National Aeronautics and Space Administration

Plume Impingement Studies in Space Environments for NASA Deep Space Logistics

Mechanical and Aerospace Engineering Graduate Seminar, UCF

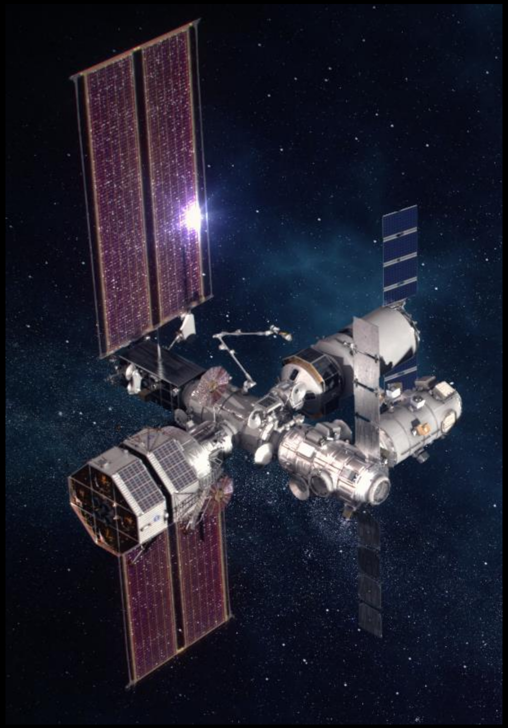
Jonathan S. Pitt, Ph.D.

Subject Matter Expert, Computational Fluid Dynamics

Kennedy Space Center (Aegis Aerospace, Inc.)

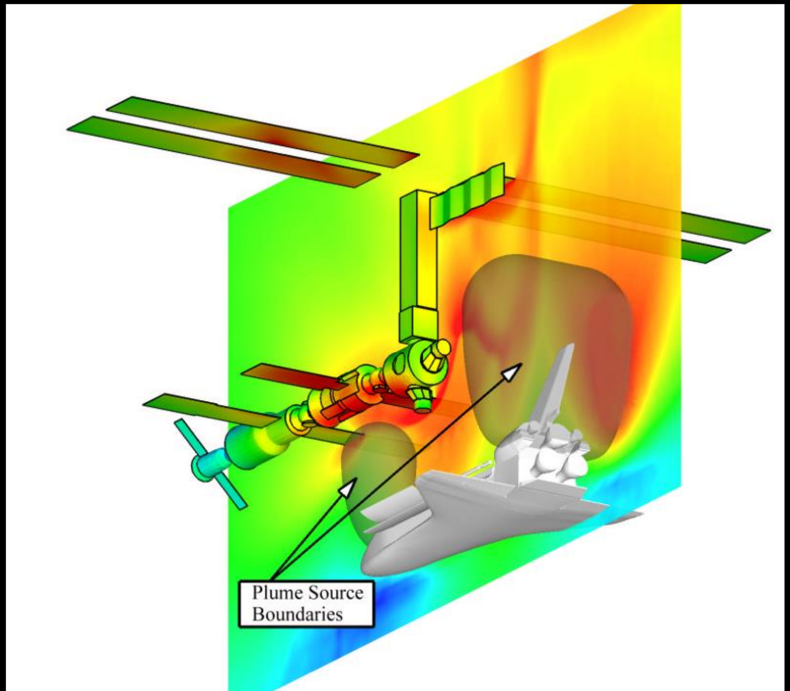
21 Jan 2022

Presentation Overview



Lunar Gateway

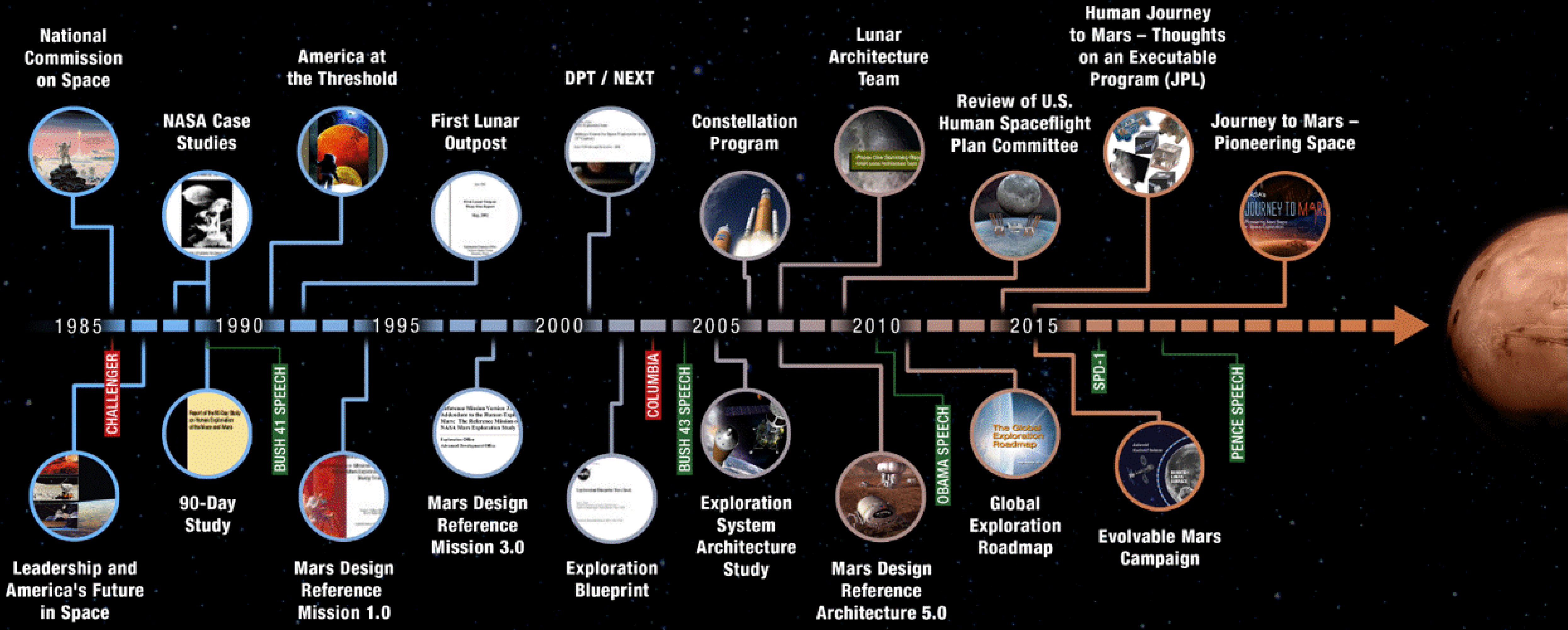
Deep Space Logistics



Reproduced from Lumpkin III et al. (2003)

Plume Impingement in Space Environments

A Brief History of Beyond LEO Human Exploration Studies



ARTEMIS

Twin sister of Apollo and goddess of the Moon in Greek mythology, Artemis is the torch-bringer personifying our path to the Moon. During the next era of human exploration, we will discover life-saving, Earth-changing science and technology along the way.

NASA’s goal is to land the first woman and first person of color on the Moon. When the Artemis astronauts land on the lunar surface, they will step into the future, bringing all of humanity with them.

Why go to The Moon?

Proves technologies and capabilities for sending humans to Mars

Establishes American leadership and strategic presence

Inspires a new generation and encourages careers in STEM

Leads civilization changing science and technology

Expands the U.S. global economic impact

Broadens U.S. industry and international partnerships in deep space

Mission Needs Drive Design

LOW EARTH RETURN

3 HOURS
3,000°F
17,500 MPH
250 MILES

LUNAR RETURN

3 DAYS
5,200°F
24,700 MPH
240,000 MILES

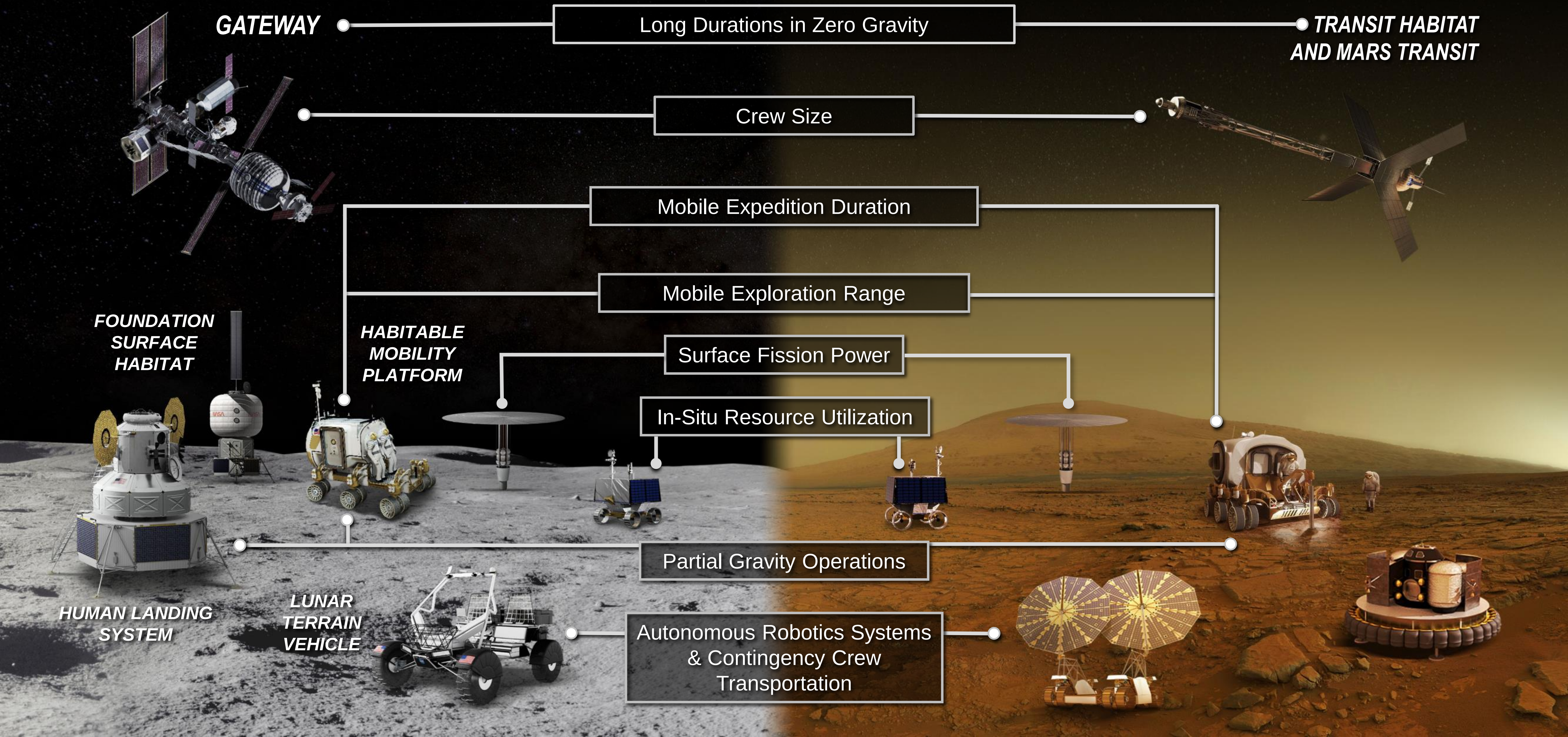
MARS RETURN

9 MONTHS
6,200°F
26,800 MPH
39,000,000 MILES

**Numbers are averages*

MOON AND MARS EXPLORATION

Operations on and around the Moon will help prepare for the first human mission to Mars



