Space Is Hard. Artemis Is Harder.

What we don’t yet know how to do

Kevin Crosby
Carthage College & Wisconsin Space Grant Consortium
Visiting Scientist, JSC EP-4
LiftOff Summer Institute 2026
June 23, 2026

Teaching Artemis

Science Lessons from Launch to Splashdown

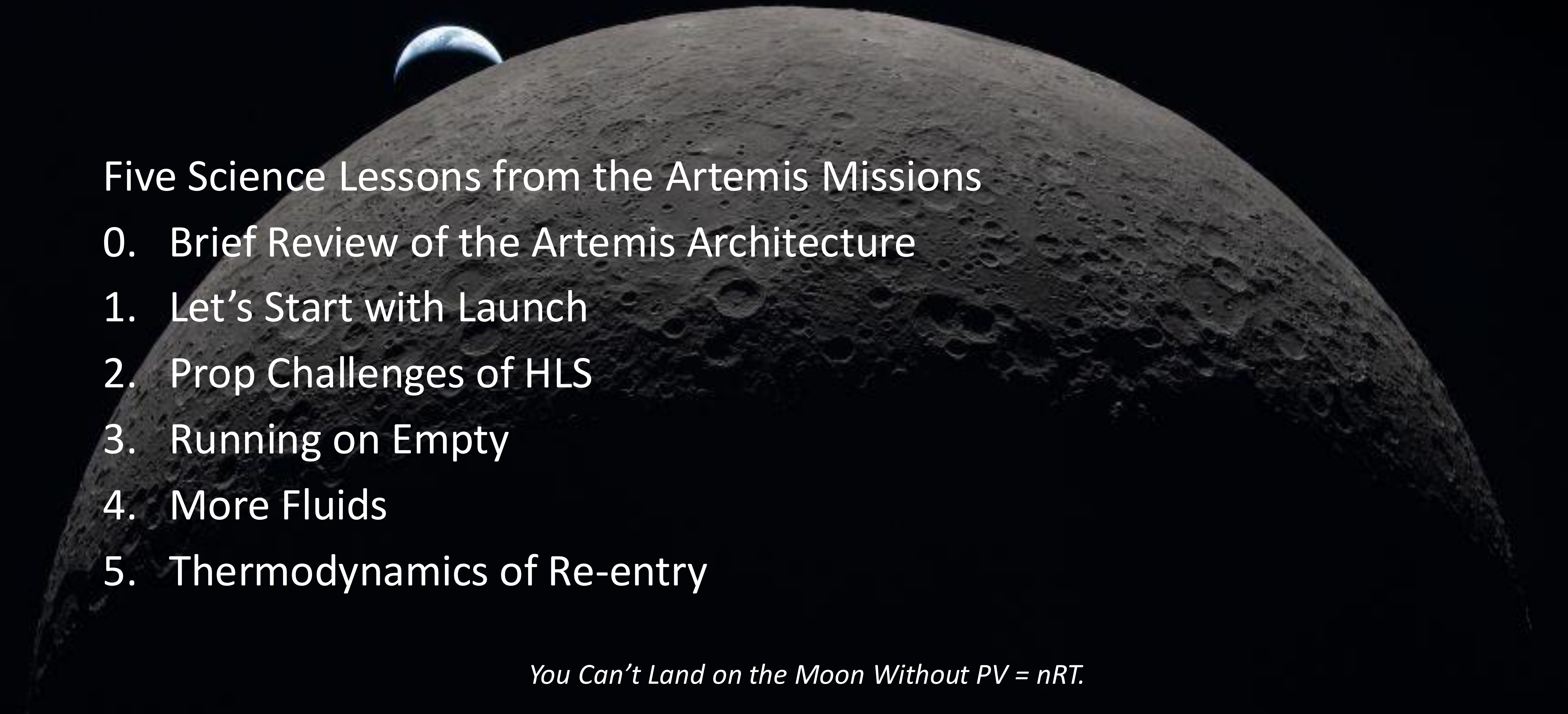
You Can’t Land on the Moon Without PV = nRT.

Teaching Artemis

- Science stories from the Artemis I flight lead to new challenges for Ar II
- Problems we haven’t solved for Ar III and beyond
- Eye candy from a suborbital test!
- Classroom connections throughout!

You Can’t Land on the Moon Without the Rocket Equation.

Teaching Artemis



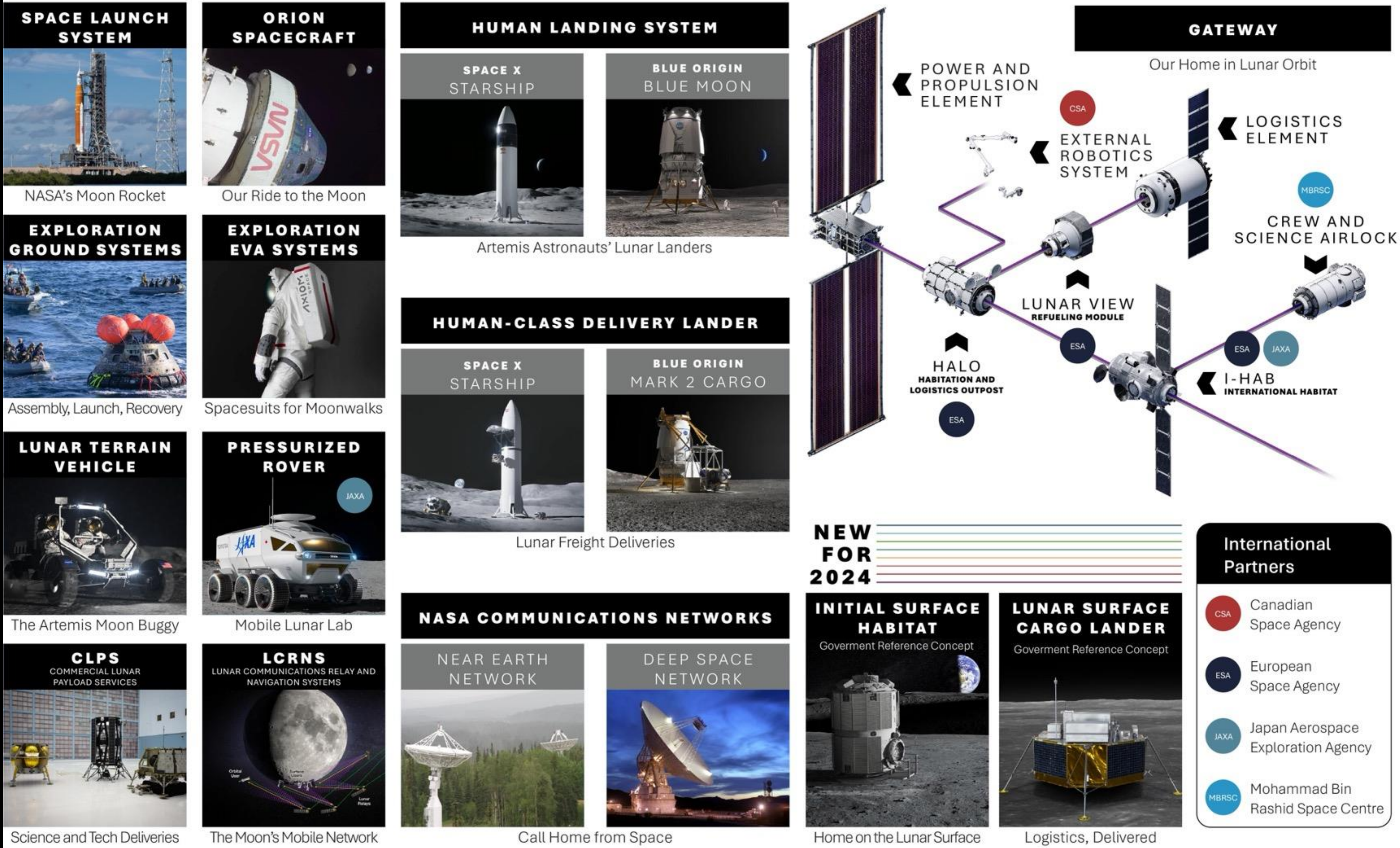
Five Science Lessons from the Artemis Missions

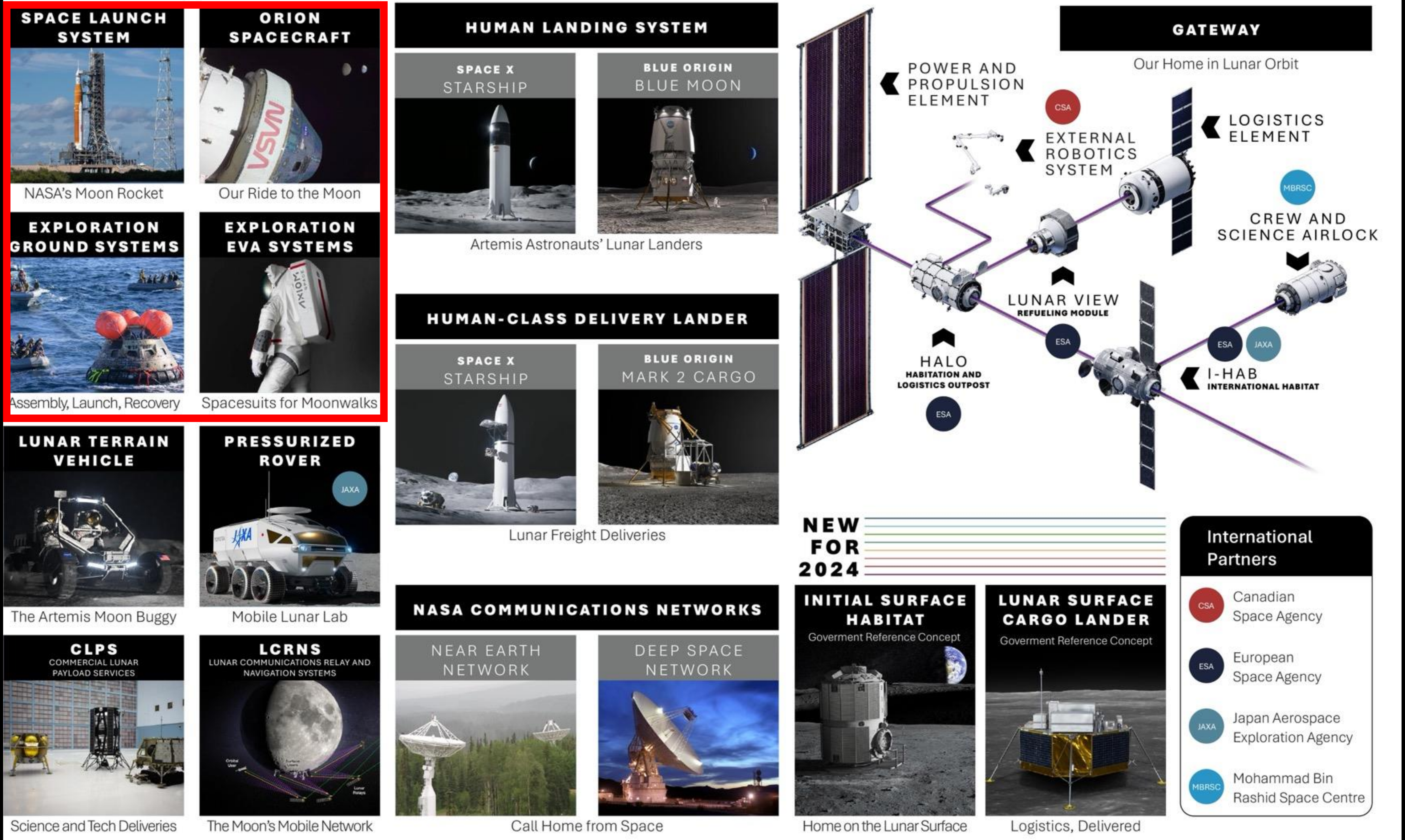
0. Brief Review of the Artemis Architecture
1. Let’s Start with Launch
2. Prop Challenges of HLS
3. Running on Empty
4. More Fluids
5. Thermodynamics of Re-entry

You Can’t Land on the Moon Without PV = nRT.

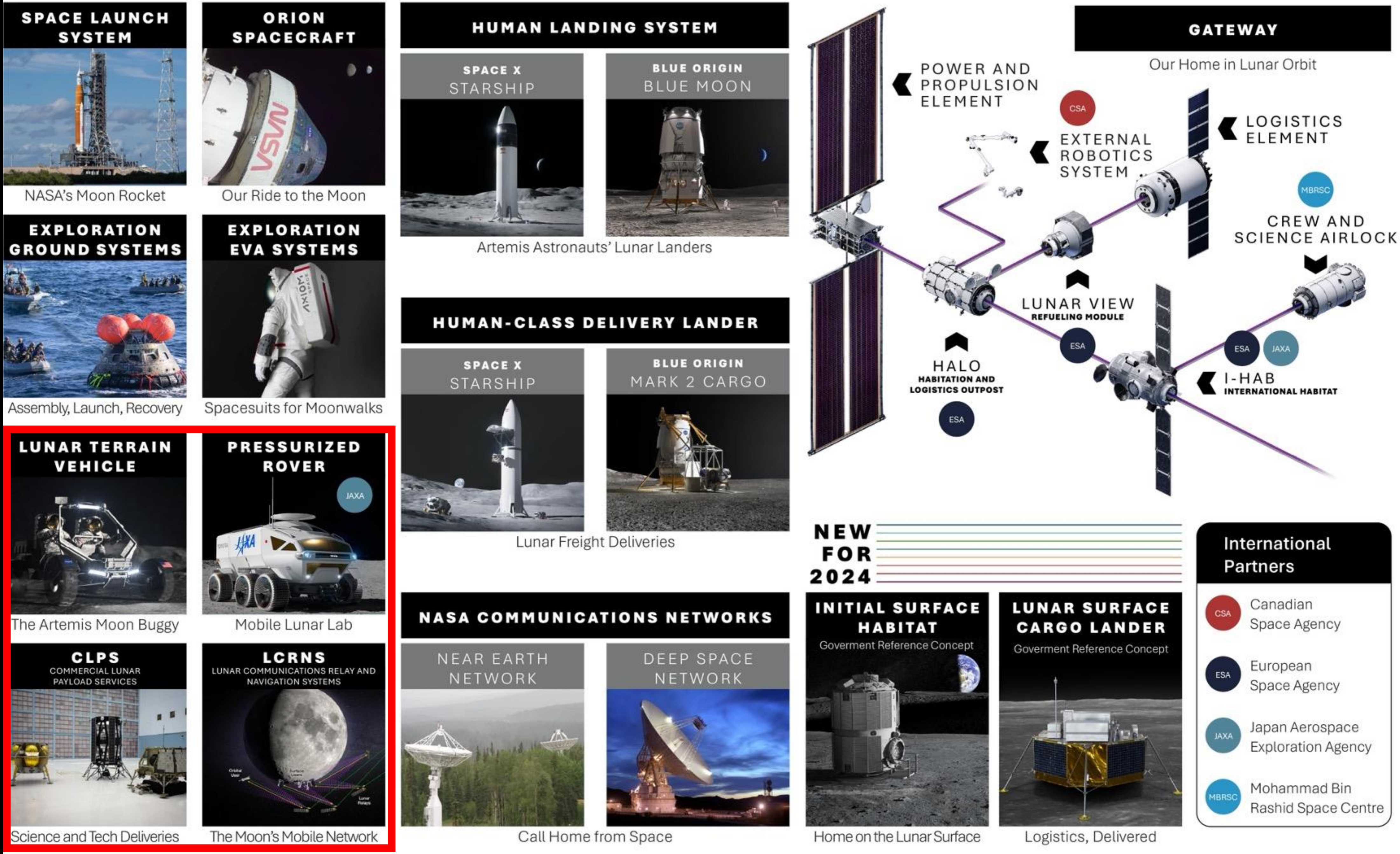
0. A brief review of the Artemis Architecture

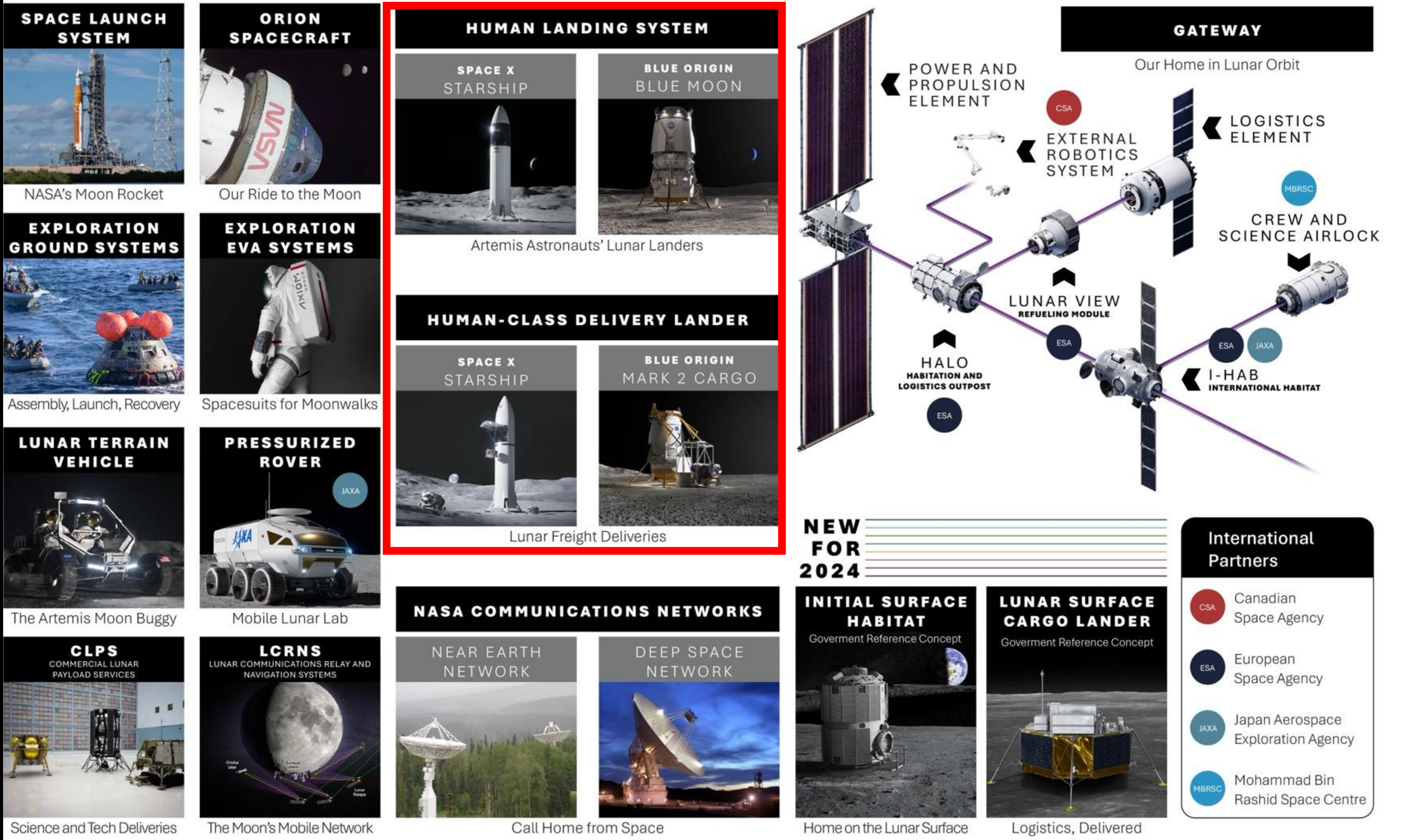
Oh no! NASA charts!

