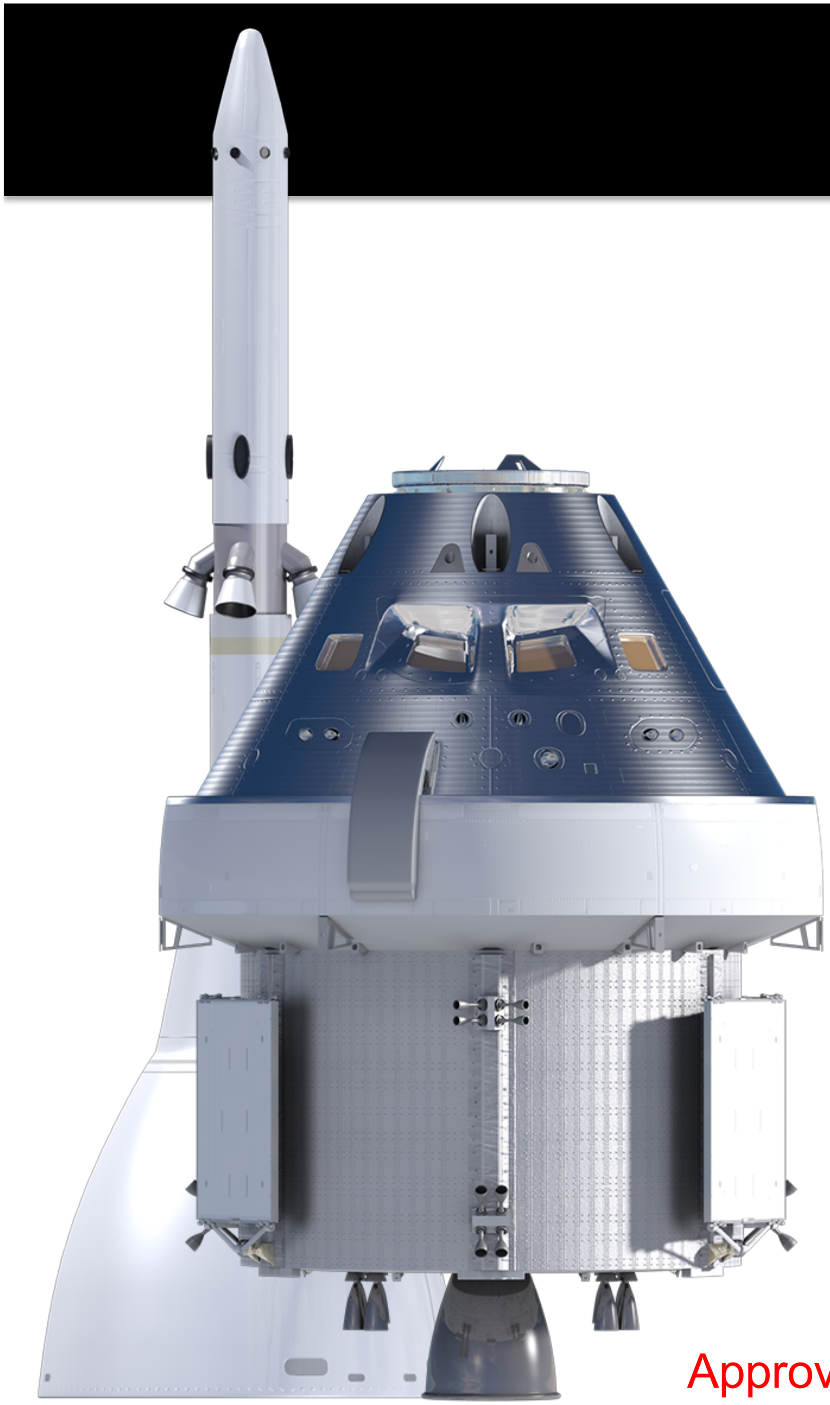


Orion Aerosciences and Thermal Protection System Overview

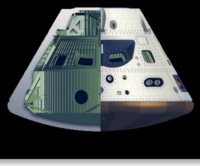
Presented at EDL Summer Seminar
July 9, 2021

Jeremy Vander Kam, Orion TPS Deputy System Manager

Adam Amar, Orion Aerothermal System Manager

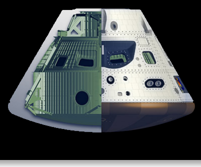
Approved for public release NF-1676 20210018325

Outline



- **Orion Program and Hardware Description**
- **Mission Schedule**
- **Mission Summaries**
- **Re-entry Scenarios**
- **Design Cycle Description**
- **Aerosciences**
  - Relevant Physics
  - Product Development
  - CFD Overview
  - Ground Testing Overview
- **Thermal Protection Systems**
  - System Description
  - Design and Testing
  - Post Flight Analysis

What is Orion?



- **Orion will send (up to 4) humans beyond LEO and into deep space. Current focus is sending crew to lunar surface**
  - Partially re-usable spacecraft

- **Orion Program is managed by NASA, but it is designed and built by a conglomerate of organizations**
  - NASA: Program management, design, hardware provider, operate
  - Lockheed Martin: Design, build/assemble, subcontracting
  - ESA and Airbus: Design, build/assemble for Service Module

- **Unlike partners (SpaceX and Boeing) in Commercial Crew Program, Lockheed Martin builds and sells spacecraft to NASA, and NASA operates spacecraft and manages mission**

- **Orion is part of Artemis Program with EGS, SLS, Gateway, HLS, and Spacesuits**

EGS

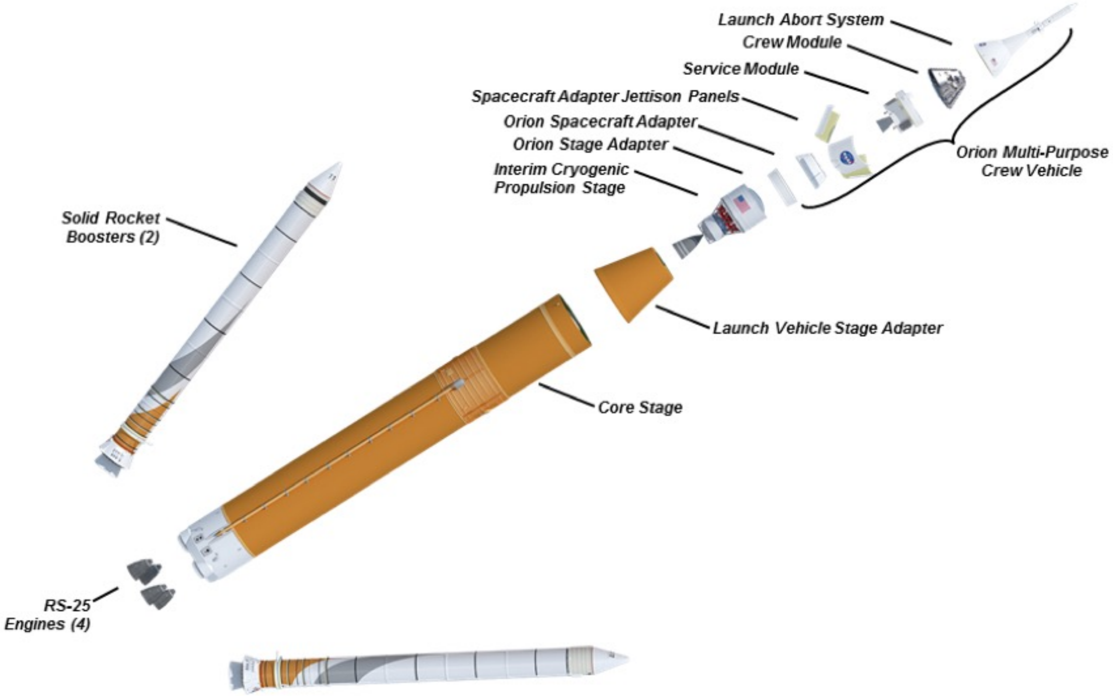
SLS

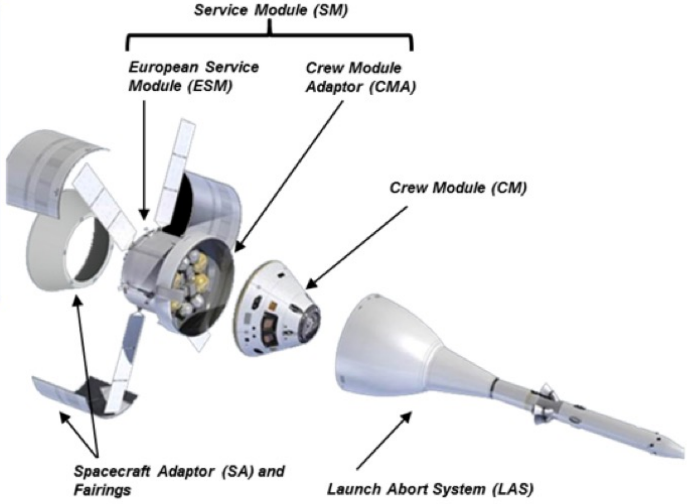
Gateway

HLS

Spacesuits

Orion Modules and Launch Vehicle Stack





Crew Module (CM) Functions

The CM provides a habitable pressurized volume to support crewmembers and cargo during all elements of a given mission - from Launch Operations to Earth Entry, Descent, Landing, and Recovery.

