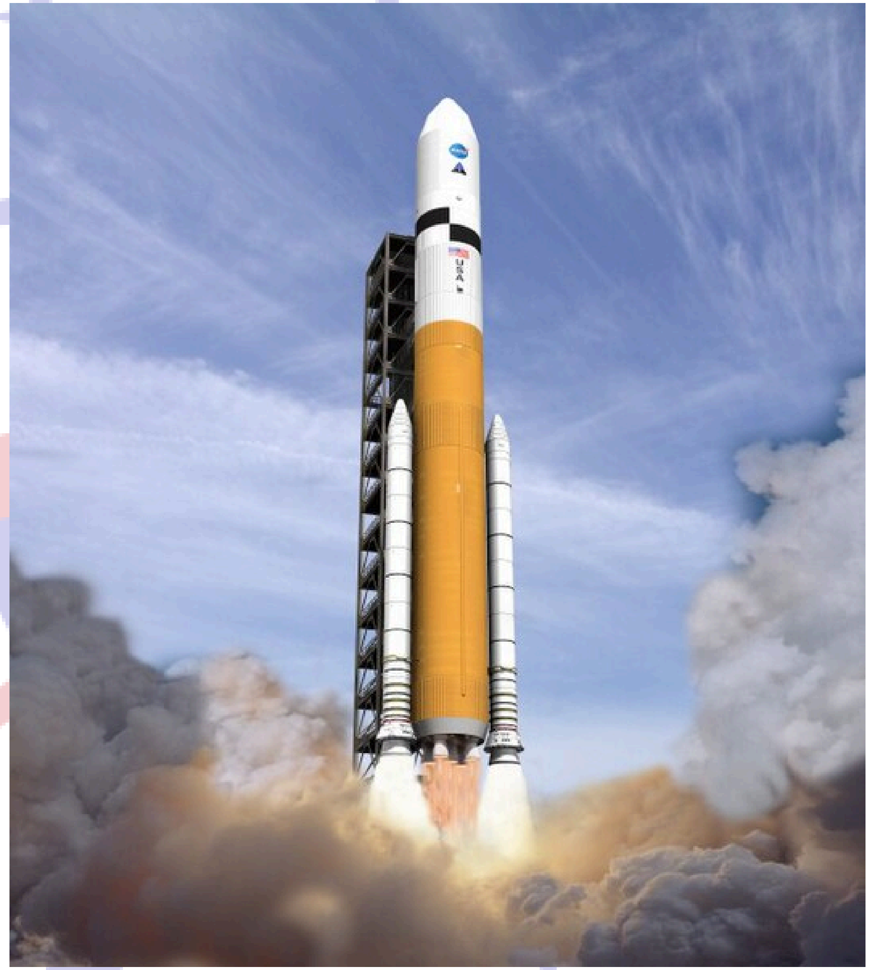


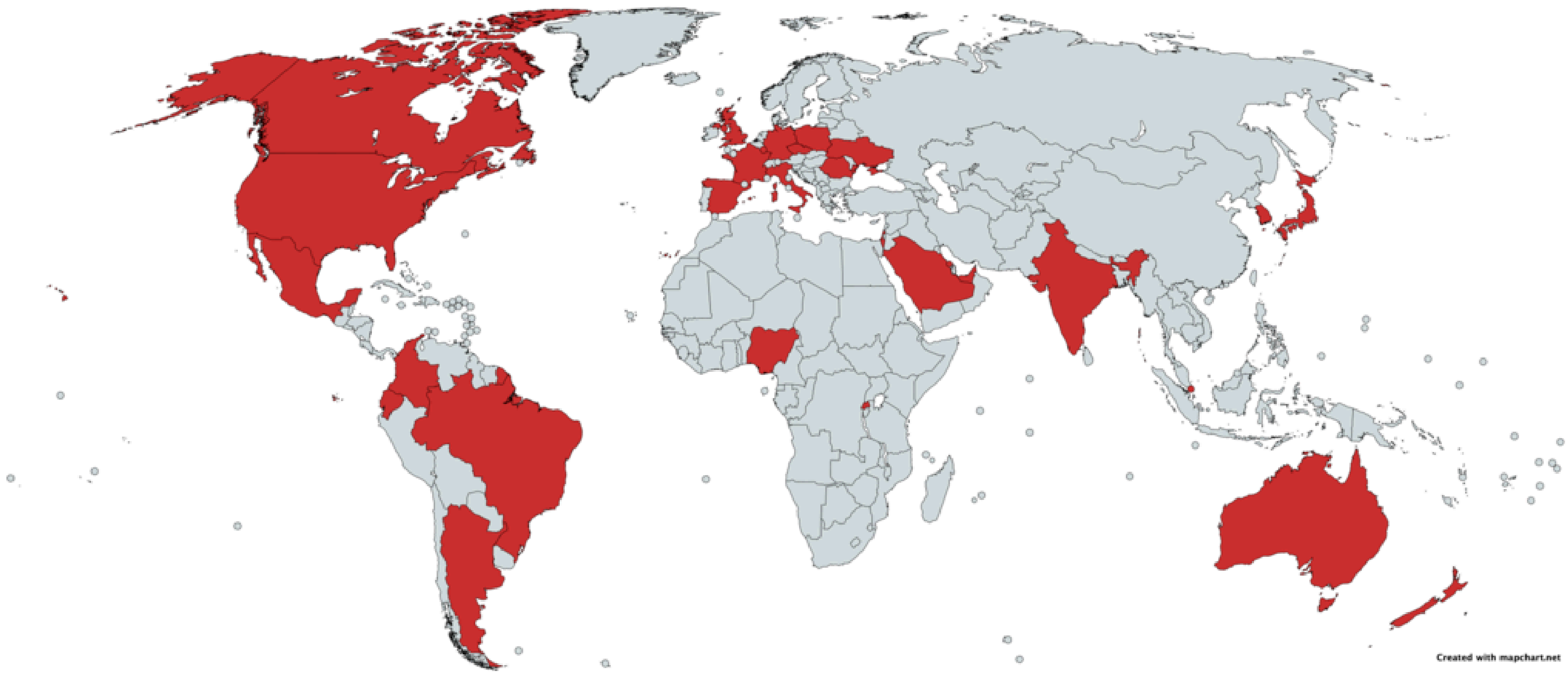
Illustration of Ares V cargo launch vehicle (*construction never started*)