Artemis: a Foundation for Deep Space Exploration

Space Launch System

Orion spacecraft

Human Landing System

Surface Operations

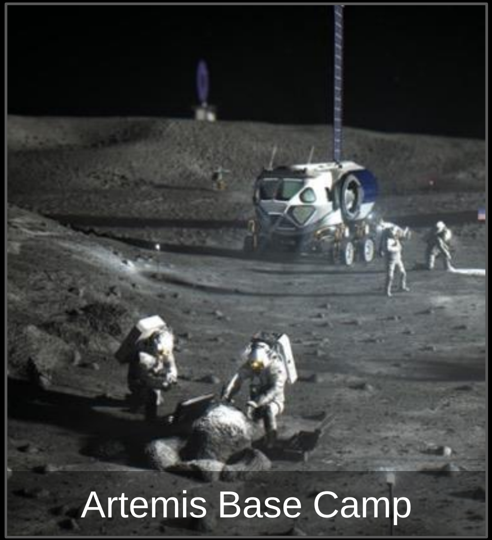
Gateway

Exploration Ground Systems

Space Communications & Navigation

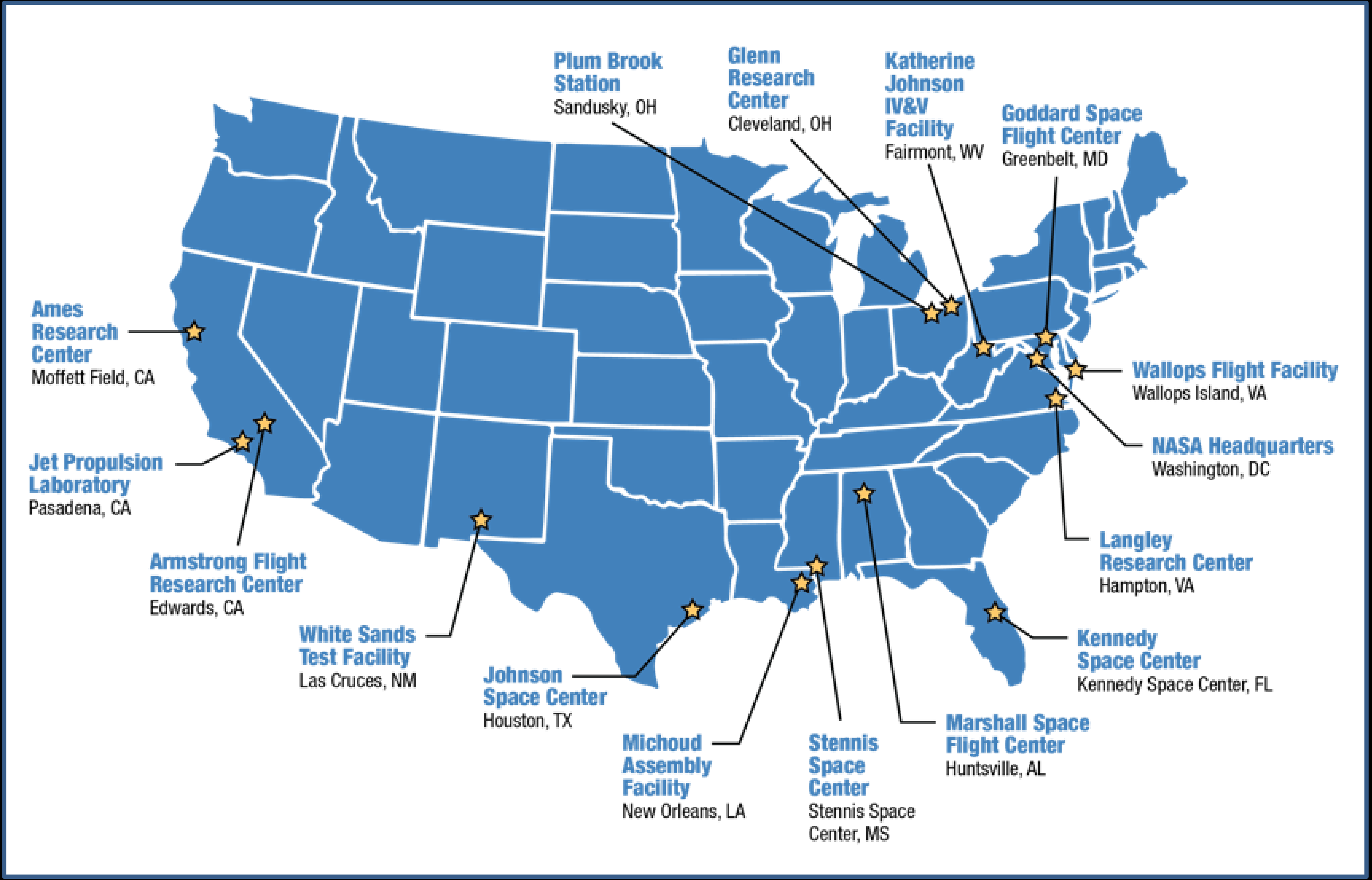
Surface Mobility

Space Suits



Artemis Base Camp

Every NASA Center Contributes to Artemis

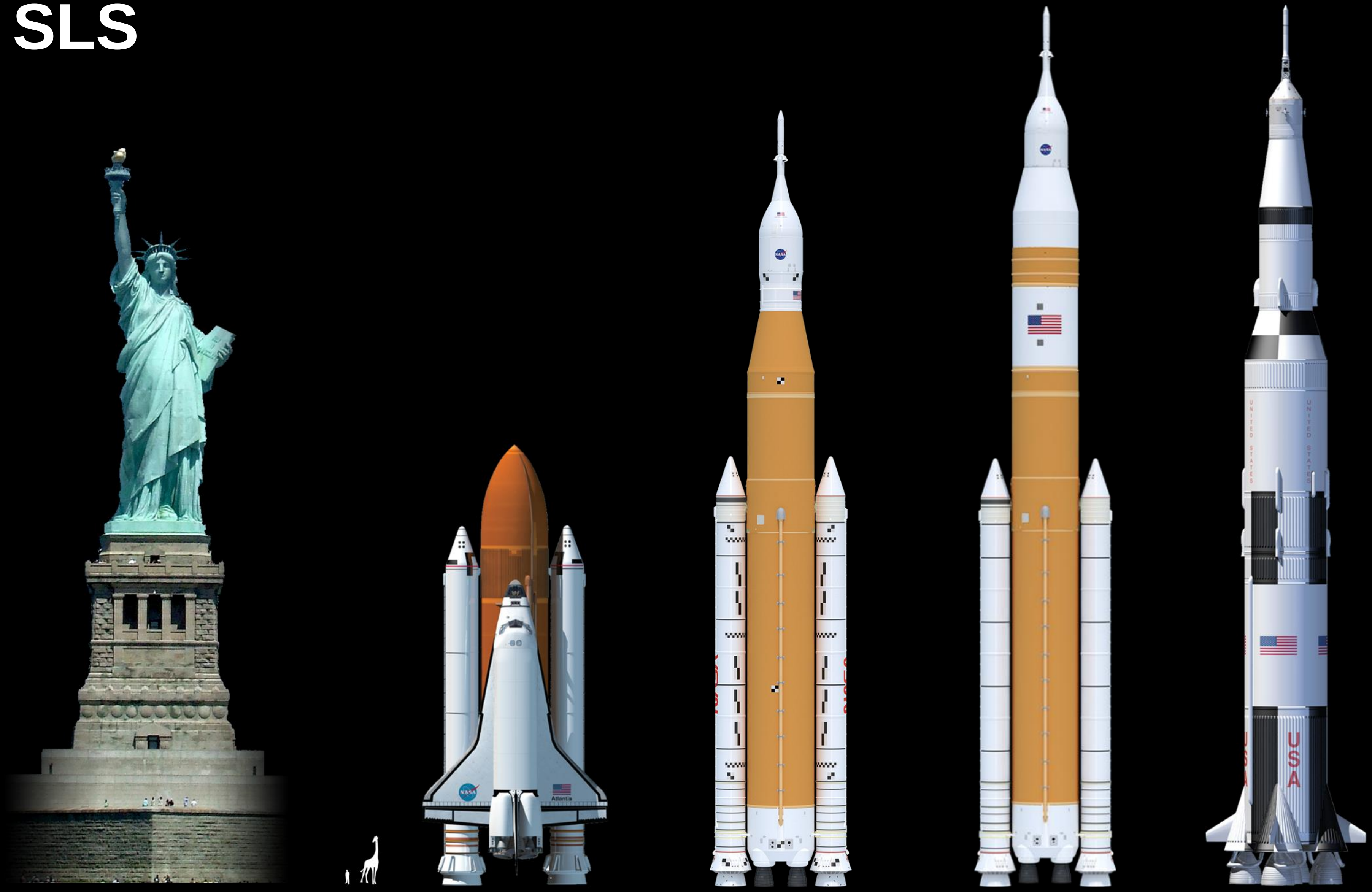


Suppliers and small businesses across America have made contributions to the success of NASA's Artemis program.

Private companies are hard at work on innovations that will help establish a sustainable human presence at the Moon. The Artemis endeavor also extends beyond our borders.

For detailed information about NASA's partners and where to find them, visit the Artemis partners map at www.nasa.gov/content/artemis-partners

Aside: SLS



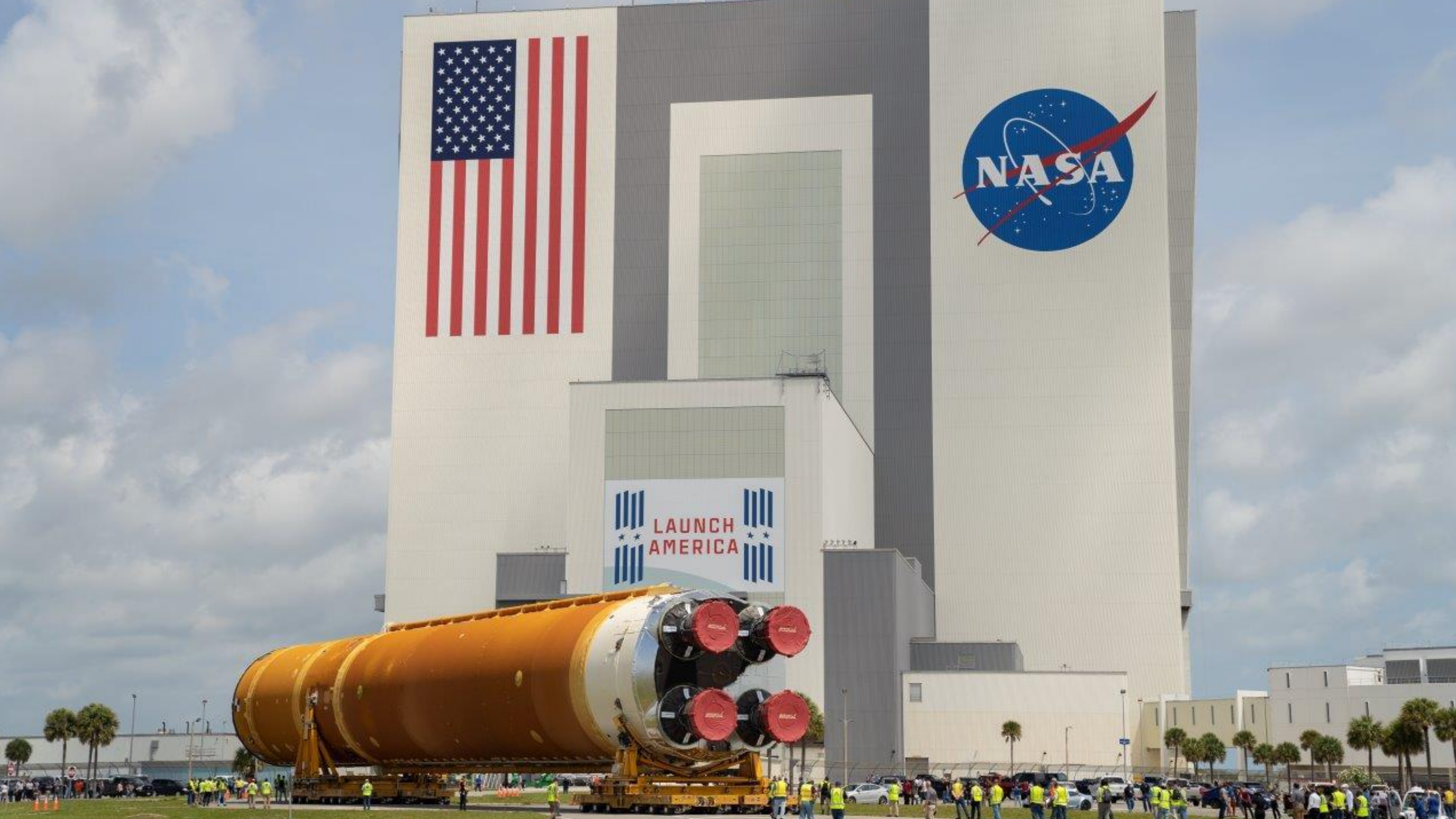
STATUE OF LIBERTY
305 ft.

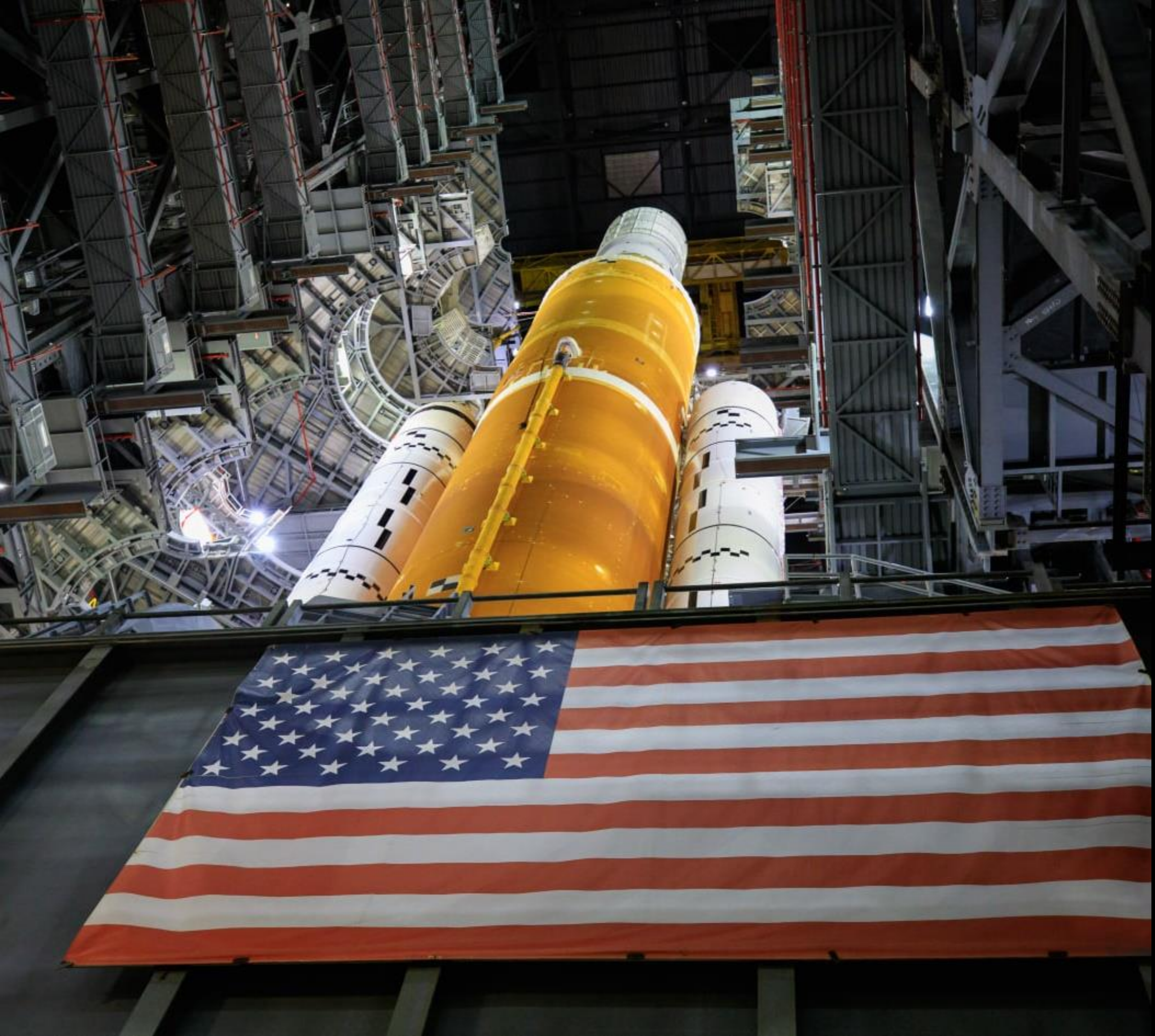
SPACE SHUTTLE
184 ft.

SLS / ORION Block I
322 ft.

SLS / ORION Block II
364 ft.

SATURN 5
363 ft.