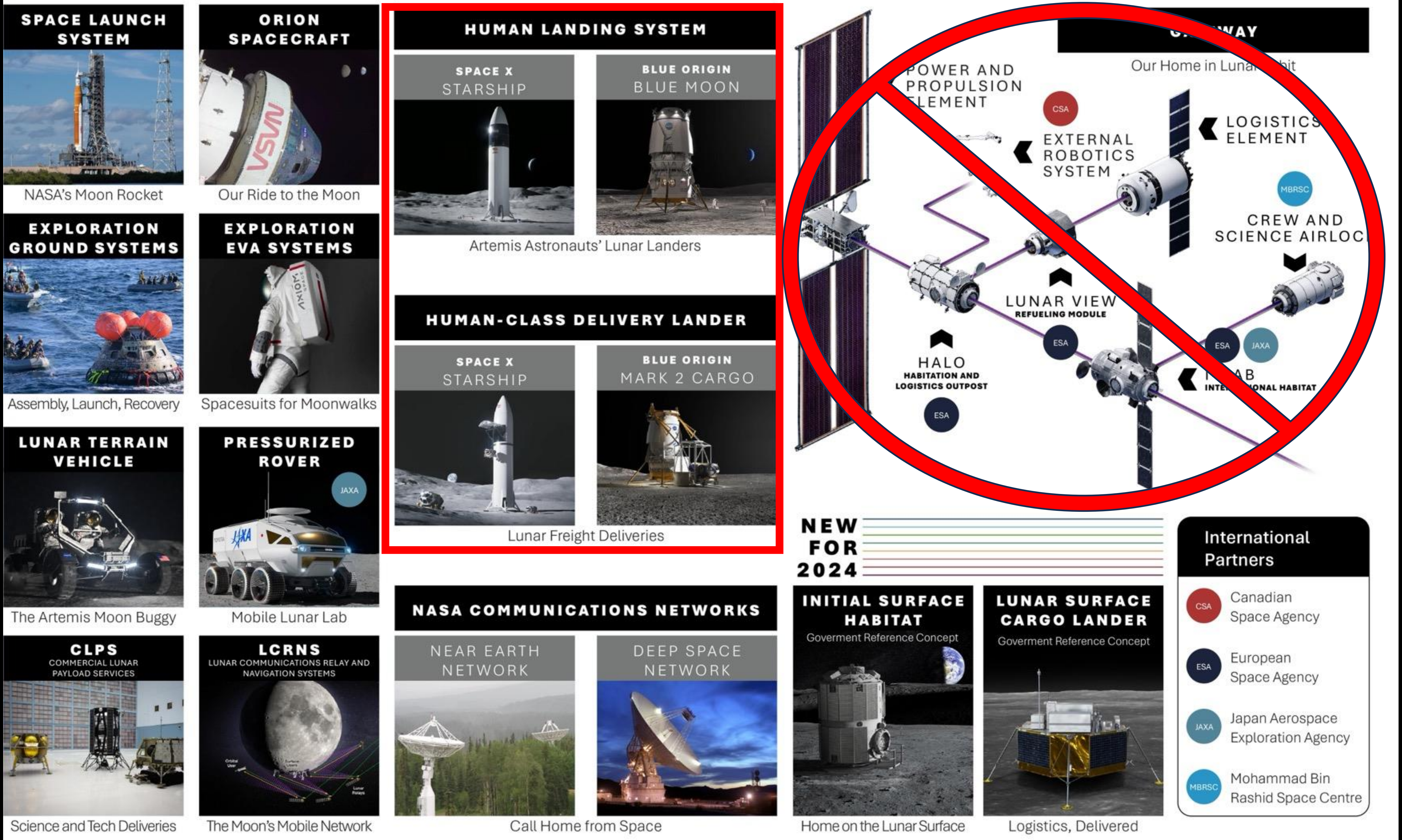

SPACE LAUNCH SYSTEM
NASA's Moon Rocket
ORION SPACECRAFT
Our Ride to the Moon
HUMAN LANDING SYSTEM
SPACE X STARSHIP
BLUE ORIGIN BLUE MOON
Artemis Astronauts' Lunar Landers
GATEWAY
Our Home in Lunar Orbit
POWER AND PROPULSION ELEMENT
CSA
EXTERNAL ROBOTICS SYSTEM
LOGISTICS ELEMENT
MBRSC
CREW AND SCIENCE AIRLOCK
LUNAR VIEW
REFUELING MODULE
ESA
HALO
HABITATION AND LOGISTICS OUTPOST
ESA
ESA
JAXA
I-HAB
INTERNATIONAL HABITAT
EXPLORATION GROUND SYSTEMS
Assembly, Launch, Recovery
EXPLORATION EVA SYSTEMS
Spacesuits for Moonwalks
HUMAN-CLASS DELIVERY LANDER
SPACE X STARSHIP
BLUE ORIGIN MARK 2 CARGO
Lunar Freight Deliveries
LUNAR TERRAIN VEHICLE
The Artemis Moon Buggy
PRESSURIZED ROVER
JAXA
Mobile Lunar Lab
NEW FOR 2024
International Partners
CSA Canadian Space Agency
ESA European Space Agency
JAXA Japan Aerospace Exploration Agency
MBRSC Mohammad Bin Rashid Space Centre
CLPS
COMMERCIAL LUNAR PAYLOAD SERVICES
Science and Tech Deliveries
LCRNS
LUNAR COMMUNICATIONS RELAY AND NAVIGATION SYSTEMS
The Moon's Mobile Network
NASA COMMUNICATIONS NETWORKS
NEAR EARTH NETWORK
DEEP SPACE NETWORK
Call Home from Space
INITIAL SURFACE HABITAT
Goverment Reference Concept
Home on the Lunar Surface
LUNAR SURFACE CARGO LANDER
Goverment Reference Concept
Logistics, Delivered



SPACE LAUNCH SYSTEM
NASA's Moon Rocket
ORION SPACECRAFT
NASA
Our Ride to the Moon
EXPLORATION GROUND SYSTEMS
Assembly, Launch, Recovery
EXPLORATION EVA SYSTEMS
AXIOM
Spacesuits for Moonwalks
HUMAN LANDING SYSTEM
SPACE X STARSHIP
BLUE ORIGIN BLUE MOON
Artemis Astronauts' Lunar Landers
HUMAN-CLASS DELIVERY LANDER
SPACE X STARSHIP
BLUE ORIGIN MARK 2 CARGO
Lunar Freight Deliveries
GATEWAY
Our Home in Lunar Orbit
POWER AND PROPULSION ELEMENT
CSA
EXTERNAL ROBOTICS SYSTEM
LOGISTICS ELEMENT
MBRSC
CREW AND SCIENCE AIRLOCK
LUNAR VIEW
REFUELING MODULE
ESA
HALO
HABITATION AND LOGISTICS OUTPOST
ESA
ESA
JAXA
I-HAB
INTERNATIONAL HABITAT
LUNAR TERRAIN VEHICLE
The Artemis Moon Buggy
PRESSURIZED ROVER
JAXA
Mobile Lunar Lab
NASA COMMUNICATIONS NETWORKS
NEAR EARTH NETWORK
DEEP SPACE NETWORK
Call Home from Space
NEW FOR 2024
INITIAL SURFACE HABITAT
Goverment Reference Concept
Home on the Lunar Surface
LUNAR SURFACE CARGO LANDER
Goverment Reference Concept
Logistics, Delivered
CLPS
COMMERCIAL LUNAR PAYLOAD SERVICES
Science and Tech Deliveries
LCRNS
LUNAR COMMUNICATIONS RELAY AND NAVIGATION SYSTEMS
The Moon's Mobile Network
International Partners
CSA Canadian Space Agency
ESA European Space Agency
JAXA Japan Aerospace Exploration Agency
MBRSC Mohammad Bin Rashid Space Centre

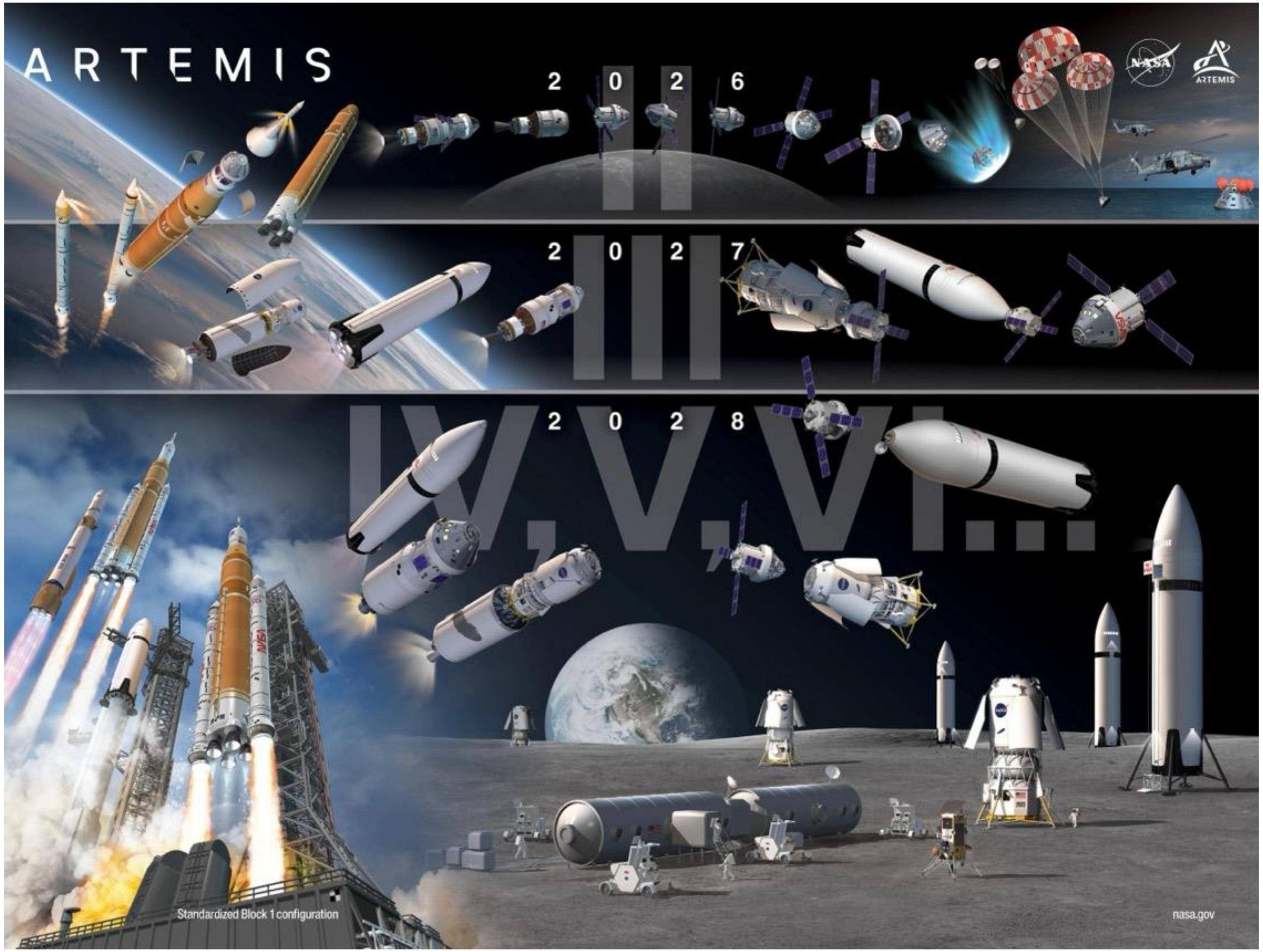

SPACE LAUNCH SYSTEM
NASA's Moon Rocket
ORION SPACECRAFT
Our Ride to the Moon
EXPLORATION GROUND SYSTEMS
Assembly, Launch, Recovery
EXPLORATION EVA SYSTEMS
Spacesuits for Moonwalks
LUNAR TERRAIN VEHICLE
The Artemis Moon Buggy
PRESSURIZED ROVER
JAXA
Mobile Lunar Lab
CLPS
COMMERCIAL LUNAR PAYLOAD SERVICES
Science and Tech Deliveries
LCRNS
LUNAR COMMUNICATIONS RELAY AND NAVIGATION SYSTEMS
The Moon's Mobile Network
HUMAN LANDING SYSTEM
SPACE X STARSHIP
BLUE ORIGIN BLUE MOON
Artemis Astronauts' Lunar Landers
HUMAN-CLASS DELIVERY LANDER
SPACE X STARSHIP
BLUE ORIGIN MARK 2 CARGO
Lunar Freight Deliveries
NASA COMMUNICATIONS NETWORKS
NEAR EARTH NETWORK
DEEP SPACE NETWORK
Call Home from Space
GATEWAY
Our Home in Lunar Orbit
POWER AND PROPULSION ELEMENT
CSA
EXTERNAL ROBOTICS SYSTEM
LOGISTICS ELEMENT
MBRSC
CREW AND SCIENCE AIRLOCK
LUNAR VIEW
REFUELING MODULE
ESA
HALO
HABITATION AND LOGISTICS OUTPOST
ESA
ESA
JAXA
I-HAB
INTERNATIONAL HABITAT
NEW FOR 2024
INITIAL SURFACE HABITAT
Goverment Reference Concept
Home on the Lunar Surface
LUNAR SURFACE CARGO LANDER
Goverment Reference Concept
Logistics, Delivered
International Partners
CSA Canadian Space Agency
ESA European Space Agency
JAXA Japan Aerospace Exploration Agency
MBRSC Mohammad Bin Rashid Space Centre


SPACE LAUNCH SYSTEM
NASA's Moon Rocket
ORION SPACECRAFT
NASA
Our Ride to the Moon
HUMAN LANDING SYSTEM
SPACE X STARSHIP
BLUE ORIGIN BLUE MOON
Artemis Astronauts' Lunar Landers
HUMAN-CLASS DELIVERY LANDER
SPACE X STARSHIP
BLUE ORIGIN MARK 2 CARGO
Lunar Freight Deliveries
GATEWAY
Our Home in Lunar Orbit
POWER AND PROPULSION ELEMENT
CSA
EXTERNAL ROBOTICS SYSTEM
LOGISTICS ELEMENT
MBRSC
CREW AND SCIENCE AIRLOCK
LUNAR VIEW
REFUELING MODULE
ESA
HALO
HABITATION AND LOGISTICS OUTPOST
ESA
ESA
JAXA
I-HAB
INTERNATIONAL HABITAT
EXPLORATION GROUND SYSTEMS
Assembly, Launch, Recovery
EXPLORATION EVA SYSTEMS
AXIOM SPACE
Spacesuits for Moonwalks
LUNAR TERRAIN VEHICLE
The Artemis Moon Buggy
PRESSURIZED ROVER
JAXA
Mobile Lunar Lab
NEW FOR 2024
International Partners
CSA Canadian Space Agency
ESA European Space Agency
JAXA Japan Aerospace Exploration Agency
MBRSC Mohammad Bin Rashid Space Centre
CLPS
COMMERCIAL LUNAR PAYLOAD SERVICES
Science and Tech Deliveries
LCRNS
LUNAR COMMUNICATIONS RELAY AND NAVIGATION SYSTEMS
The Moon's Mobile Network
NASA COMMUNICATIONS NETWORKS
NEAR EARTH NETWORK
DEEP SPACE NETWORK
Call Home from Space
INITIAL SURFACE HABITAT
Goverment Reference Concept
Home on the Lunar Surface
LUNAR SURFACE CARGO LANDER
Goverment Reference Concept
Logistics, Delivered



SPACE LAUNCH SYSTEM
NASA's Moon Rocket
ORION SPACECRAFT
Our Ride to the Moon
HUMAN LANDING SYSTEM
SPACE X
STARSHIP
BLUE ORIGIN
BLUE MOON
Artemis Astronauts' Lunar Landers
EXPLORATION GROUND SYSTEMS
Assembly, Launch, Recovery
EXPLORATION EVA SYSTEMS
Spacesuits for Moonwalks
HUMAN-CLASS DELIVERY LANDER
SPACE X
STARSHIP
BLUE ORIGIN
MARK 2 CARGO
Lunar Freight Deliveries
LUNAR TERRAIN VEHICLE
The Artemis Moon Buggy
PRESSURIZED ROVER
JAXA
Mobile Lunar Lab
CLPS
COMMERCIAL LUNAR PAYLOAD SERVICES
Science and Tech Deliveries
LCRNS
LUNAR COMMUNICATIONS RELAY AND NAVIGATION SYSTEMS
The Moon's Mobile Network
NASA COMMUNICATIONS NETWORKS
NEAR EARTH NETWORK
DEEP SPACE NETWORK
Call Home from Space
Our Home in Luna
POWER AND PROPULSION ELEMENT
CSA
EXTERNAL ROBOTICS SYSTEM
LOGISTICS ELEMENT
MBRSC
CREW AND SCIENCE AIRLOC
LUNAR VIEW
REFUELING MODULE
HALO
HABITATION AND LOGISTICS OUTPOST
ESA
ESA
ESA
JAXA
NEW FOR 2024
INITIAL SURFACE HABITAT
Goverment Reference Concept
Home on the Lunar Surface
LUNAR SURFACE CARGO LANDER
Goverment Reference Concept
Logistics, Delivered
International Partners
CSA Canadian Space Agency
ESA European Space Agency
JAXA Japan Aerospace Exploration Agency
MBRSC Mohammad Bin Rashid Space Centre