CONSTELLATION

Artemis Accords

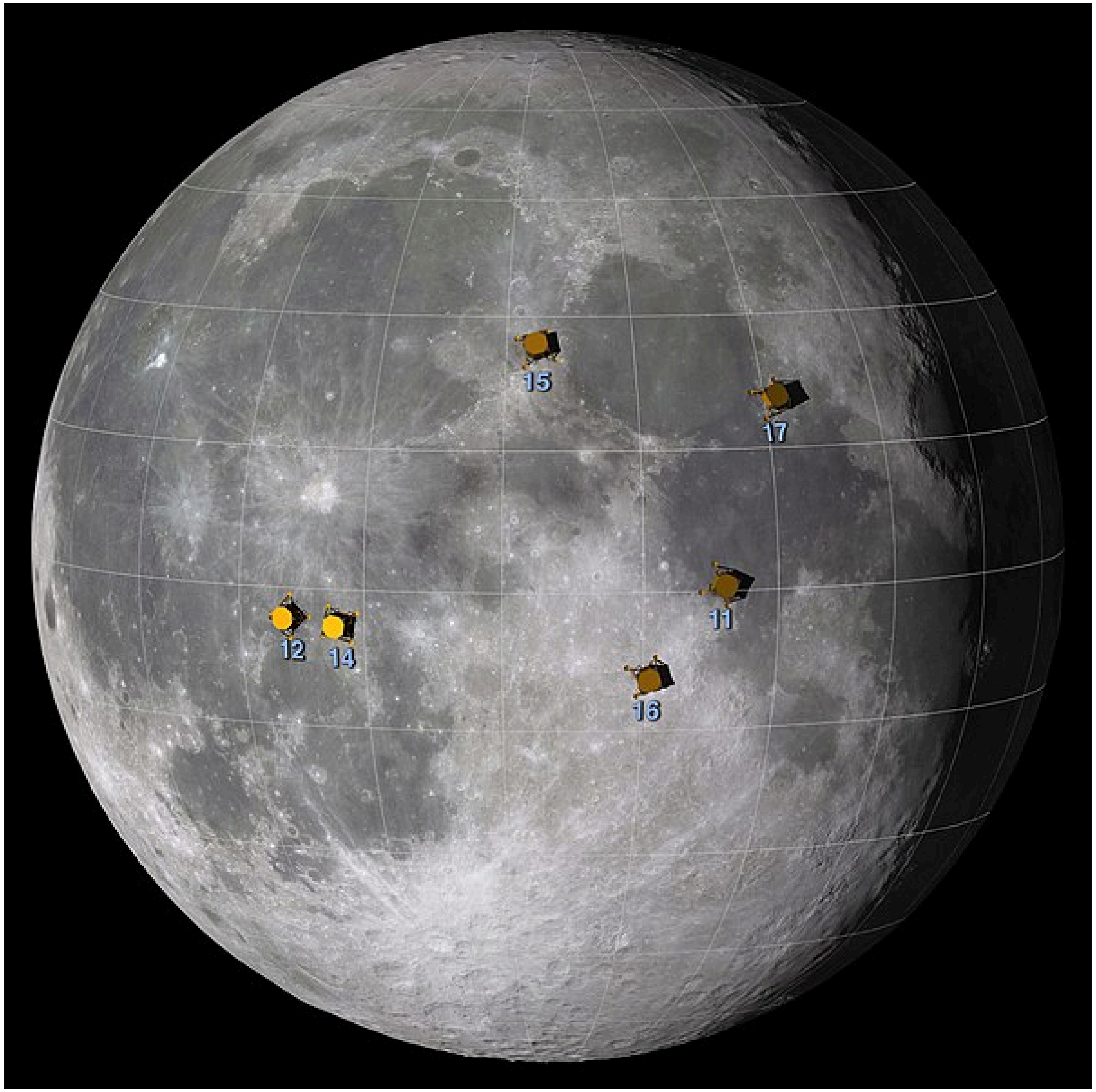
Agreement currently signed by 29 countries (09-13-2023) that reaffirm the Outer Space Treaty and allow for extraction of resources from space (e.g. Helium-3 from lunar regolith)

Argentina, Australia, Bahrain, Brazil, Canada, Colombia, Czech Republic, Ecuador, France, Germany, India, Israel, Italy, Japan, Luxembourg, Mexico, New Zealand, Nigeria, Poland, South Korea, Romania, Rwanda, Singapore, Spain, Saudi Arabia, Ukraine, United Arab Emirates, United Kingdom, United States, Isle of Man

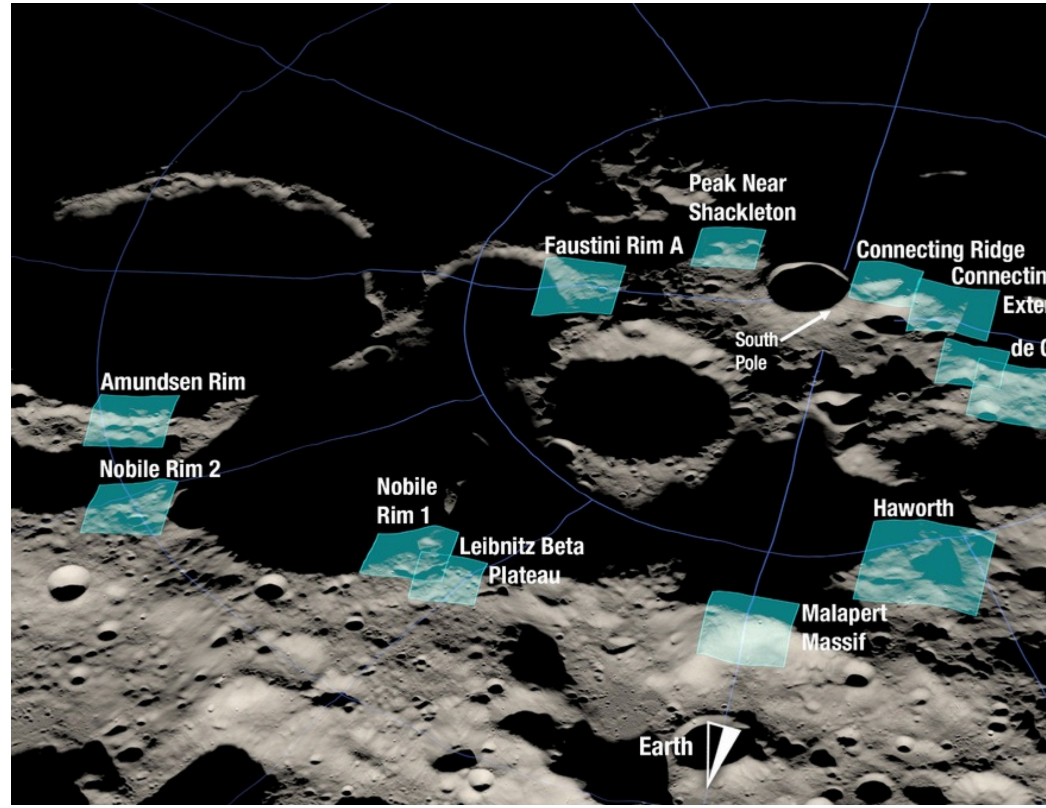


Credit: Mapchart.net & Wikimedians
https://creativecommons.org/licenses/by-sa/4.0/deed.en

More interesting landing sites



Credit: NASA GSFC



Credit: NASA

The Lunar south pole region has craters whose bottoms never see sunlight. That means water ice can persist there! (Moon's axial tilt is only 1.54°, compared to Earth's 23.4°)

Acknowledgments

Exploration Systems Development Mission Directorate (ESDMD)

- Space Launch System Program (SLSP)
- Orion Program
- Exploration Ground Systems (EGS)

NASA High-End Computing

- NASA Advanced Supercomputing Division
- High-End Computing Capability (HECC)
- *Pleiades*, *Electra*, and *Aitken* supercomputers

CFD software highlighted in this work

- FUN3D (Langley)
- OVERFLOW (Langley)
- LAVA (Ames)
- Cart3D (Ames)
- Kestrel (DoD)

Artemis I: We Are Ready video

- Producer: Lisa Allen, Barbara Zelon, Alysia Lee
- Writer & Director: Paul Wizikowski
- Appearances by Keke Palmer, Randy 'Komrade' Bresnik, Rick Labrode, Holly Ridings, Judd Frieling, Fiona Turret, Nujoud Merancy, Howard Hu, Vanessa Wyche

Ames SLS CFD Team

- Stuart Rogers, Jamie Meeroff, Aaron Burkhead, Guy Schauerhamer, Josh Diaz
- Many previous members, especially Thomas Pulliam and Jeff Onufer