Spacecraft Adapter (SA) Functions

- Provide structural connection to the launch vehicle from ground operations through orbital injection
- Provide protection for SM components from atmospheric loads and heating during first stage flight

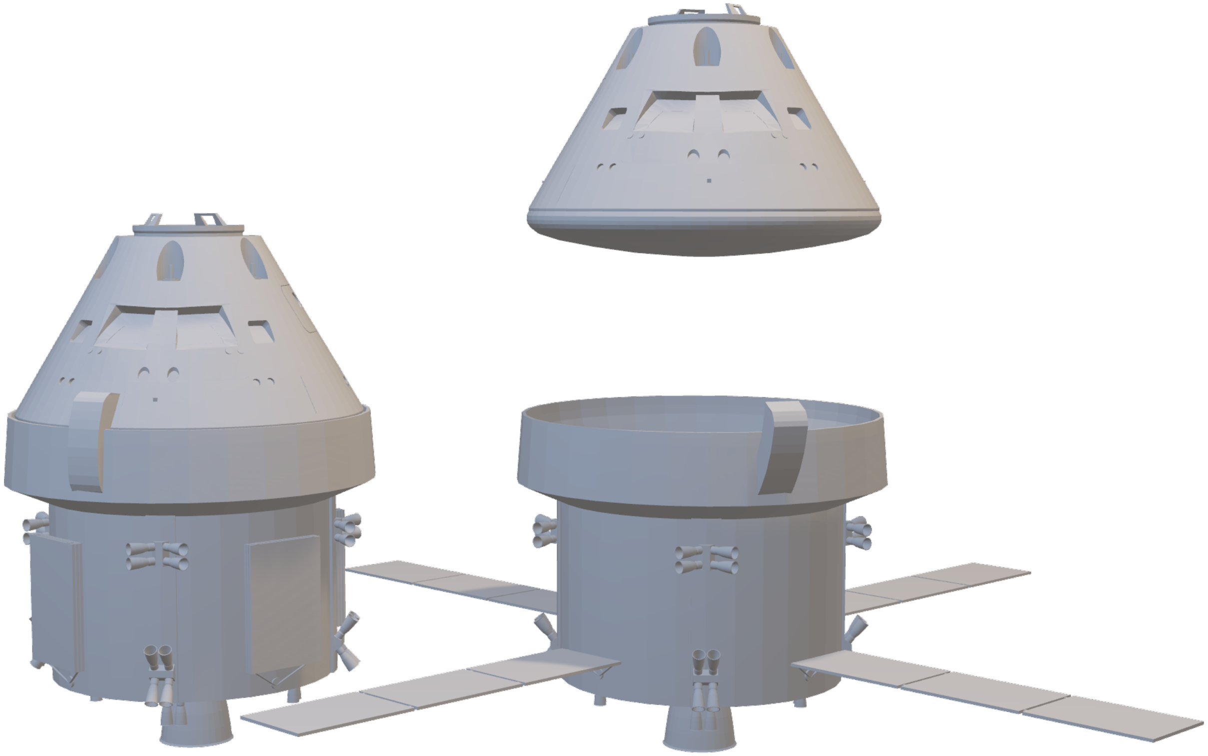
Launch Abort System (LAS) Functions

The LAS provides an abort capability to safely transport the CM away from the launch vehicle stack in the event of an emergency on the launch pad or during ascent.

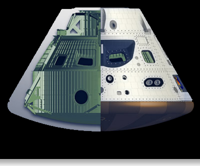
Service Module (SM) Functions

The SM, comprised of the two subcomponents the Crew Module Adapter (CMA) and the European Service Module (ESM), provides services to the CM in the form of propulsion, consumables storage, heat rejection and power generation.

Interactive Orion Model



Schedule



- **Pad Abort 1 (PA-1): May 2010, LAS test of abort initiation at pre-launch (pad) conditions. Included parachute deployment sequence**

- **Exploration Flight Test 1 (EFT-1): December 2014, high-speed entry test of EDL systems**

- **Ascent Abort 2 (AA-2): July 2019, LAS test at maximum dynamic pressure conditions. Did not include parachute deployment sequence.**

- **Artemis I: December 2021, un-crewed ~1 month mission to lunar distant retrograde orbit (DRO)**

- **Artemis II: Late 2023, First crewed mission. Lunar fly-by. Rendezvous and proximity operations (RPO) demonstration with SLS upper stage**

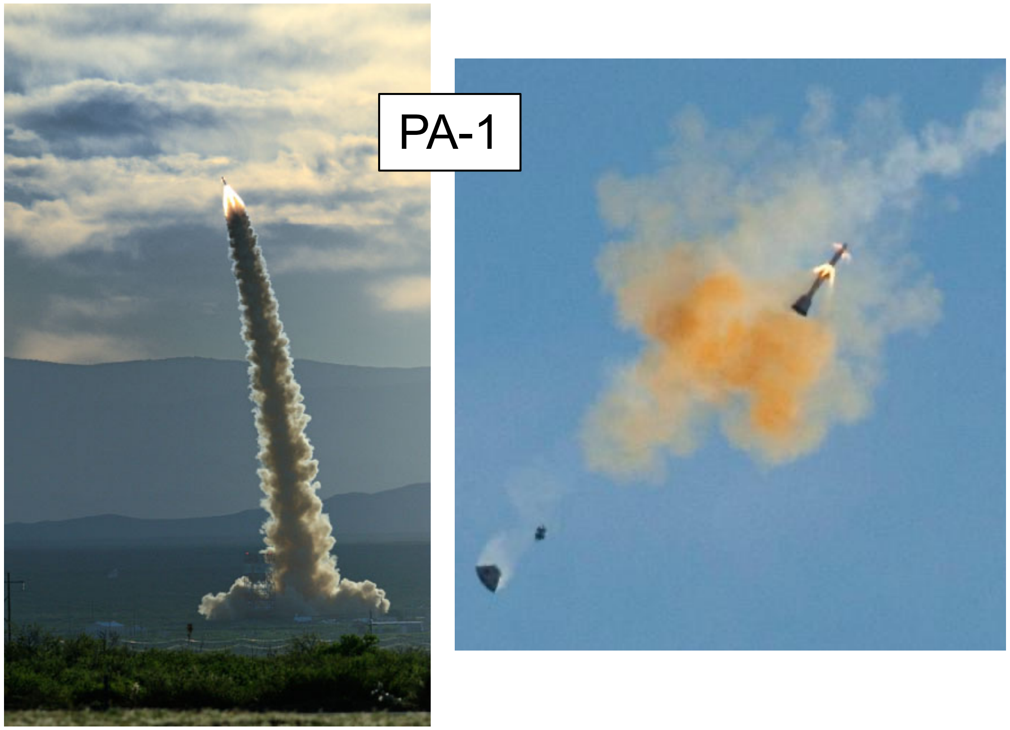
- **Artemis III: Late 2024, Mission objectives TBD, but likely that we’ll dock with a target in lunar orbit**

- **Artemis IV: 2026, Lunar landing. First flight with SLS Block 1B**

- **Beyond….expecting one flight per year**

Abort Test Summary

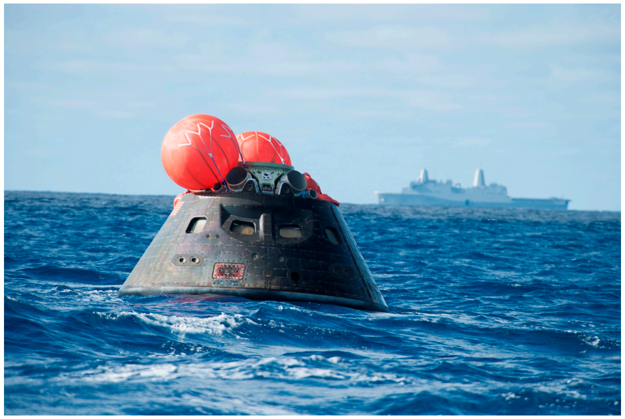
- **PA-1**
  - – Tested pad abort through landing, including parachute sequence
    - Utilized old LAS config
- **AA-2**
  - – Tested abort through LAS jettison at maximum dynamic pressure conditions (highest loads, lowest control authority)
- **Both tests included Aerosciences, TPS, Thermal, L&D and structures instrumentation**
- **Both tests had fully-successful Aerosciences and TPS flight test objectives**