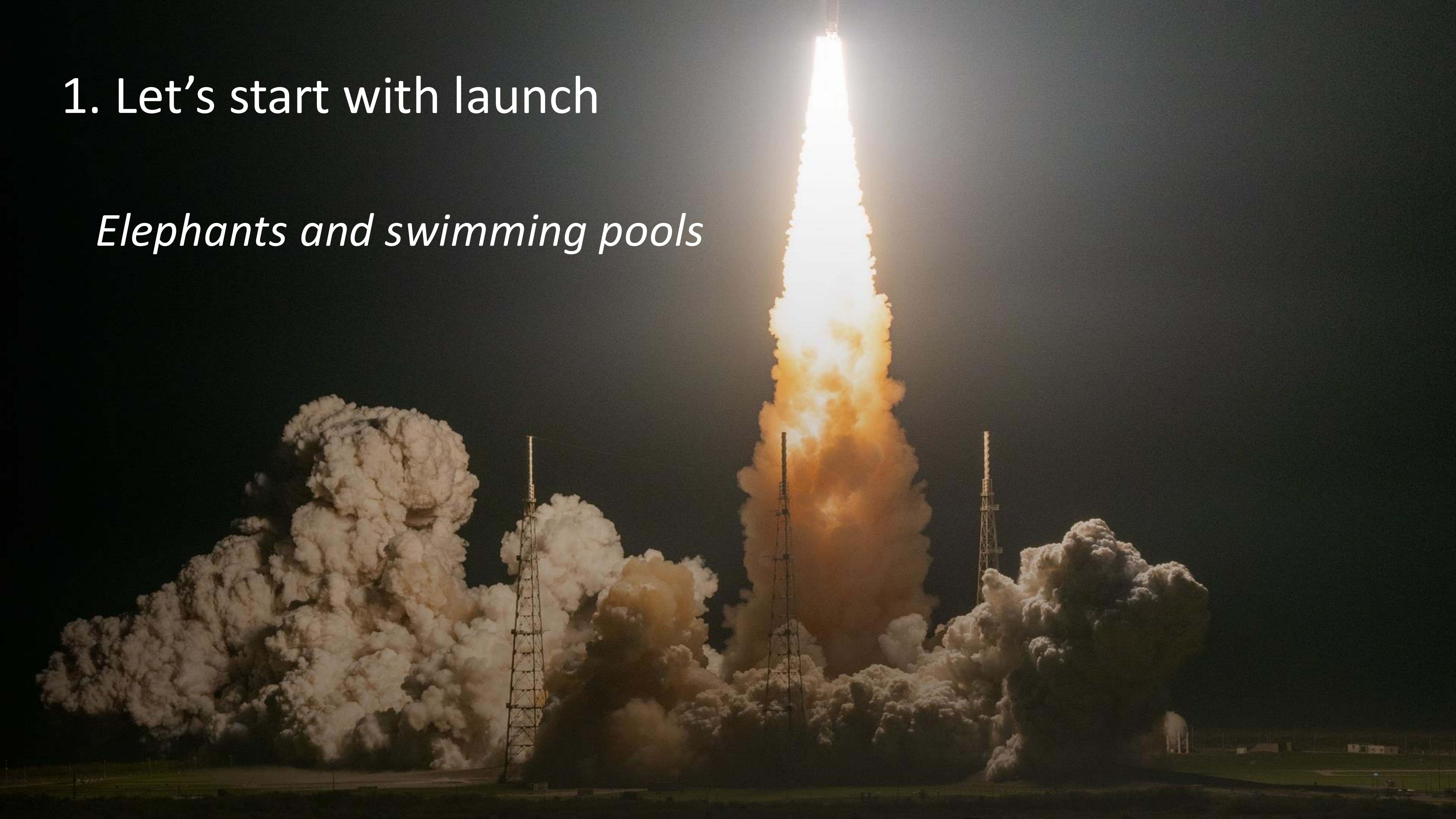
Artemis Architecture Updated Yet Again



Artemis Architecture Updated Yet Again

1. Let’s start with launch

Elephants and swimming pools

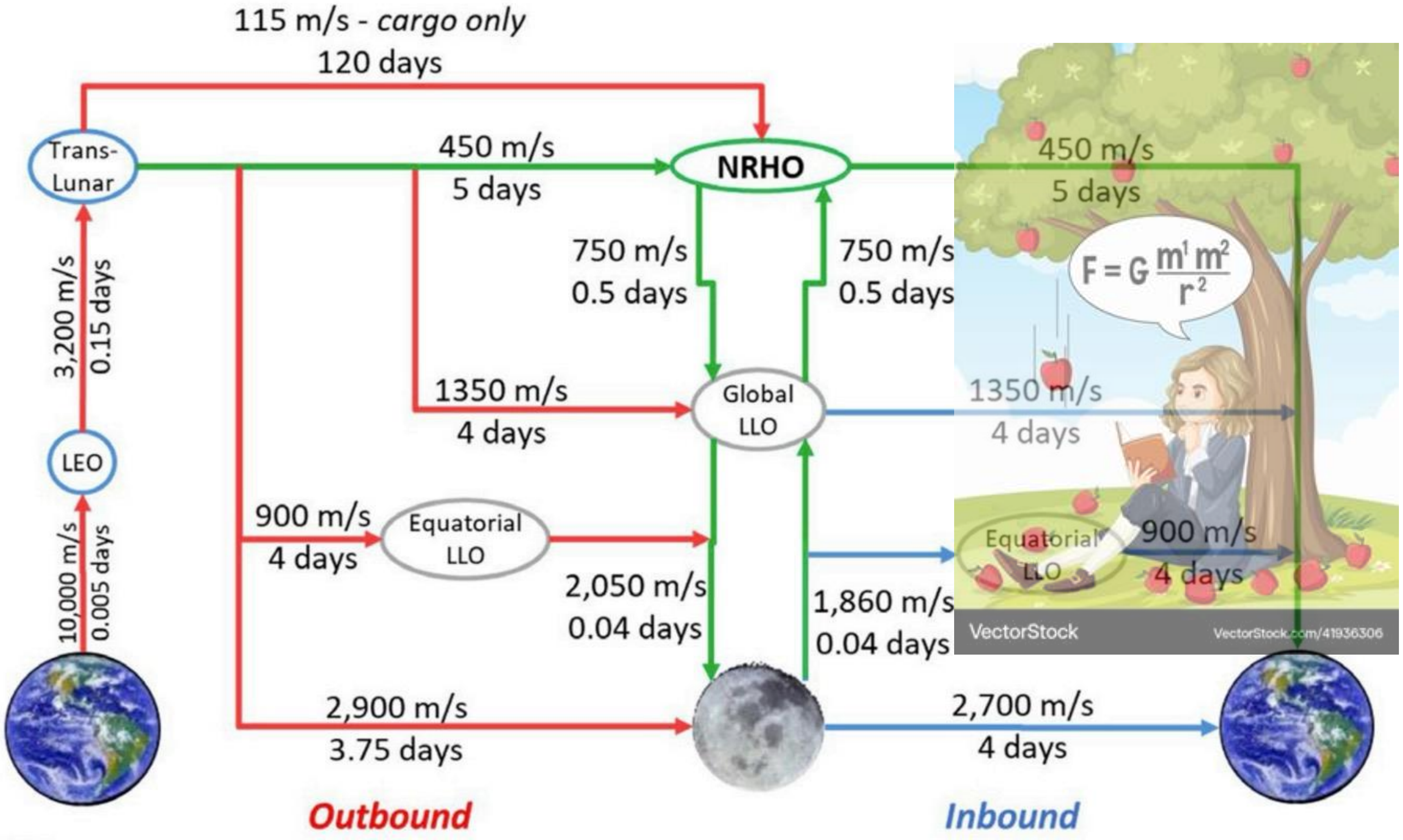


1. Let’s start with launch

Δv is the Metric of Space

Energy requirements are set by the masses in the solar system via Newtonian gravity.

These energies are expressed in Δv: the required speed change a vehicle must achieve to climb and brake in gravity wells.

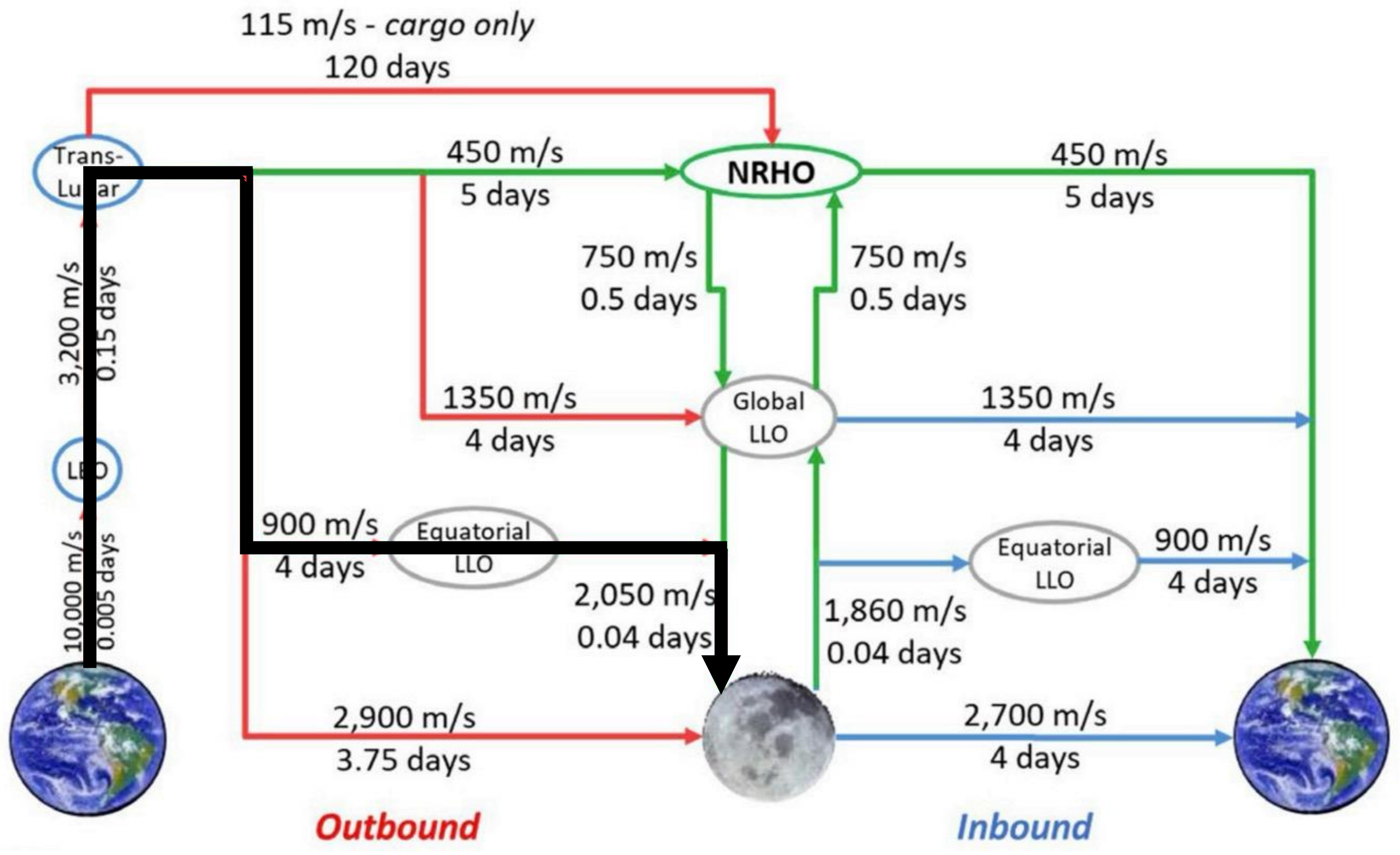


Δv is the Metric of Space

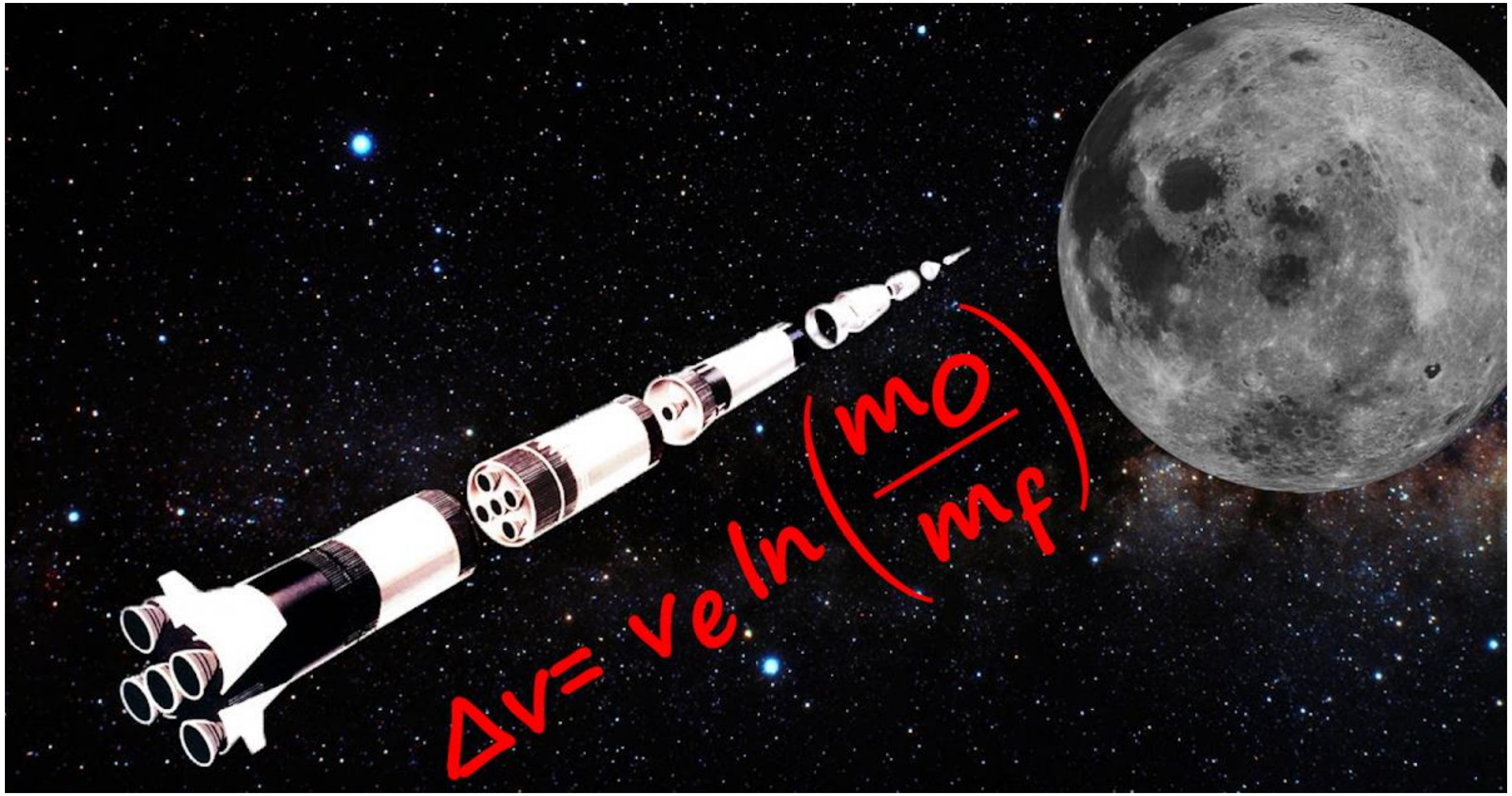
Example: Earth to LLO to Lunar Surface:

ES-LEO: 10 km/s
LEO-TLO: 3.2 km/s
TLO-LLO: 0.9 km/s
LLO-LS: 2.05 km/s

Total: 16.15 km/s



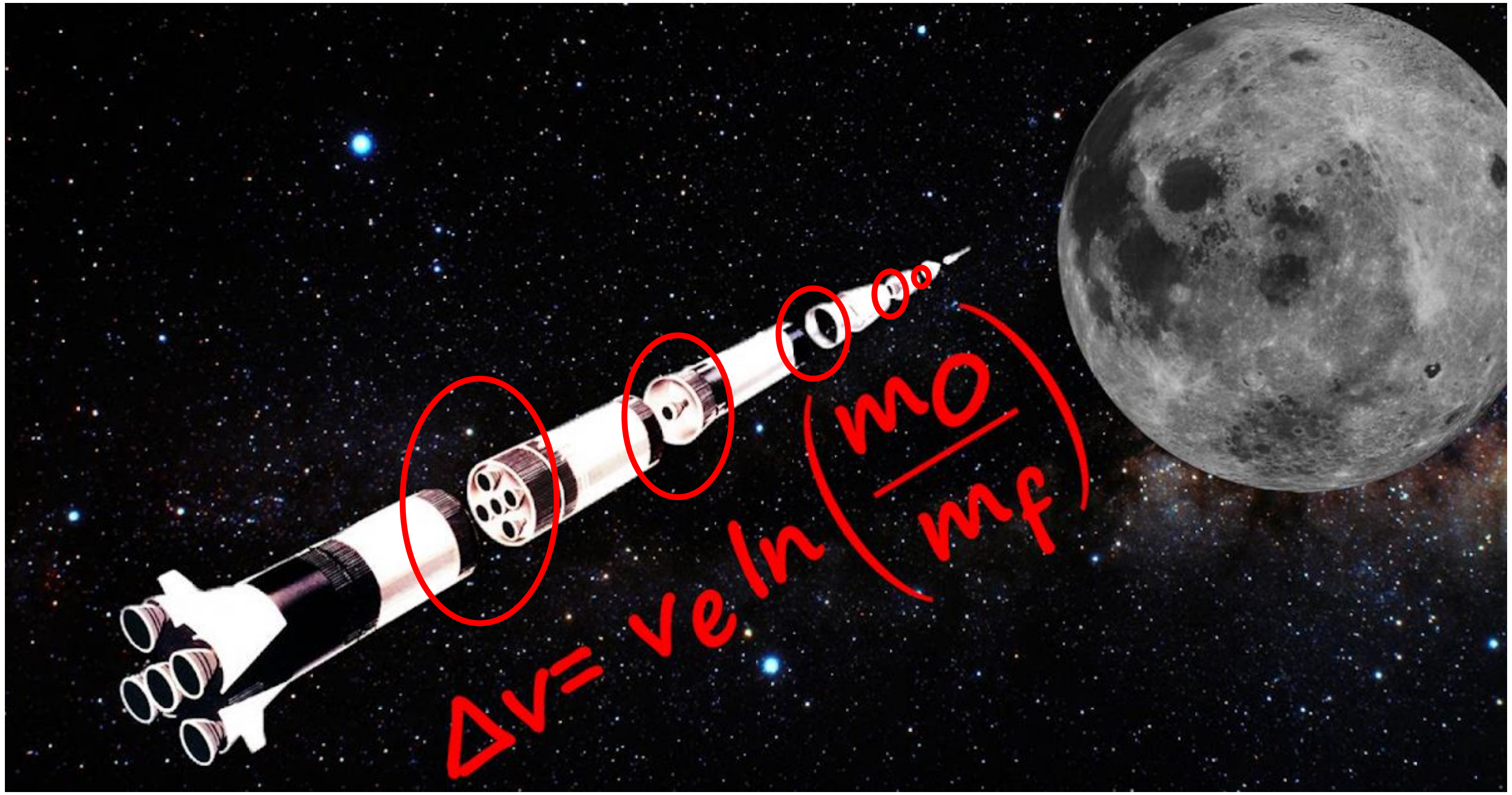
Tyranny of the Rocket Equation



m_0 = initial mass
m_f = final mass
Δv = change in speed
v_e = exhaust speed

To achieve required Δv, there are only two dials: engine design (v_e) and vehicle mass.

Tyranny of the Rocket Equation



$$m_0 = \text{initial mass}$$
$$m_f = \text{final mass}$$
$$\Delta v = \text{change in speed}$$
$$v_e = \text{exhaust speed}$$

Saturn V solves the Tyranny by *staging masses*

Tyranny of the Rocket Equation

$$m_0 = \text{initial mass}$$
$$m_f = \text{final mass}$$
$$\Delta v = \text{change in speed}$$
$$v_e = \text{exhaust speed}$$

Starship HLS must carry all its mass back and forth. Starship solves Tyranny by brute force (mass)

What would you bring to the Moon?

The Artemis Packing List:

Pick **three things** you would take to the Moon. Estimate their mass in kg.

In spaceflight, mass is money, propellant, risk, and choice.

What would you bring to the Moon?

Now estimate the additional propellant required for your payload mass

Rocket Equation applied to Artemis IV:

One way trip: 90 kg propellant per kg payload mass

Round trip: 165 kg propellant per kg payload mass

How much propellant are you going to need for your mementos?

What would you bring to the Moon?