Craig Streett (NASA/Langley)

Completed NASA programs

- Apollo program
- Space Shuttle program

NAS Viz Group

- Timothy Sandstrom
- Chris Henze

NASA Ames LAVA Group

- Special thanks to Michael Barad, Jeff Housman, Jared Duensing, Francois Cadieux
- Many other members
- Previous members including Jordan Angel and Cetin Kiris

NASA Langley SLS CFD Team

- Brent Pomeroy, TJ Wignall, Steve Krist

NASA Engineering & Safety Council (NESC)

SLS Aerodynamic Task Team

- Thomas Steva (Lead)
- Ray Gomez (Co-chair)
- Jeremy Pinier
- Andy Herron (previous lead)
- John Blevins (previous lead)

Appendix: Supercomputing in the Artemis Program

Artemis I: We Are Ready

Credit: NASA

Producer: Lisa Allen, Barbara Zelon, Alysia Lee

Writer & Director: Paul Wizikowski

https://youtu.be/wKwoBudYIiI

Supercomputing in the Artemis Program { background-image="figs/jedi125-q1-1-001-m110a0-y0-mach.png"}

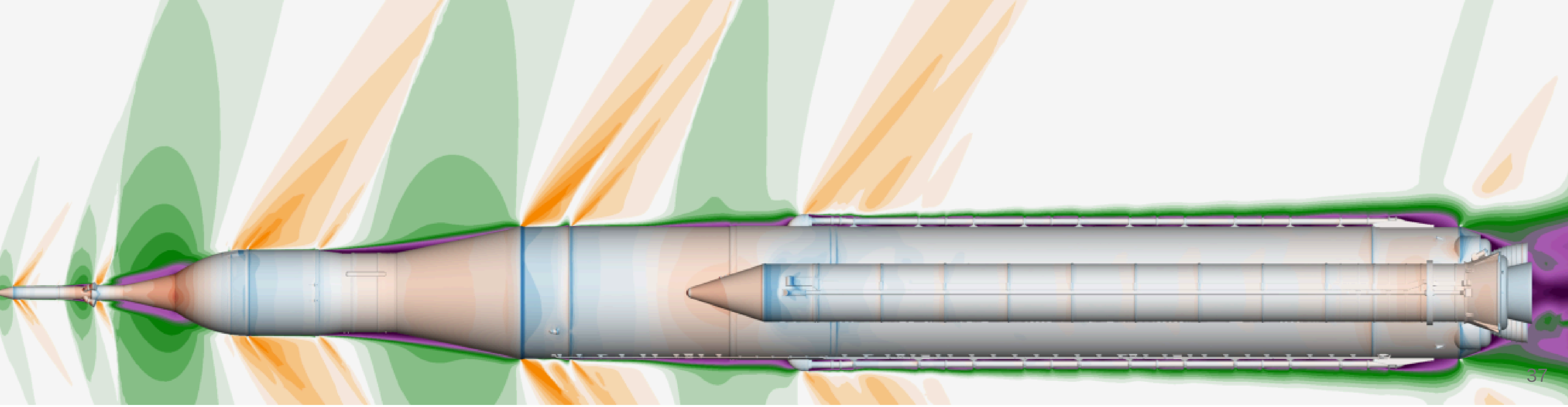
What's the deal with "aerosciences"?

Or, why does creating this image need more computing power than simulating 30,000+ launch trajectory simulations?

Supercomputing in the Artemis Program

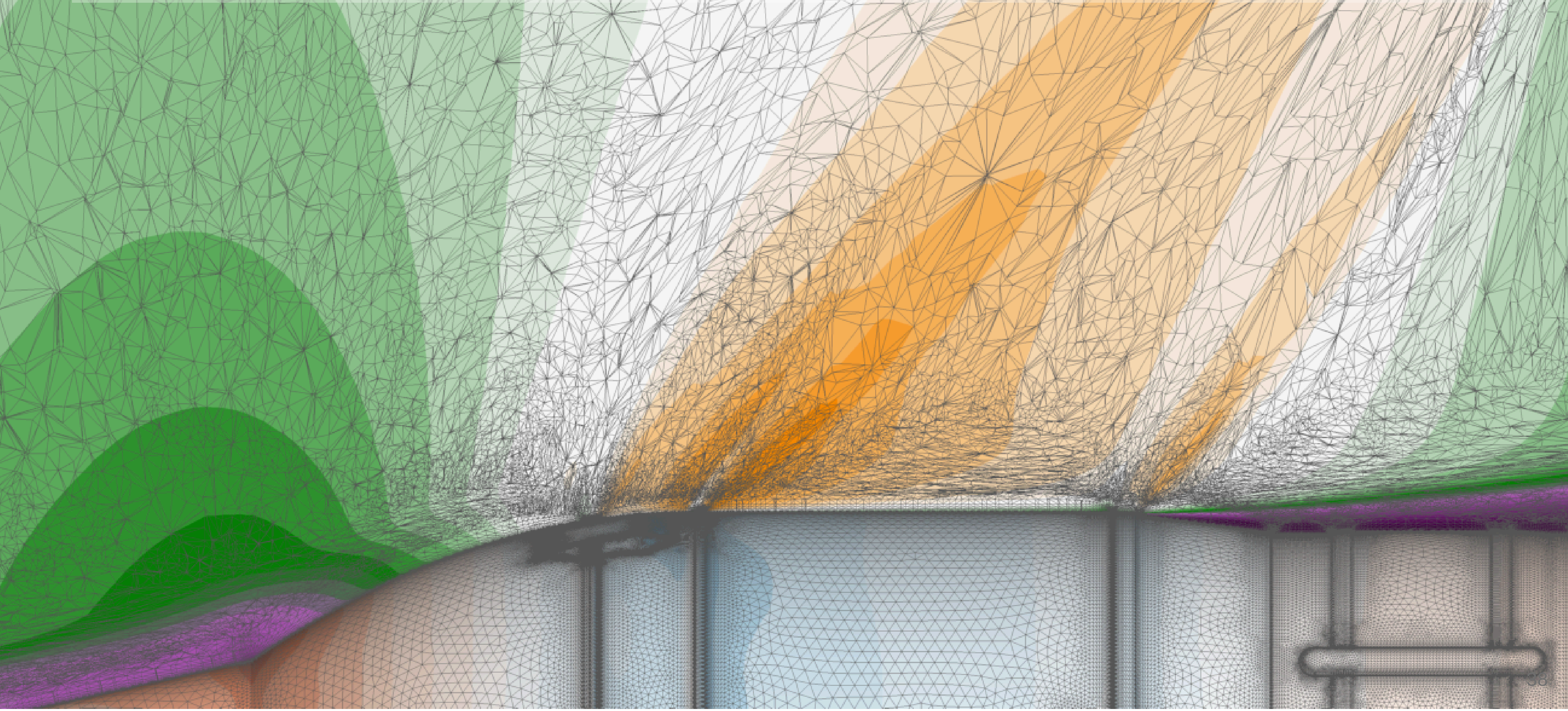
What's the deal with "aerosciences"?

Or, why does creating this image need more computing power than simulating 30,000+ launch trajectory simulations?