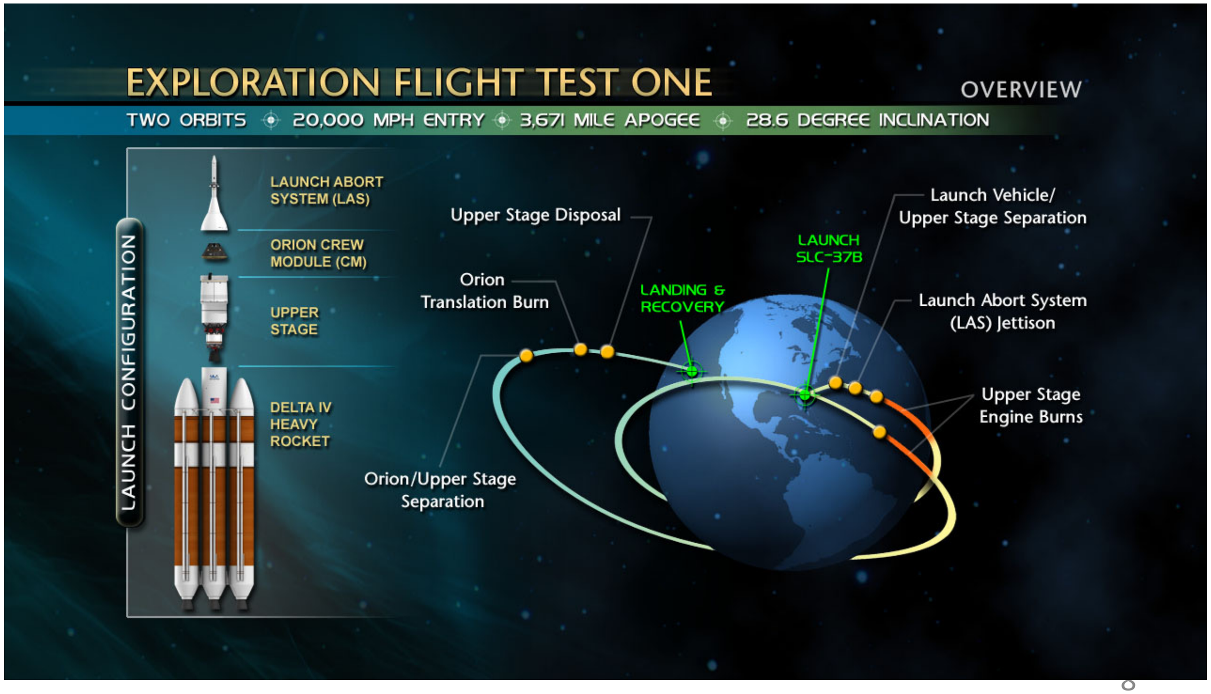

PA-1


AA-2

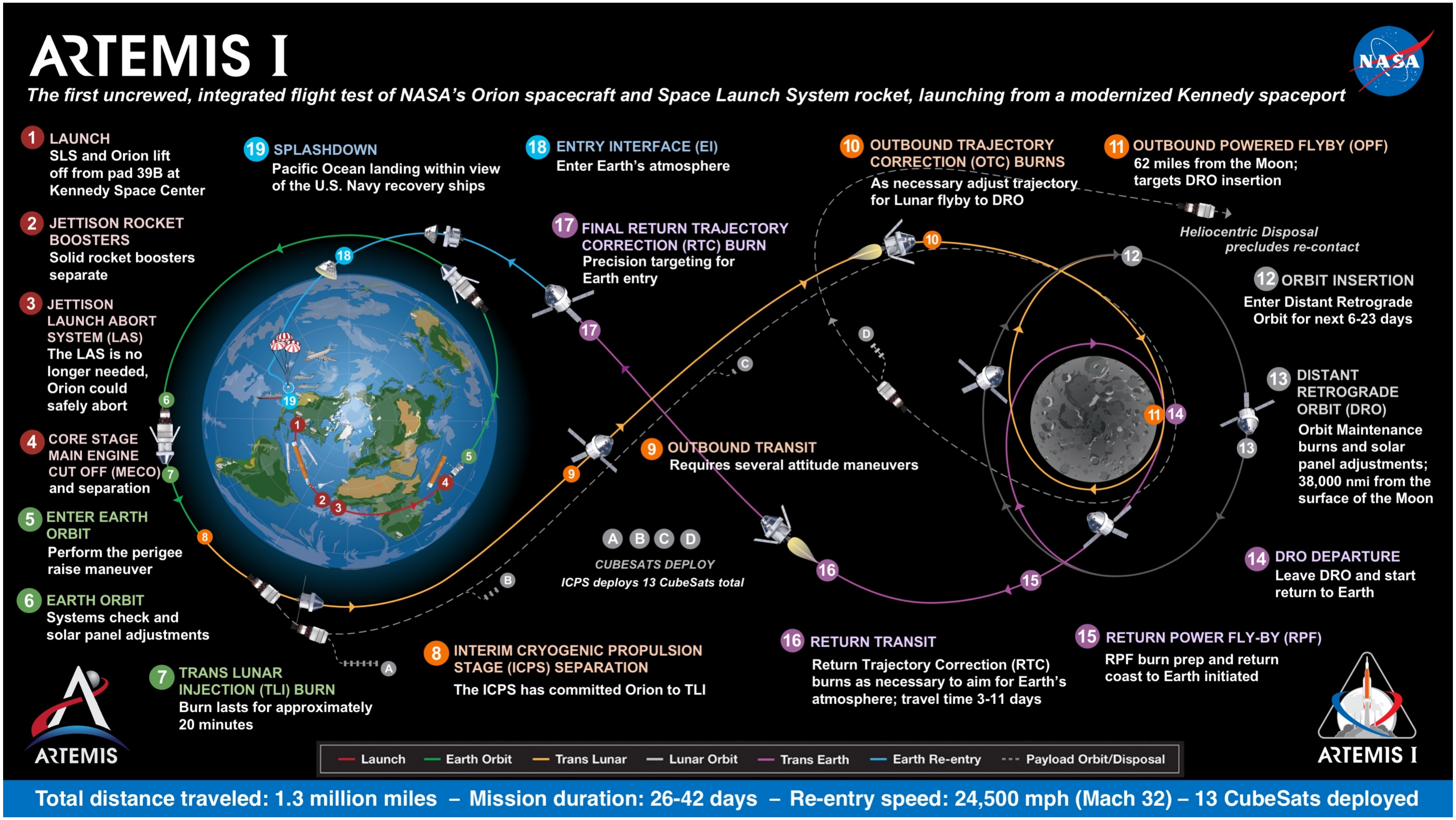
EFT-1 Summary

- **Test of entry, descent, and landing systems with entry speed between LEO and Lunar (~8.5 km/sec)**
- **Trajectory was designed to maximize heating rates and likelihood of laminar-to-turbulent transition**
- **Included large suite of Aerosciences, TPS, L&D, Thermal, and Structures instrumentation**
- **All Aerosciences and TPS flight test objectives were achieved and data was invaluable resource for Artemis design**





Artemis I Mission Description



ARTEMIS I

The first uncrewed, integrated flight test of NASA's Orion spacecraft and Space Launch System rocket, launching from a modernized Kennedy spaceport

1 **LAUNCH**
SLS and Orion lift off from pad 39B at Kennedy Space Center

2 **JETTISON ROCKET BOOSTERS**
Solid rocket boosters separate

3 **JETTISON LAUNCH ABORT SYSTEM (LAS)**
The LAS is no longer needed, Orion could safely abort

4 **CORE STAGE MAIN ENGINE CUT OFF (MECO) and separation**

5 **ENTER EARTH ORBIT**
Perform the perigee raise maneuver

6 **EARTH ORBIT**
Systems check and solar panel adjustments

7 **TRANS LUNAR INJECTION (TLI) BURN**
Burn lasts for approximately 20 minutes

8 **INTERIM CRYOGENIC PROPULSION STAGE (ICPS) SEPARATION**
The ICPS has committed Orion to TLI

9 **OUTBOUND TRANSIT**
Requires several attitude maneuvers

10 **OUTBOUND TRAJECTORY CORRECTION (OTC) BURNS**
As necessary adjust trajectory for Lunar flyby to DRO

11 **OUTBOUND POWERED FLYBY (OPF)**
62 miles from the Moon; targets DRO insertion

12 **ORBIT INSERTION**
Enter Distant Retrograde Orbit for next 6-23 days

13 **DISTANT RETROGRADE ORBIT (DRO)**
Orbit Maintenance burns and solar panel adjustments; 38,000 nmi from the surface of the Moon

14 **DRO DEPARTURE**
Leave DRO and start return to Earth

15 **RETURN POWER FLY-BY (RPF)**
RPF burn prep and return coast to Earth initiated

16 **RETURN TRANSIT**
Return Trajectory Correction (RTC) burns as necessary to aim for Earth's atmosphere; travel time 3-11 days

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

18 **ENTRY INTERFACE (EI)**
Enter Earth's atmosphere

19 **SPLASHDOWN**
Pacific Ocean landing within view of the U.S. Navy recovery ships

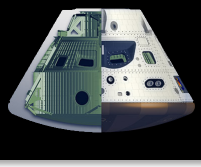
Heliocentric Disposal precludes re-contact

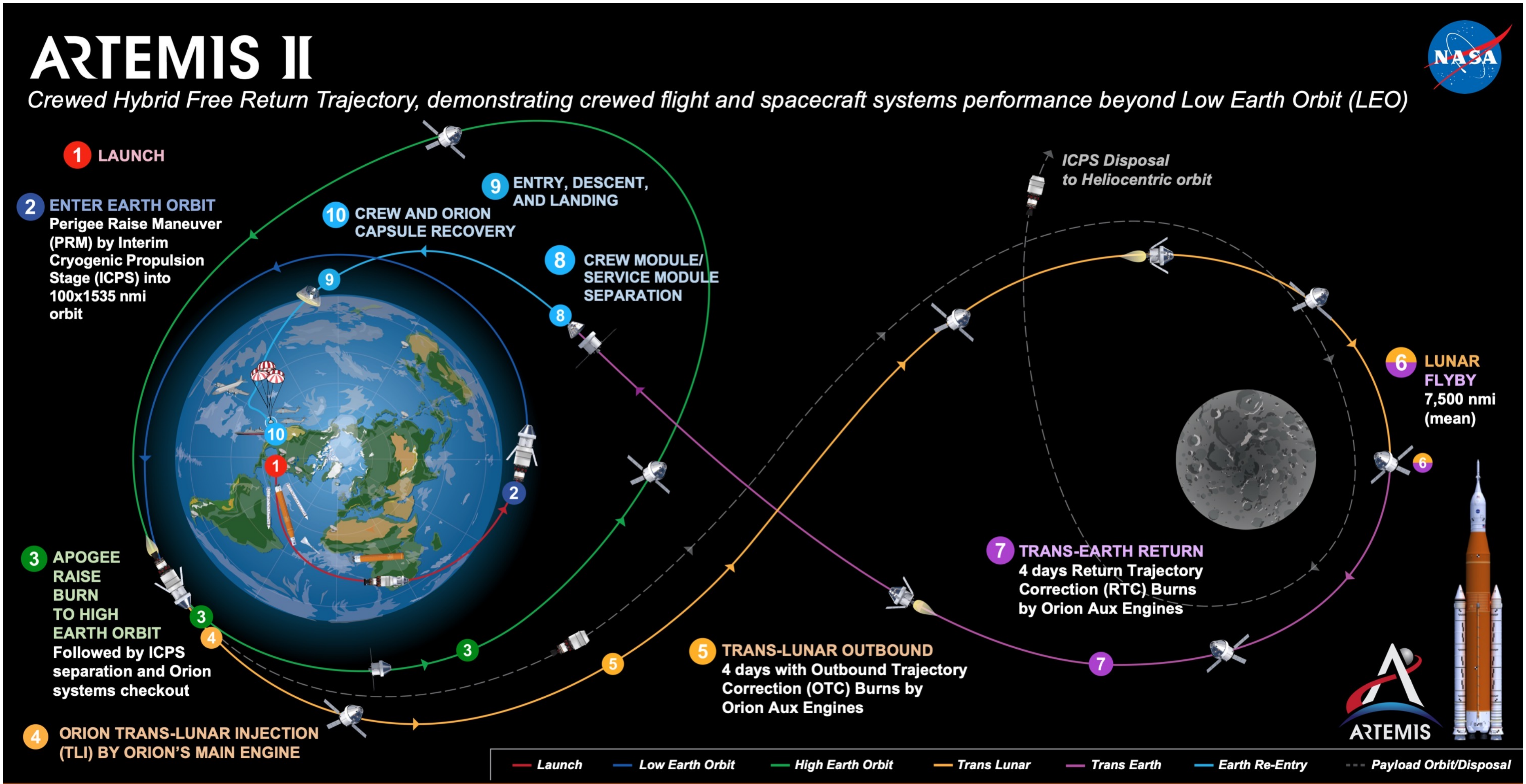
A B C D
CUBESATS DEPLOY
ICPS deploys 13 CubeSats total

— Launch — Earth Orbit — Trans Lunar — Lunar Orbit — Trans Earth — Earth Re-entry - - - Payload Orbit/Disposal

Total distance traveled: 1.3 million miles – Mission duration: 26-42 days – Re-entry speed: 24,500 mph (Mach 32) – 13 CubeSats deployed

Artemis II Mission Description





ARTEMIS II

Crewed Hybrid Free Return Trajectory, demonstrating crewed flight and spacecraft systems performance beyond Low Earth Orbit (LEO)

1 **LAUNCH**

2 **ENTER EARTH ORBIT**
Perigee Raise Maneuver (PRM) by Interim Cryogenic Propulsion Stage (ICPS) into 100x1535 nmi orbit

3 **APOGEE RAISE BURN TO HIGH EARTH ORBIT**
Followed by ICPS separation and Orion systems checkout

4 **ORION TRANS-LUNAR INJECTION (TLI) BY ORION'S MAIN ENGINE**

5 **TRANS-LUNAR OUTBOUND**
4 days with Outbound Trajectory Correction (OTC) Burns by Orion Aux Engines

6 **LUNAR FLYBY**
7,500 nmi (mean)

7 **TRANS-EARTH RETURN**
4 days Return Trajectory Correction (RTC) Burns by Orion Aux Engines

8 **CREW MODULE/ SERVICE MODULE SEPARATION**

9 **ENTRY, DESCENT, AND LANDING**

10 **CREW AND ORION CAPSULE RECOVERY**

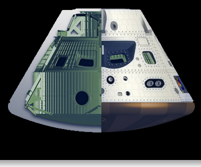
ICPS Disposal to Heliocentric orbit

— Launch — Low Earth Orbit — High Earth Orbit — Trans Lunar — Trans Earth — Earth Re-Entry - - - Payload Orbit/Disposal

SLS Configuration (Block 1) with Human Rated ICPS | 15x1200 nmi insertion orbit | 28.5 deg inclination

4 astronauts | Mission duration: 10 Days | Re-entry speed: 24,500 mph (Mach 32)