Moon-Bag Challenge Worksheet

Propellant shadow = mass x 90 | Average mission-cost share = mass x $150,000

Item	Estimated mass	Propellant shadow	Average cost share
	kg	mass x 90	mass x $150,000
	kg	mass x 90	mass x $150,000
	kg	mass x 90	mass x $150,000

Moon-Bag Quick Reference

A classroom estimate for Artemis-scale Moon-bound mass

Item	Typical mass	Propellant shadow	Average cost share
Photo, patch, letter, or small charm	0.02 kg	1.8 kg	$3,000
Phone	0.2 kg	18 kg	$30,000
Paperback book	0.3 kg	27 kg	$45,000
Journal and pens	0.5 kg	45 kg	$75,000
1 liter of water	1.0 kg	90 kg	$150,000
Laptop	1.5 kg	135 kg	$225,000
Camera kit	2.5 kg	225 kg	$375,000
Guitar	2.0 kg	180 kg	$300,000
10 kg comfort bag	10.0 kg	900 kg	$1,500,000

ARTEMIS II

Official Flight Kit

OFK for ArII is 4.5 kg

ITEM	QTY
Shavings from SLS (Space Launch System) core stage	1
Mini U.S. flags	5
U.S. flags	3
Artemis II rubber stamp	1
Copy of JPL Ranger Program lunar photo negative	1
U.S flags	50
Lockheed Martin patches	17
U.S. flags	50
Exploration Ground System (EGS) program flags	40

ITEM	QTY
Extravehicular Activity and Human Surface Mobility Program (EHP) patches	15
Artemis embossing discs	4
America 250 flags	3
Artemis embroidered ribbons	5
Artemis II holographic seals	850
Artemis II pins	150
Artemis II patches	200
SD card ("Send Your Name to Space" campaign)	1
Unflown Apollo 18 mission flag	1

2. Propellant Challenges of HLS

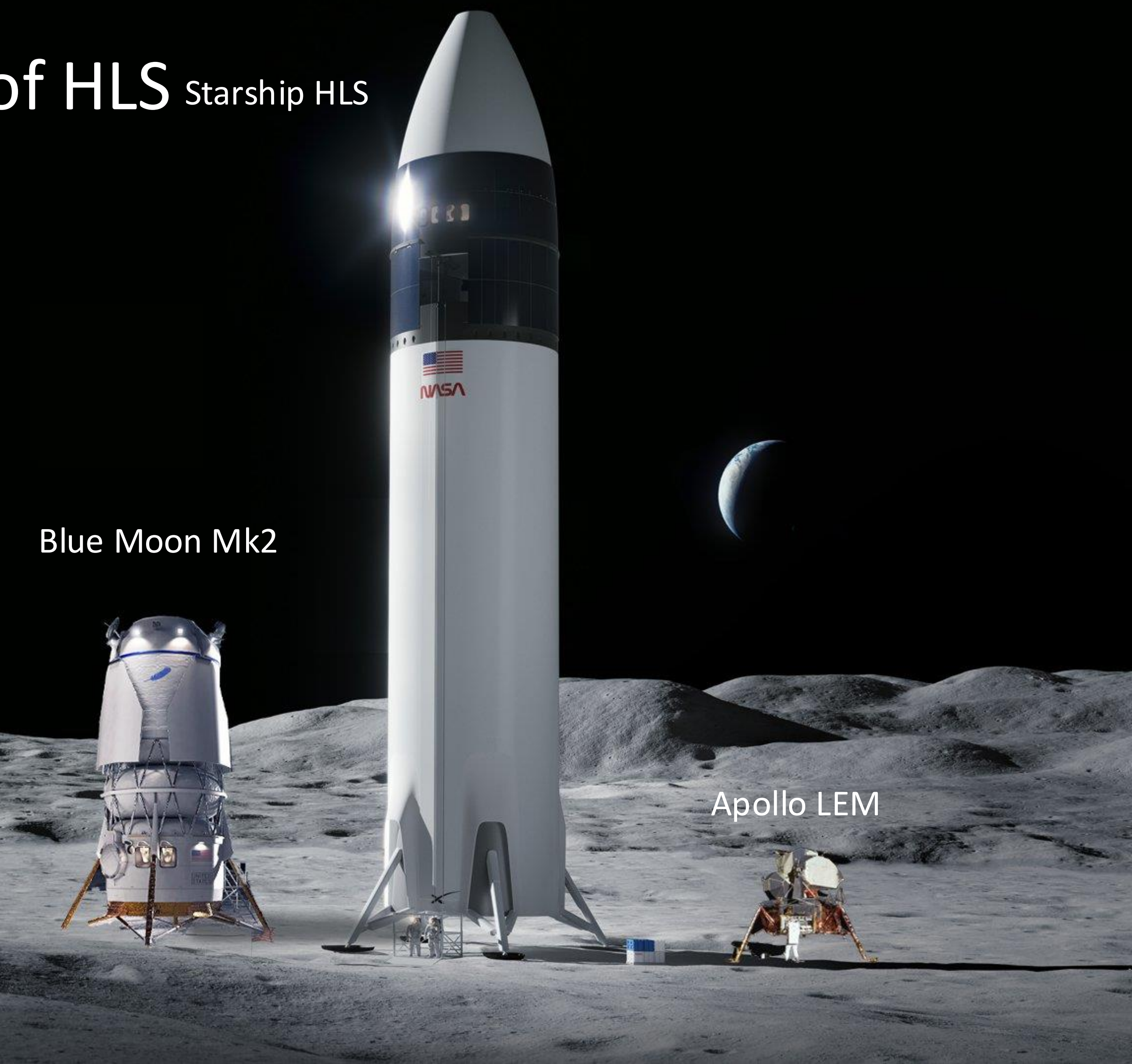
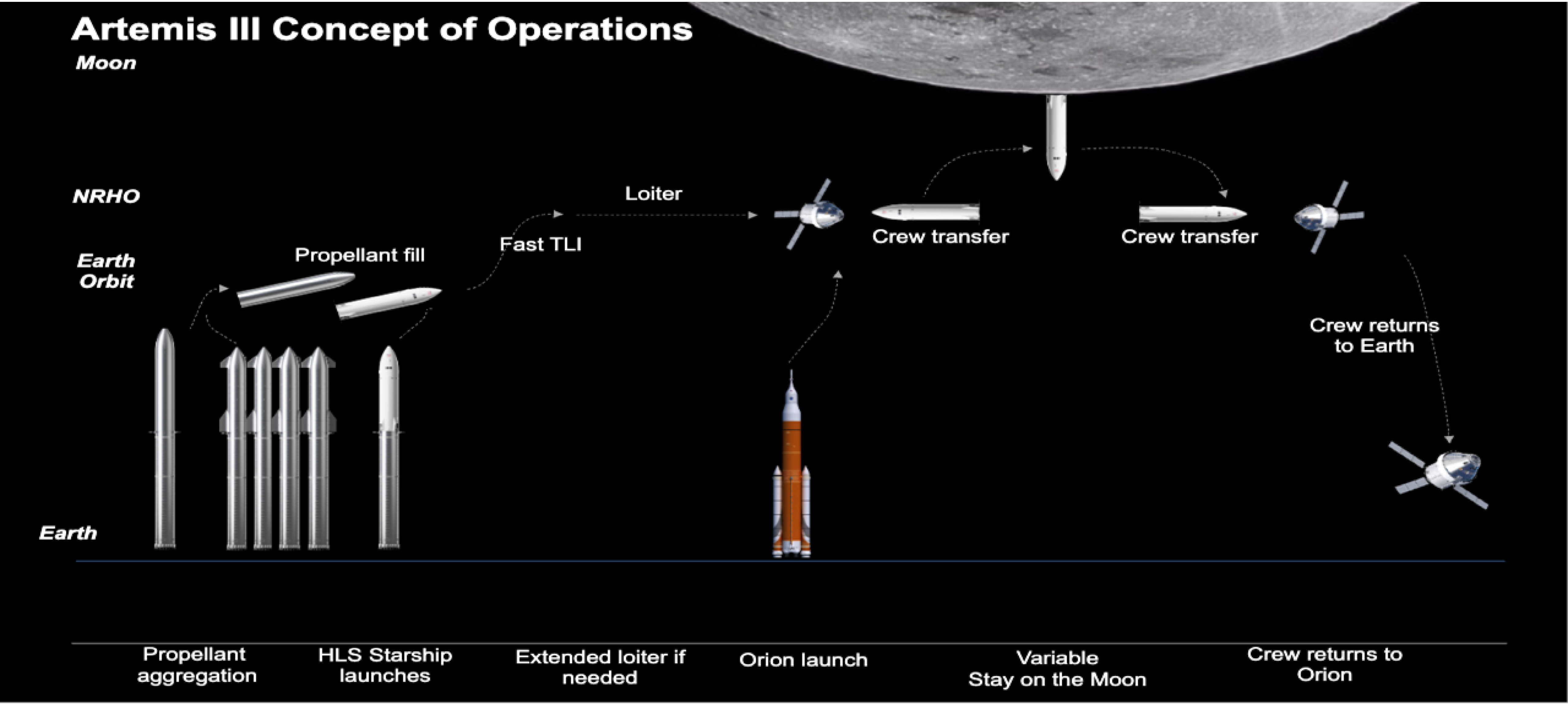
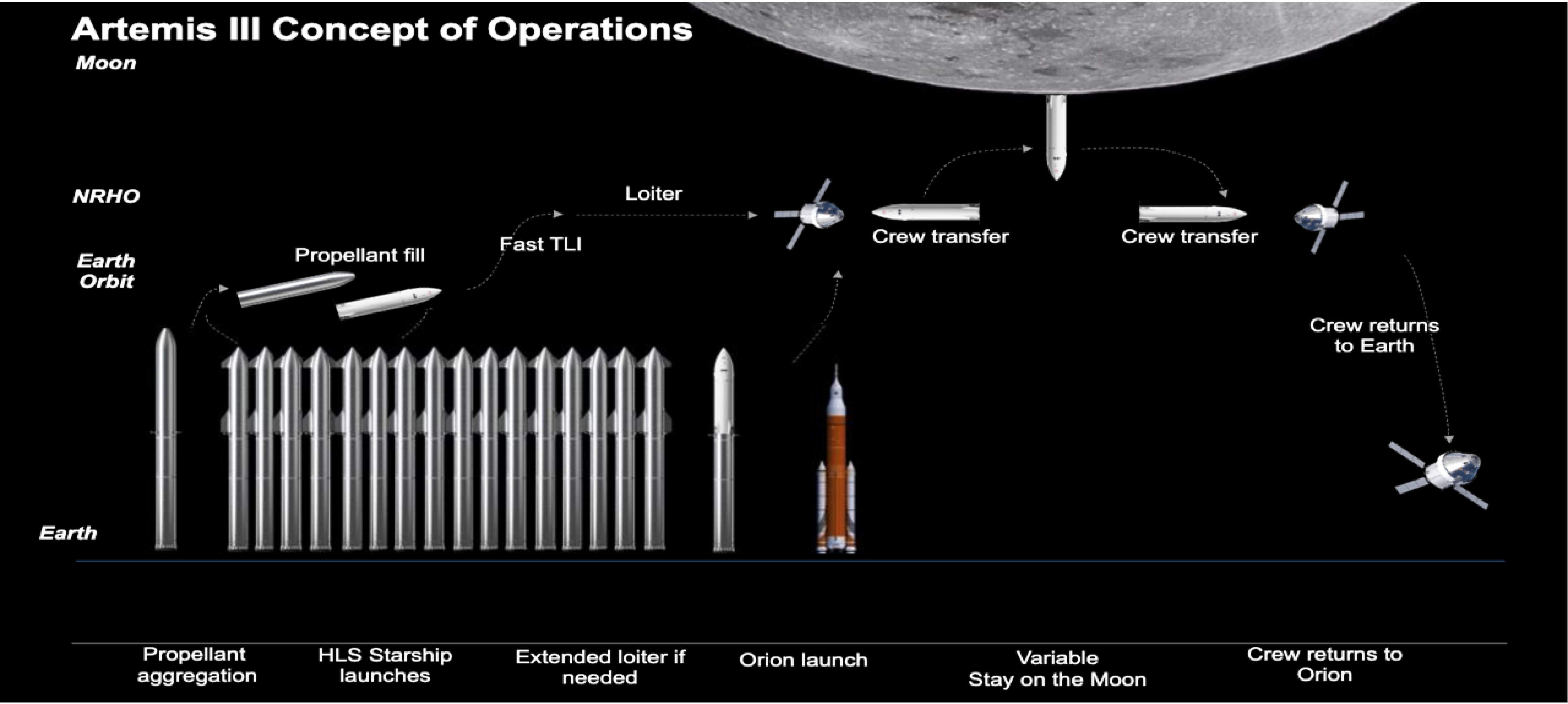


Image credit: Ken Kirtland IV
@KenKirtland17

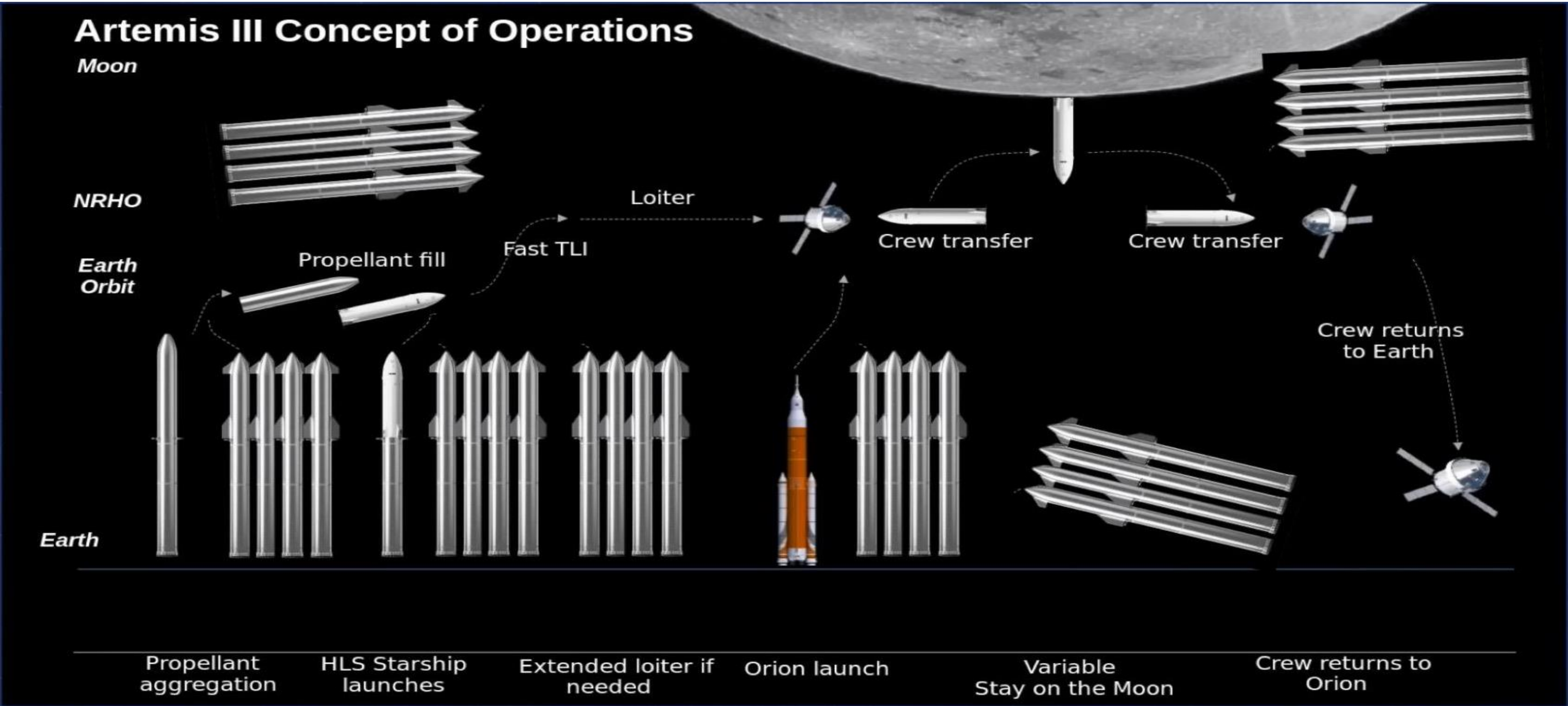
Cryogenic Propellant Transfer and Storage



Cryogenic Propellant Transfer and Storage



Cryogenic Propellant Transfer and Storage



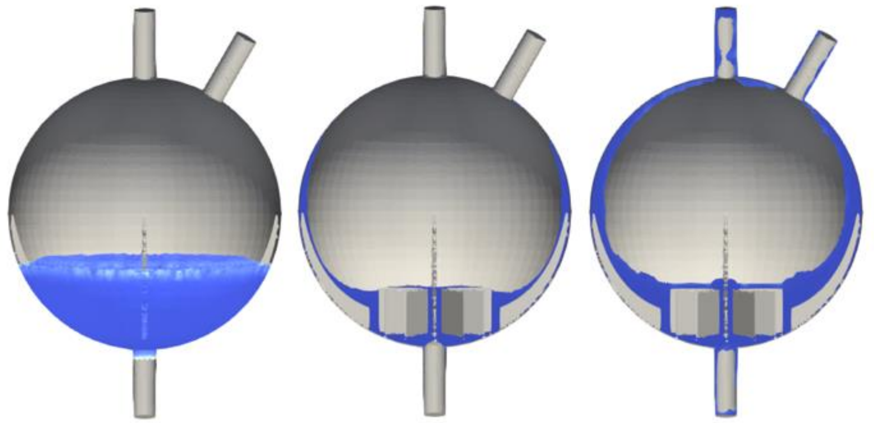
Why So Hard?