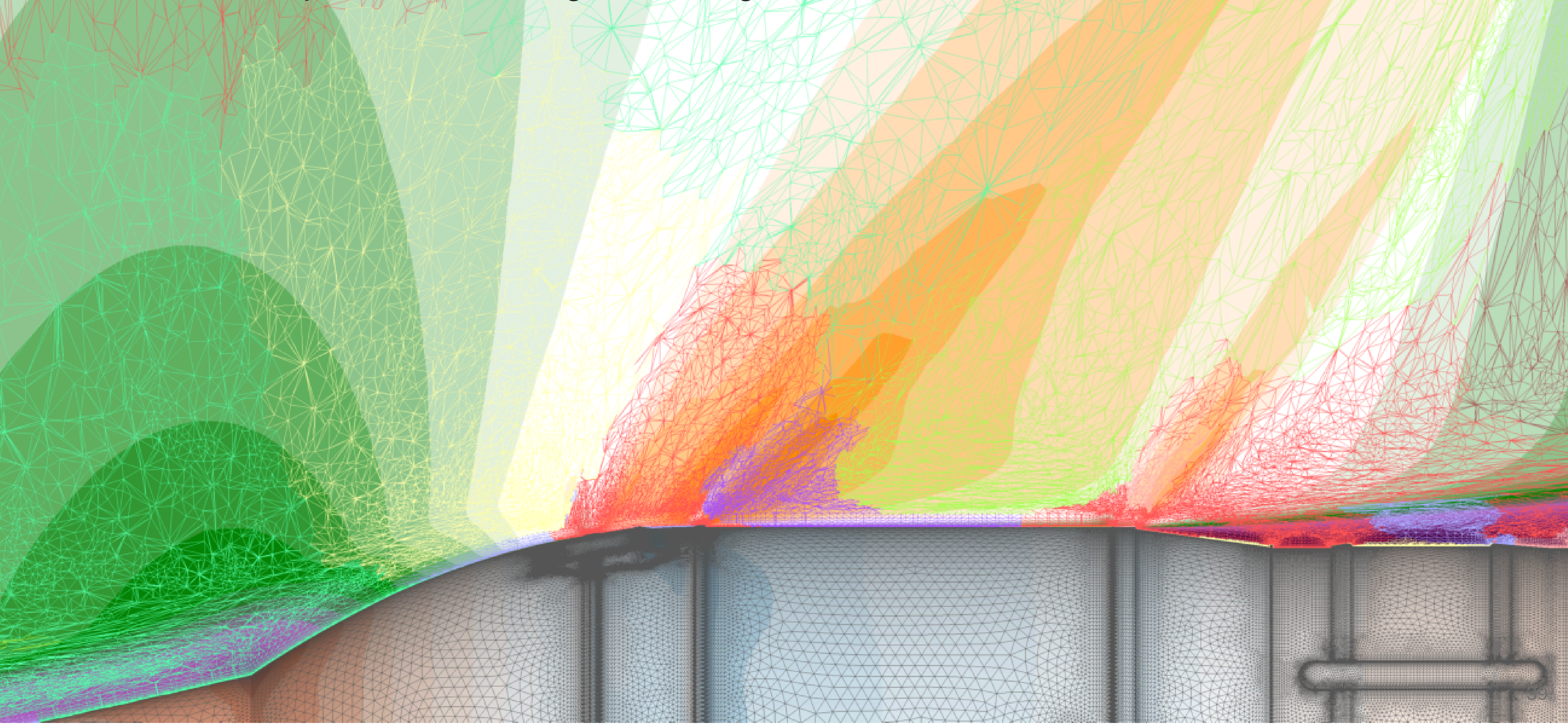
High-Performance Computing and Aerosciences

- Does this picture help explain it?
- Predicting aerodynamics (or aerothermodynamics or acoustics…) at a single flight condition means solving for state variables at *millions* of points
- And the points are highly interrelated, so you can't solve one at a time



How Does it Work?

- Split the flow into smaller chunks
- Each computer "core" works on one chunk
- Lots of communication between the cores
- Each boundary between color changes in this image



How Does it Work?