Entry Interface (EI) States

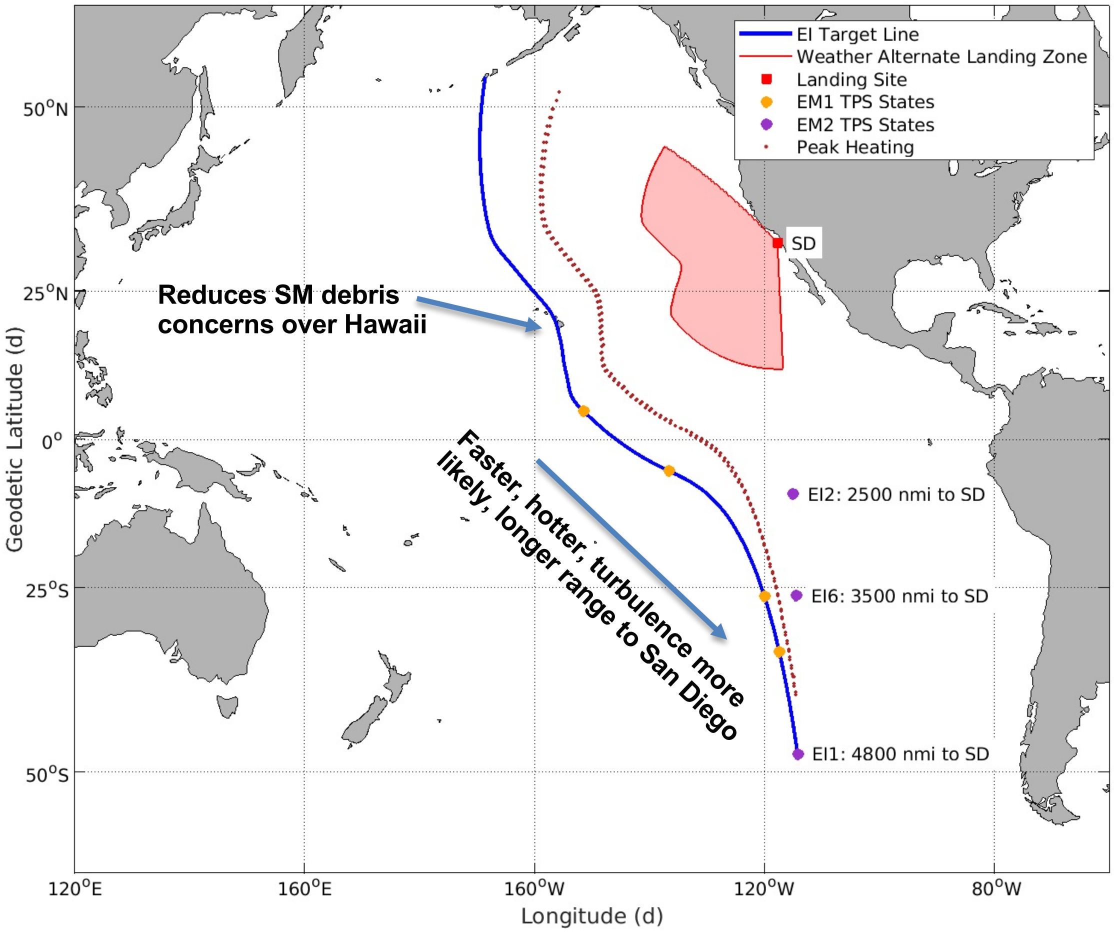


- **Orion is designed to:**
  1. Always (nominally) land near San Diego (SD): minimizes recovery costs
  2. Return any time from the moon: maximizes launch availability

- **Nominal trajectories are between 2190 nm and 4800 nmi range from EI to SD, which is accomplished by skipping out of the atmosphere during re-entry**

- **Range of acceptable flight path angles (steepness of entry) is dictated by heating, loads, GN&C performance, and debris disposal constraints**

- **Contingency return capability available for wide range of off-nominal scenarios including: low-prop, GN&C failures, and weather**

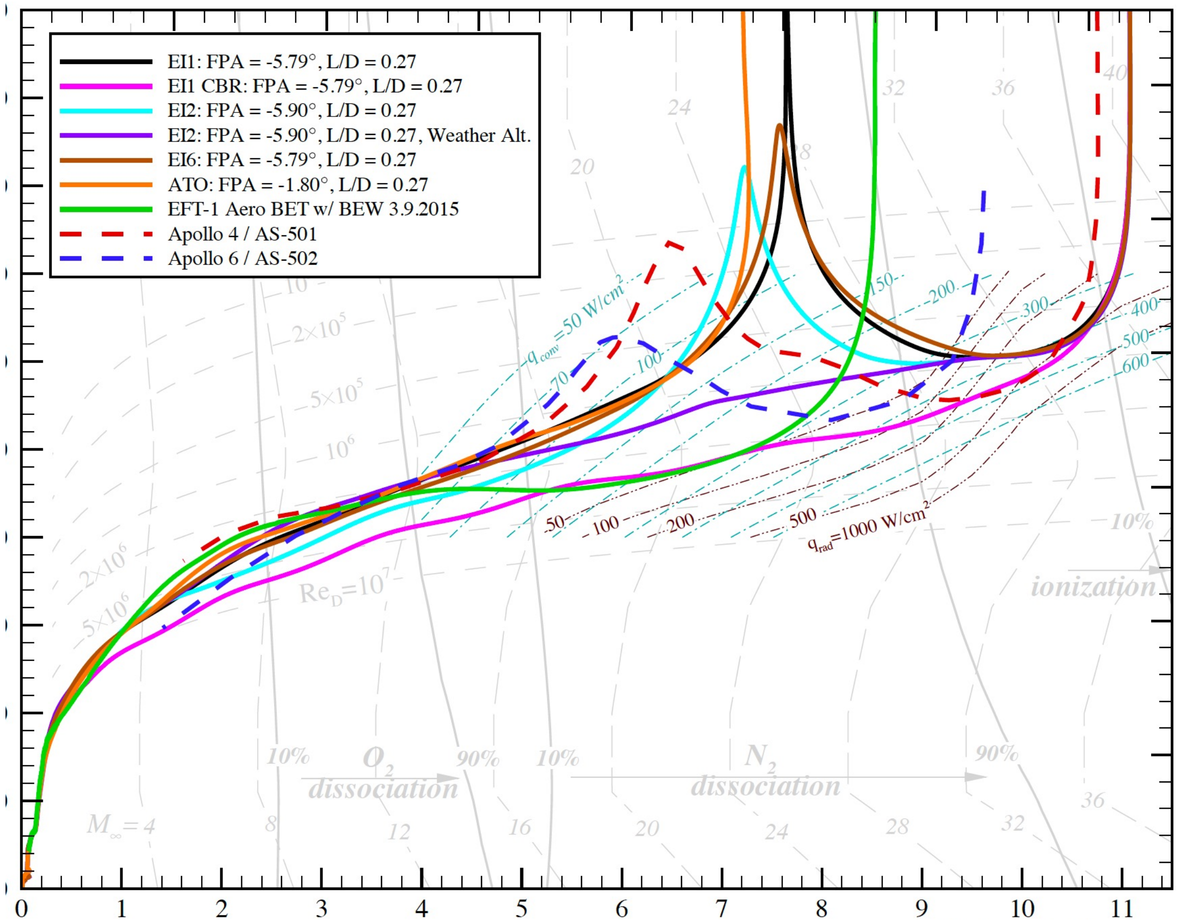


Reduces SM debris concerns over Hawaii

Faster, hotter, turbulence more likely, longer range to San Diego

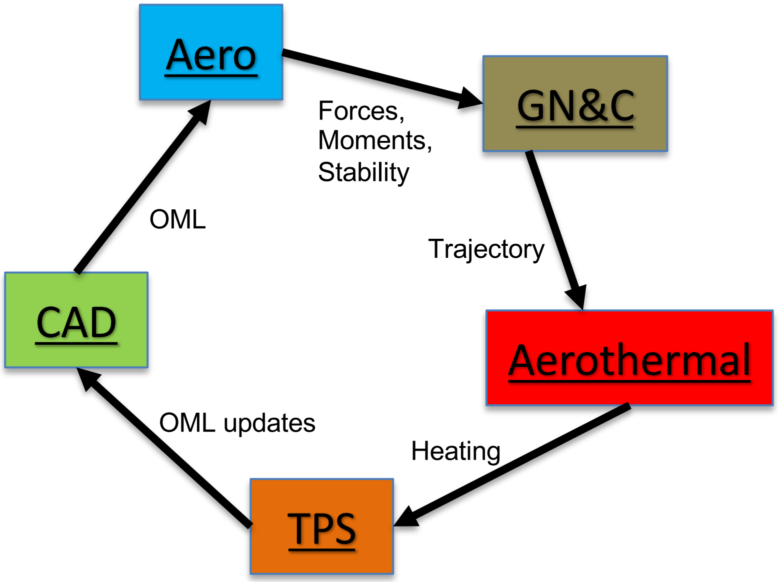
Trajectory Description

- **Critical trajectory parameters for TPS design**
  - Velocity, flight path angle, L/D, and mass → Dictate max. heat flux → Dictates material selection
  - Downrange and time under parachutes → Dictates heat load and thermal soakback → Dictates material thickness
- **Lunar return environments are much more extreme than LEO return**
  - Convective heating scales with V^3 and radiation heating scales with V^{8+}
  - Mars return is even more challenging at 14 km/sec!
- **Orion designed to enter faster than and fly further than Apollo**

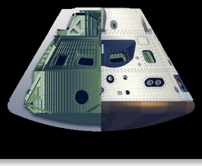


Design Cycle (I)

- Vehicle design undergoes many cycles where data is exchanges between interacting systems all of which may concurrently mature at their own pace
- Simplified design analysis cycle for TPS