Cryogenic Challenges:

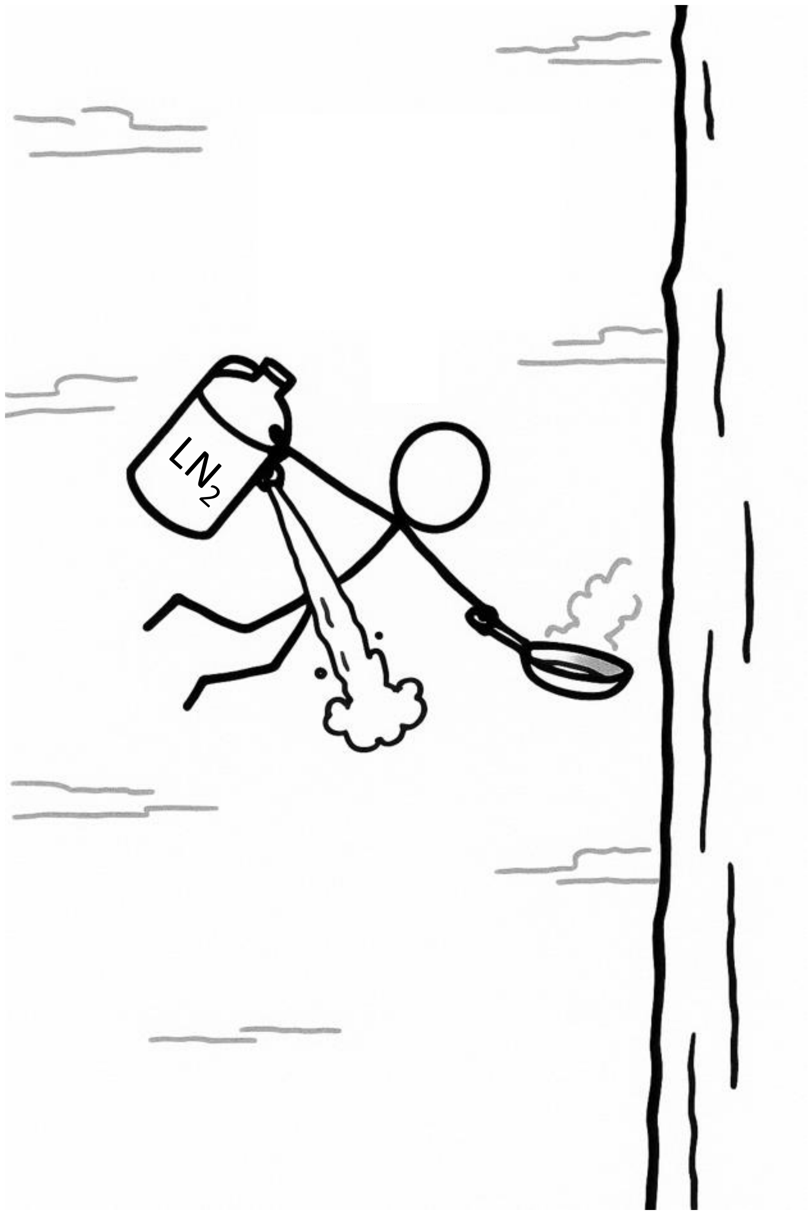
- Transfer lines cause propellant boil-off
- Storage in space causes propellant boil-off
- Boil-off causes autogenous pressurization
- Propellant becomes a frothy mixture of gasses and liquid

Micrograviity Challenges

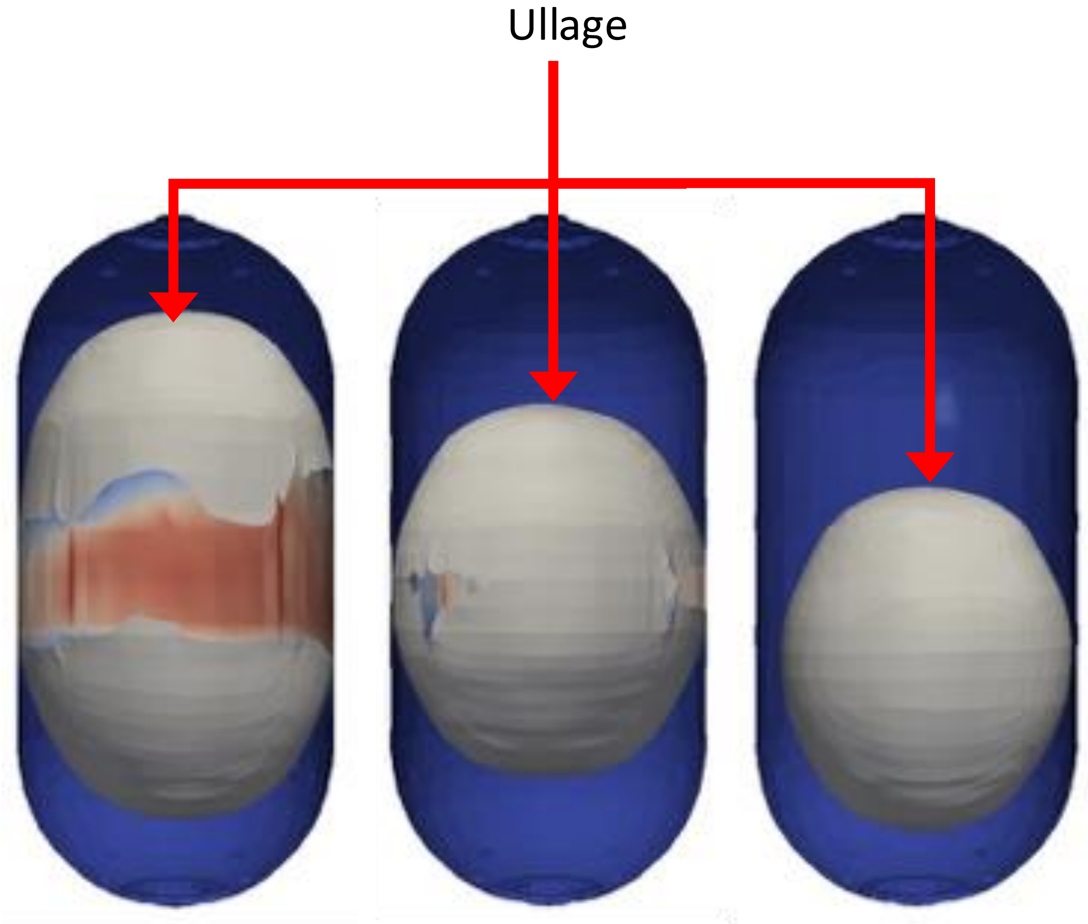
- Pressure must be vented: need *phase separation*
- Capillary adhesion causes propellant to cling to tank walls
- No reliable mass gauge



(a) Settled 1-g (b) 10 sec 0-g (c) 30 sec 0-g



In-Space Propellant Transfer



Your Turn

Transfer propellant from the service to the client tank:

1. Without allowing propellant to escape
2. Without moving the tanks


PLT4
JAXA

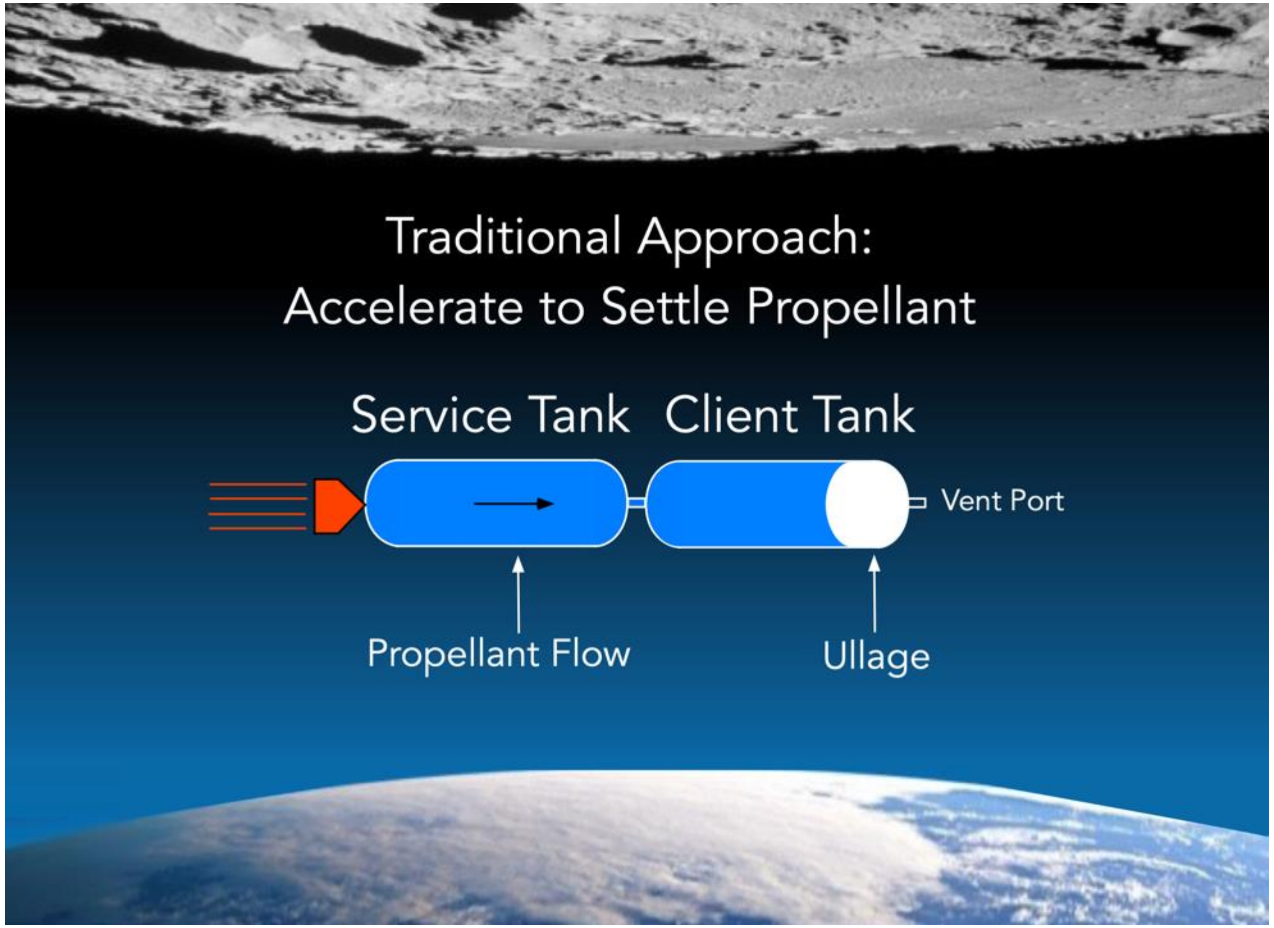
Microgravity Ullage Trapping

To transfer propellant from Service to Client tank, we need the ullage at the vent port.

In microgravity, the ullage drifts and has no preferential location in the tank.

Most methods of prop transfer involve moving the primary ullage.

Microgravity



Ullage Settling is the proposed (but untested) approach to *phase separation* for Artemis HLS vehicles.

Ullage Settling creates artificial gravity that separates the gas and liquid phases.

Drawback: complexity and risk

Microgravity Ullage Trapping

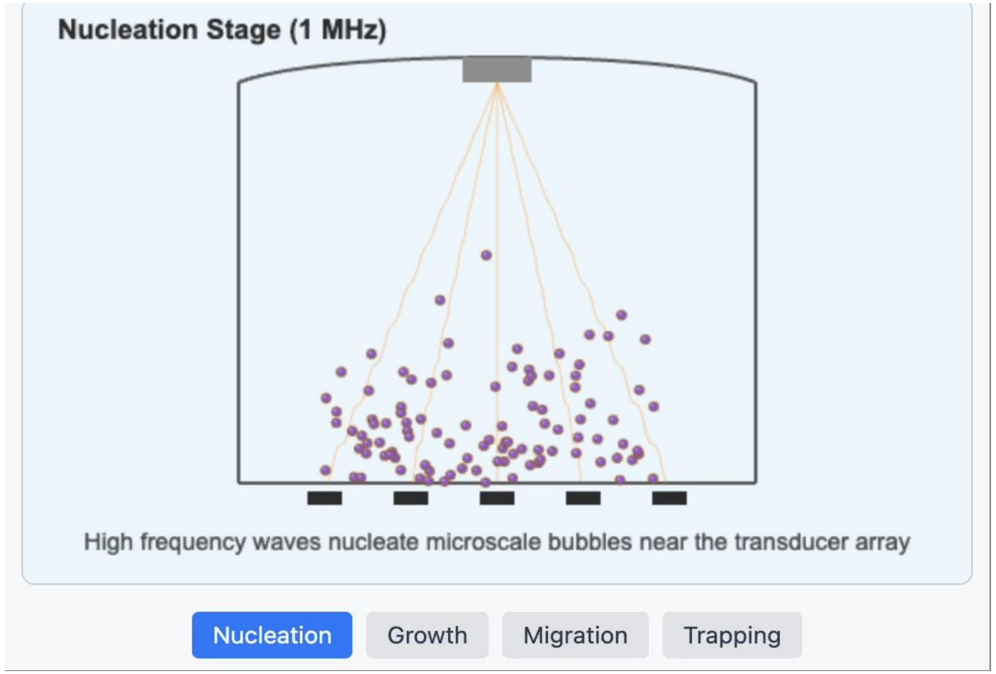
We propose desaturating the client tank to form a *secondary* ullage.

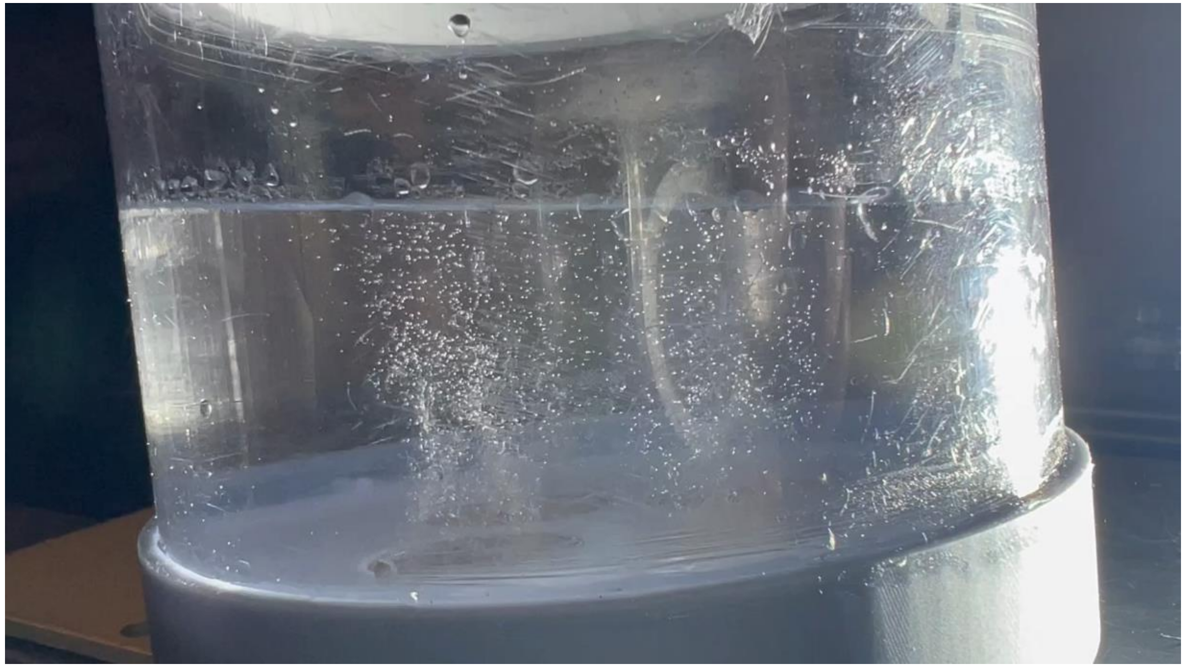
Desaturating: drop the client tank pressure by a small amount. Saturated pressurant (helium) comes out of solution.

Acoustic transducers evolve, migrate, and trap the secondary ullage near the vent port.

Bubble Trapping as Closed-Loop State Control

A phased acoustic array can create, move, and hold a secondary ullage near a vent port when the drive is adapted to the evolving bubble population.





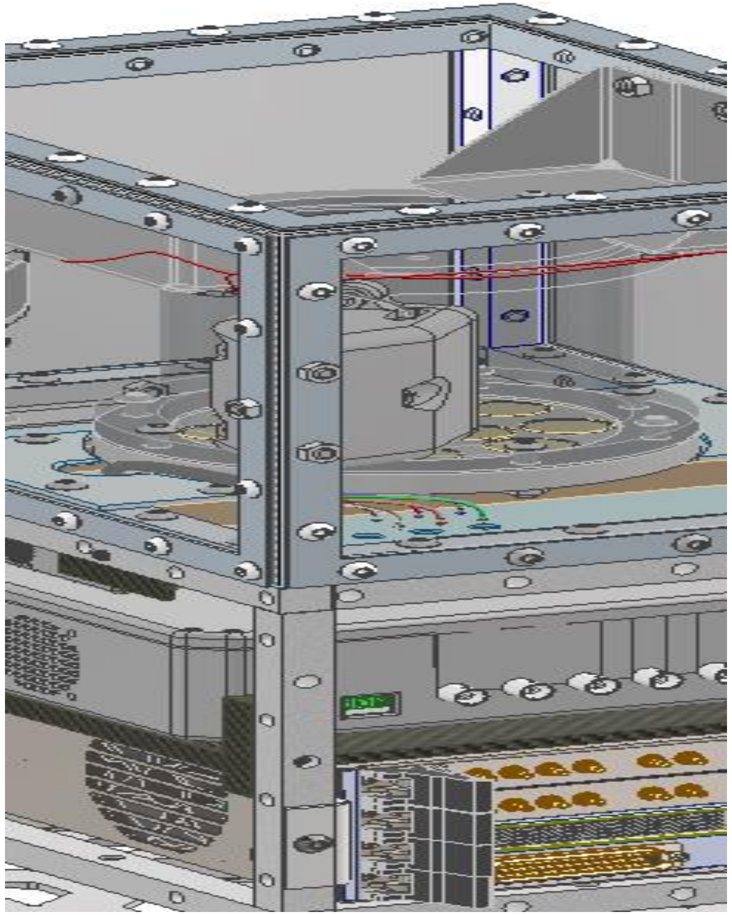
Hidden State
- Bubble size distribution
- Void fraction
- Sheet location
- Local sound speed
- Trap stability

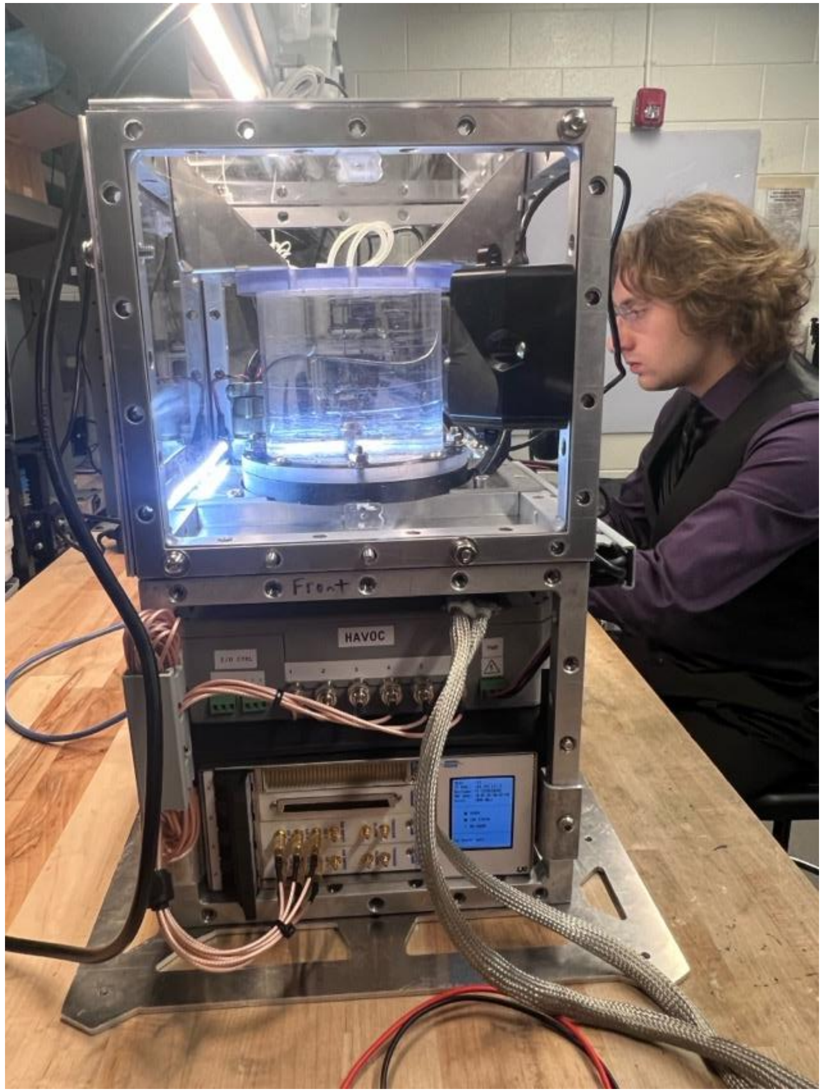
Sensor / Data Inputs
- Acoustic response
- Drive frequency, phase,
- Amplitude
- Temperature
- Vent / flow response

Estimator
- Bubble-sheet state
- Average bubble size
- Minnaert frequency band
- Trap confidence

Control Outputs
- Retuned frequency
- Phase pattern
- Amplitude envelope
- Migration wave
- Trapping wave