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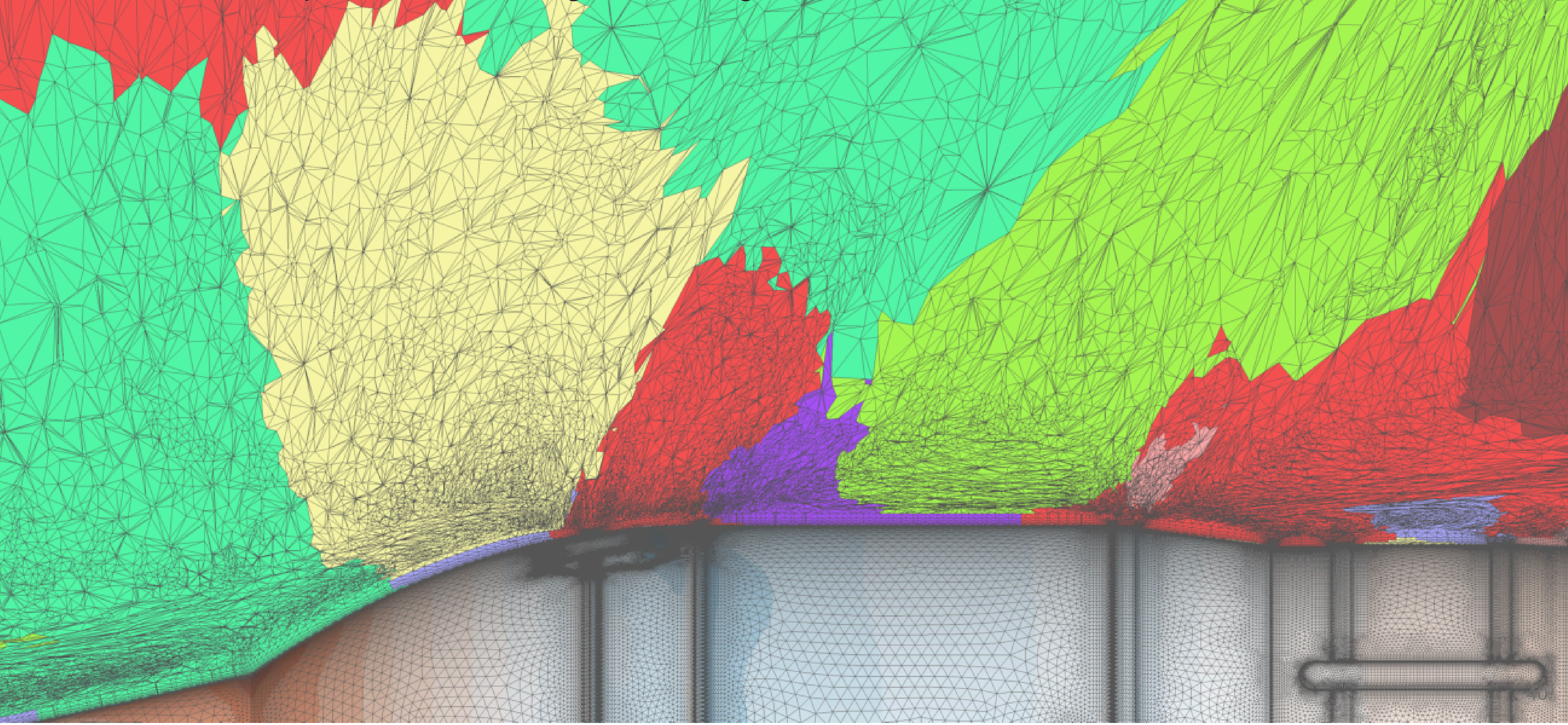
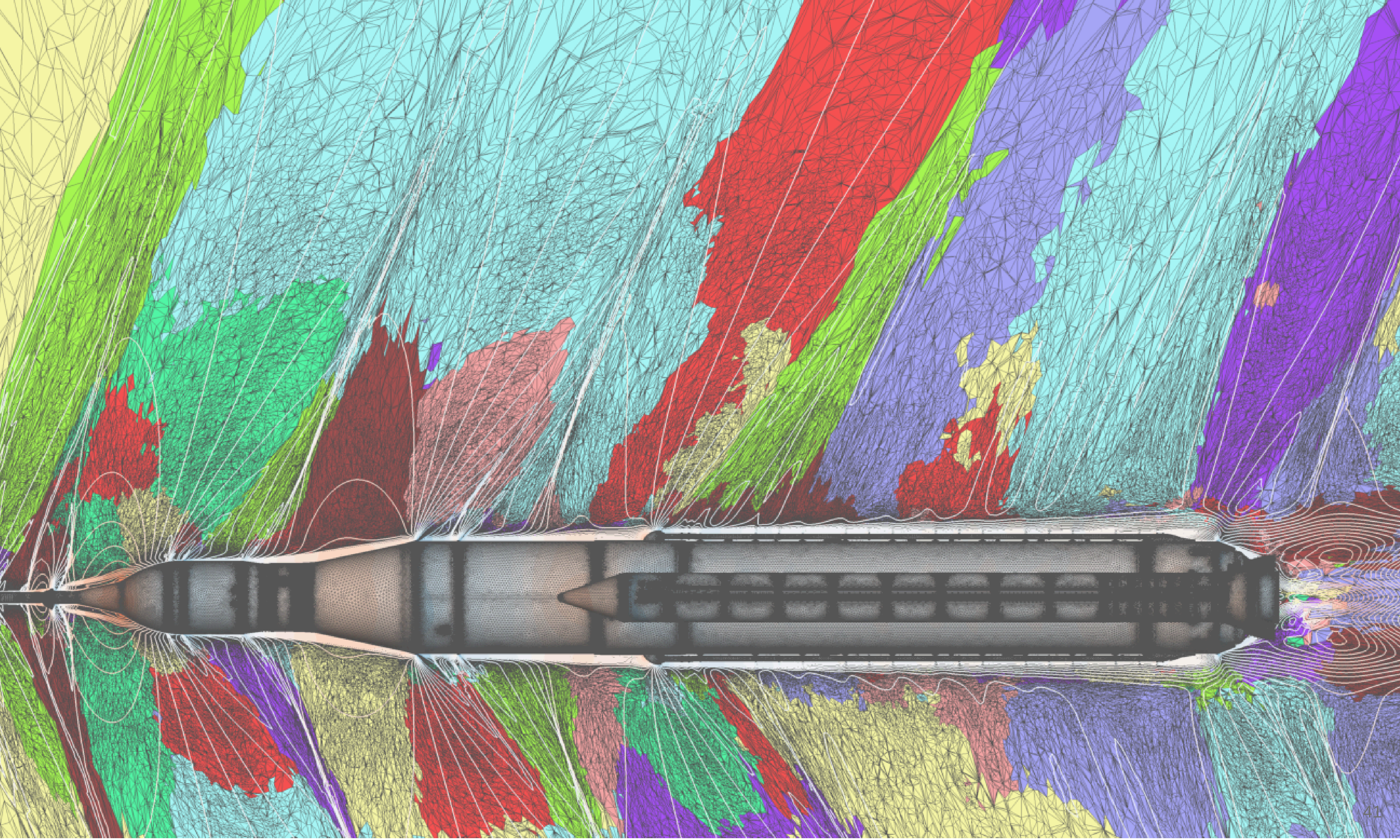
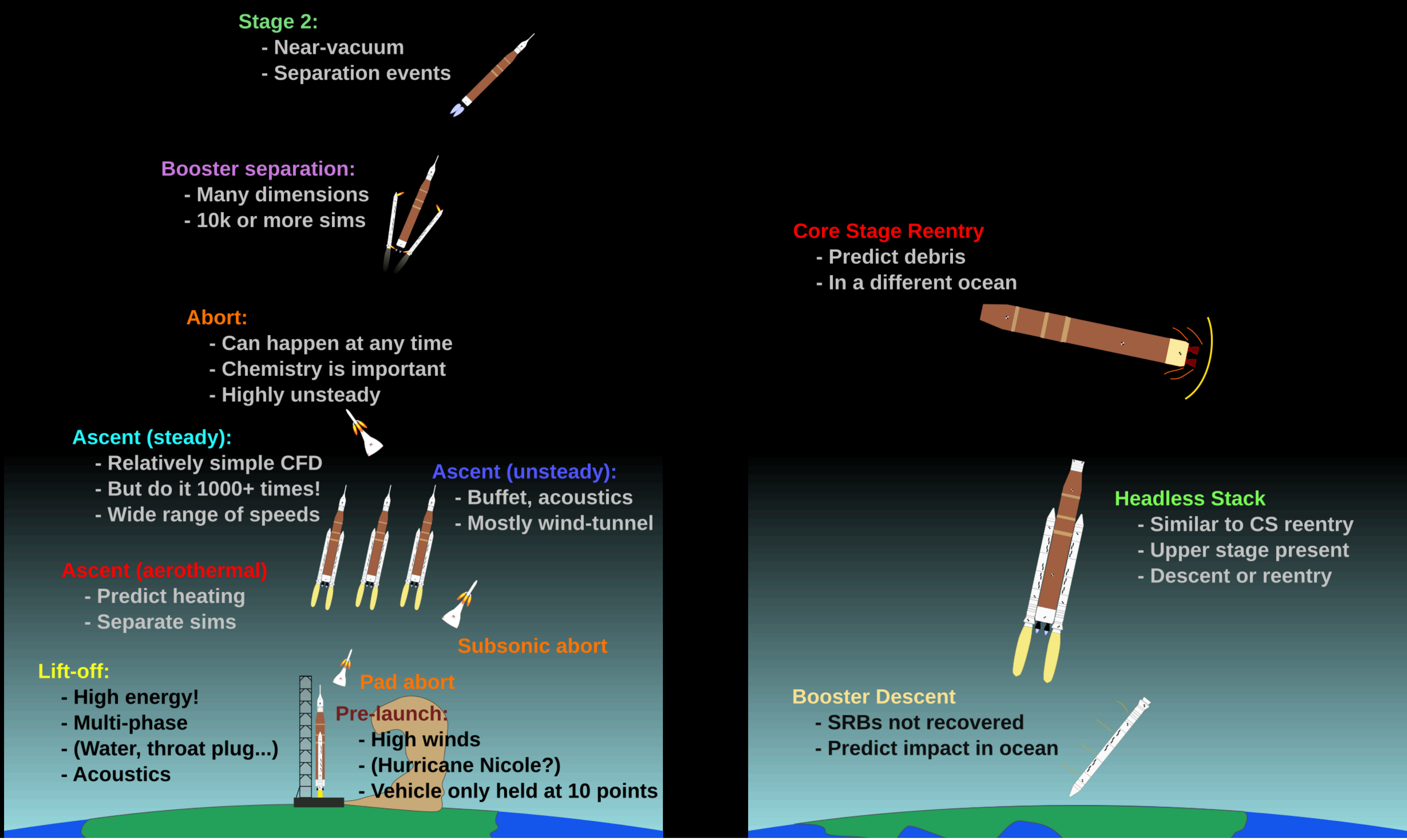