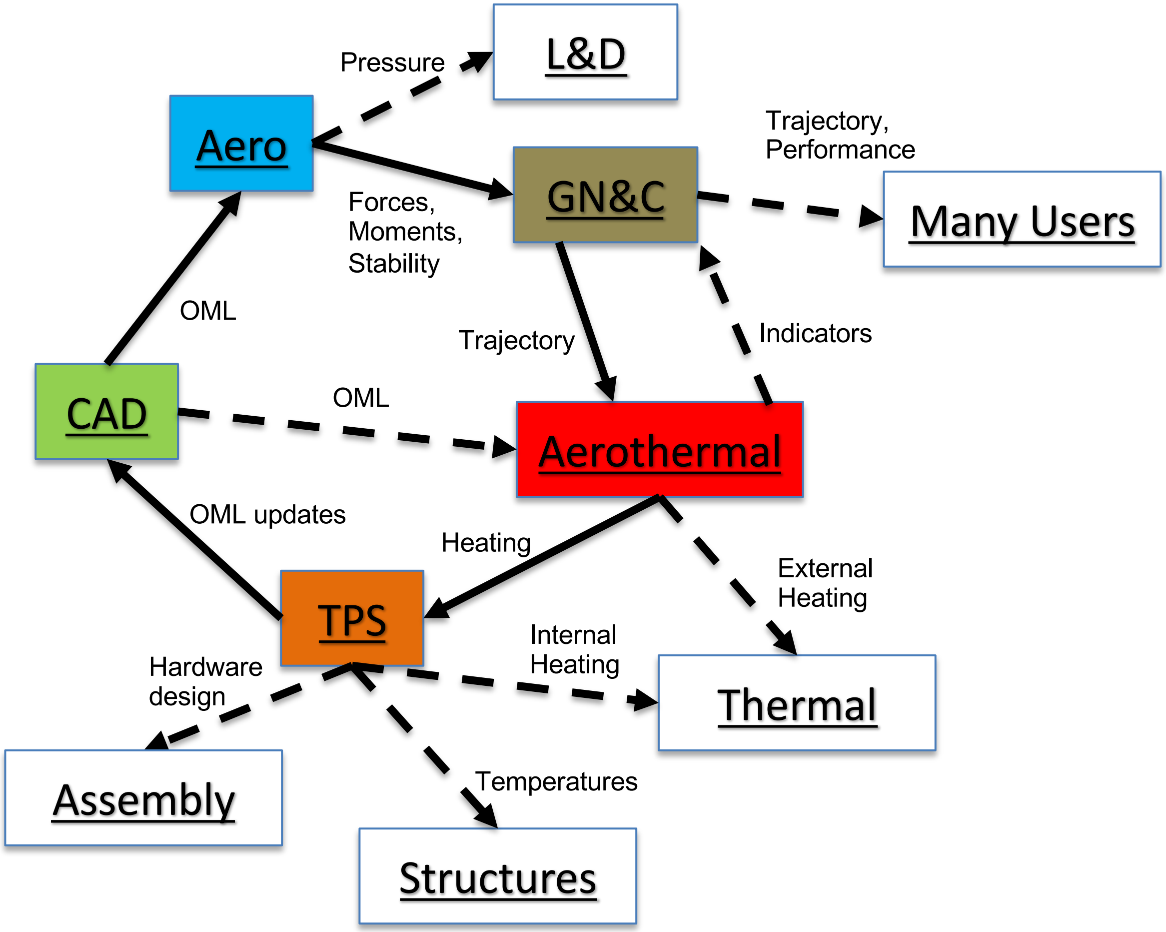


Design Cycle (II)



- Vehicle design undergoes many cycles where data is exchanges between interacting systems all of which may concurrently mature at their own pace

- Expanded design analysis cycle



Aerosciences Overview

- **Orion Aerosciences includes both Aerodynamics and Aerothermodynamics disciplines and responsibilities are split between several organizations**
  - NASA → Aero, aerothermal, & rarefied gas dynamics (RGD) for aborts and entry
  - Lockheed Martin → Product integration, RGD, venting, purge
  - SLS → Nominal ascent aero and aerothermal
  - ESA/Airbus→ RGD for European hardware

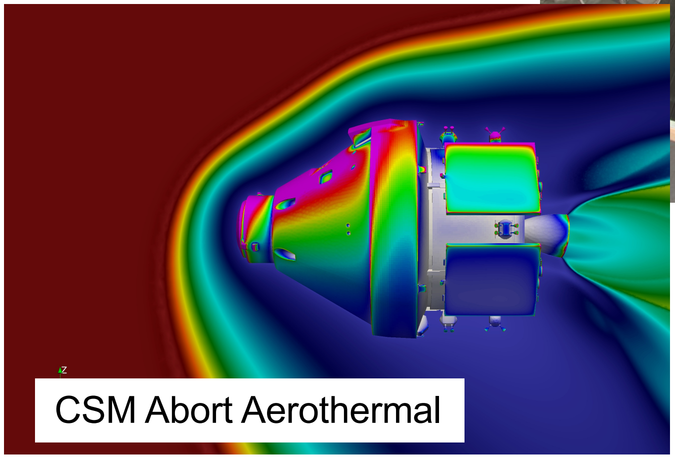
- **The Aerosciences "Databases" are collections of Government Furnished Data (GFD) products that define aero and aerothermal environments to Orion hardware**
  - Product development led by NASA. Primary participation by ARC, LaRC, JSC, & LM
  - Product implementation and delivery to end-users led by LM (Aerothermal) and NASA (Aero)

- **Primary customers for aerothermal environments**
  - Thermal Protection System
  - Thermal and various hardware designers
  - GN&C

- **Primary customers for aerodynamic environments**
  - GN&C
  - Loads and Dynamics

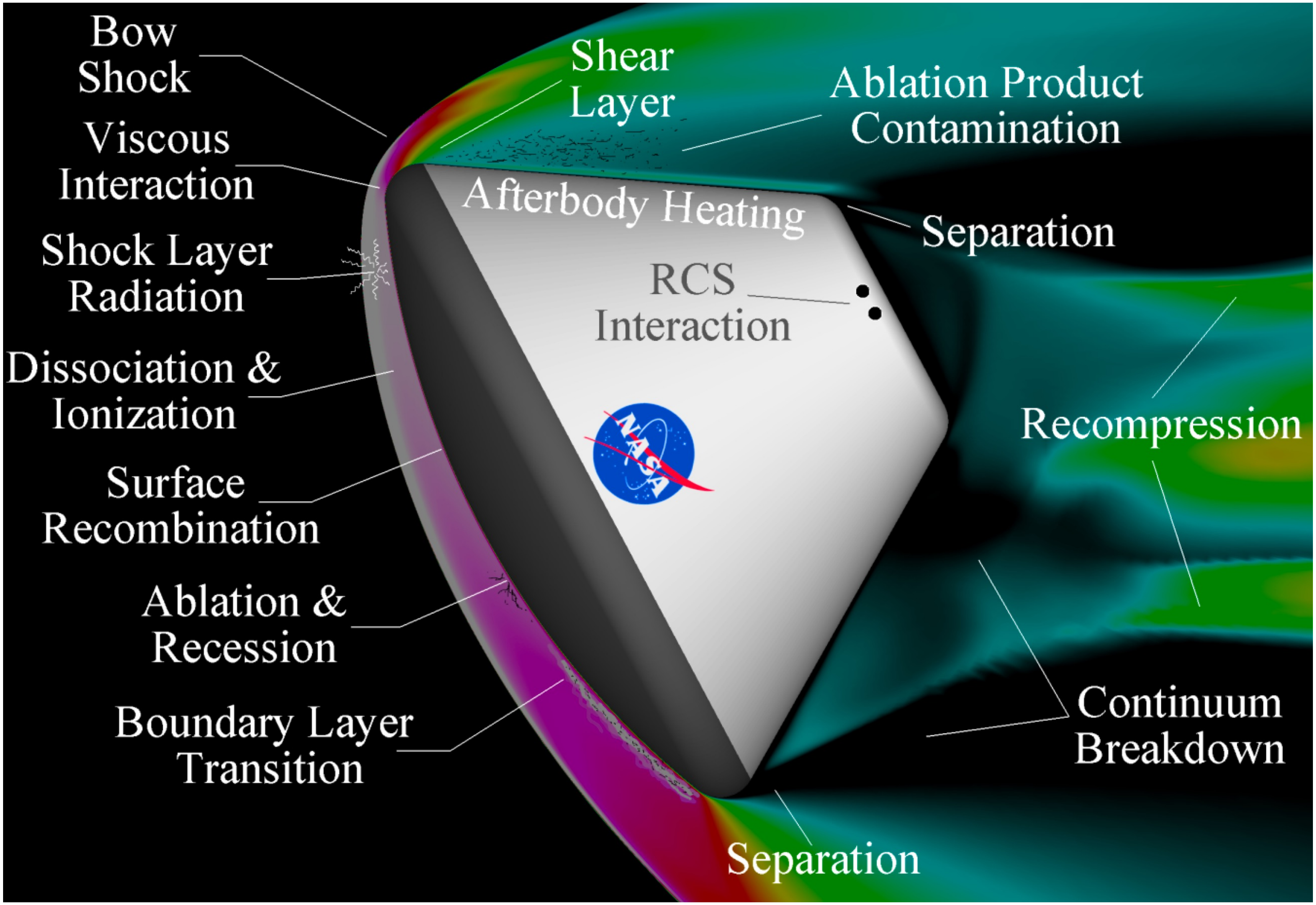
Entry Aero and Aerothermal

LAS Abort Aero and Aerothermal



CSM Abort Aerothermal

Entry Physics

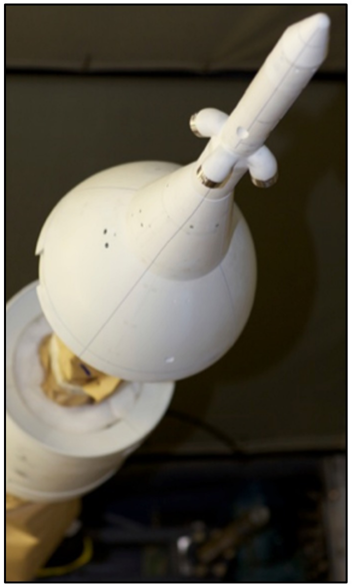


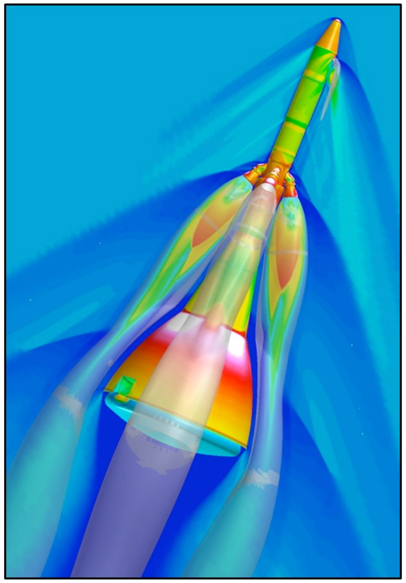
Database Development Approach

- **Products are developed leveraging various data sources and levels of fidelity**
  - Historical flight data (mainly Apollo and Orbiter)
  - Historical ground test data
  - Engineering methods
  - MPCV-specific ground test
  - Orion flight testing
    - PA-1, EFT-1, AA-2, EM-1
  - High-fidelity computational methods
    - DPLR, LAURA, Loci-CHEM, OVERFLOW, DAC, HARA, NEQAIR, FUN3D, US3D, CHAR, Cart3D

- **Products are typically built on multiple data sources (ie 2 ground tests OR 1 ground test and CFD) to help validate approach and develop design margins and prediction uncertainties**

Data Source	Pros	Cons
Ground Test	Some real physics	$$, small scale, not all physics, long lead
Mod. & Sim.	All physics at full scale, $, quick	modeling errors
Flight Test	All physics at full scale	$$$, infrequent, sparse data, challenge to interpret