Suborbital Flight Experiment: MUTT

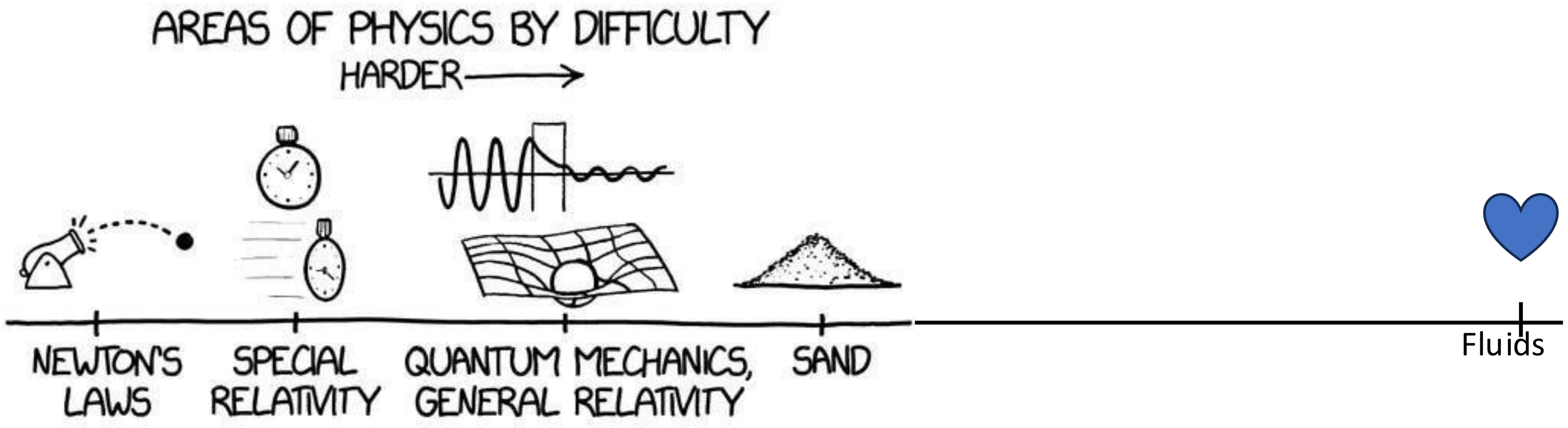




3. Running on Empty

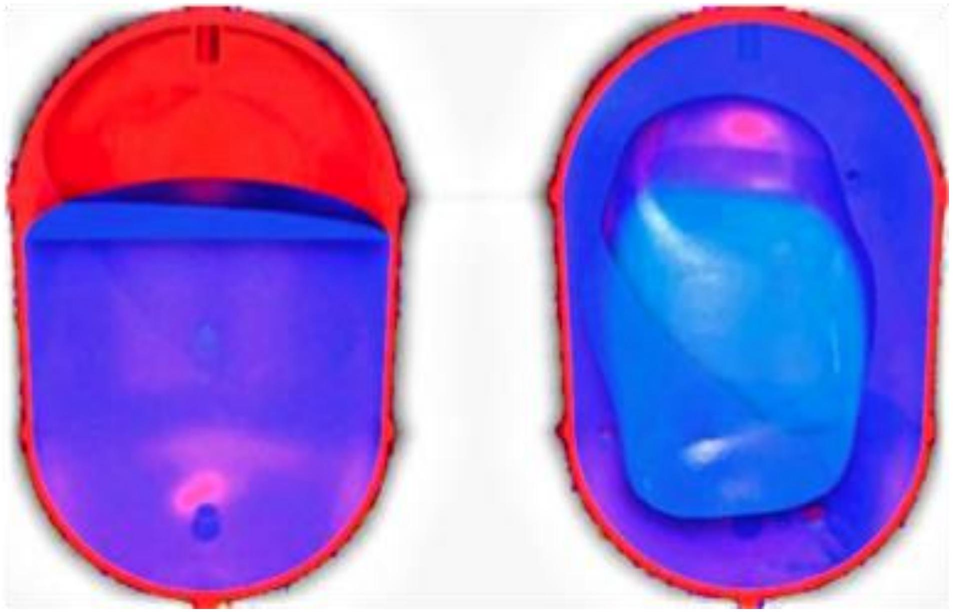
Subortbital Testing of Propellant Mass Gauging Technology

- 56 years post Apollo 11: still no reliable mass gauge
- No buoyancy in microgravity means no level sensors



Modal Propellant Gauging

Using sound to infer fluid distribution inside the tank



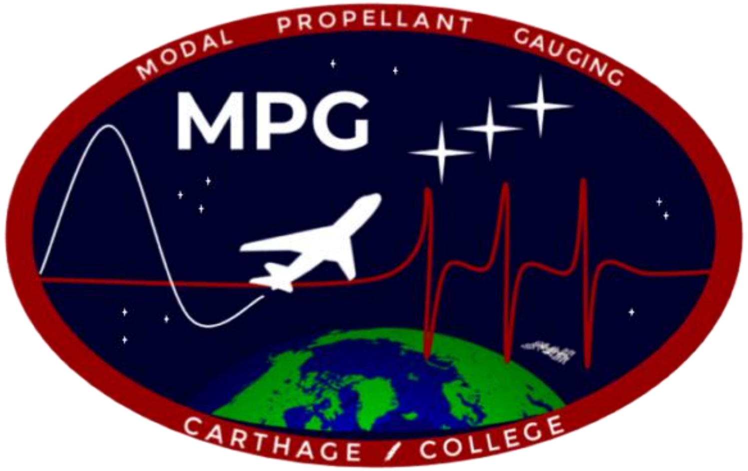
1-g 0-g

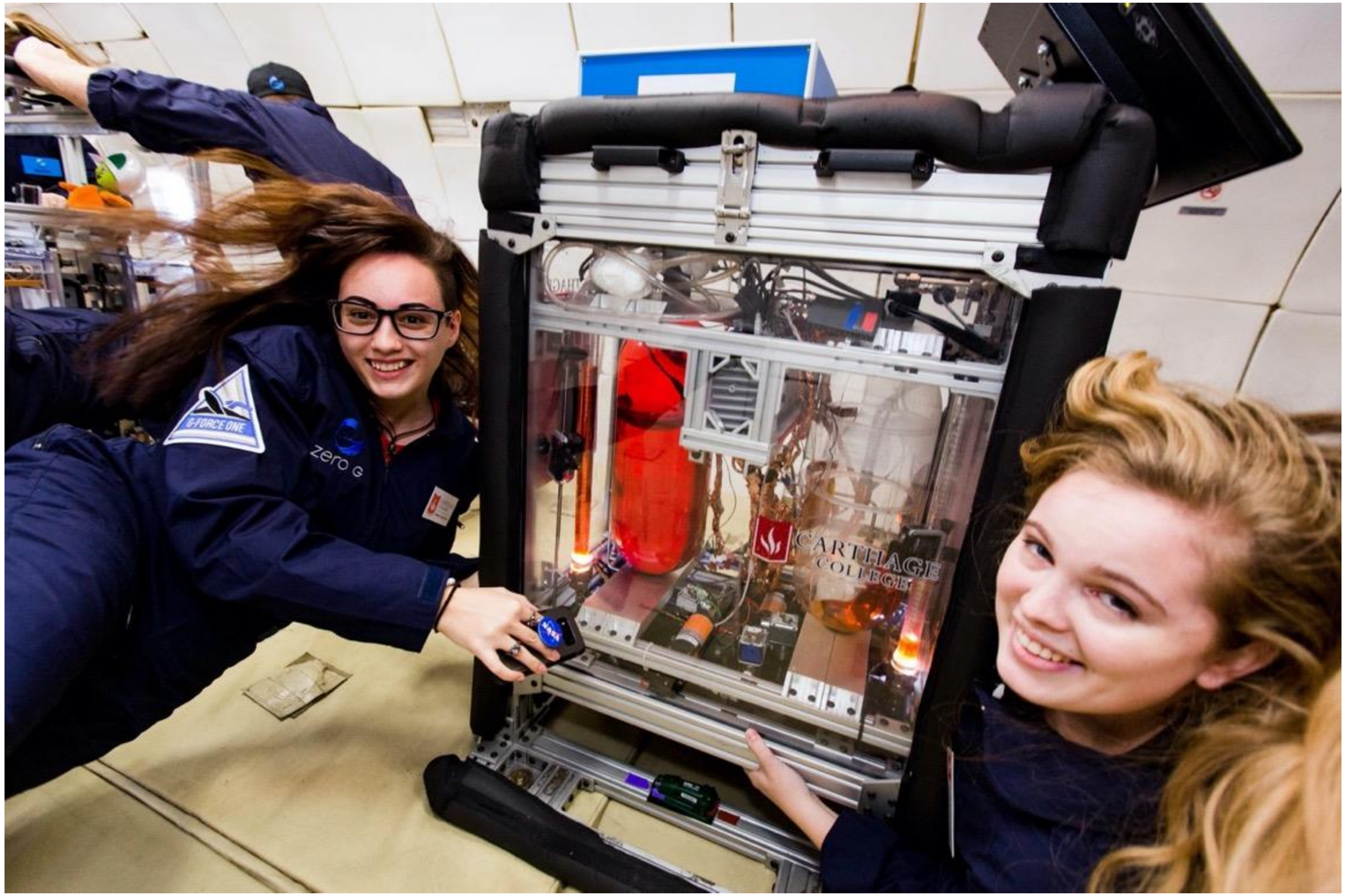
In 0-g, liquid mass sticks to the walls and **mass loads** the surface

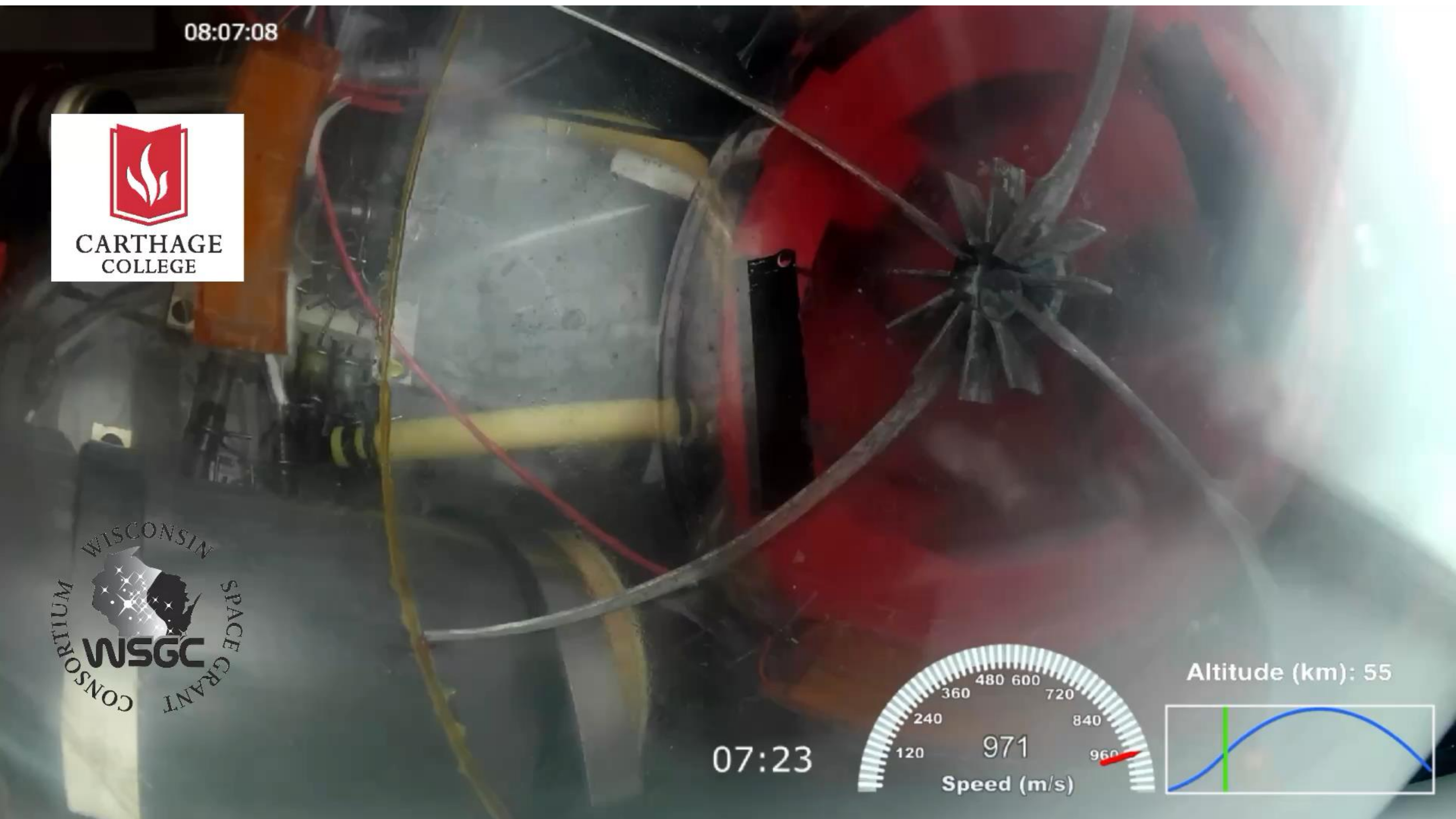
Zero-g Complications

- Wetting
- Stratification
- Film boiling
- Slosh memory

MPG uses *Modal Response* of Tank to Estimate Contained Mass



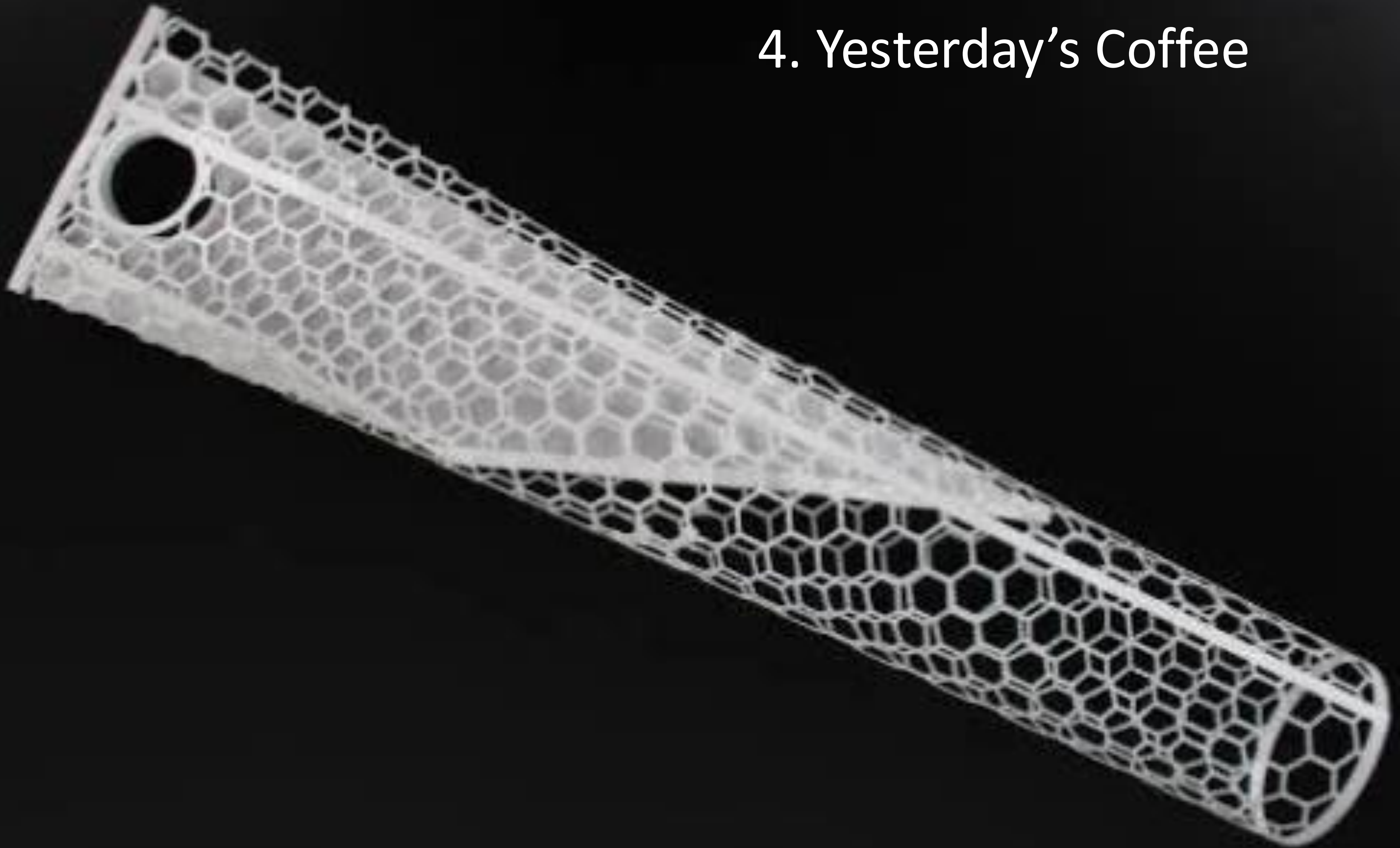




08:07:08
CARTHAGE
COLLEGE
WISCONSIN
SPACE GRANT
CONSORTIUM
WSGC
07:23
120
240
360
480 600
720
840
960
971
Speed (m/s)
Altitude (km): 55

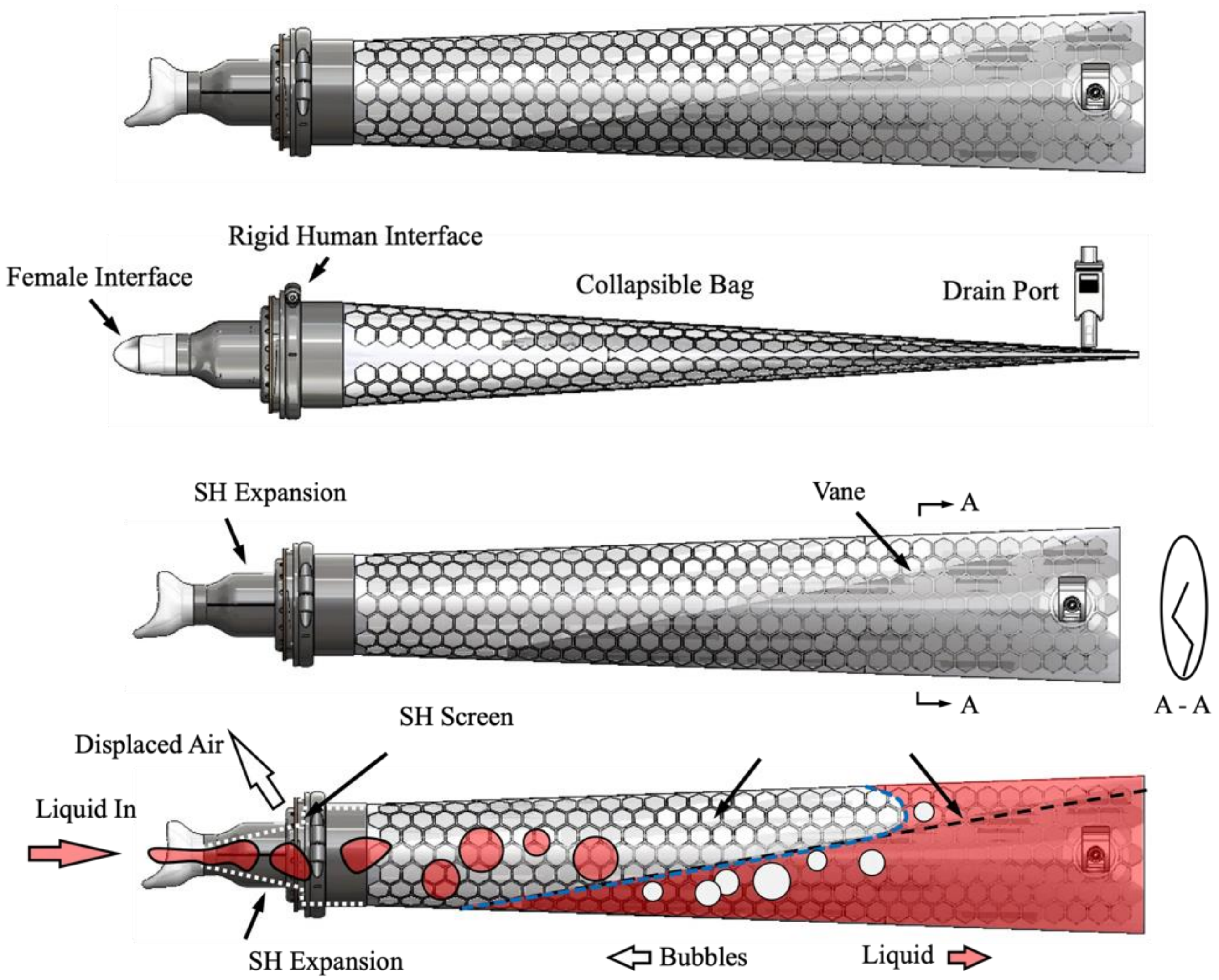
Don’t Spill the Water!