Put it All Together

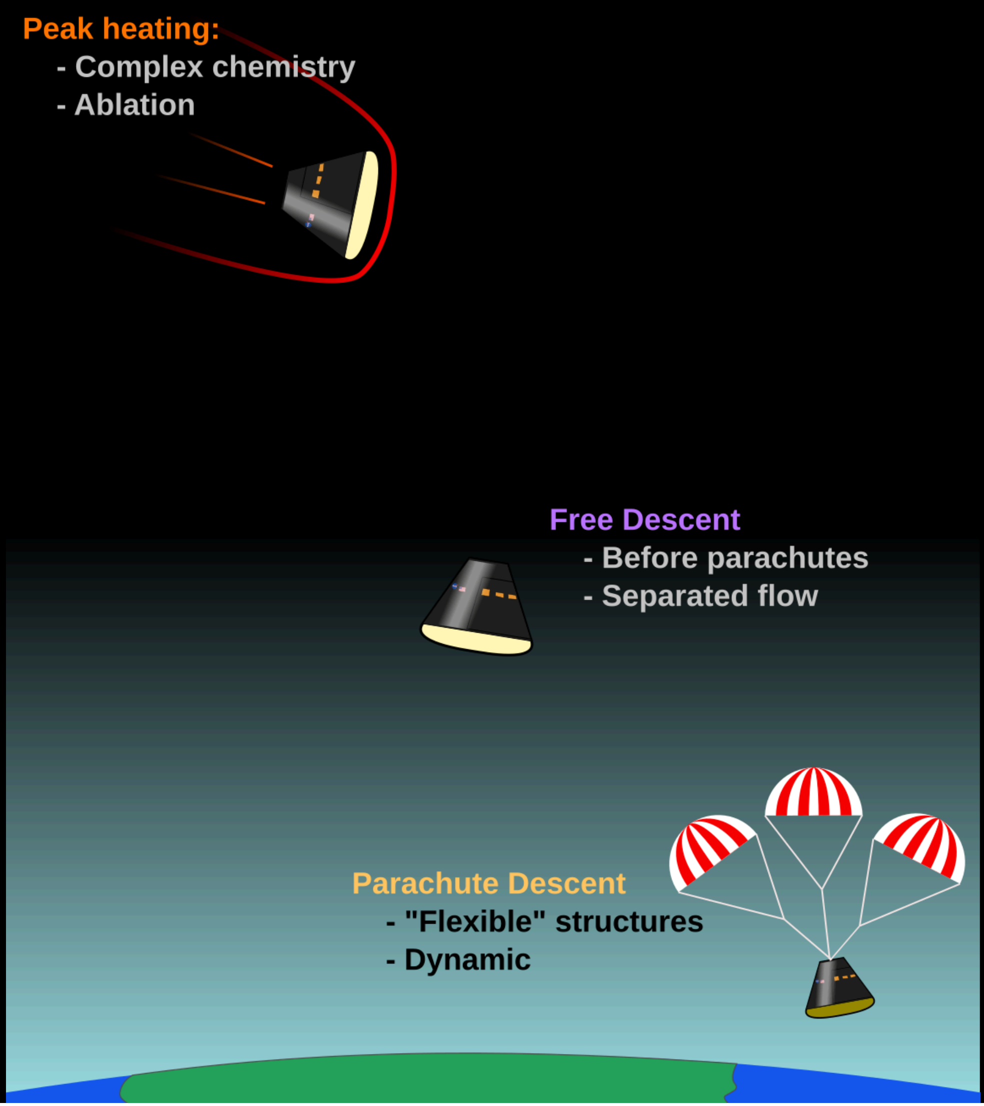


Environments

Artemis Launch Environments



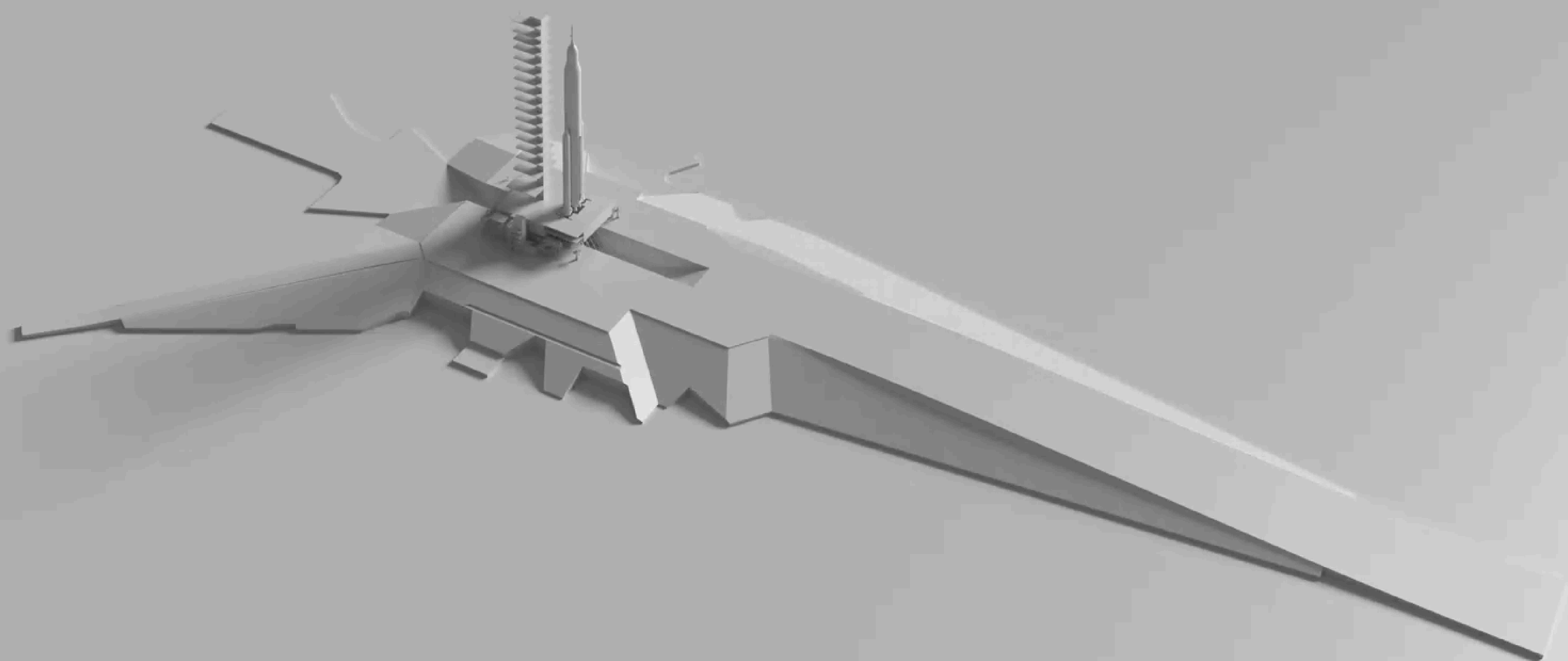
Reentry Environments

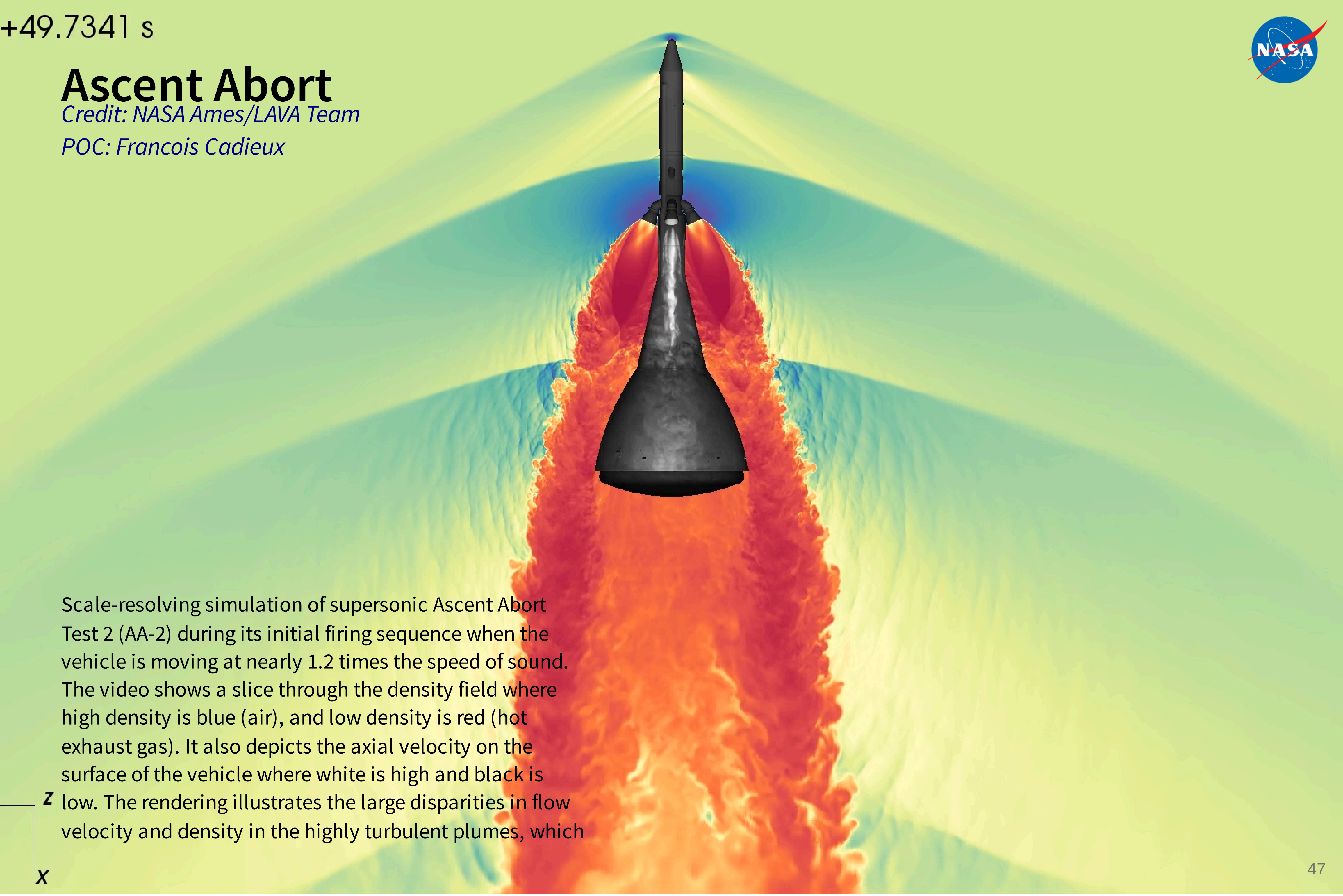


Liftoff and Related Environments

Credit: NASA Ames/LAVA Team
Video: Tim Sandstrom
POC: Michael Barad

This visualization depicts the Space Launch System geometry and a volume rendering of mass fractions for liquid water (blue), water vapor (white), and vehicle exhaust (purple low, yellow high). The water system and liquid engines are started and allowed to reach a quasi-steady state before the solid motor engines are started.





Ascent Abort

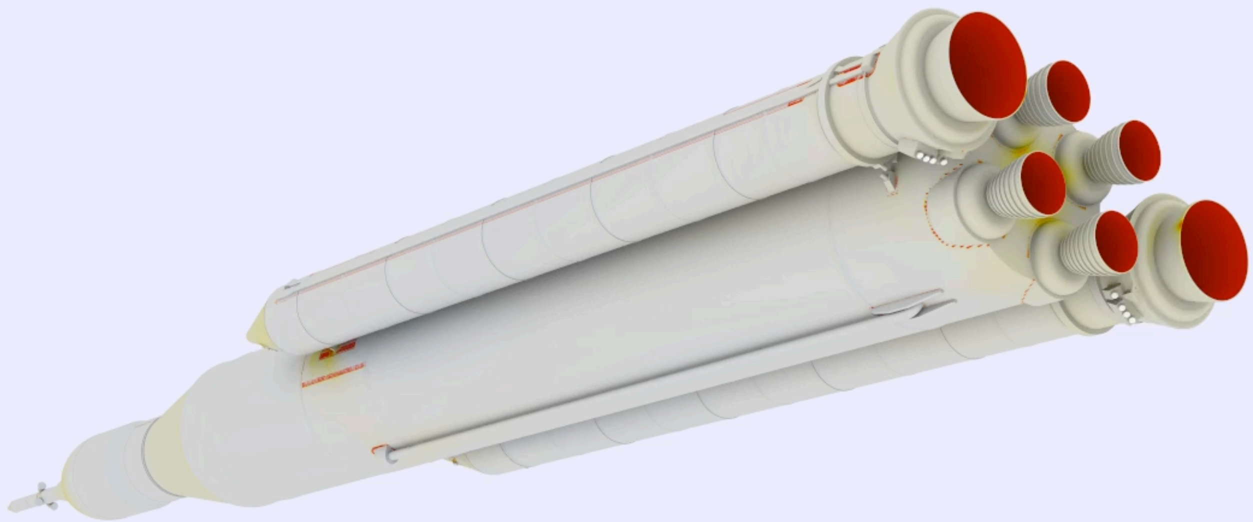
Credit: NASA Ames/LAVA Team

POC: Francois Cadieux