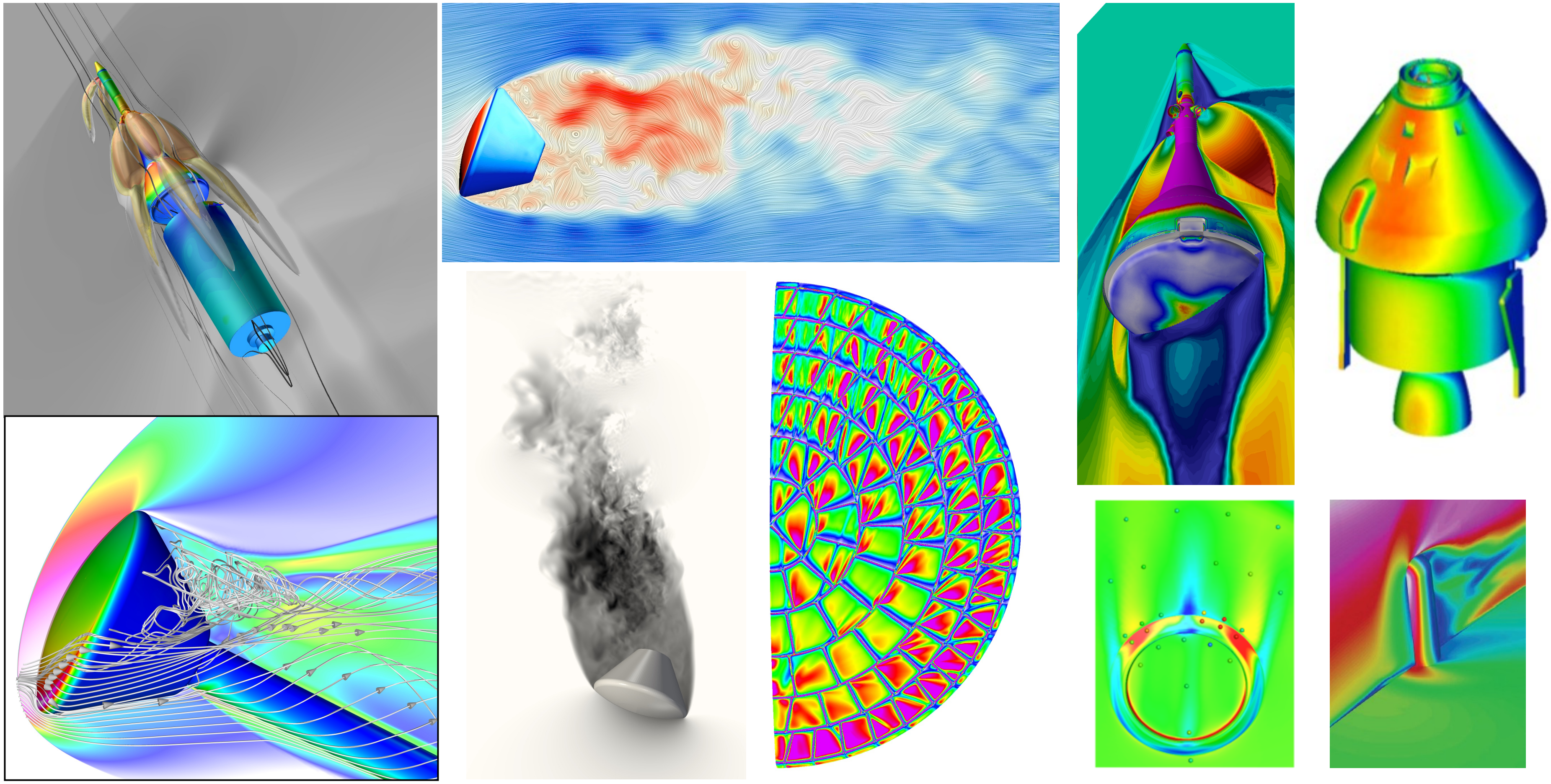

Ground Testing


Modeling and Simulation

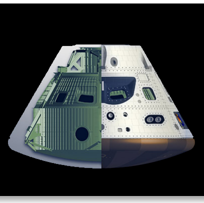

Flight Testing

CFD Overview

- **CFD is used to develop environments for Aerodynamics and Aerothermodynamics for all phases of flight**
- **We attempt to validate CFD tools utilizing ground and flight test data before applying it in design analyses**
- **Key challenges for CFD in Orion Aerosciences**
  - Aero: Complex geometries, turbulence, wake flows, plume flows, fluid-structure interaction (parachutes)
  - Aerothermal: Complex geometries, turbulence, wake flows, plume flows, gas-surface chemical interaction, radiation



Aerosciences Testing for Critical Phases



Test Campaign Color Key

Orion Aerothermal Ground Test

Orion Aerodynamic Ground Test

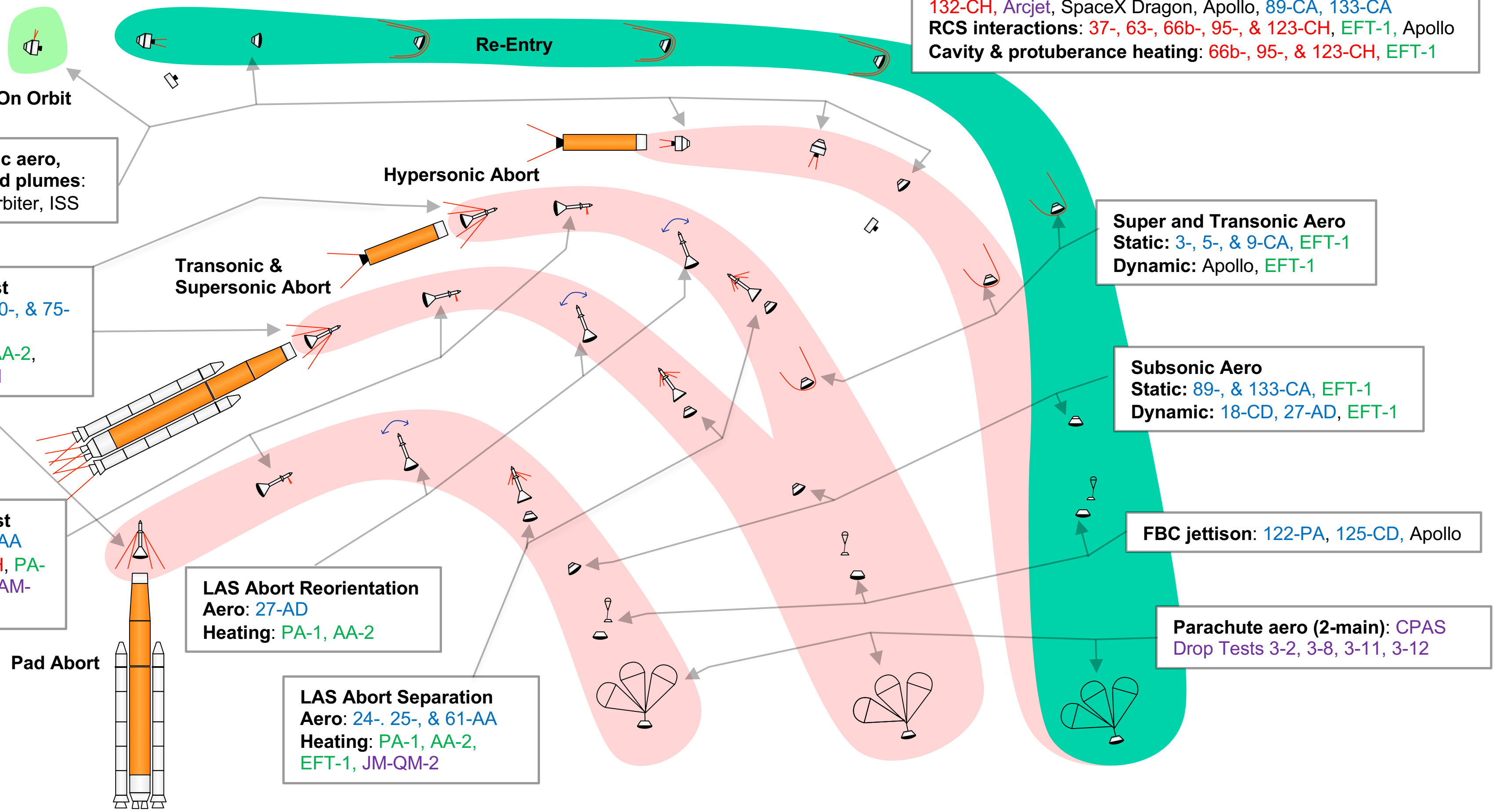
Orion Flight Test

Other Orion Test

Non-Orion Data Source

Radiative heating: 33-, 34-, 43-, 44-, 71-, 72-, 96-, & 97-CH, Apollo, FIRE II, EFT-1
Convective heating: 31-, 35-, 36-, 40-, 56-, 67-, 91-, 113-, & 124-CH, Apollo, EFT-1
Hypersonic aero: Apollo

CM-SM R&R heating: 30-, 64-, 66a-, 86-, 87-, 102-, 126-, & 127-CH, EFT-1
Boundary layer transition: 35-, 36-, 40-, 56-, 67-, 127-, 128-, 131-, & 132-CH, Apollo, EFT-1
Ablator interactions: EFT-1, 39-, 41-, 69-, 127-, 128-, 131-, & 132-CH, Arcjet, SpaceX Dragon, Apollo, 89-CA, 133-CA
RCS interactions: 37-, 63-, 66b-, 95-, & 123-CH, EFT-1, Apollo
Cavity & protuberance heating: 66b-, 95-, & 123-CH, EFT-1



Exo-atmospheric aero, aerothermal, and plumes: Space Shuttle Orbiter, ISS

LAS Abort Boost
Aero: 26-, 83-, 60-, & 75-AA, PA-1, AA-2
Heating: PA-1, AA-2, PITP (SLS), ST-1

LAS Abort Coast
Aero: 75-, & 76-AA
Heating: 103-AH, PA-1, AA-2, EFT-1, AM-QM-1

LAS Abort Reorientation
Aero: 27-AD
Heating: PA-1, AA-2

LAS Abort Separation
Aero: 24-. 25-, & 61-AA
Heating: PA-1, AA-2, EFT-1, JM-QM-2

Super and Transonic Aero
Static: 3-, 5-, & 9-CA, EFT-1
Dynamic: Apollo, EFT-1

Subsonic Aero
Static: 89-, & 133-CA, EFT-1
Dynamic: 18-CD, 27-AD, EFT-1

FBC jettison: 122-PA, 125-CD, Apollo

Parachute aero (2-main): CPAS Drop Tests 3-2, 3-8, 3-11, 3-12

High risk environments utilize flight testing and ground testing from multiple facilities
- Aero example: Transonic LAS abort
- Aerothermal example: Boundary layer transition