4. Yesterday’s Coffee



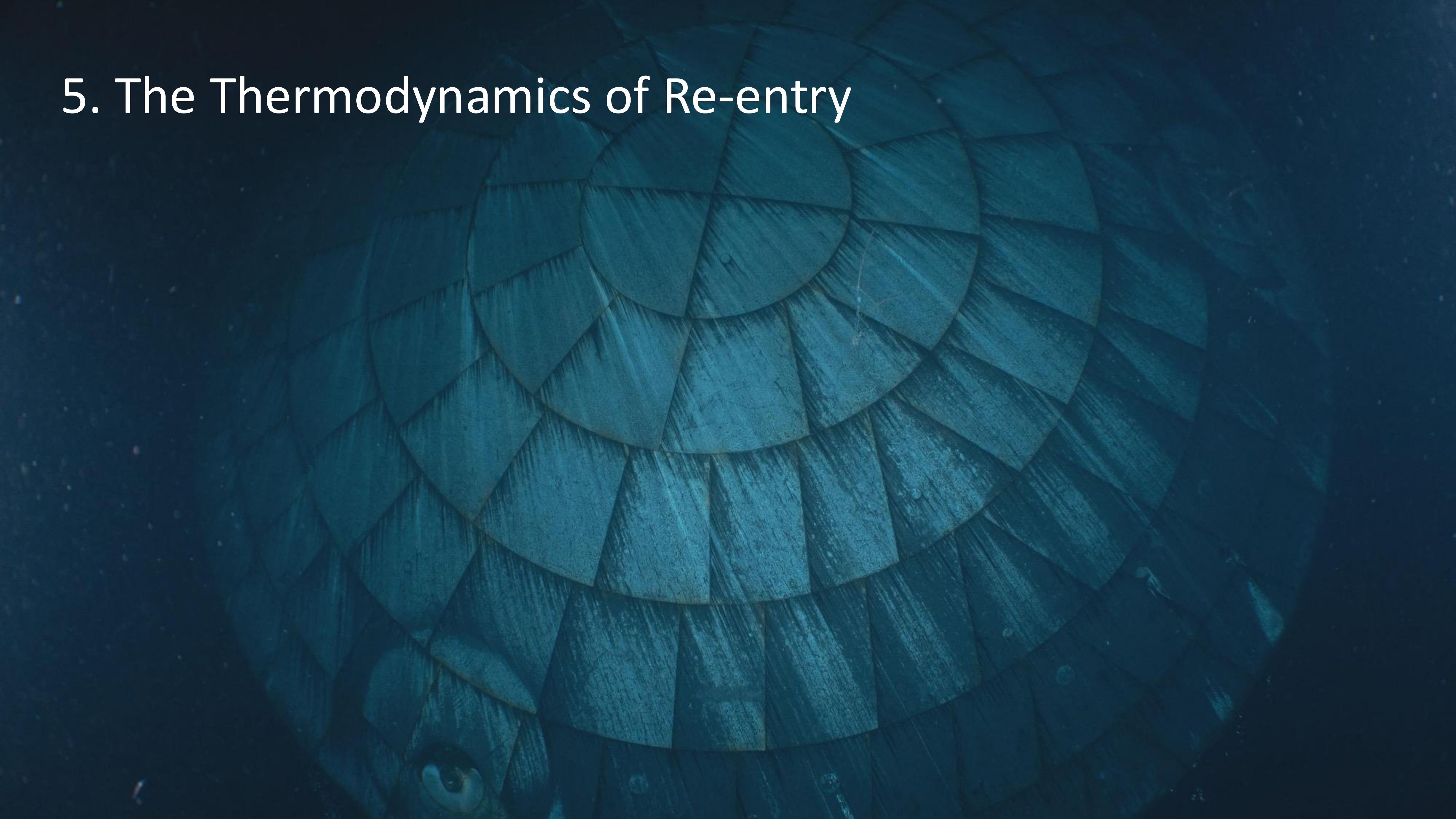
CCU Saves the Day

- The CCU is a passive microgravity fluid device that replaces gravity with surface chemistry and geometry:
- Water-repelling surfaces push urine away from the body, water-loving surfaces wick it into the bag,
- The tapered honeycomb-supported liner gives the liquid a preferred "downhill" direction.

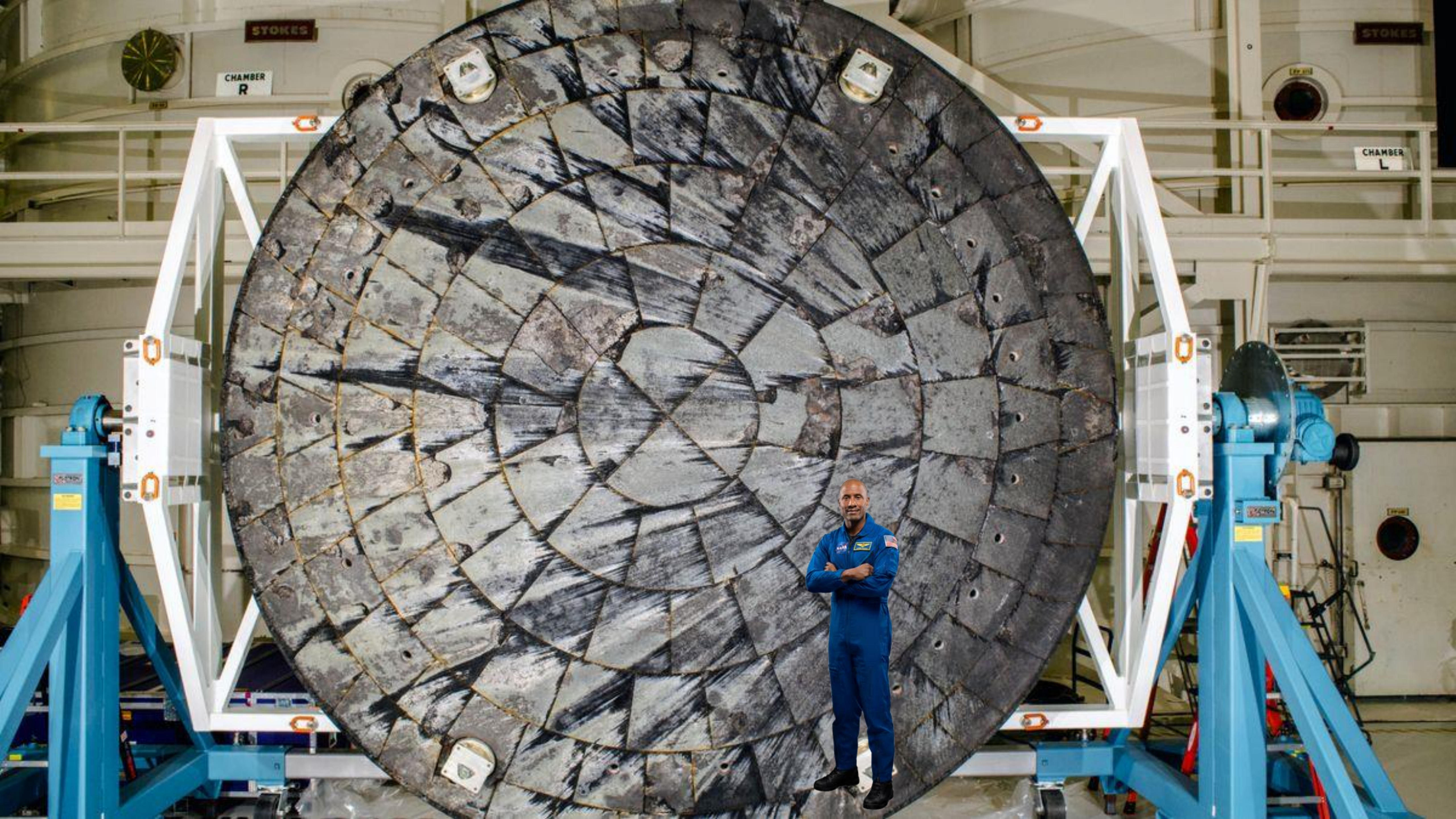



NASA

5. The Thermodynamics of Re-entry

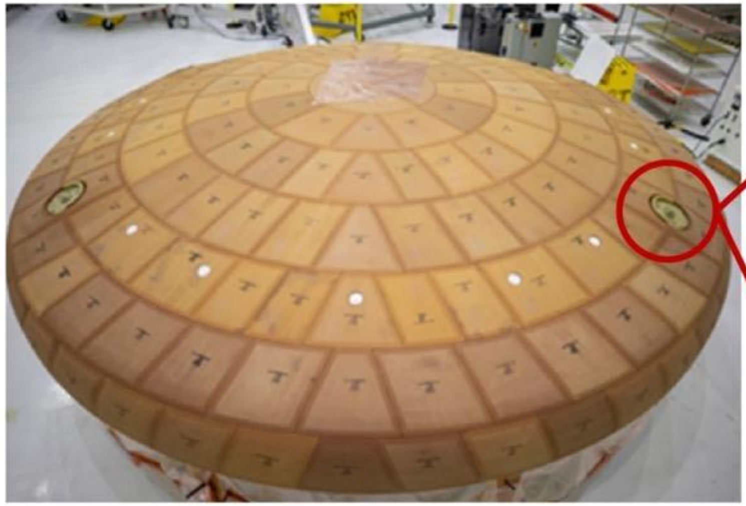



STOKES
CHAMBER
R
Artemis I Heat Shield
STOKES
CHAMBER
L

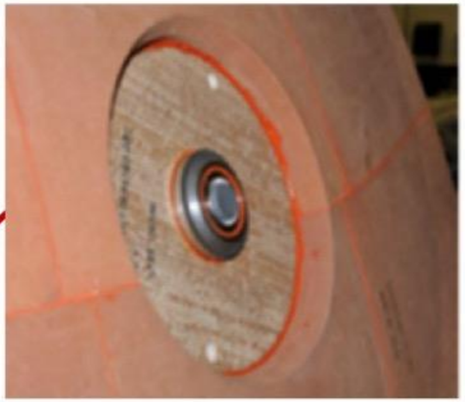

STOKES
CHAMBER
R
STOKES
CHAMBER
L


STOKES
CHAMBER
R
STOKES
CHAMBER
L

Figure 4: Orion Crew Module/Service Module Separation Bolt Melting and Erosion



Orion heat shield prior to the Artemis I mission, showing the separation bolt circled in red

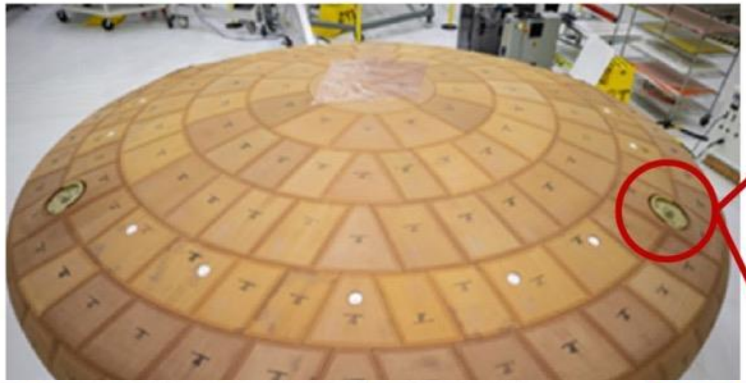


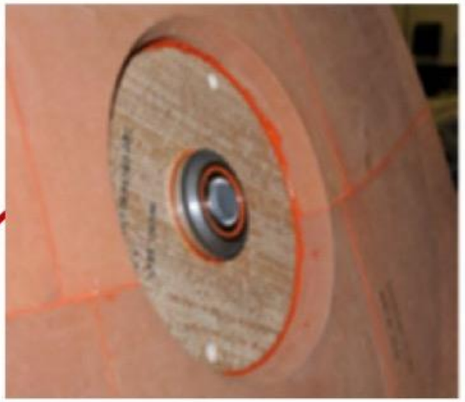
Close up of Orion separation bolt prior to Artemis I mission

Separation bolt melting and erosion post-Artemis I reentry

Source: NASA.

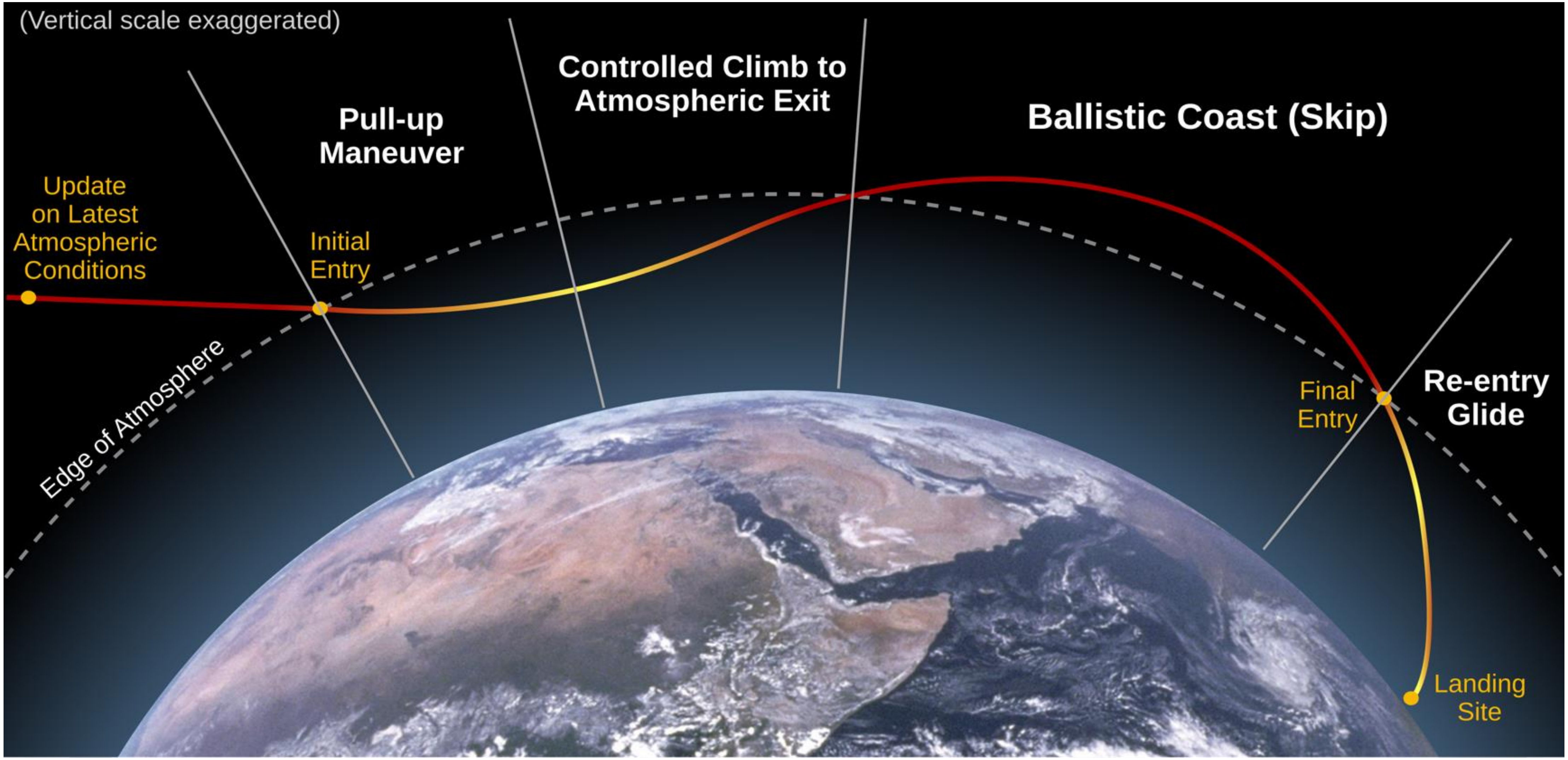
Figure 4: Orion Crew Module/Service Module Separation Bolt Melting and Erosion