Scale-resolving simulation of supersonic Ascent Abort Test 2 (AA-2) during its initial firing sequence when the vehicle is moving at nearly 1.2 times the speed of sound. The video shows a slice through the density field where high density is blue (air), and low density is red (hot exhaust gas). It also depicts the axial velocity on the surface of the vehicle where white is high and black is low. The rendering illustrates the large disparities in flow velocity and density in the highly turbulent plumes, which

Booster Separation

Credit: NASA Ames/Jeff Onufer, Tom Pulliam
Video: Tim Sandstrom
POC: Derek Dalle



0 ' 0 "

novement of booster noses
and inches:

Then and Now

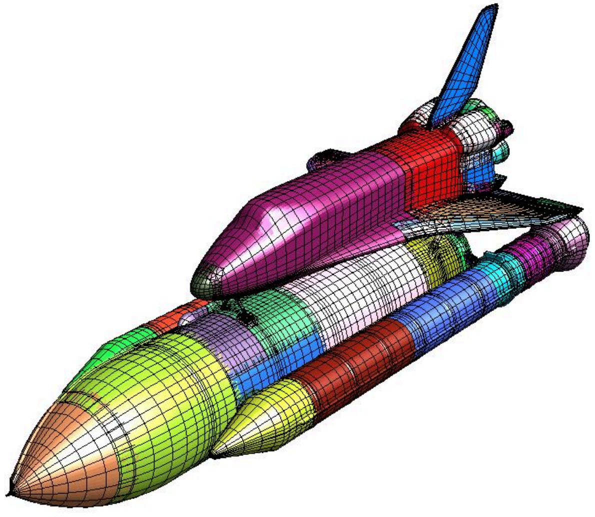
High-Performance Computing for Apollo, Space Shuttle, and Artemis