NASA
LAUNCH
AMERICA



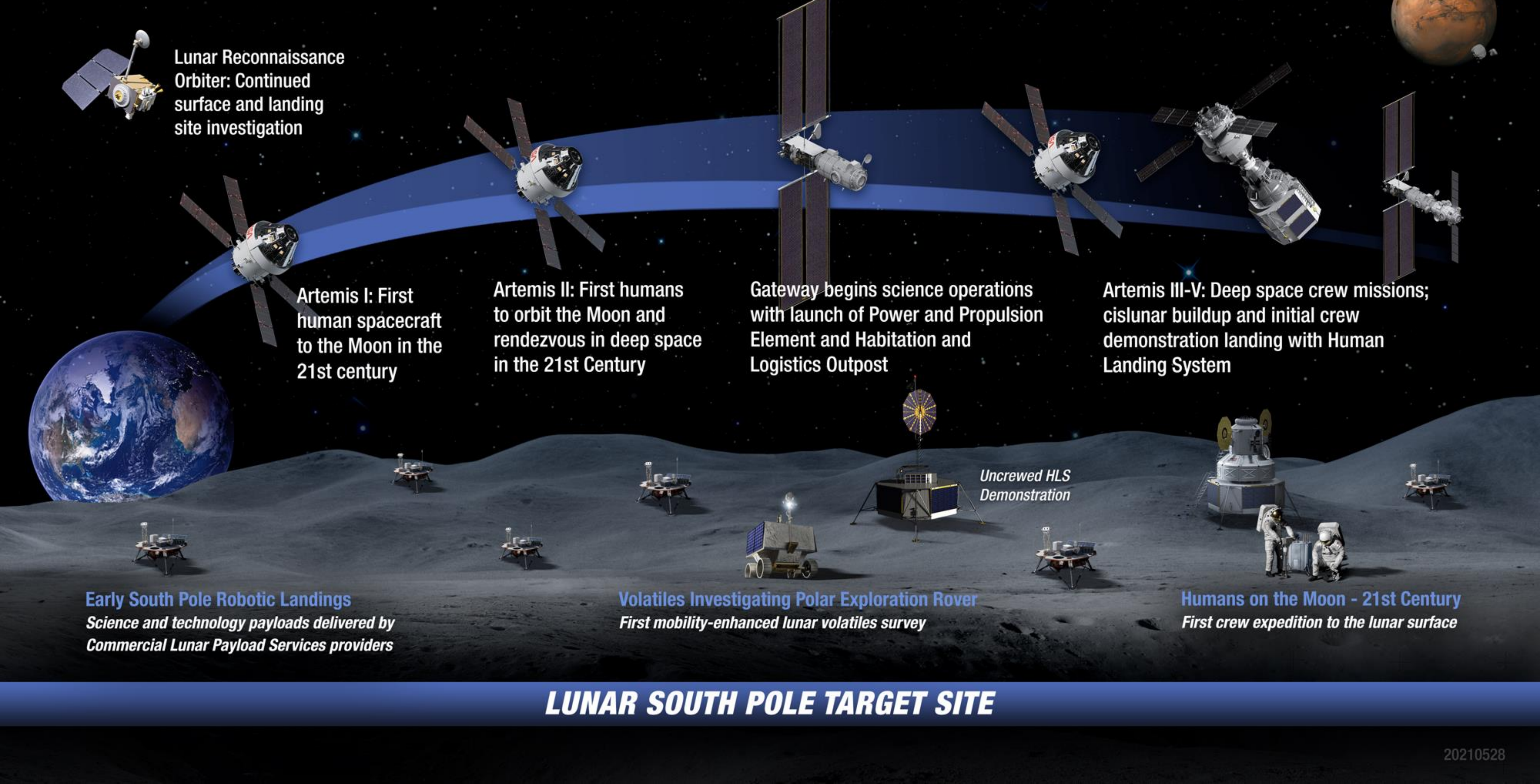


United States
NASA
esa
ARTEMIS
WE ARE GOING!
KAMAG

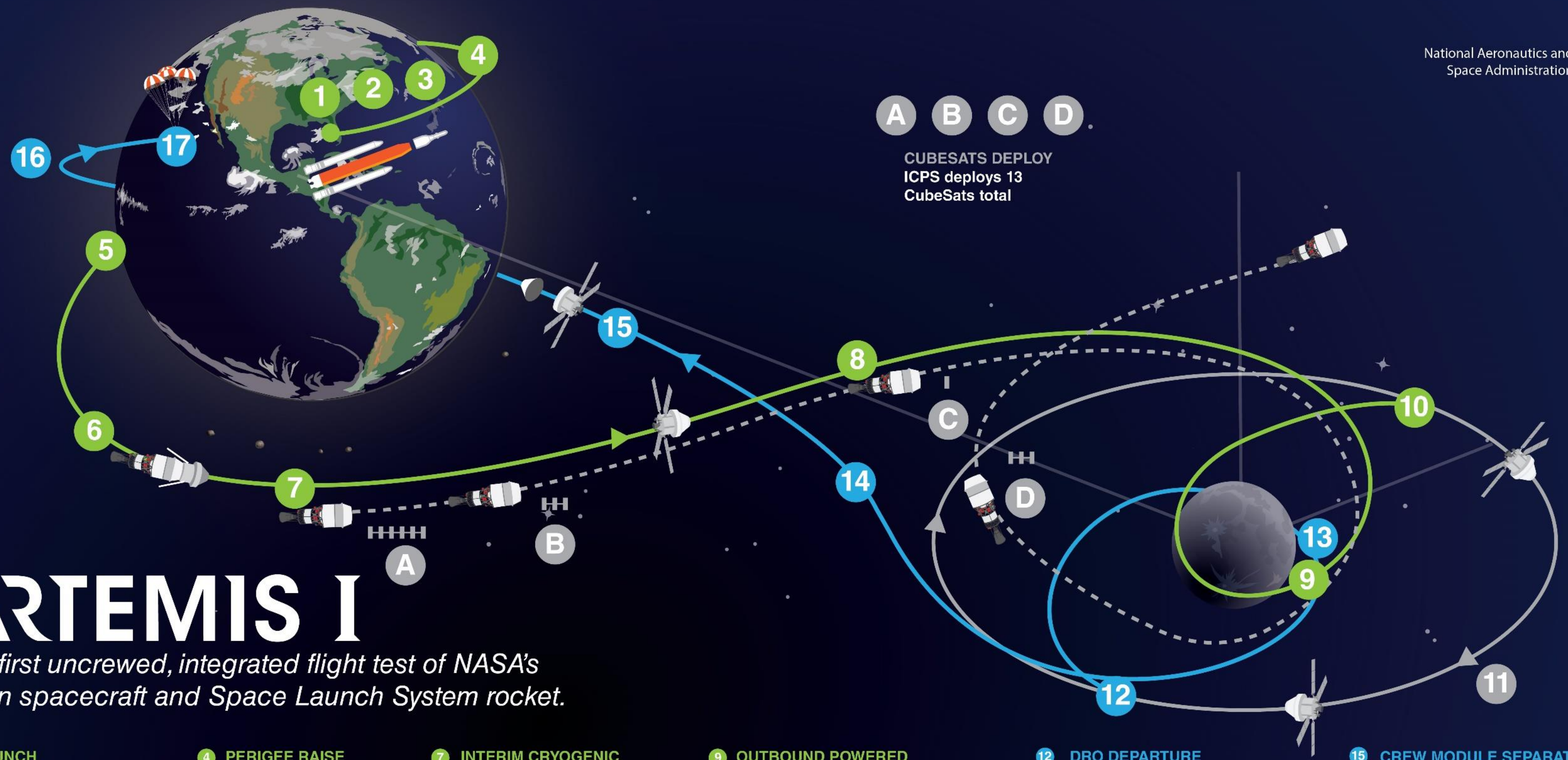

United States
NASA
esa


NASA
esa

Artemis: Landing Humans On the Moon



National Aeronautics and
Space Administration



ARTEMIS I

The first uncrewed, integrated flight test of NASA's Orion spacecraft and Space Launch System rocket.

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**
   The ICPS has committed Orion to 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 for next 6-23 days.

11. **DISTANT RETROGRADE ORBIT**
    Perform half or one and a half revolutions in the 12 day orbit period 38,000 nmi from the surface of the Moon.

12. **DRO DEPARTURE**
    Leave DRO and start return to Earth.

13. **RETURN POWER FLY-BY (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; travel time 5-11 days.

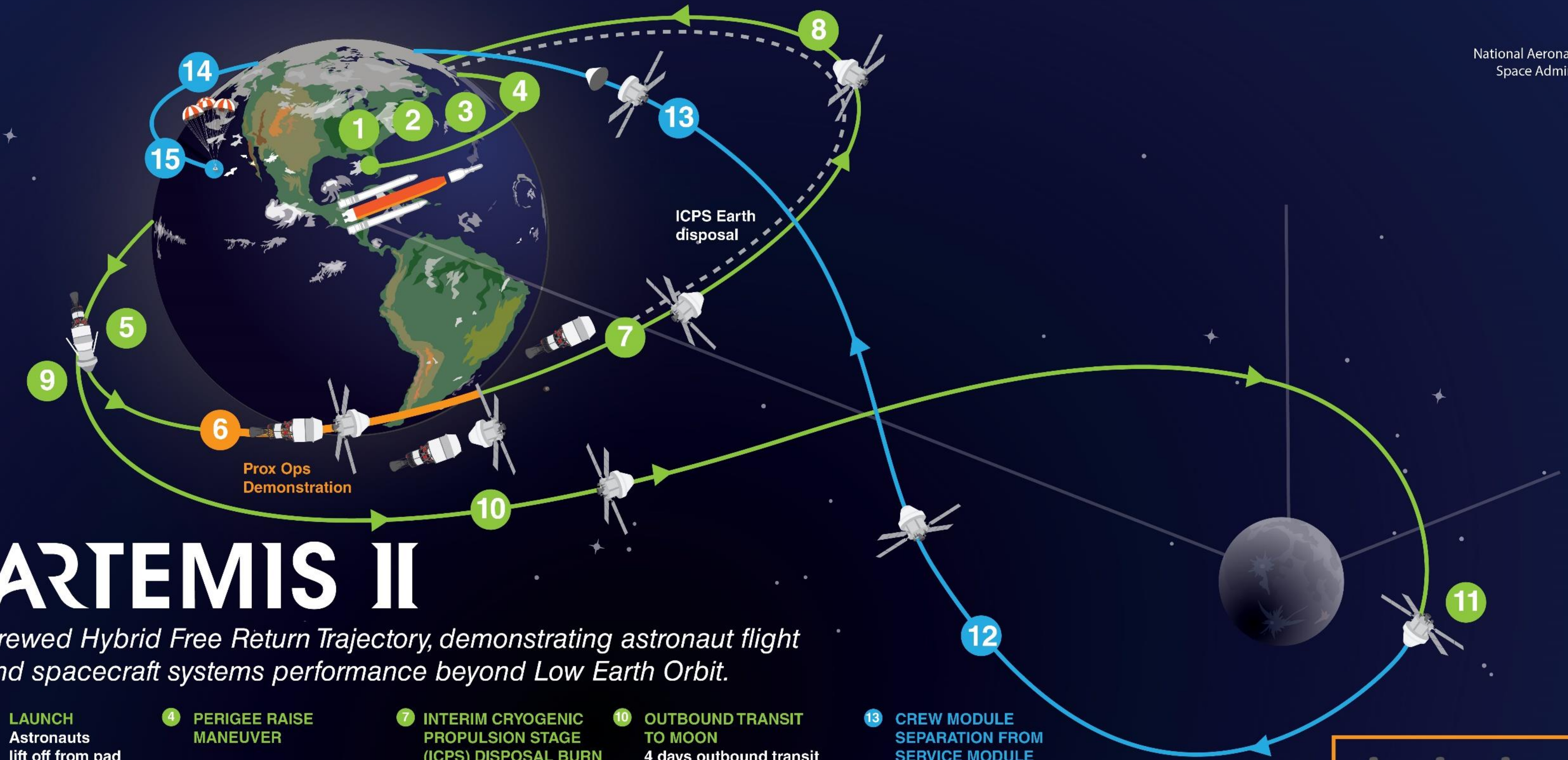
15. **CREW MODULE SEPARATION FROM SERVICE MODULE**

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

17. **SPLASHDOWN**
    Pacific Ocean landing within view of the U.S. Navy recovery ship.

3/1/2021

National Aeronautics and Space Administration

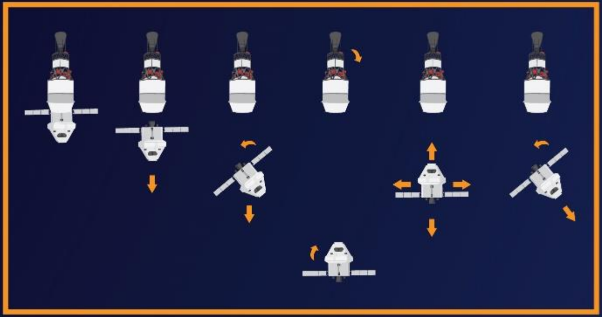


ARTEMIS II

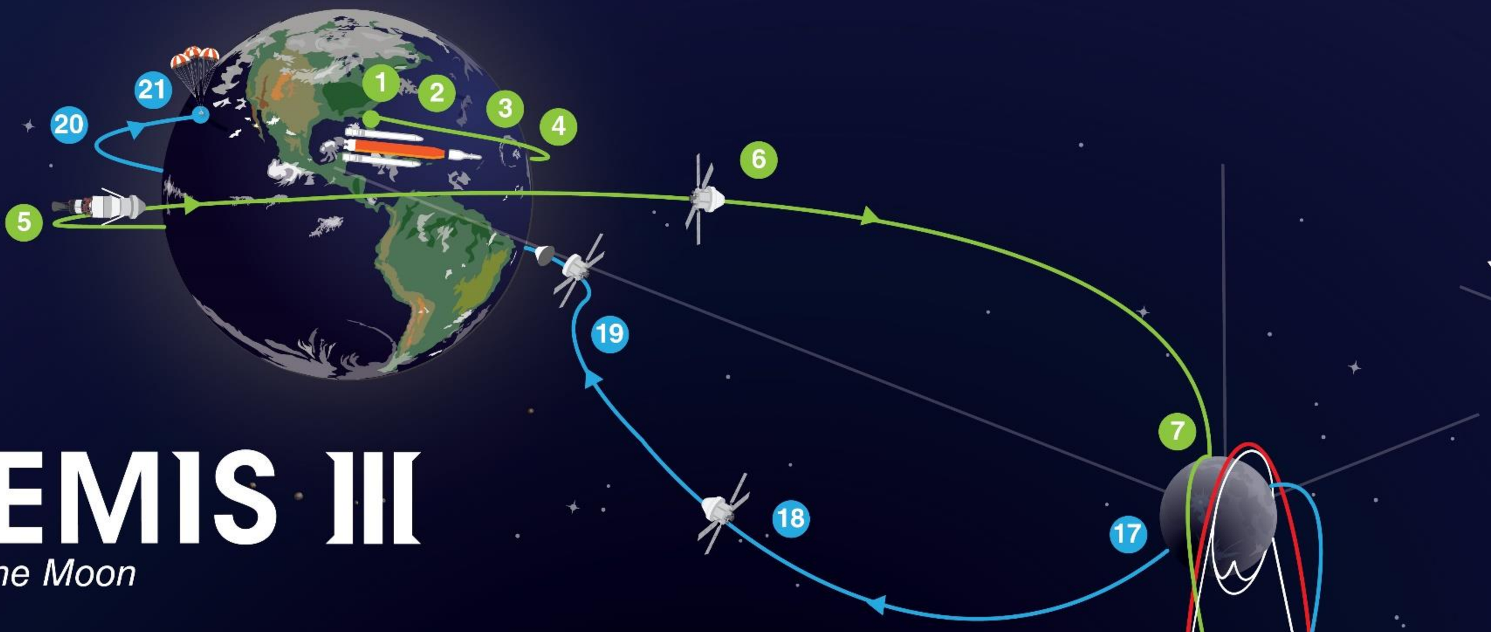
Crewed Hybrid Free Return Trajectory, demonstrating astronaut flight and spacecraft systems performance beyond Low Earth Orbit.

1. **LAUNCH**
   Astronauts 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. **APOGEE RAISE BURN TO HIGH EARTH ORBIT**
   Begin 42 hour checkout of spacecraft.
6. **PROX OPS DEMONSTRATION**
   Orion proximity operations demonstration and manual handling qualities assessment for up to 2 hours.
7. **INTERIM CRYOGENIC PROPULSION STAGE (ICPS) DISPOSAL BURN**
8. **HIGH EARTH ORBIT CHECKOUT**
   Life support, exercise, and habitation equipment evaluations.
9. **TRANS-LUNAR INJECTION (TLI) BY ORION'S MAIN ENGINE**
10. **OUTBOUND TRANSIT TO MOON**
    4 days outbound transit along free return trajectory.
11. **LUNAR FLYBY**
    4,000 nmi (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**
    Astronaut and capsule recovery by U.S. Navy ship.