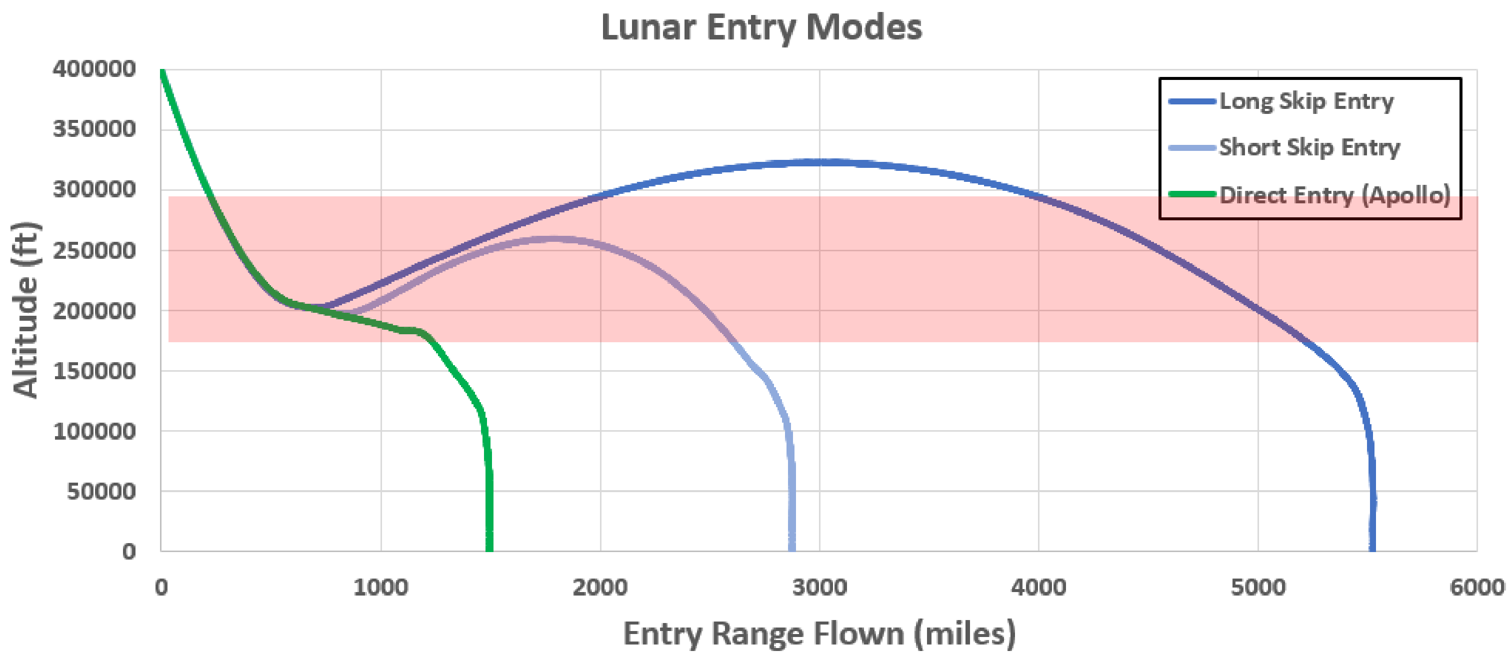


Close up of Orion separation bolt prior to Artemis I mission

Skip-Entry

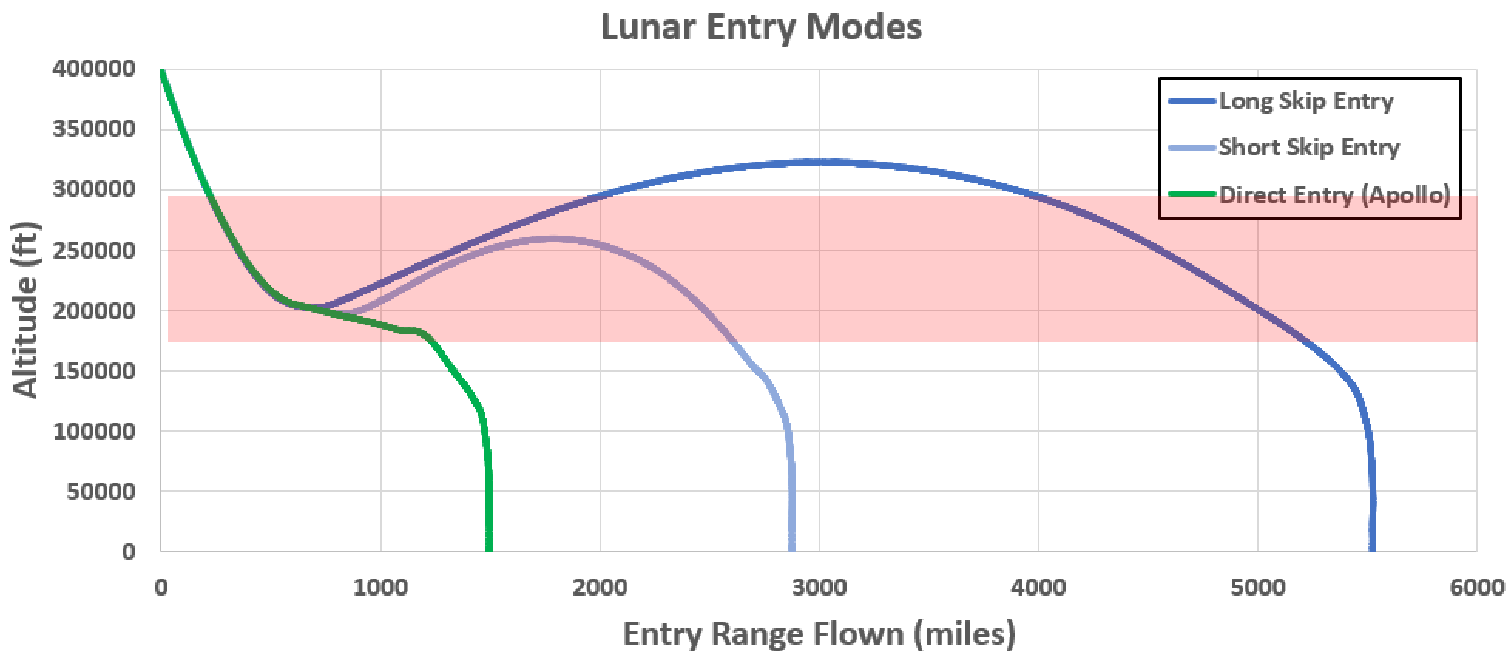

(Vertical scale exaggerated)
Controlled Climb to Atmospheric Exit
Pull-up Maneuver
Ballistic Coast (Skip)
Update on Latest Atmospheric Conditions
Initial Entry
Edge of Atmosphere
Final Entry
Re-entry Glide
Landing Site

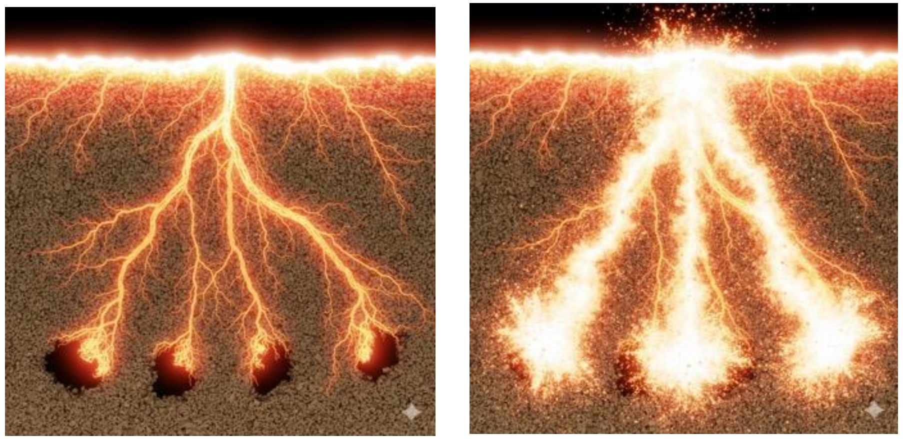
Culprit: Skip-Entry



Heat Shield Cross-section
Intended behavior

Culprit: Skip-Entry

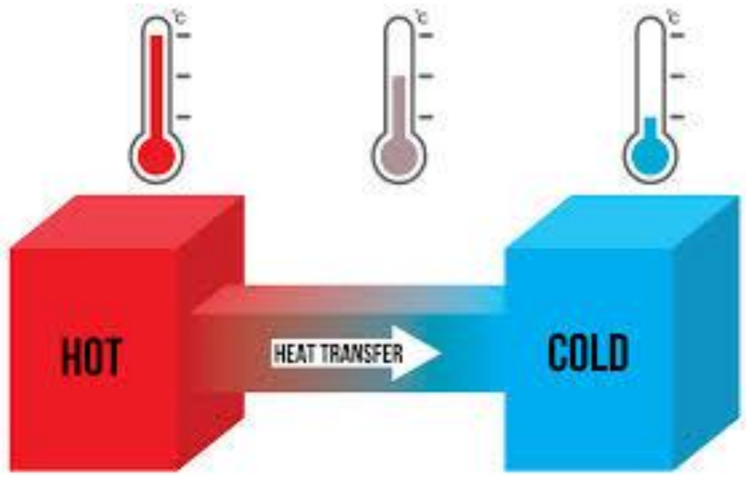


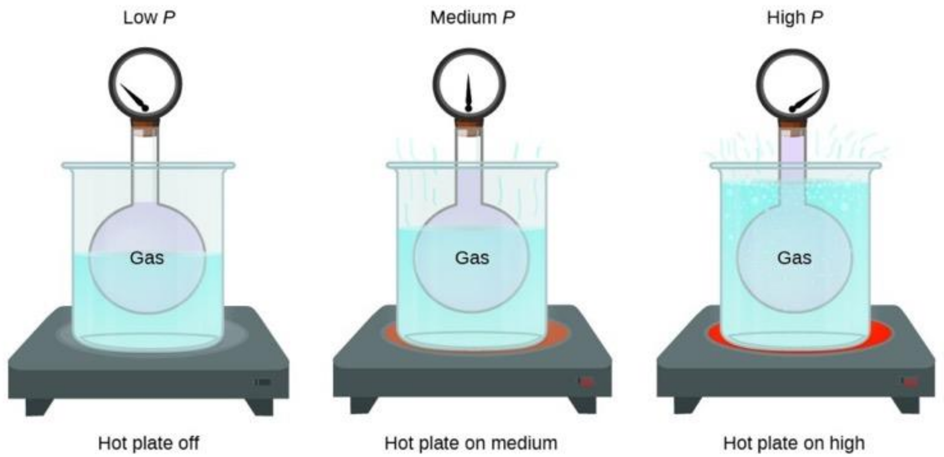


Heat Shield Cross-section: void formation during excessive heating from skip-entry

Classroom Connections

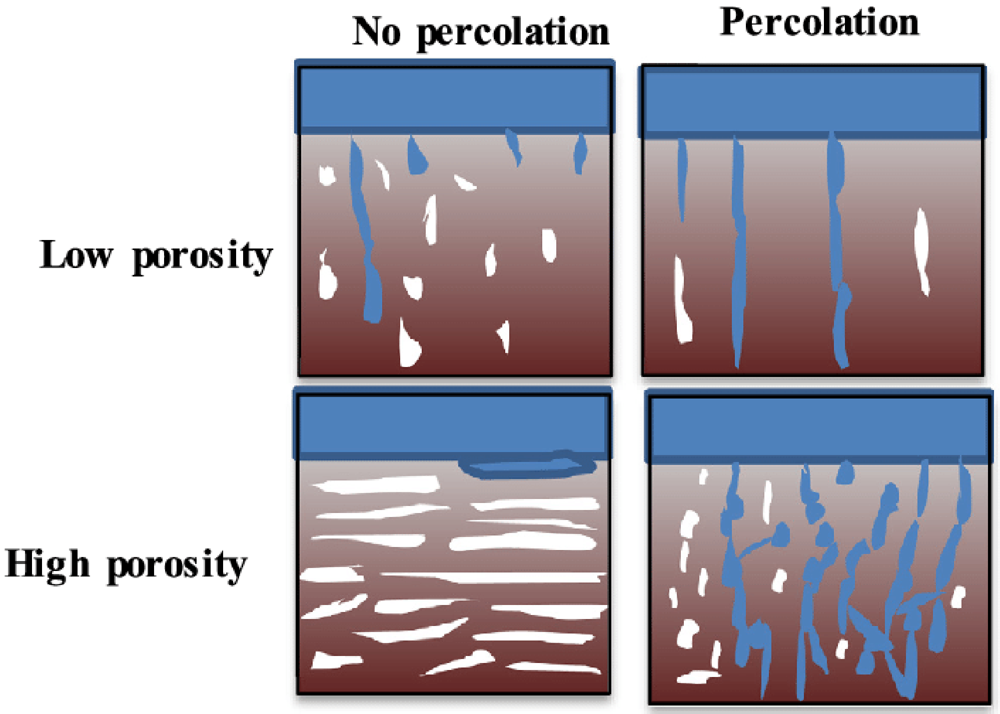
- Transport and Ideal Gas Law



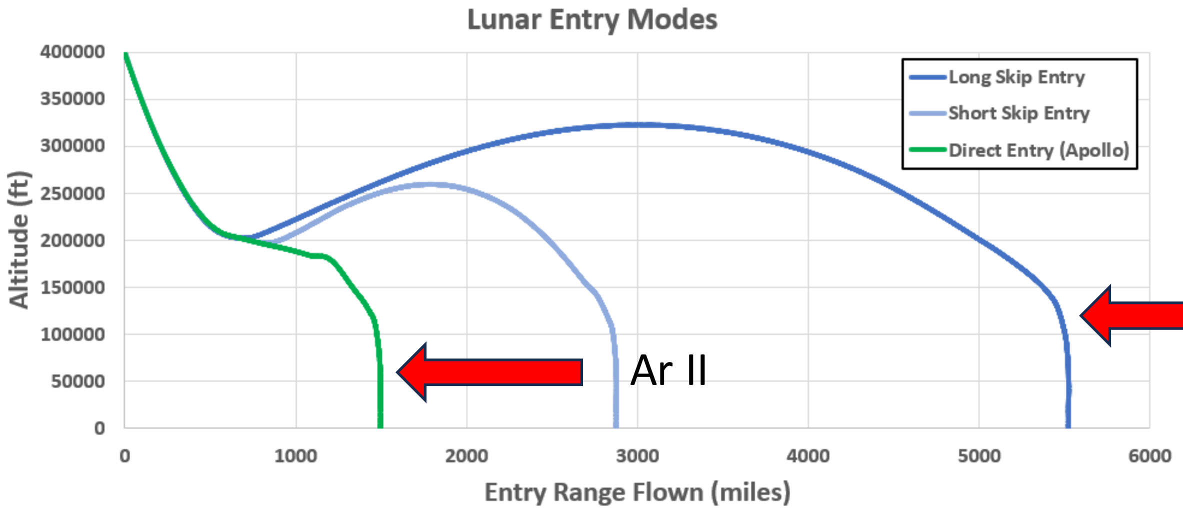


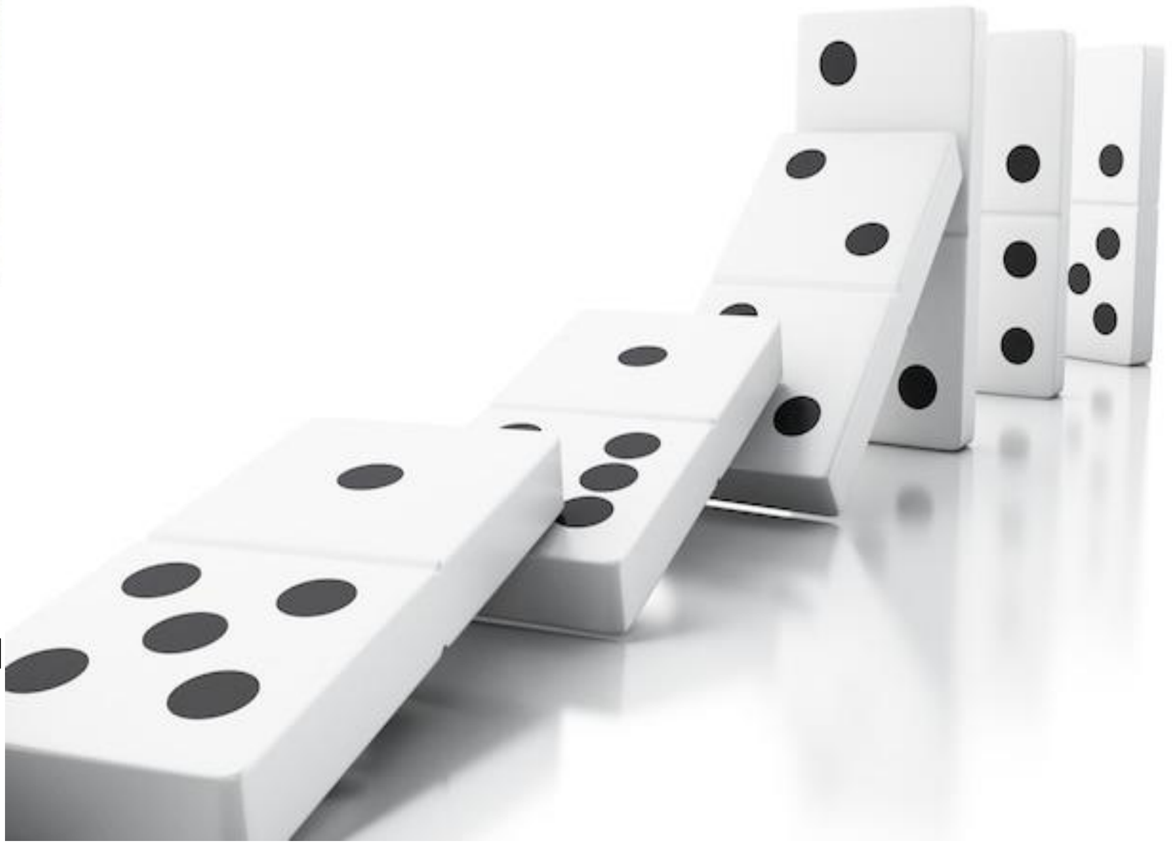
Classroom Connections

- Percolation Theory

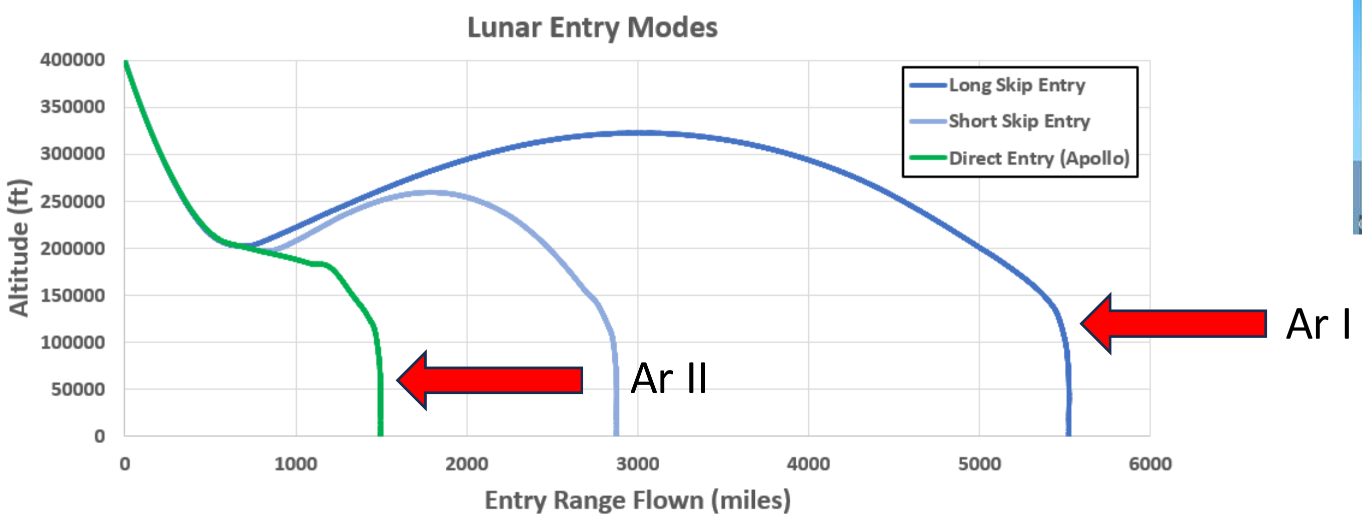


ECLSS System + Heat Shield Issue





ECLSS System + Heat Shield Issue



Reduced splashdown range; higher uncertainty in Ar II Orion splashdown

More Artemis Challenges

- Landing Large Masses on the Moon
- Dust Mitigation and Surface Operations
- Human-Robot Interaction in Lunar Operations
- Habitat Scalability and Power Distribution
- Medical Autonomy
- The list goes on … and each is directly related to basic concepts we teach.

Harrison Schmitt retrieves lunar samples during Apollo 17. Lunar dust impacts suits, mechanisms, lungs, and solar panels.

Summary

- Progress in exploration is often gated by *the pace of science*, not just policy and funding
- The pace of discovery depends on people who think from first principles.
- How we teach shapes the questions students learn to ask and the problems they believe are solvable.

Gratitude

- As with all science, the students do the actual work.
- Over 50 Carthage College, Purdue, and Georgia Tech students have contributed to the projects described here.
- NASA has supported this work through SMD MOSAICS, STMD Flight Opportunities Program, and the TechLeap Program.
- Thank you to collaborators at Johnson Space Center, Kennedy Space Center, and Georgia Tech.

Thank you!