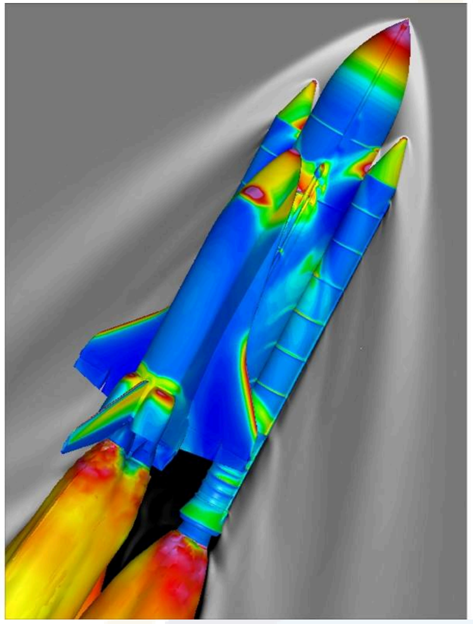
Supercomputing for Apollo?

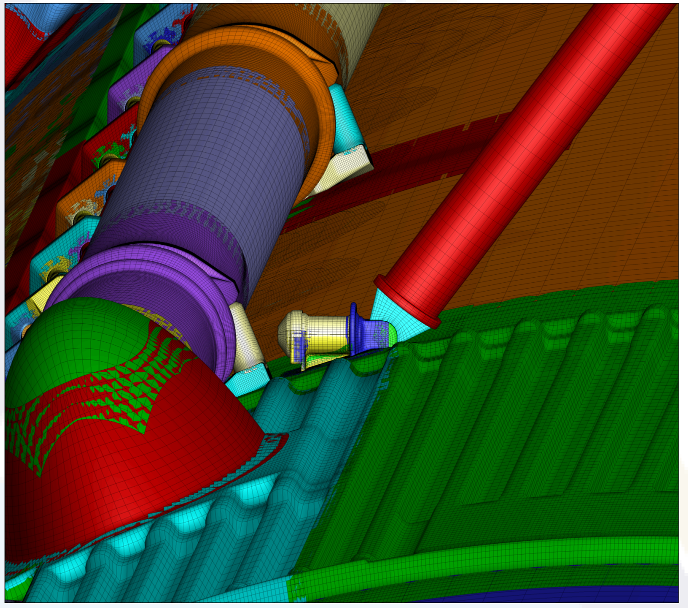
Supercomputing for Space Shuttle

> Accurately predicting the Space Shuttle ascent aerodynamic environment has proven a very elusive goal.

Fred Martin and Jeff Slotnick, **1989**: F.W. Martin Jr. and J.P. Slotnick. “Flow Computations for the Space Shuttle in Ascent Mode Using Thin-Layer Navier-Stokes Equations.” *Applied Computational Aerodynamics*, edited by P. Henne, chap. 24, AIAA 1990, pp. 863–886.

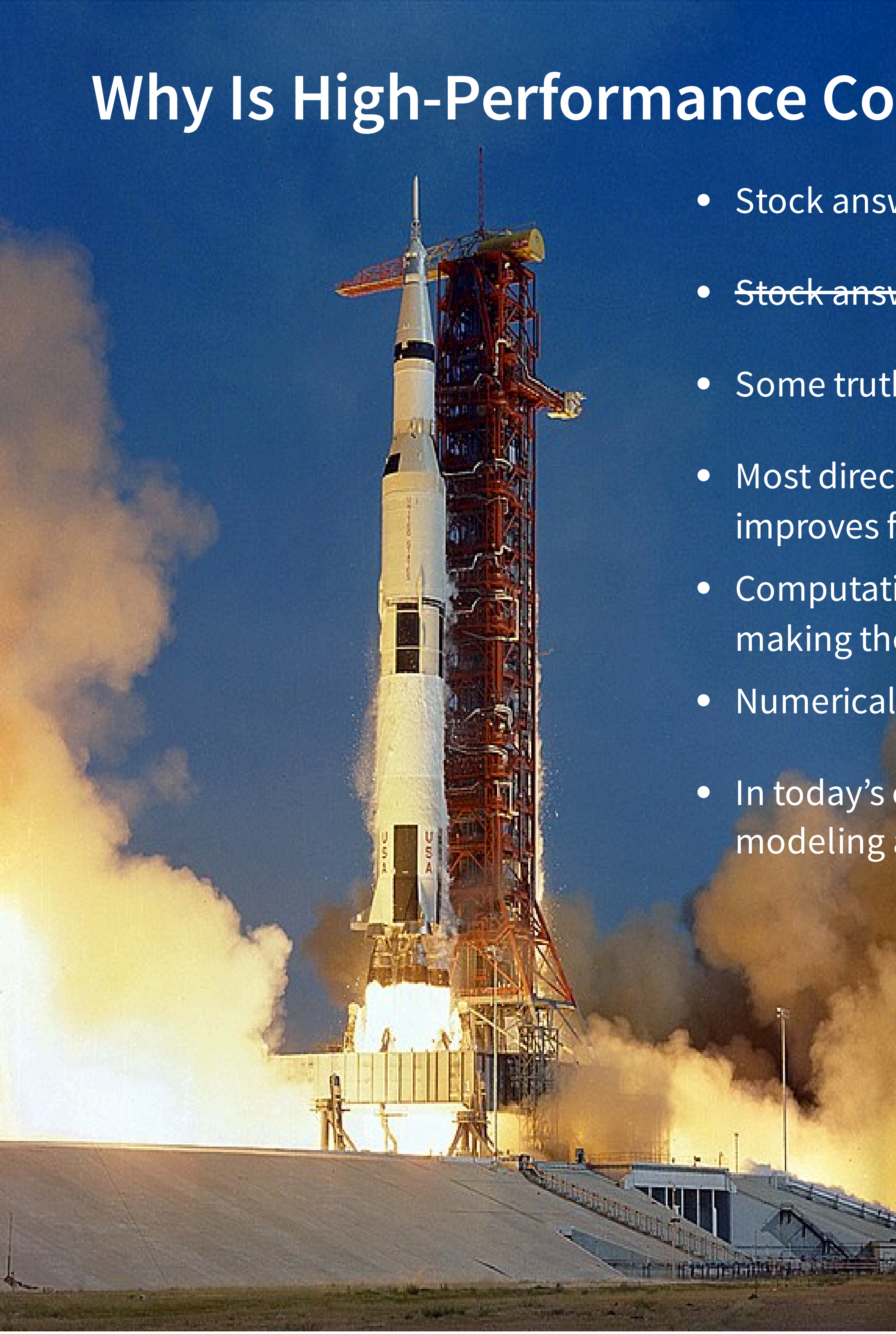






By the end of the program, use of supercomputing for aerosciences looks a lot like today.

Why Is High-Performance Computing Necessary?



- Stock answer: Modeling is cheaper than other types of testing
- ~~Stock answer: Modeling is cheaper than other types of testing~~
- Some truth to that overall, but reality is more complicated
- Most direct reason to use HPC: would it be rational to **not** use a tool that improves flight safety?
- Computational/numerical models are much quicker to set up and change, making them really useful in the early stages of a program
- Numerical models can incorporate physics that are hard to ground-test
- In today's environment, ground testing, flight testing, and supercomputing modeling are highly complementary