PROXIMITY OPERATIONS DEMONSTRATION SEQUENCE

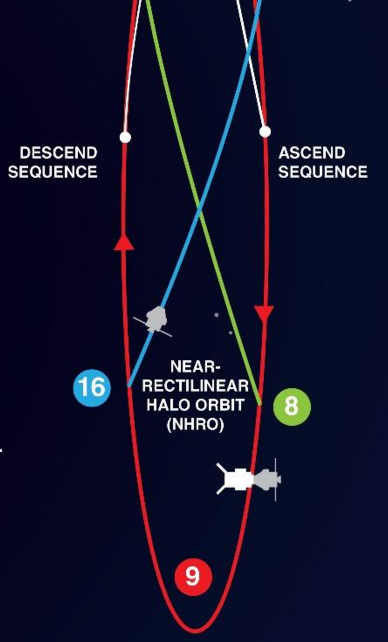


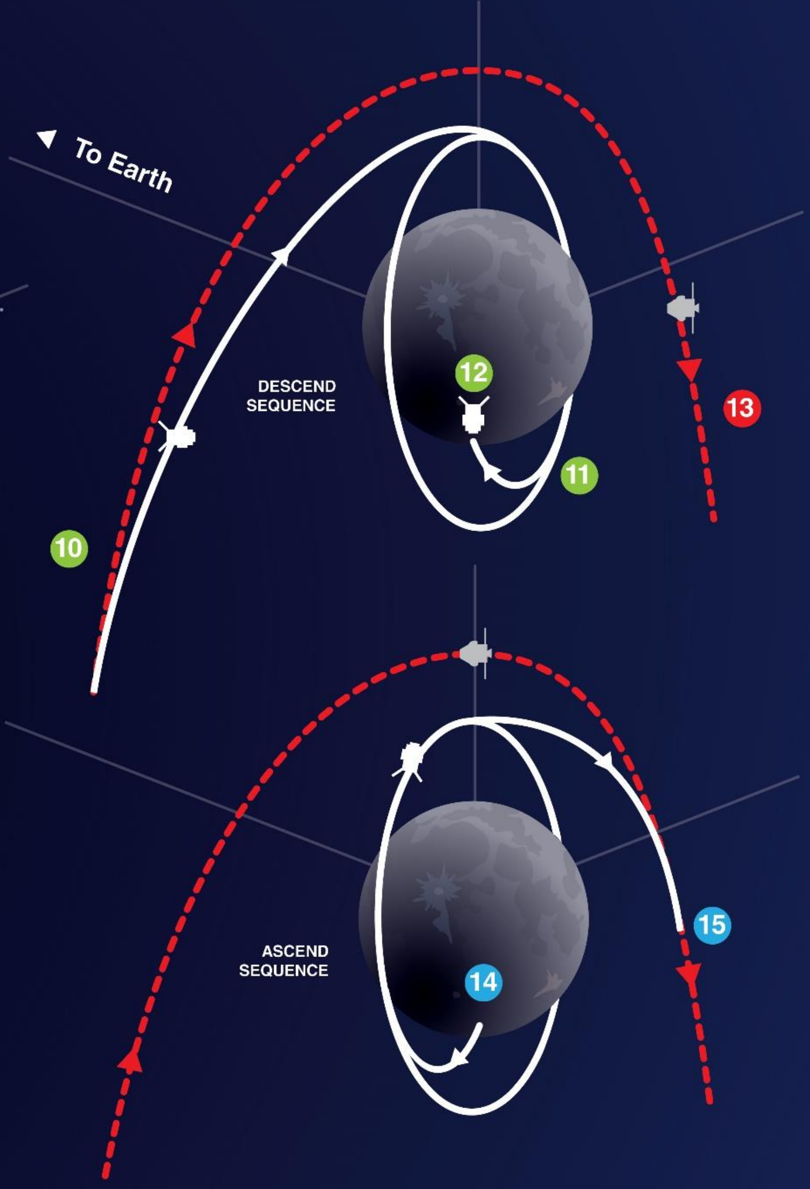
3/1/2021



ARTEMIS III

Landing on the Moon



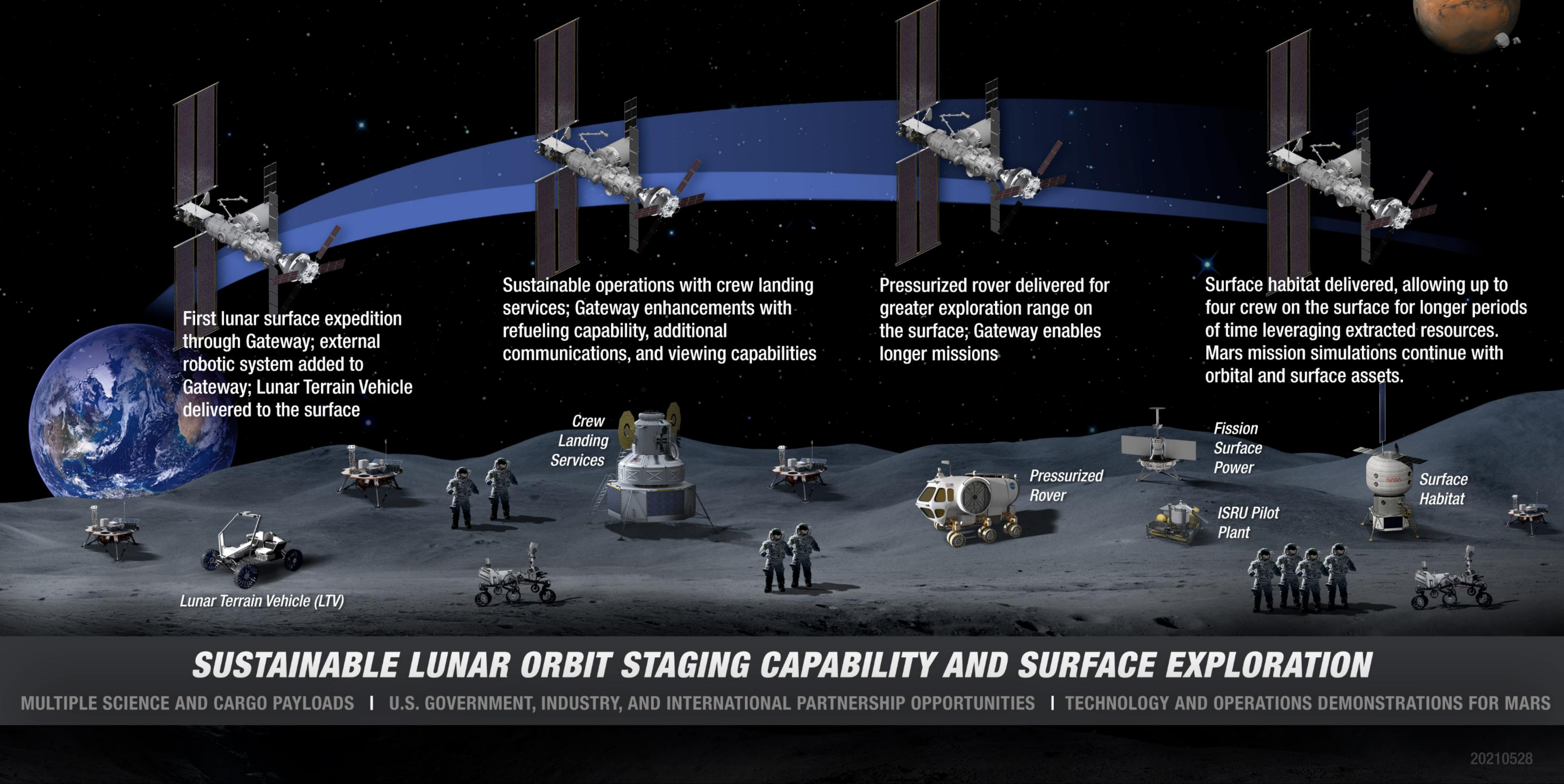


1. **LAUNCH**
   SLS and Orion lift off from Kennedy Space Center.
2. **JETTISON ROCKET BOOSTERS, FAIRINGS, AND LAUNCH ABORT SYSTEM**
3. **CORE STAGE MAIN ENGINE CUT OFF**
   With separation.
4. **ENTER EARTH ORBIT**
   Perform the perigee raise maneuver. Systems check and solar panel adjustments.
5. **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 ORBIT 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 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**
    Astronaut and capsule recovery by U.S. Navy ship.

National Aeronautics and Space Administration

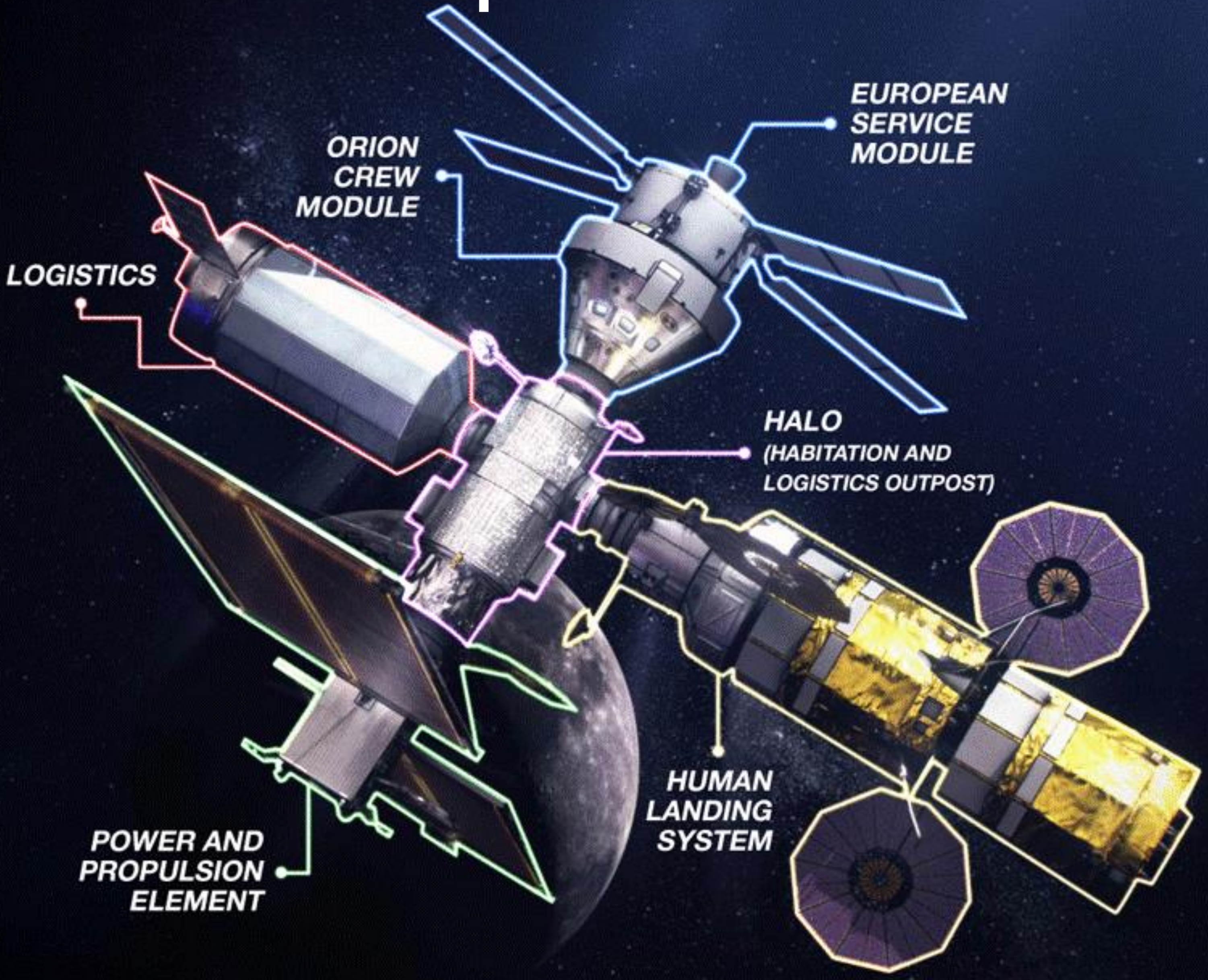
3/1/2021

Artemis Base Camp Buildup



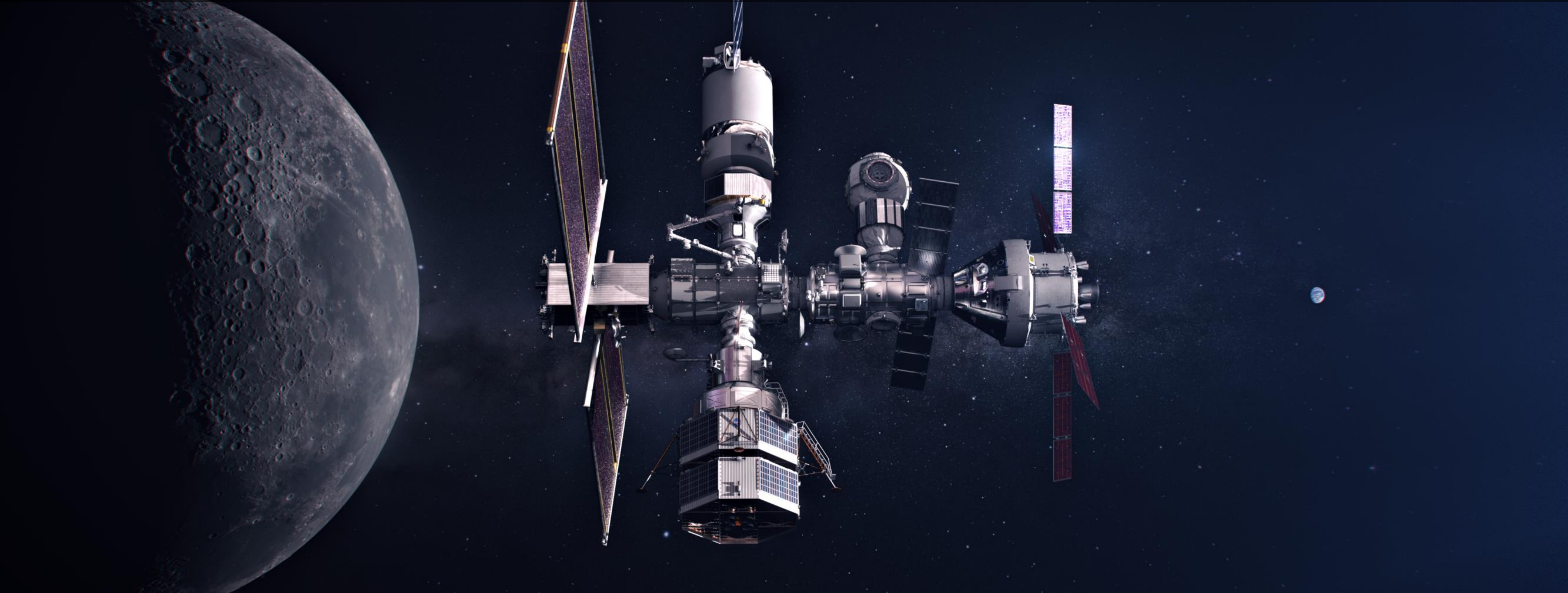
Gateway Enables Lunar and Mars Exploration

- Minimum systems required to support a 2024 human landing while also supporting Phase 2
- Command center and aggregation point for 2024 human landing
- Strategic presence around the Moon
- Resilience, sustainability and robustness in the lunar architecture
- Open architecture and interoperability standards are building blocks for partnerships and future expansion



Gateway International Partners

Building on ISS partnerships to expand deep space capabilities



NASA
CSA ASC
esa
European Space Agency
JAXA

Gateway Logistics Services

U.S. industry to begin delivering cargo, experiments, and supplies to deep space beginning in 2024.

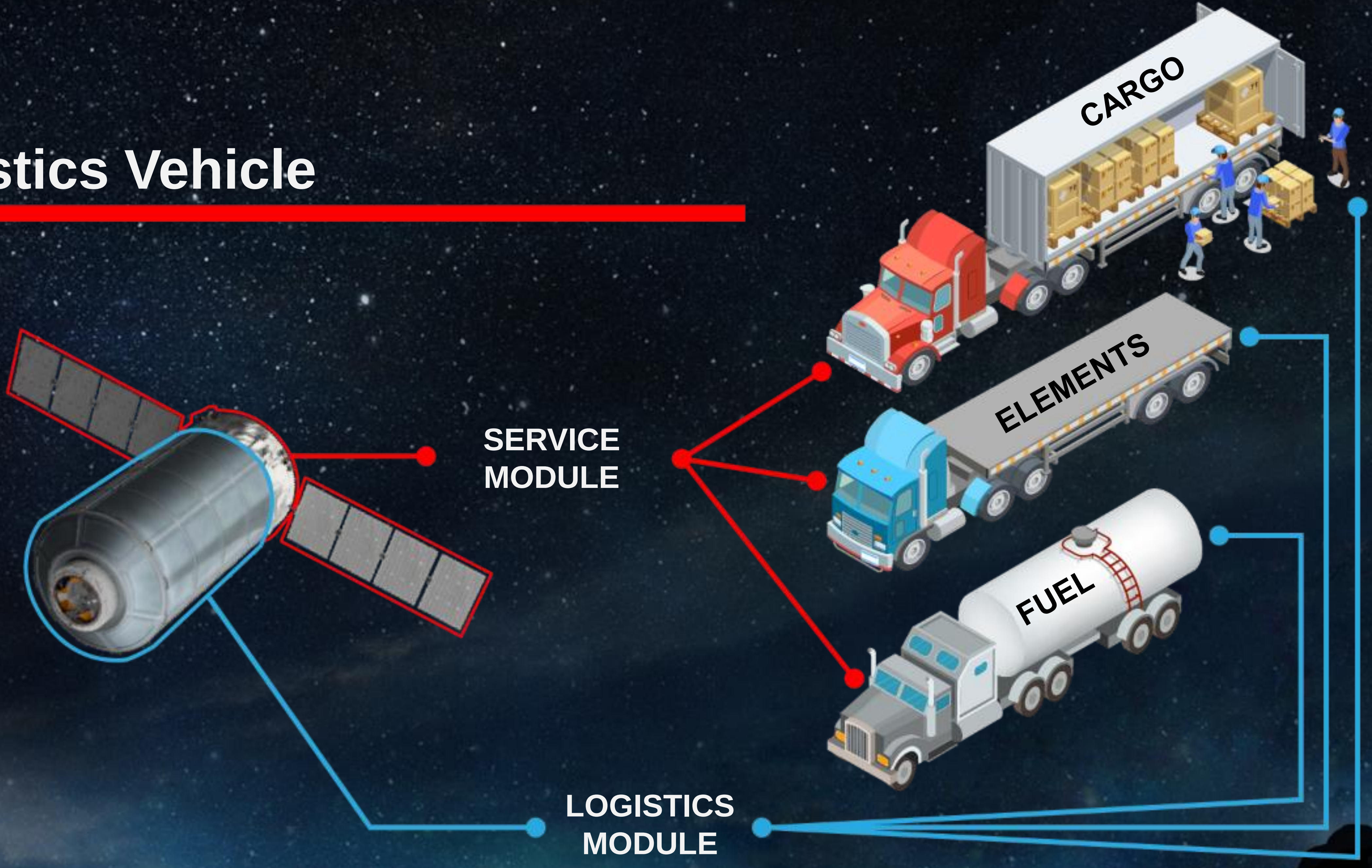
KSC Gateway Deep Space Logistics

Kennedy Space Center is home to the Gateway Deep Space Logistics (DSL) project, leading NASA's commercial supply chain for deep space

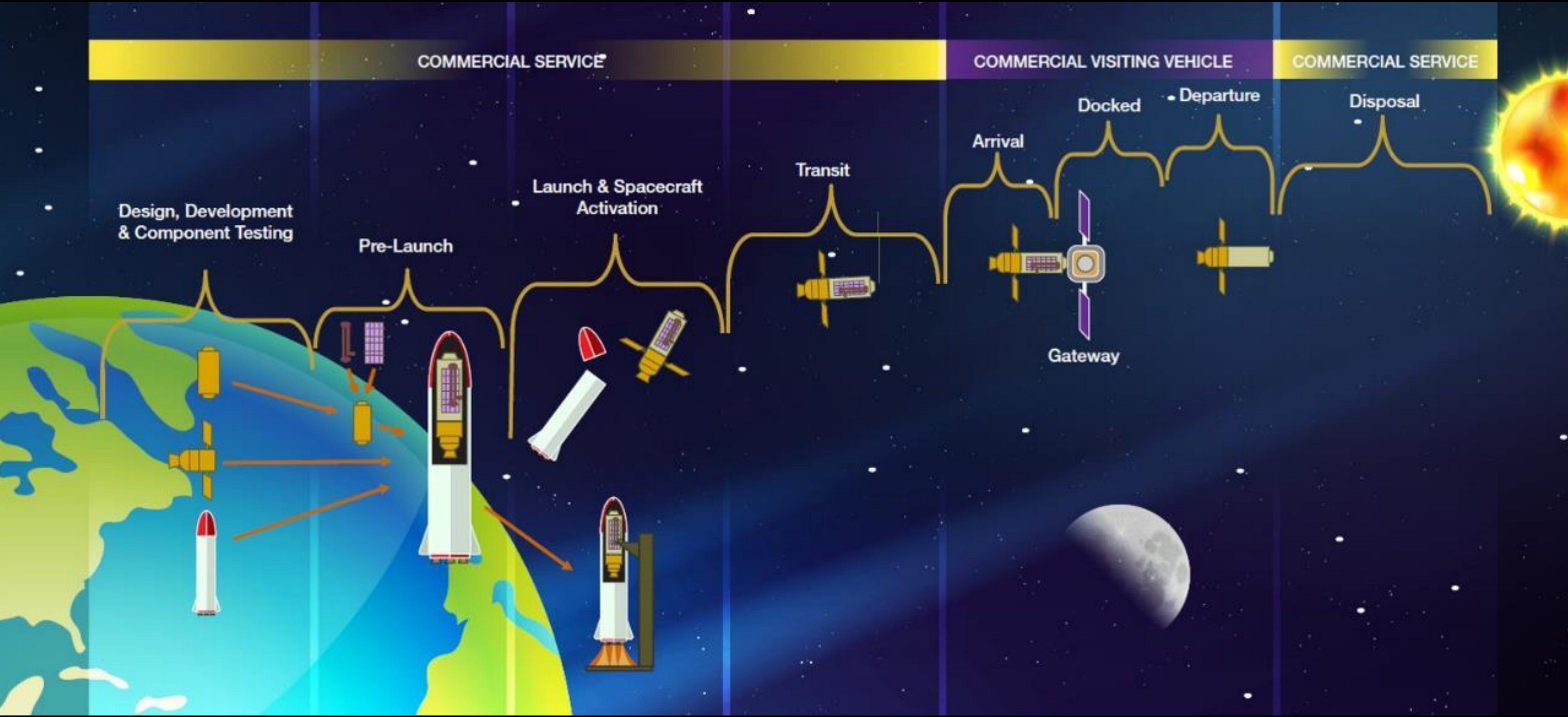
DSL leverages specialized expertise and capability at KSC:

- Launch Services Program (LSP) provides commercial launch vehicle expertise as well as commercial business, contract management, and legal support
- Exploration Research & Technology (ER&T) provides commercial spacecraft expertise as well as cargo processing integration support
- KSC Technical Authorities provided by Engineering and Safety & Mission Assurance teams with expertise in supporting KSC commercial service Programs (LSP & CCP)

Logistics Vehicle

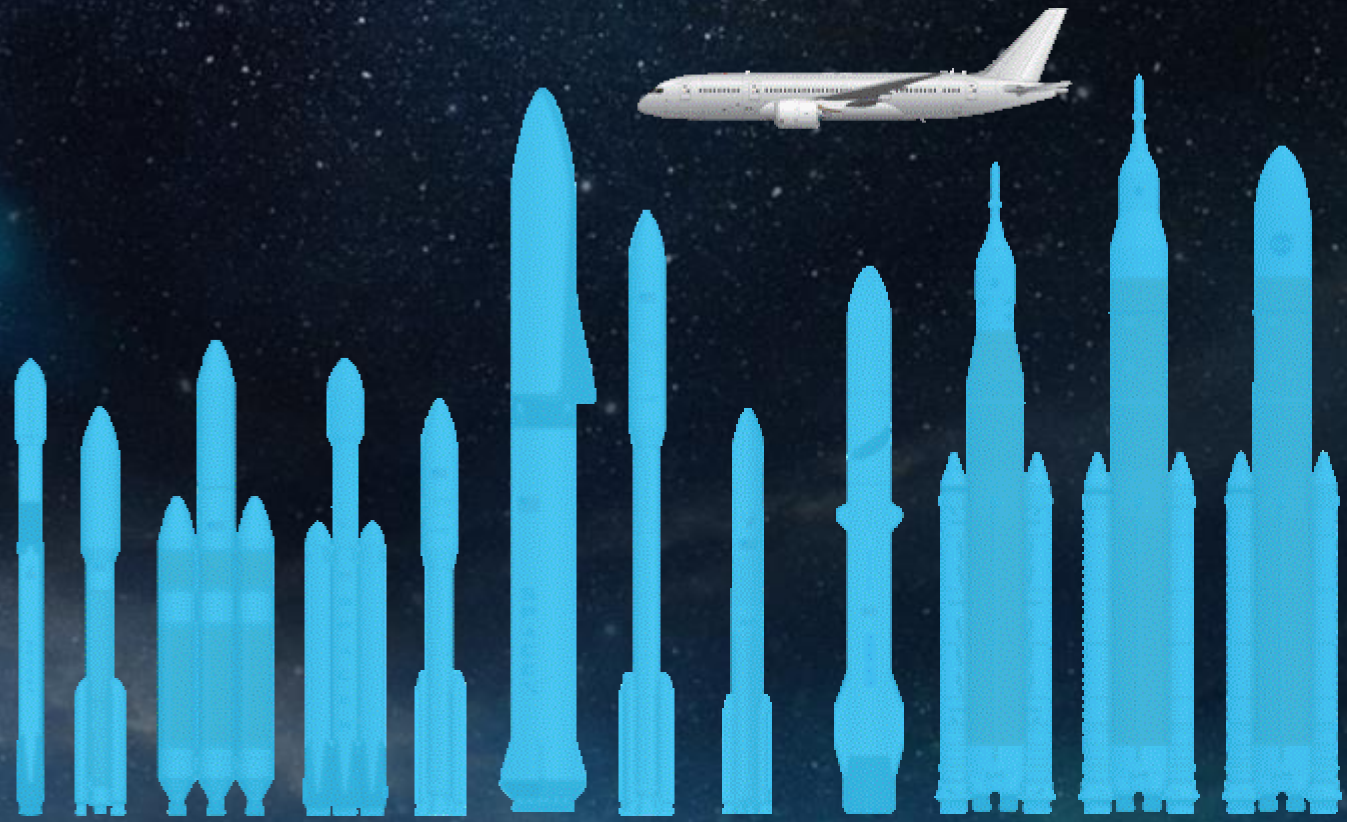


Logistics Mission Concept of Operations



DSL Launch Vehicles

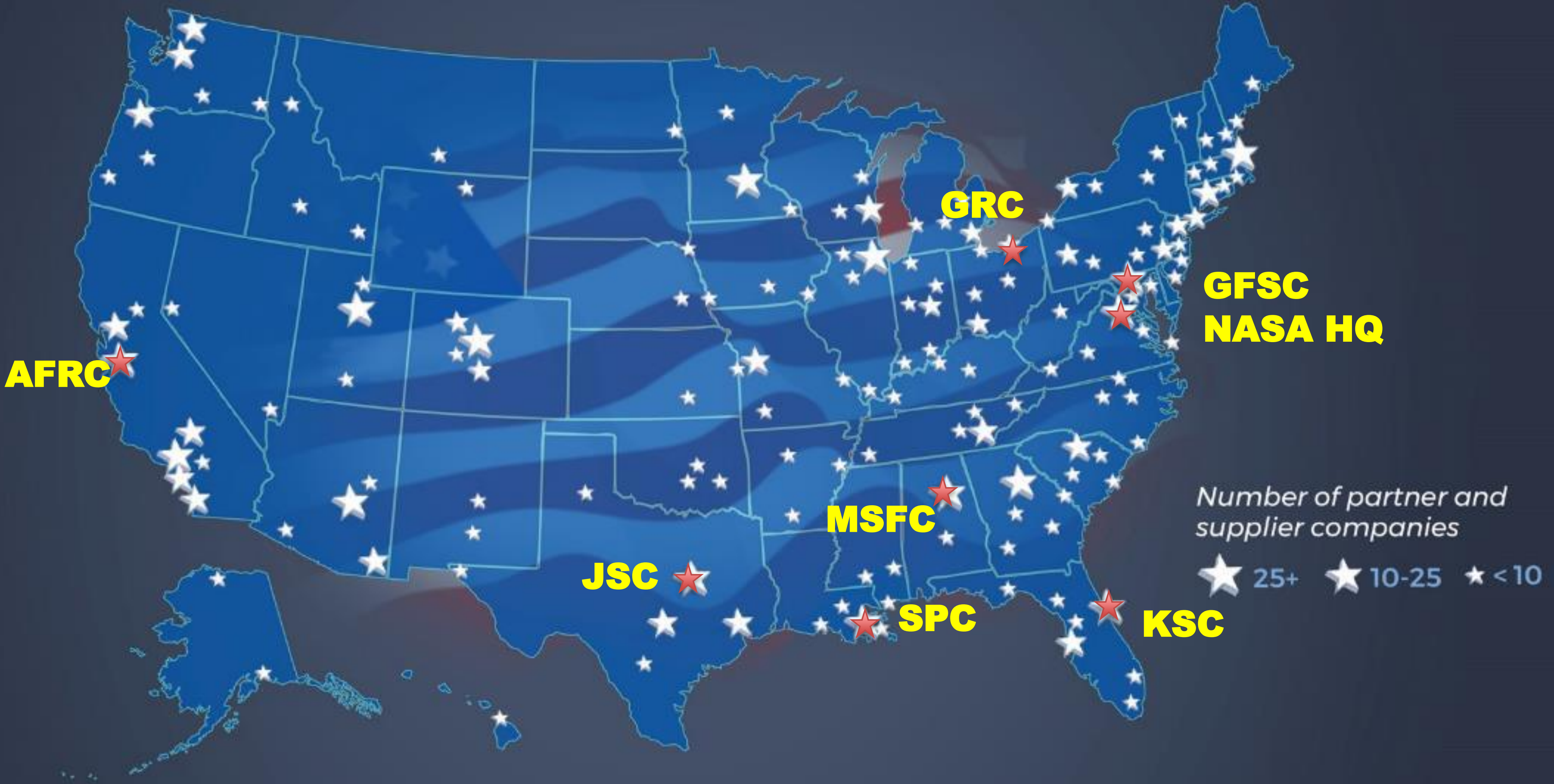
COMMERCIAL



GOVERNMENT

Deep Space Exploration Systems

Partners and Suppliers in America



NASA's Deep Space Systems for human exploration are being built in all 50 states.

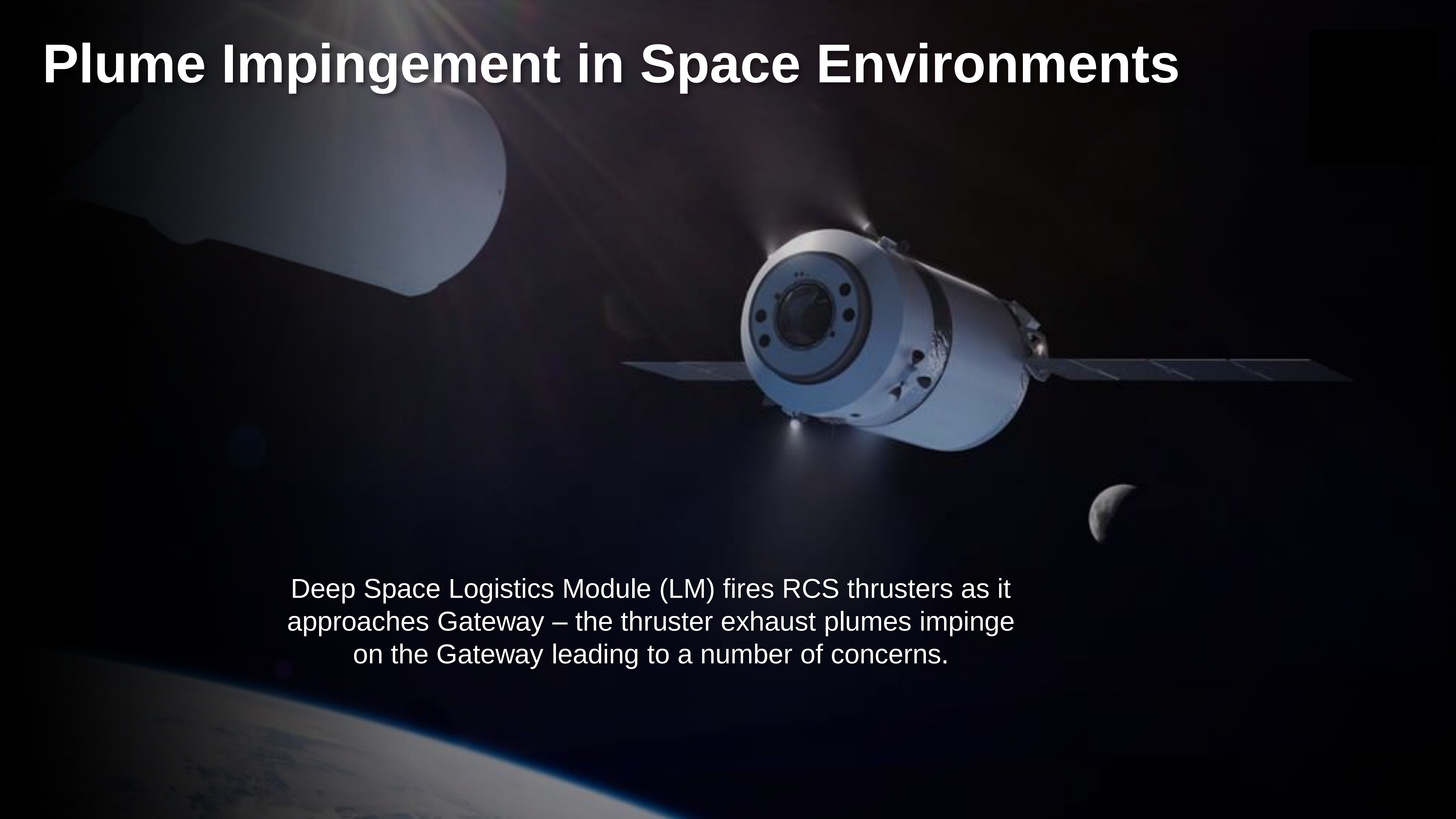
Gateway Logistics Services (GLS)

- SpaceX selected as the first U.S. commercial provider under the Gateway Logistics Services contract to deliver cargo, experiments and other supplies to the agency’s Gateway in lunar orbit

- Multiple supply missions planned in which the cargo spacecraft will stay at the Gateway for six to 12 months at a time
  - 5 MT delivered cargo capability
  - Power to internal and external payloads
  - Trash removal
  - Automated RPOD (docking/undocking)

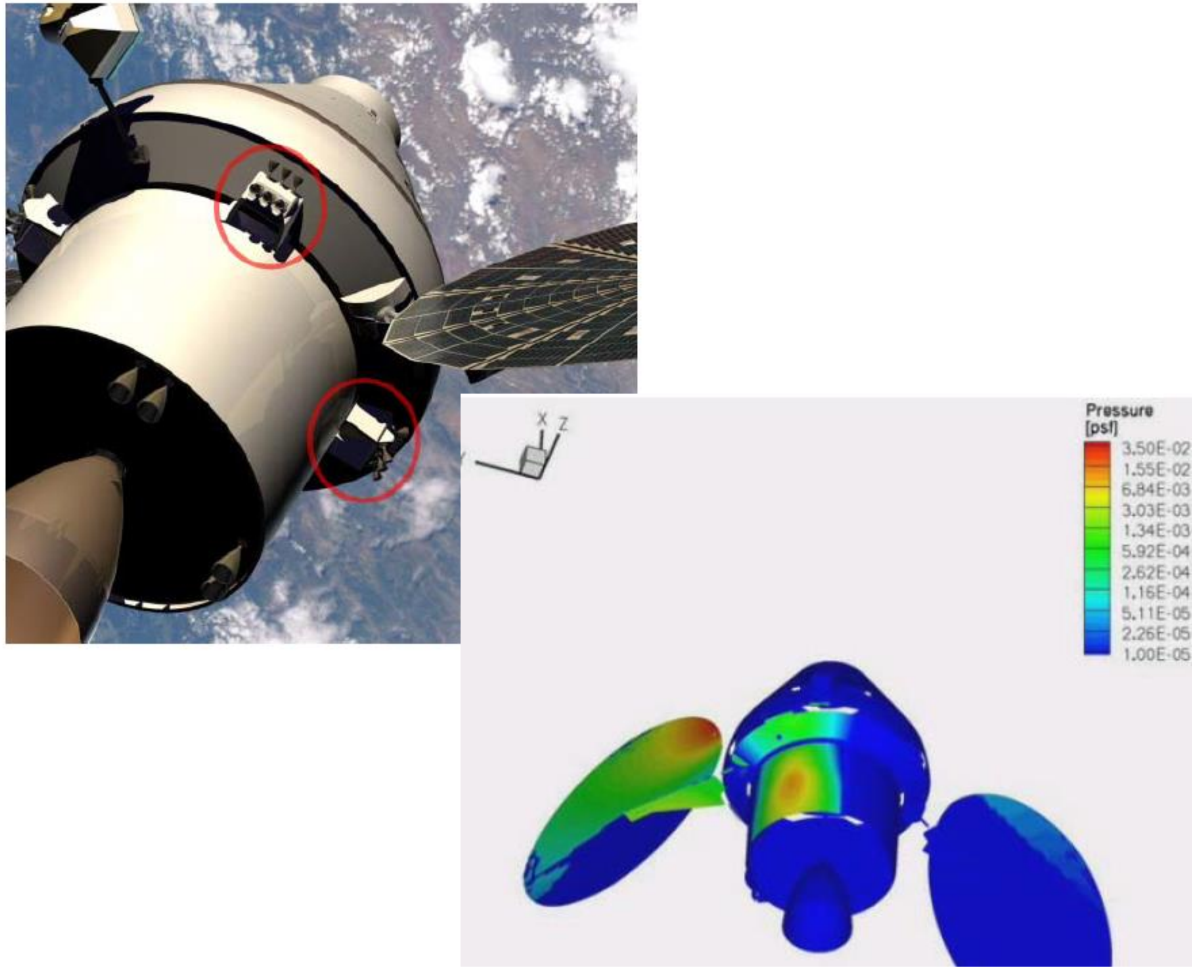
- Firm-fixed price, indefinite delivery/indefinite quantity contract
  - Guaranteed two missions per logistics services provider with a maximum total value of $7 billion across all contracts as additional missions are needed