All phases utilize high-fidelity computational modeling
- 10's of thousands of simulations used for database development
- Validation rooted in ground tests, flight tests, and historical data

Aerodynamics Ground Testing Overview

Aerodynamics utilizes ground test facilities all over the world

- US. Non-US, government, private, and university

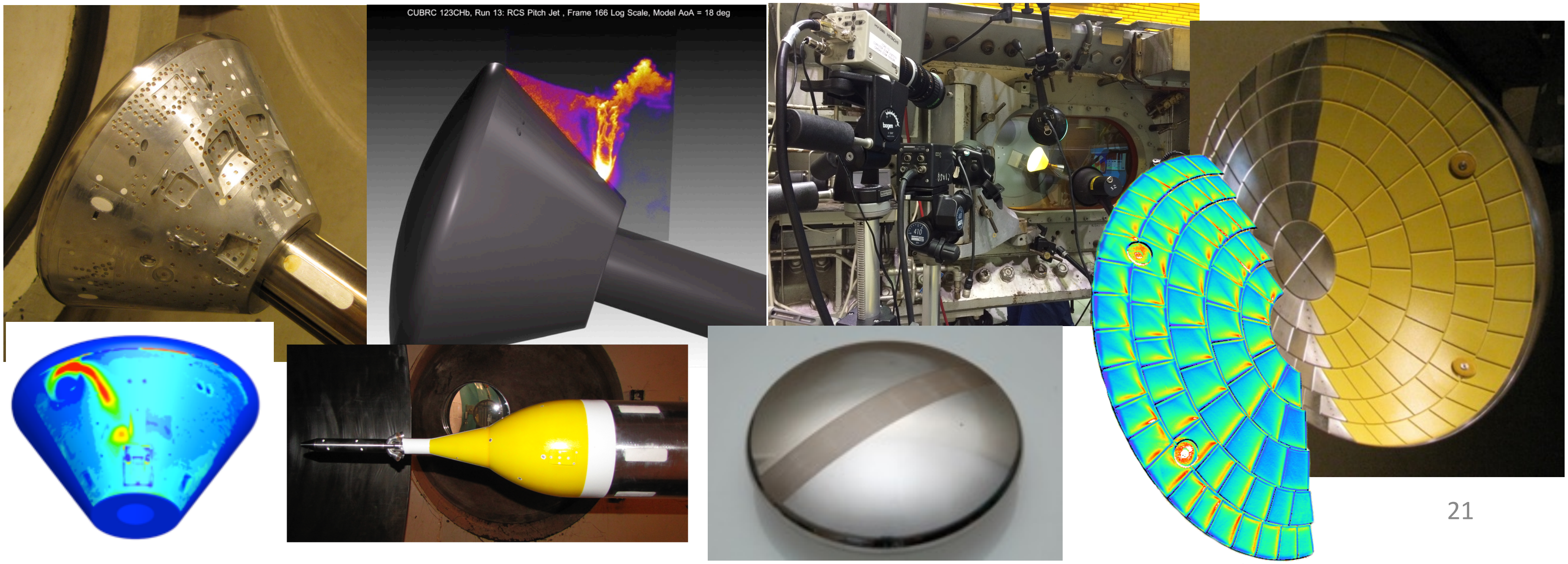
Facility	Type	Data type
Ames Unitary, AEDC 16T	Large scale pressurized closed circuit tunnels	Primary facility for high fidelity static aero test data, including plume flows and separation
Ames NFAC	Large scale subsonic facility	Facility used for parachute testing
GRC AAPL	Jet flow test facility	Facility used to measure plume flows
LaRC NTF	Closed circuit cryogenic tunnel	Facility used for flight scale Reynolds numbers
LaRC TDT, VST	Closed circuity tunnels for dynamics	Facility used forced and free to oscillation for dynamic damping
LM HSWT, Boeing PSWT, AEDC 4T	Small scale blowdown facilities	Facilities used for configuration assessments
University tunnels (UCF, TAMU)	Subsonic, jet plume, acoustics	Facilities used to obtain data on unit problems
Ames HFF, Eglin ARF, Army APG	Ballistic range facilities	Facilities used to assess dynamic damping

Aerothermal Ground Testing Overview

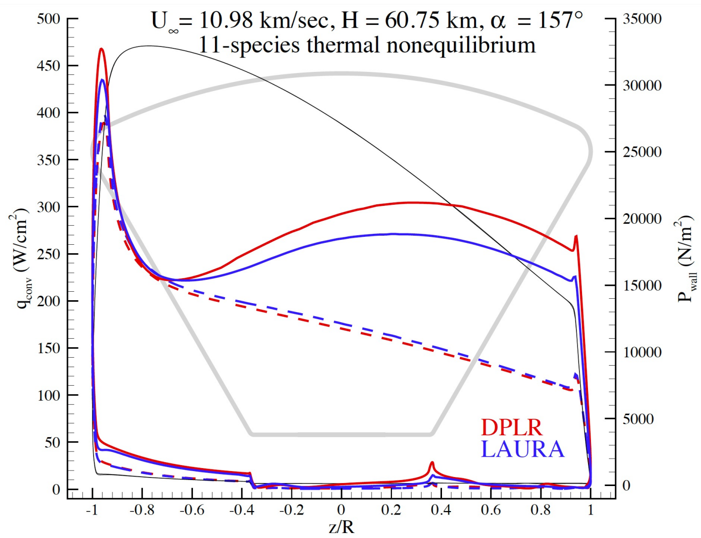
Aerothermal utilizes ground test facilities all over the world

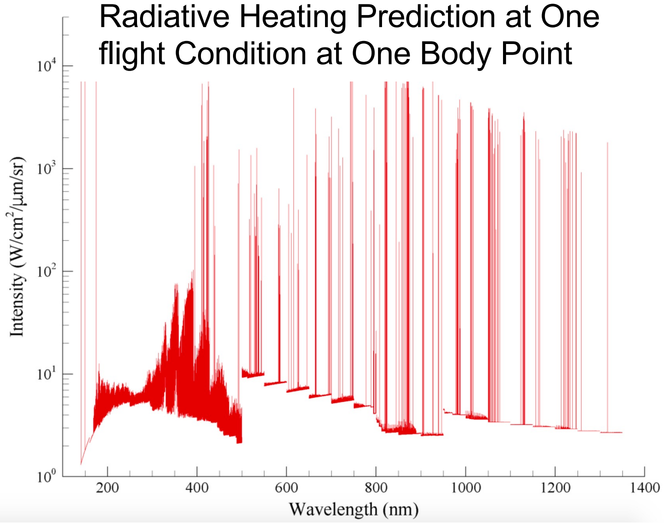
- US. Non-US, government, private, and university

Type	Flow	Instrumentation	Duration	Enthalpy
Blowdown	High-pressure tank to low pressure-tank with nozzle and model in between	Discrete: Thermocouple, thin film RTD, calorimeter, spectrometers, radiometers, Kulite Global: TSP, IR & Phosphor Thermography Flow: schlieren, shadowgraph, LIF	0.1-120 sec	Low
Shock Tunnel	Traveling shock wave heats and pressurizes reservoir before flow expands in nozzle and flows over model into low-pressure tank		ms	Low or High

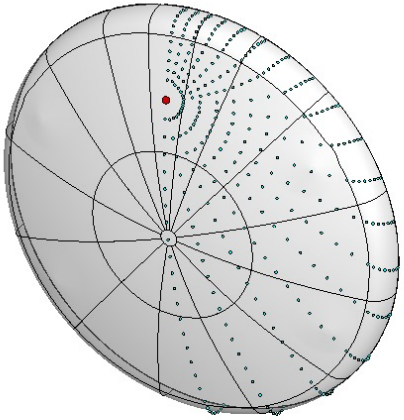


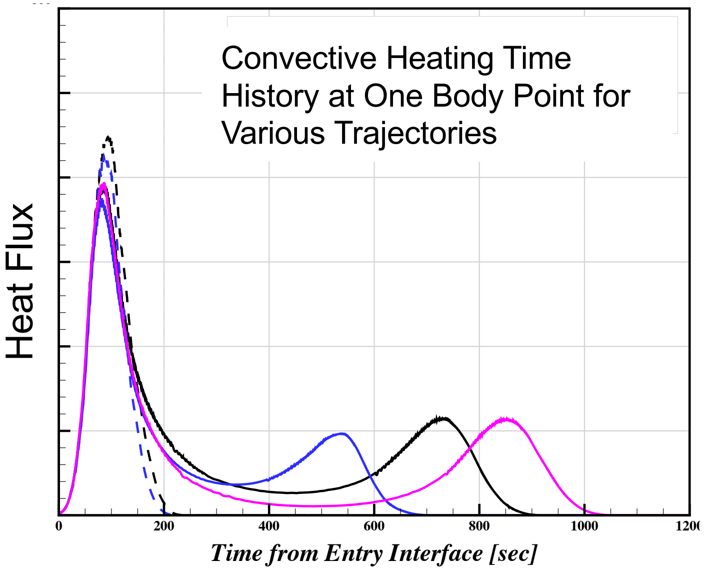
Generic Aerothermal Products Used by TPS