Plume Impingement in Space Environments

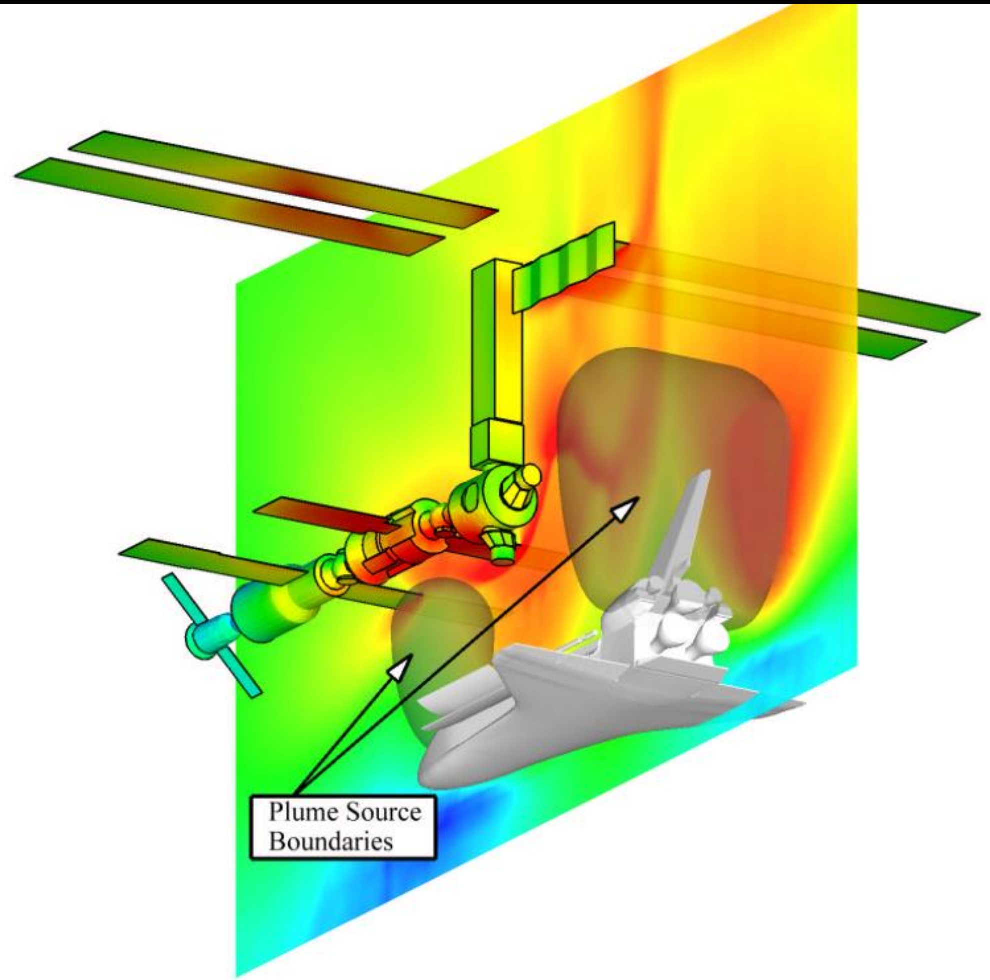


Deep Space Logistics Module (LM) fires RCS thrusters as it approaches Gateway – the thruster exhaust plumes impinge on the Gateway leading to a number of concerns.

Plume Sources: Reaction Control System (RCS) Engines



Self-Impingement from RCS Thruster Plume
Reproduced from Bury and Kerslake (2008)



Visiting Vehicle Plume Impingement during Docking
Ex: ISS from Shuttle Orbiter
Reproduced from Lumpkin III et al. (2003)

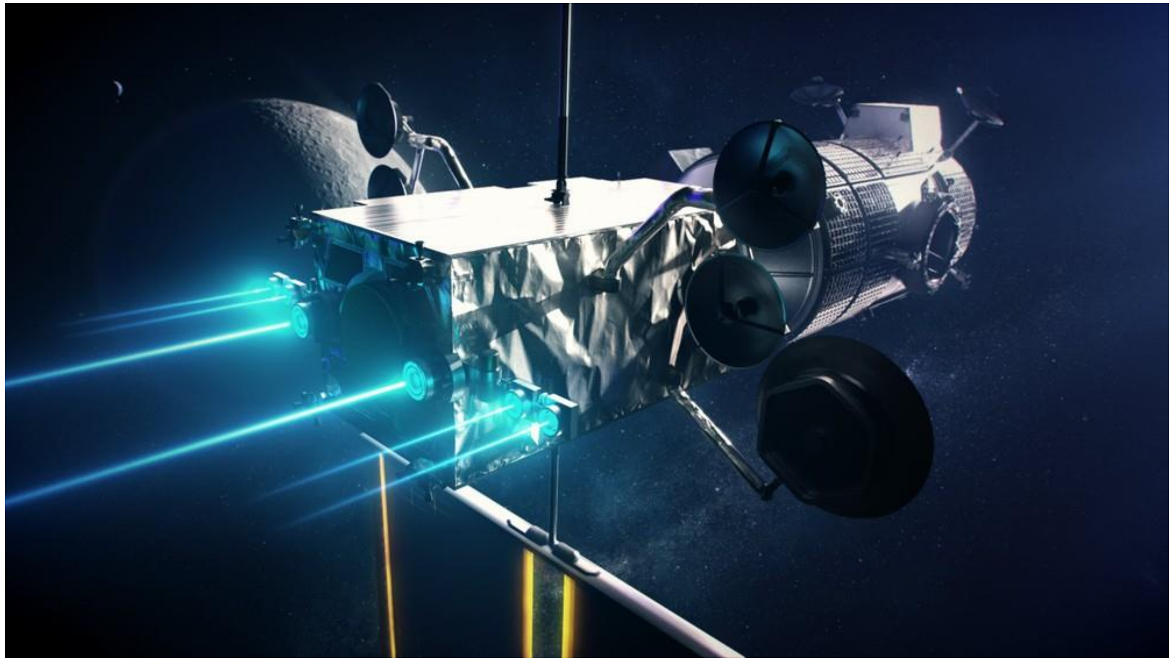
Plume Sources: Electric Propulsion Engines

- The Gateway Power and Propulsion Element (PPE) was designed by Maxar to include several Xenon Electric Propulsion Thrusters for station keeping of Gateway in the NRHO

- These thrusters employ the Hall Effect to generate thrust by accelerating Xenon gas using electromagnetic fields.

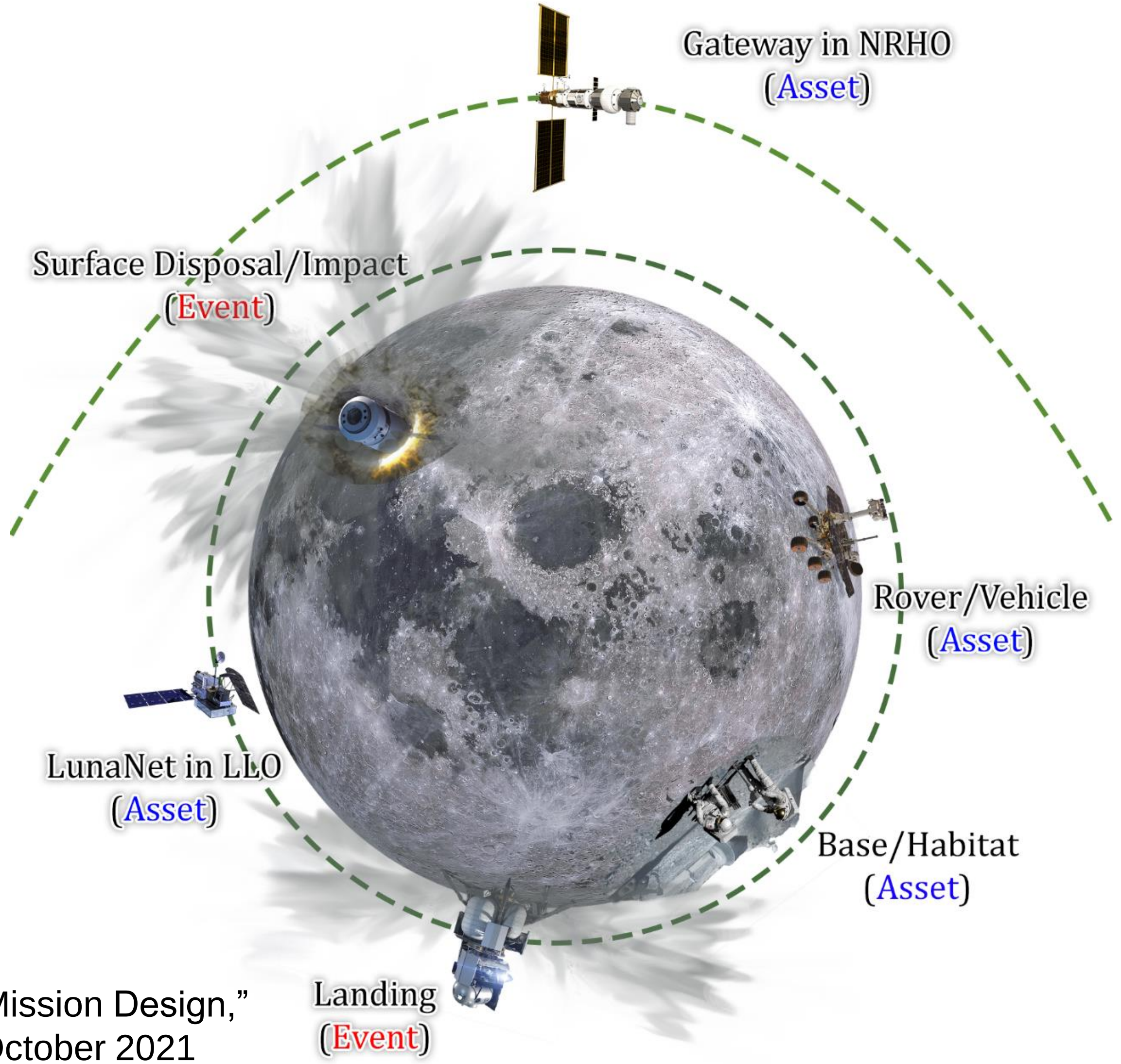
- A plasma plume of ions is created, and there are impingement concerns: primarily contamination/accretion on and erosion of Gateway Structures

- Significant effort and body of literature regarding plasma plume modeling and impingement codes:
  - HALL2DE
  - HALLPLUME2D
  - NASPAS/DRACO



From Wittal and Butts (2021):

- Events on the lunar surface are not as isolated as they are on Earth.
- High-velocity lunar dust from landings or impacts can affect assets on the ground or in orbit even on the opposite side of the moon.
- It is of interest to consider the risk imposed by these events in the design of your spacecraft.
- Generalized mathematical and system methodologies are not known to exist for lunar dust on this scale.



Wittal, M. and S. Butts, “System-Level Model-Based Risk Determination for Lunar Mission Design,” 11th International Association for the Advancement of Space Safety, Virtual, 19-21 October 2021

Outcomes from Plume Impingement

Mechanical Loads

- Unplanned torques; GNC responses
- Mechanical tractions and stress; damage

Thermal Heating

- Temperature excursions
- Thermomechan-ical stresses and damage
- Cumulative heating

Contamination

- FORP accretion
- Corrosion
- Obscured optical surfaces

Erosion

- High speed particle impact crating on surface
- Cumulative impact damage
- Brittle surfaces (glass) at risk

FORP = Fuel Oxidation Reaction Product

Overall Approach – VV Docking Approach to Station Scenario

Define/choose a scenario 1
Ex: LM approach Gateway Y+ docking port

Develop Jet Firing Histories (JFHs) 2c
Ex: Position/orientation/firing times of LM thrusters on nominal/off-nominal approach

DSMC = Direct Simulation Monte Carlo Method

Thruster Plume Characterization 2a
Ex: R-4D thruster plume in vacuum

Define station geometry/configuration 2b
Ex: Gateway in a particular attitude / solar array position

Compute Impingement Loads/Effects 3
Ex: Tractions, heat fluxes, contamination accretion, mass flux, erosion

Two methods for step 3:
- High-fidelity DSMC simulation (expensive/long)
- Source flow engineering model (relatively fast)

Decisions on LM Design and LM Requirements 4
Ex: Does LM design conform to Gateway Requirements and are those requirements adequate?

- **Scenario**
  - Defined in Concept of Operations
  - Defines the visiting vehicle, target station, docking port, and nominal approach

Jet Firing Histories (JFHs)

- **Jet Firing Histories**
  - Records the position, orientation, and firing status of each RCS thruster on the VV during an approach
    - Many approaches are simulated with Monte Carlo random perturbations (N = # of approaches)
    - The VV has M number of thrusters
    - The approach time-line is divided into T discrete time intervals

  - ***Total possible N x M x T plume positions and orientations to compute thermomechanical loading and contamination imparted to the station!***

  - Example: 100 approaches, for a vehicle with 12 RCS thrusters, over 30 minutes with 1 second intervals yields 100 x 12 x 1800 = 2.16E6 individual plume analyses!
    - Alternatively, 1800 multiple plume analyses where several RCS are firing at once

  - Labor intensive step to interpret and prepare JFHs from providers
  - Each record contains:

    time, thruster number, position, direction cosine matrix (orientation), on/off indicator

Station Geometry

DSMC = Direct Simulation Monte Carlo Method

- **Surface Geometry**
  - Defeatured CAD
  - Only need surface elements
  - Must be closed “air tight”

- **High-Fidelity DSMC Simulations**
  - Triangle surface mesh format
  - Preprocessing required

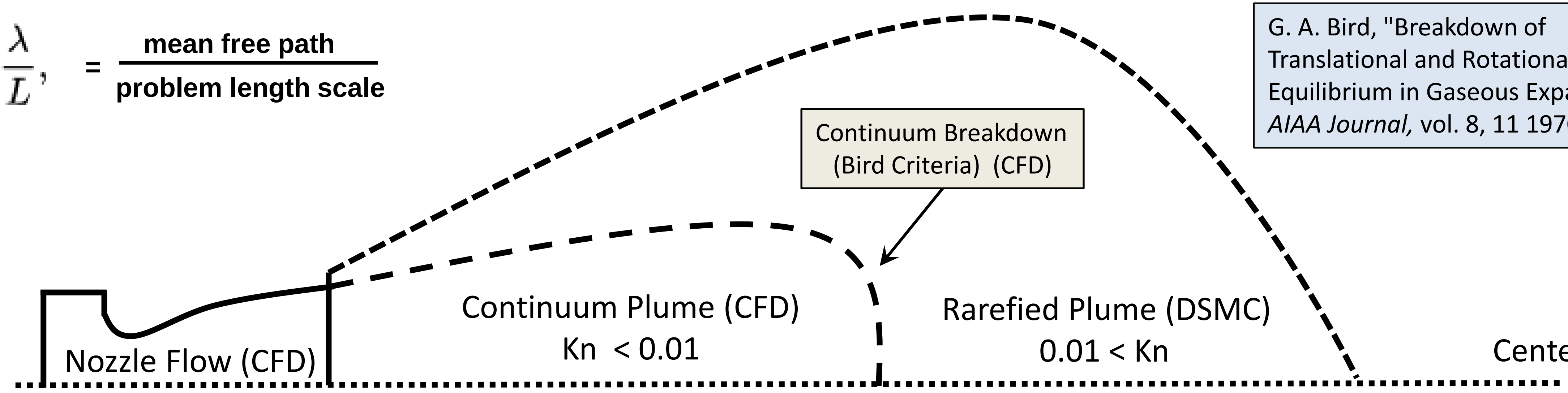
- **Source Flow Models/Simulations (NASA In-House Codes)**
  - CAD is manually decomposed into “primary” or “primitive” shapes with characteristic lengths and each shape is manually added to input deck

- **Either way, some labor-intensive intervention required**

Physics of Plumes in Space Environments

$$\mathrm{Kn} = \frac{\lambda}{L}, = \frac{\text{mean free path}}{\text{problem length scale}}$$

G. A. Bird, "Breakdown of Translational and Rotational Equilibrium in Gaseous Expansions," *AIAA Journal,* vol. 8, 11 1970.



Measure of Rarefication of a Flow:

Kn < 0.01: Continuum Flow
0.01 < Kn < 0.1: Slip Flow
0.1 < Kn < 10: Transitional Flow
Kn > 10: Free-Molecular Flow

Transition from Continuum to Molecular Flow:

- Common to use the Bird Criteria (Bird, 1970)
- Computed from continuum (CFD) quantities
- Choice is **somewhat arbitrary** for going lower on transition Kn; however, lower Kn increases Rarefied Flow simulations substantially.

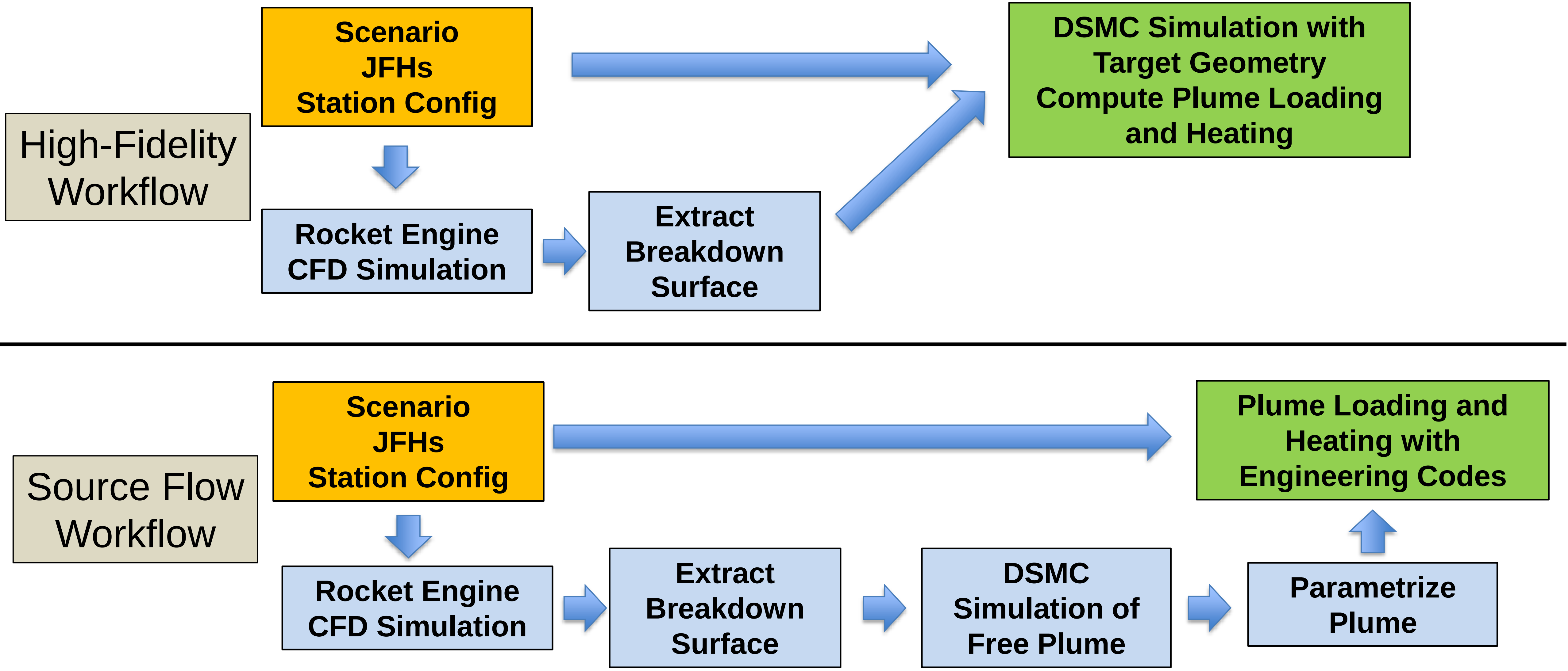
CFD = Computational Fluid Dynamics; DSMC = Direct Simulation Monte Carlo method

CFD vs. DSMC

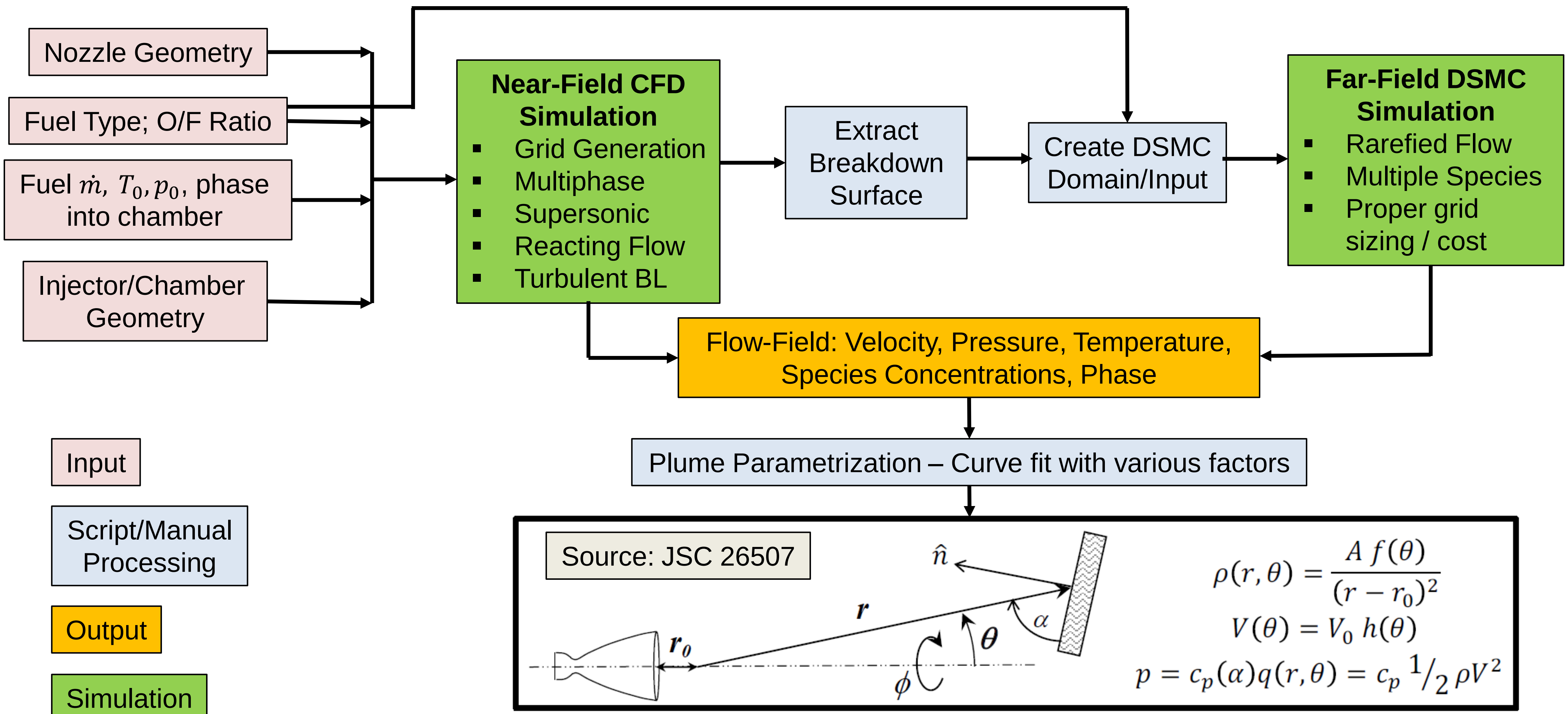
- **Computational Fluid Dynamics (CFD)**
  - Standard tool for continuum flows; traditional fluid mechanics
  - Core technology is generally stagnant from 90’s, with improvements in implementation/features
  - Solves continuum balance of mass, momentum, and energy
  - Solves additional transport equations: turbulence closure, species reaction/balance
  - Near universal use of Finite Volume (spatial) and Finite Difference (time) discretization methods

- **Direct Simulation Monte Carlo Method (DSMC Method)**
  - Developed by Graeme Bird in 70’s; generally accepted by the 90’s
  - Reached present form within the last decade; some new development is still underway
  - Popular simulation methodology for Rarefied Gas Dynamics flows for Knudsen numbers above the continuum limit (though very large Kn flow can be further simplified with Free Molecular Dynamics)
  - Not based on first principles physics; explicit particle code with stochastic models for collision and other gas dynamics phenomena

Plume Impingement Modeling Process



Inputs and Outputs for Plume Characterization (Unobstructed)



Parametrized Thruster Plume

Reproduced from Lumpkin and Stewart (2021)

Models and Codes

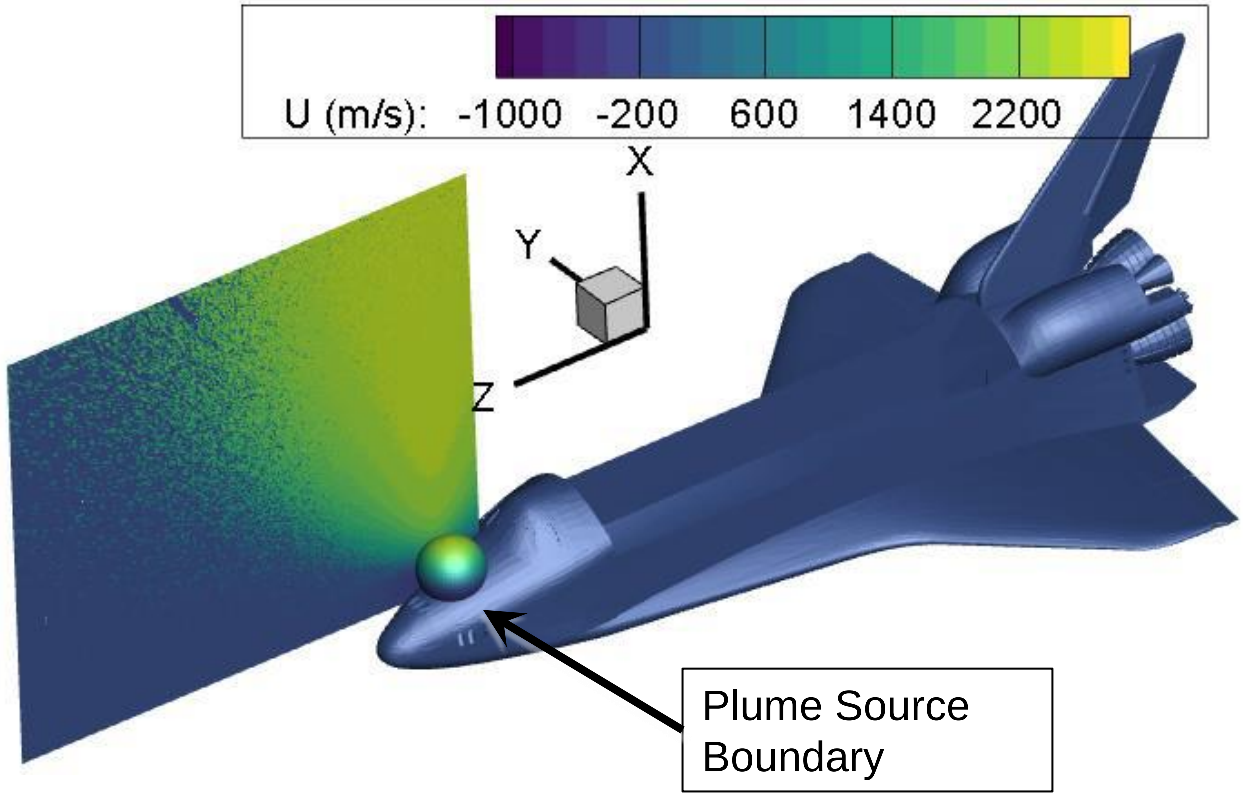
Table 2. Plume physics modeling hierarchy

Model	Requirements	Excludes	Examples
Multi-Phase Reacting Flow	Complex equation of state (EoS), detailed finite-rate chemistry (hard to find), multi-phase closure, large computational expense	–	Research codes, some commercial codes with limited success
Multi-Species Reacting Flow	Complex EoS, detailed finite-rate chemistry, significant computational expsense	Liquid and solid phases	Loci-CHEM, DPLR, LAURA, commercial codes
Multi-Species Thermally Perfect Gas	Complex EoS for each species, $c_p(T)$ and $c_v(T)$	All of the above, finite-rate chemistry	Loci-CHEM, DPLR, LAURA, commercial codes
Multi-Species Calorically Perfect Gas	EoS for each species, c_p and c_v, reasonable simulation time	All of the above, temperature effects	OVERFLOW, Loci-CHEM, commercial codes
Single Perfect Gas	EoS	All of the above, multi-species gas physics	OVERFLOW, USM3D, Cart3D

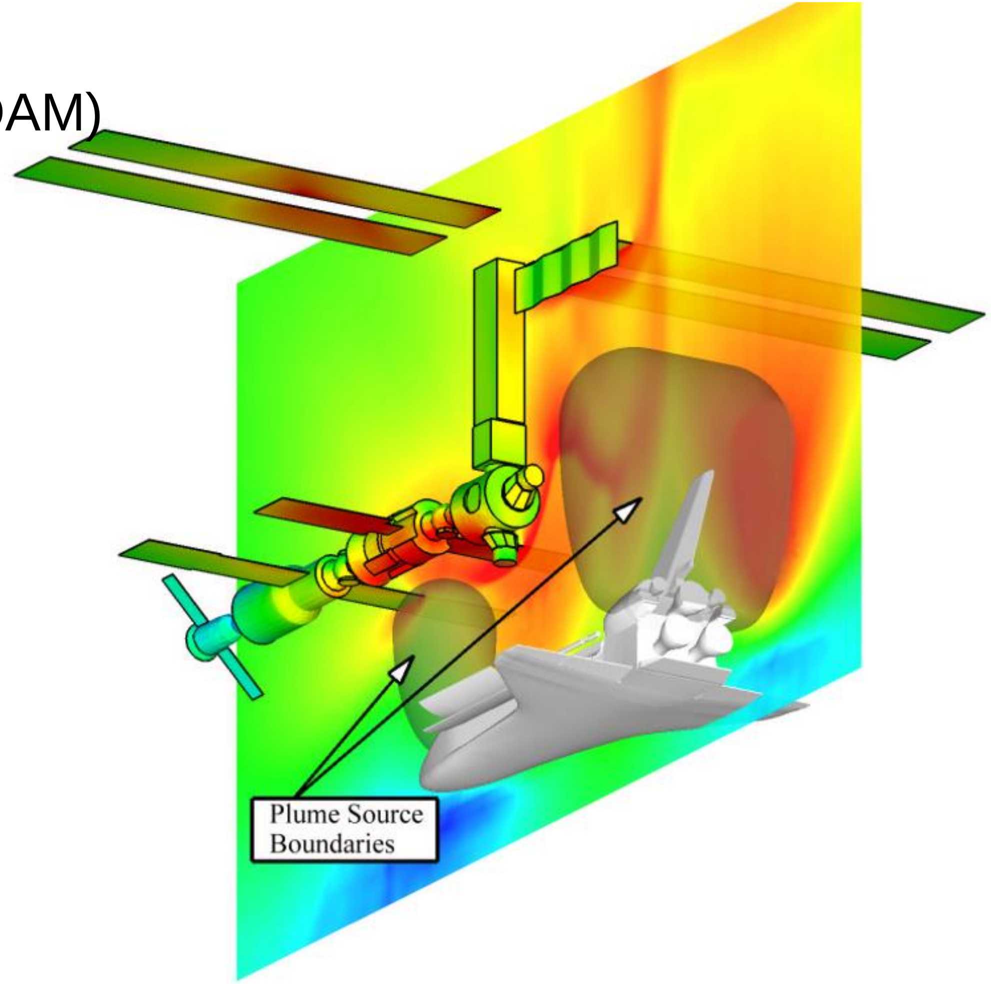
M. Gusman et al., "Best Practices for CFD Simulations of Launch Vehicles Ascent with Plumes – OVERFLOW Perspective, 49th AIAA Aerospace Science Meeting, Jn. 4-7, 2011, Orlando, FL.

High-Fidelity Plume Impingement Loads and Heating Calculations

- **DAC97** is NASA/Industry Standard Tool
- **Other options:** SPARTA (Sandia), dsmcFoam+ (OpenFOAM)



VV Plume Impingement during Docking
Ex: Shuttle Orbiter SPIFEX Simulation
Reproduced from Brown (2020)



VV Plume Impingement during Docking
Ex: ISS from Shuttle Orbiter
Reproduced from Lumpkin III et al. (2003)

High-Fidelity Impingement Algorithm Structure

- **Pre-processing**
- **Loop over each Monte Carlo generated approach**
  - Loop over all time steps of approach
    - DSMC simulation for each given timestep with all enabled thrusters
    - Calculate loads/thermal; update totals
  - End time step loop
- **End approach loop**
- **Post-Process contamination and erosion predictions**

Recent studies 500M-1.3B unknowns

Potentially 500-1000 CPU cores for 2-4 days in computational expense: significant expense that makes this approach not viable for routine analysis

Example:

- **100 MC approaches**
- **1800 timesteps (1 sec for 30 minutes)**
- **1.8E5 steady DSMC simulations**
- **~9T core hours!! 285 years of compute time**

Source Flow Impingement Algorithm Structure

- **Pre-Processing**
- **Loop over each Monte Carlo generated approach**
    - Loop over all time steps of approach
        - Loop over all firing thrusters at that time
            - Loop over all geometrical parts of the station
                - Compute forces and thermal loads
                    - **Evaluate engineering models (efficient)**
                - Sum contribution from each plume on each part (forces and thermal)
            - End part loop
        - End thruster loop
    - End time step loop
- **End approach loop**

- **Post-Process contamination and erosion predictions**

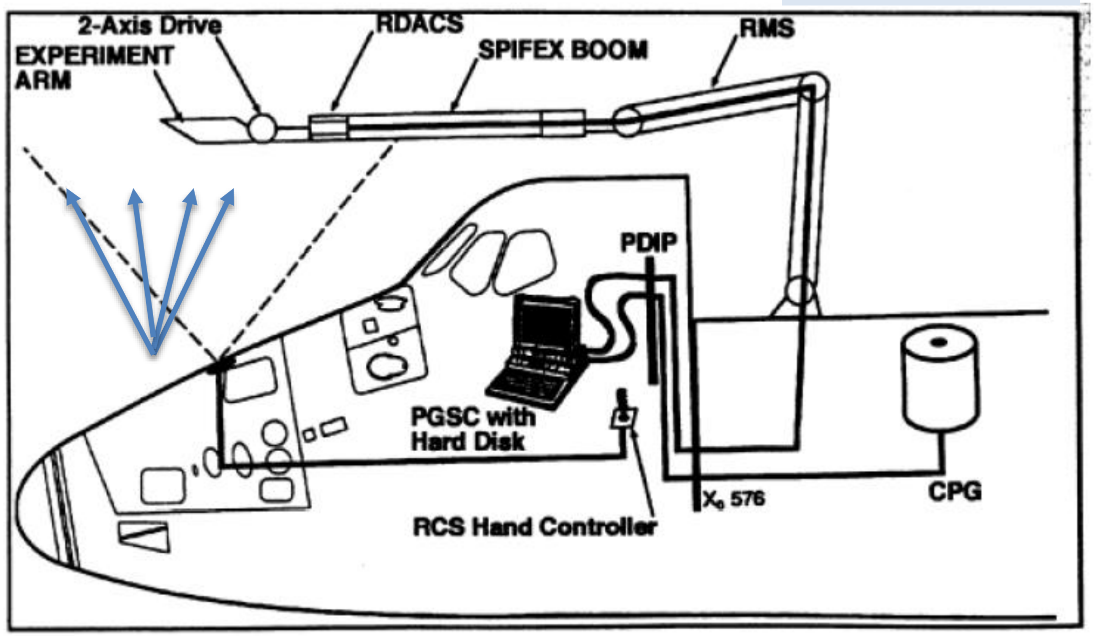
High-Fidelity vs. Source-Flow Models

	High-Fidelity	Source Flow
Component Shading (flow is blocked by upstream object)	Inherently resolved in the solution	Available as an option; however, not generally used. *This produces a more conservative result*.
Run-Time	Larger simulations – e.g. 800 cores x 48 hours	Minutes for individual plume/JFH step
Parallel Scalable	Domain Decomposition; typical MPI scaling	Embarrassingly Parallel
Pre-Processing	CAD defeaturing and creation of surface grid	Manual decomposition of target into primitive shapes with characteristic lengths – *requires experience and engineering judgement*
Thermal Wall	First principal boundary condition	Various options; cold wall without re-radiation produces a *more conservative result*
Pressure Loads	First principal boundary condition	Minimum Energy and Bridging Models
Contamination/Erosion	Not included	Not included*
Multiple Plumes	Inherently resolved in the solution	Superposition or correction factors; can *produce a more conservative result*

Validation: SPIFEX and PIC Experiments

SPIFEX
(Shuttle Plume Impingement Flight Experiment)
STS-64 in 1994

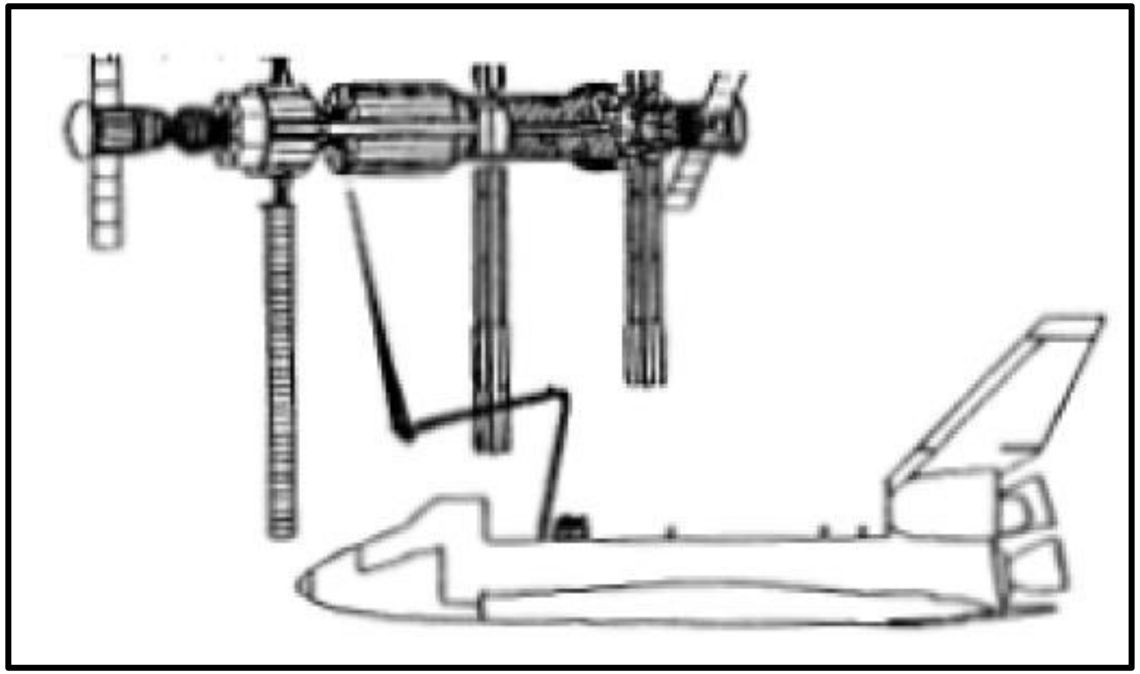
Shuttle Only



Reproduced from Soares (2002)

PIC
(Plume Impingement Contamination)
STS-74 in 1996

Shuttle & MIR



Reproduced from Soares (2002)

Measured pressure (loads), thermal heating, and importantly damage material coupons where the size and frequency of impacts from droplets could be measured, and for which contaminate accretion/erosion rates could be measured.

Contamination (FORP)

- Hypergolic bi-propellent MMH/NTO thrusters
- Burnt and unburnt fuel products constitute the plume, and can be in gas or liquid phase droplets
- Upon impingement on a surface some fraction of mass sticks to the surface (imparting pressure, thermal energy, and contamination accretion)
- Products that accrete on the surface are called Fuel-Oxidizer Reaction Product (FORP)
- The primary constituent of FORP is **MMH-HNO_3** (monomethylhydrazium nitrate)

Table 1
Ion Chromatographic Analysis of Laboratory FORP and FORP Components

Analyte	MMHN	MMHDN	FORP 9[a]	FORP 14	FORP 15	FORP 16	FORP 17/18	FORP 19
	(wt. %)							
MMH_2^+	44	27	20	6.6	ND	8.7	3.1	7.6
$N_2H_5^+$	ND	0.7	0.3	ND	ND	0.5	0.03	1.0
$UDMH_2^+$	ND	ND	0.7	1.3	ND	1.2	0.5	ND
NH_4^+	0.3	0.4	2.0	3.3	7.4	2.2	3.3	1.3
$CH_3NH_3^+$	ND	1.8	22	26	33	27	33	37
$(CH_3)_2NH_2^+$	ND	ND	2.6	ND	ND	2.5	2.5	1.8
NO_3^-	55	71	53	62	59	58	58	51
NO_2^-	ND	ND	ND	ND	ND	ND	ND	0.06
F^-	ND	ND	ND	ND	ND	ND	ND	ND
Cl^-	0.9	ND	ND	ND	ND	0.5	0.5	0.5

[a] Numbers in this row indicate a batch identifier.
Note: ND = Not detected

Reproduced from Davis (1996)

Contamination Model

- At a minimum needs the following pieces of information
  - Mass flux of incident plume
  - Thruster firing time
  - "Sticking Fraction" – Measured during SPIFEX

- Straightforward computation of field multiplication for a given component

- Mass flux can be derived from DSMC simulations or parametrized plume model

Erosion

- Spacecraft bipropellant thrusters impact spacecraft surfaces with **high-speed droplets** of unburned and partially burned propellant.
- These impacts can produce erosion damage to optically sensitive hardware and systems (e.g., **windows, camera lenses, solar cells and protective coatings**)

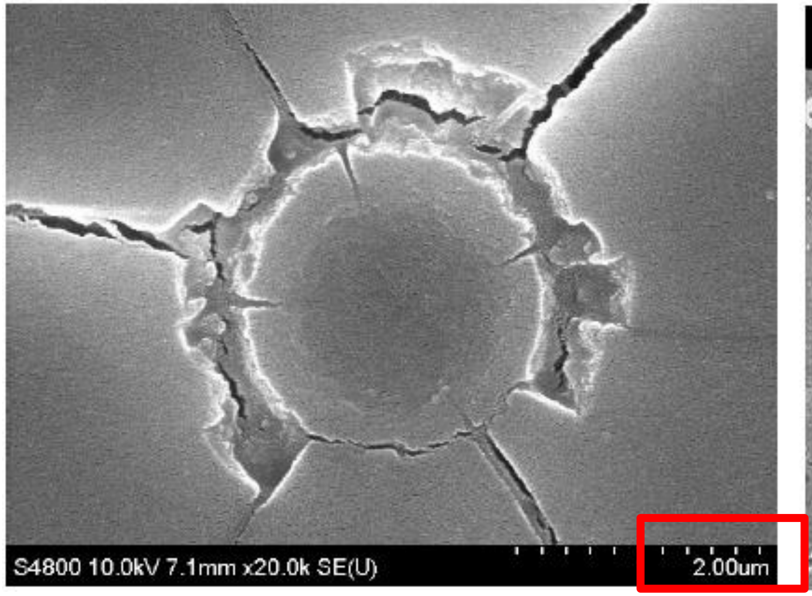
Original Erosion Model (Soares 2002, 2015)

- Originally documented in NASA JSC 29181 publication
- Model provides percent area damaged as a function of range and incidence angle with plume
- Developed using SPH code SPHINX from LANL and **laboratory** data
- Was determined to **overpredict** plume erosion
- The over prediction resulted in more **conservative operations / requirements**

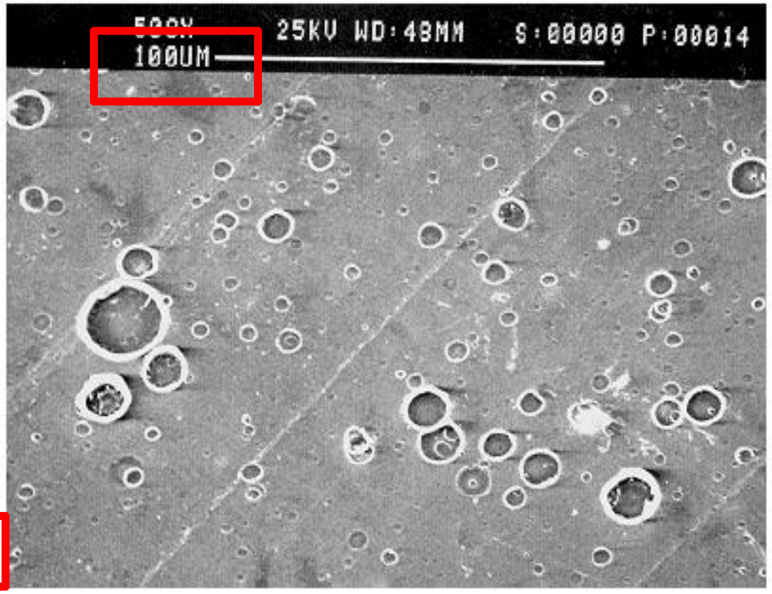
Improved Erosion Model (On-Going)

- On-going work in ES4 at JSC with Boeing collaboration
- Modified the original model to remove sources of conservatism
- Increased realism in plume droplet density
- Increased realism in impact simulations
- Calibrated model to **full-scale** SPIFEX and PIC experiments
- Estimates are made as an **additional step after plume parametrization**

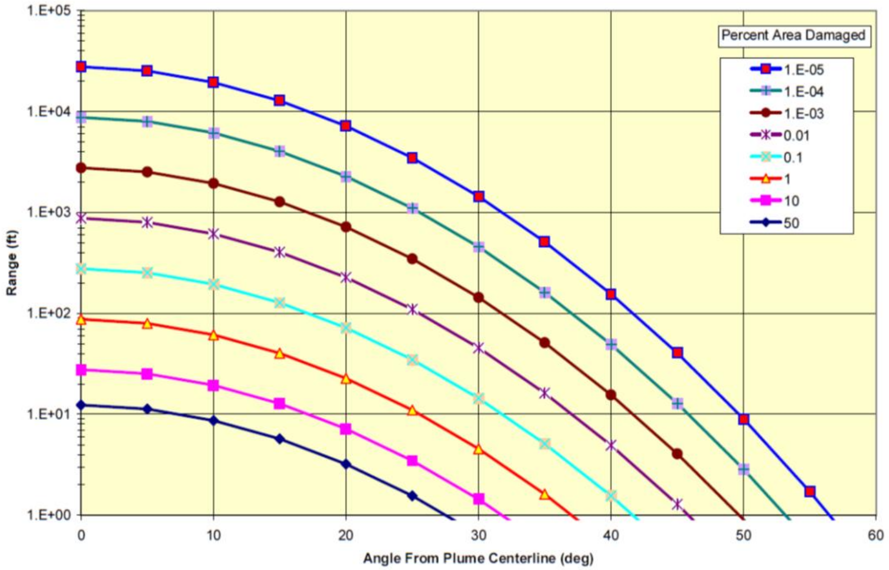
Erosion Damage – Pitting and Cratering



Single Droplet Impact Crater, Soares et al. (2015)



Droplet Craters, Soares et al. (2015)



Damaged Area Curves, Bury and Kerslake (2008)

Damage is generally caused by unburnt fuel products/droplets.

Plume Impingement Summary

- Focus here has been on RCS chemical rocket engine plume impingement; however, other plume sources exist and are under active investigation at NASA and with industry partners.
- RCS thruster plume impingement modeling and simulation is a complex process that covers many physics topics:
  - Fluid dynamics – multiphase, reacting, supersonic flows with particulates
  - Rarefied Gas Dynamics – range of flows from continuum through transitional into free molecular motion
  - Fluid-Structure Interaction – the interaction of rarefied multi-species flows with particulates impinging on objects in a vacuum
- Impingement effects are Multiphysics and include:
  - Loading, Thermal, Chemical Contamination and Accretion, and Erosion (damage mechanics)
- End-to-End computational models are complex, labor intensive, and computationally expensive

References

1) Lumpkin III, F.E., K. A. Boyles and G. L. LeBeau, "Recent Advances in High-Fidelity Simulation of Plume Impingement to Satellite," in *27th JANNAF Exhaust Plume Technology Subcommittee Meeting*, NASA Stennis Space Center, 2003.

2) Davis, D. and L. A. Dee, "Chemical Characterization and Reactivity Testing of Fuel-Oxidizer Reaction Product," NASA Report TR-833-001, 1996.

3) Brown, A., “A STUDY INTO VALIDATING A COUPLED METHOD OF CHARACTERISTICS AND DIRECT SIMULATION MONTE CARLO METHOD AGAINST EMPIRICAL DATA,” M.S. Thesis, *University of Central Florida*, 2012.

4) Soares, C., R. Olsen, C. Steagall, A. Huang, R. Mikatarian, B. Myers, S. Koontz and E. Worthy, "Improvements in Modeling Thruster Plume Erosion Damage to Spacecraft Surfaces," in *13th International Symposium of Materials in the Space Environment*, 2015.

5) Bury, K.M. and T. W. Kerslake, "The Effect of Reaction Control System Thruster Plume Impingement on Orion Service Module Solar Array Power Production," in *Sixth International Energy Conversion Engineering Conference (IECEC),* Cleveland, 2008

6) Soares, C., H. Barsamian and S. Rauer, "Thuster Plume Induced Contamination Measurements From the PIC and SPIFEX Flight Experiments," in *Optical Systems Contamination: Effects, Measurements, and Control VII*, Seattle, 2002

Lets go. *The Time is Now.*

We have the capability

We have the purpose

We have the charge

We have the responsibility