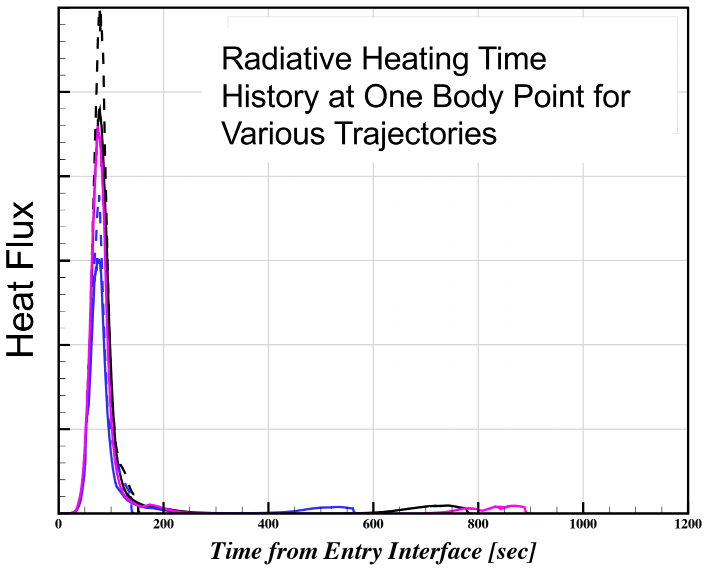



Radiative Heating Prediction at One flight Condition at One Body Point

Example Body Point Map Showing where environments are provided to TPS




Convective Heating Time History at One Body Point for Various Trajectories


Radiative Heating Time History at One Body Point for Various Trajectories

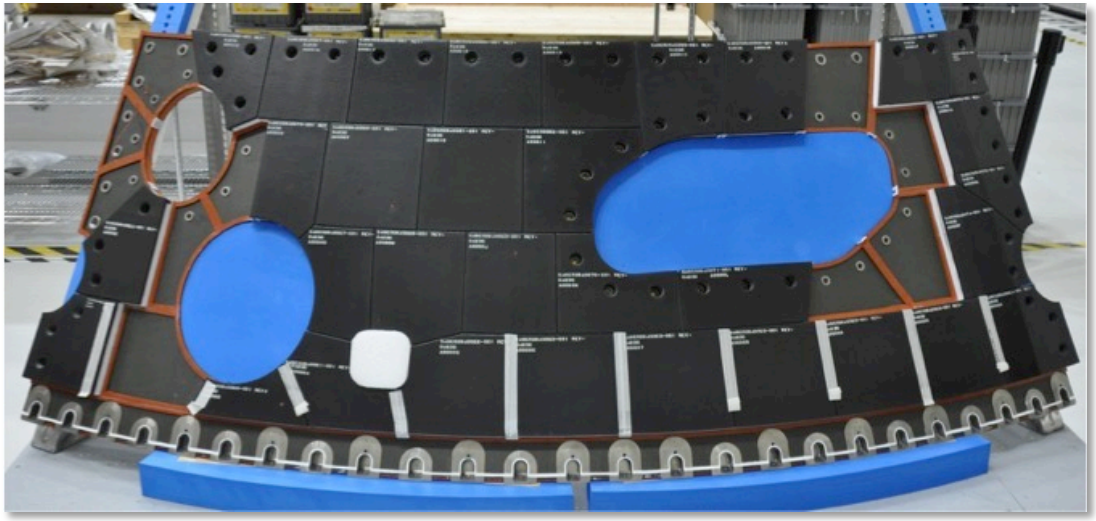
TPS uses products to:

1. Select materials
2. Determine material thicknesses
3. Derive environments for testing materials

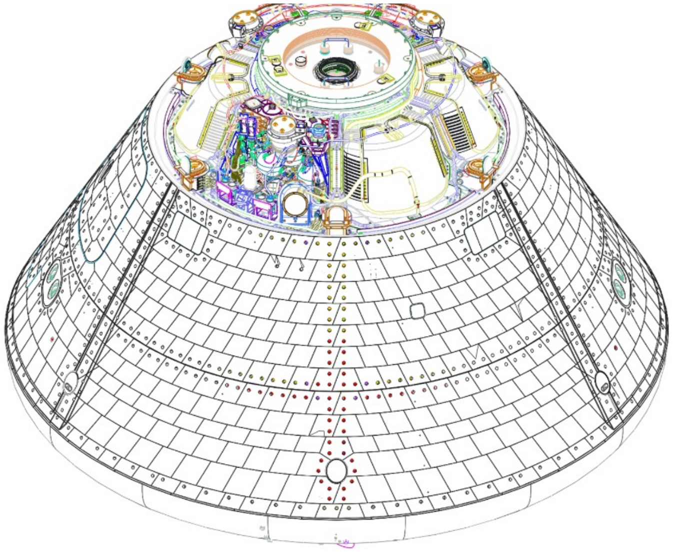
Orion TPS Description – Backshell & FBC

- **Alumina-Enhanced Thermal Barrier (AETB-8 tiles) with RCG over TUFI coating (Shuttle heritage)**
- **Removable panels with threaded tile plugs providing fastener access**
- **Flexible Reusable Surface Insulation (FRSI) used on upper apex surface**
- **Penetrations utilized thermal barriers, carbon phenolic, RTV and FRSI**

Forward Bay Cover, with Side Panel Remov



Panel A, Tiles Partially Installed



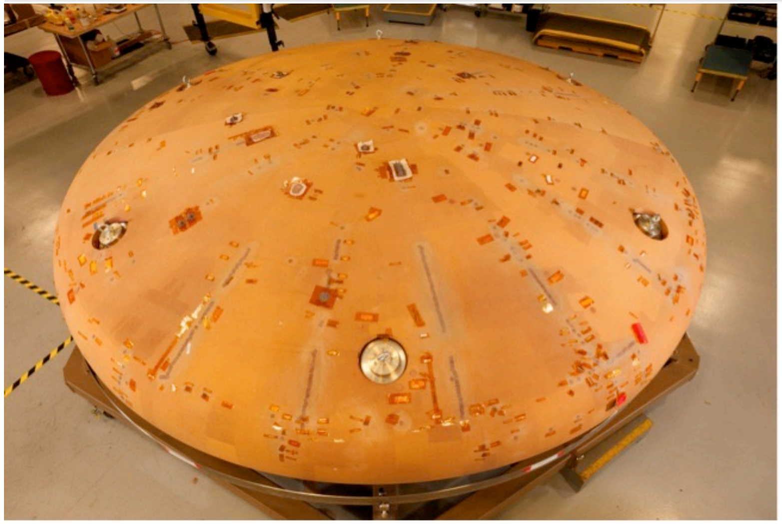
Back Shell TPS, Windward Side

(Forward Bay Cover Not Shown)

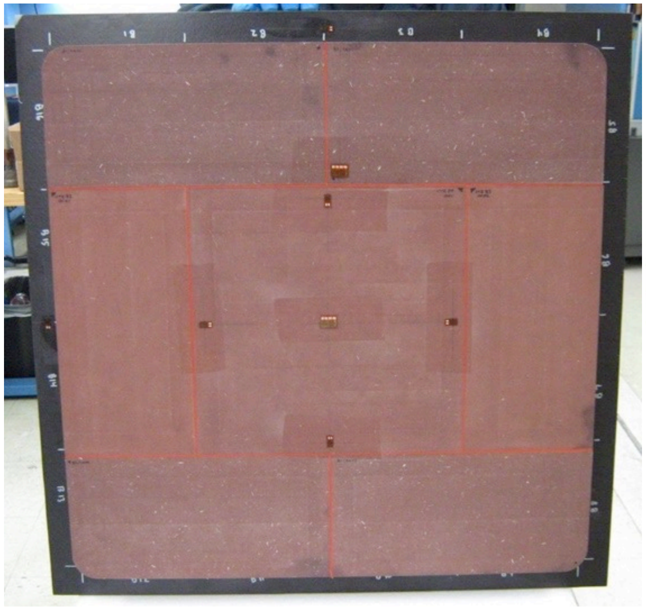
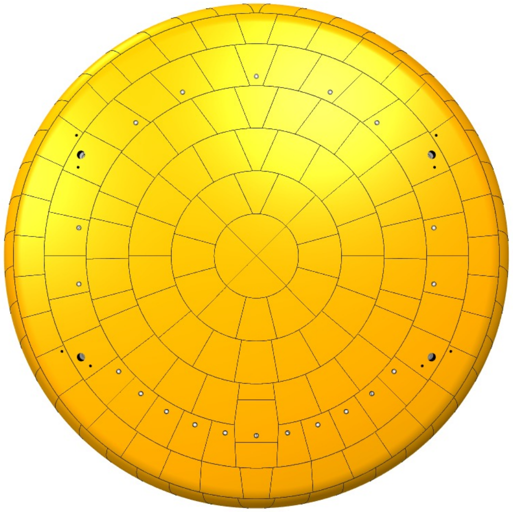
Orion TPS Description - Heat Shield

- **The Apollo Honeycomb/Gunned (HC/G) system was flown on EFT-1 in 2014**
  - Avcoat 5026-39 HC/G
  - Composite/Ti carrier structure

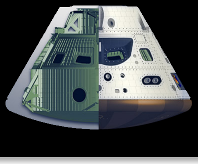




- **For Artemis missions, the Orion baseline is Molded Avcoat blocks**
  - Avcoat 5026-39 M
    - No honeycomb
    - Bonded to the carrier with EA9394 epoxy
  - RTV-560 between blocks
  - Composite/Ti carrier structure
    - Reduced mass from EFT-1

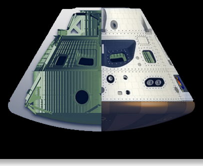



Heatshield Thermal Sizing Process

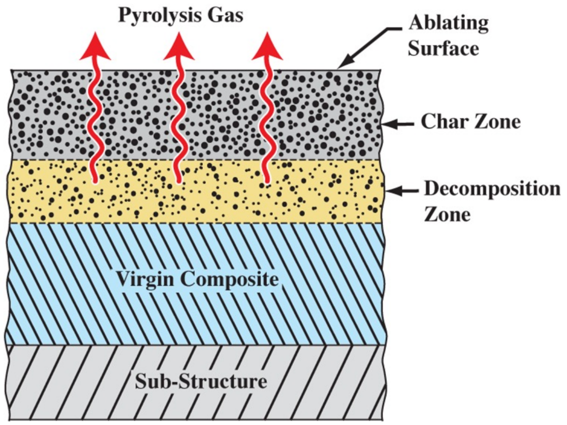


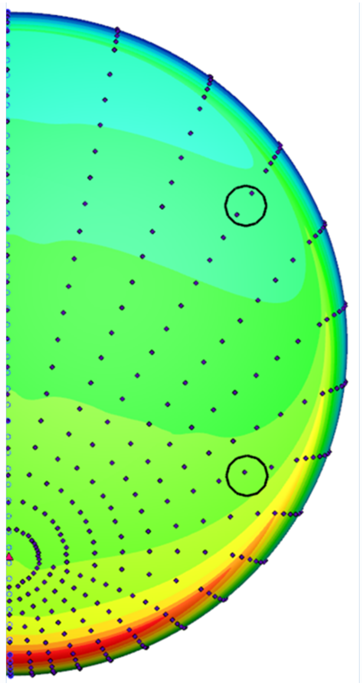
- **The block architecture presents challenges due to the presence of fencing/gapping at the block interfaces**
  - Molded Avcoat and RTV ablate at different rates resulting in fences or gaps depending on the heating environment
  - Fencing and gapping is a highly coupled process between the material and environments
    - Environment is dependent on time-varying feature geometry, primarily influencing heating augmentation and turbulent transition
    - Transition tripping introduces another coupling by linking downstream environments to upstream response
- **A two phased approach was developed to address the sizing**
  - Phase I provides a sizing of the block heatshield using arc jet test derived fencing profiles for limited environments (currently in use)
  - Phase II provides improved sizing of the block heatshield using a model based approach (still in-work)
    - Direct predictive approach of the differential recession between the block and gap filler materials which can augment the downstream environments
    - Models will evaluate the heatshield from the stagnation point and progress through downstream locations to capture the effects of fencing

Molded Avcoat Thermal Response Model

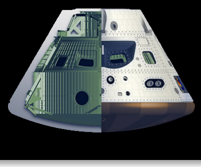


- **Developed a material response model for molded Avcoat**
  - CHarring Ablator Response (CHAR) code used for HS analyses
    - Finite element code that solves the energy and mass transport equations for pyrolyzing ablative materials
  - Utilized basic thermal property testing on virgin and charred molded Avcoat (e.g. TGA, thermal conductivity, specific heat, elemental analysis, etc.)
  - Aerotherm Chemical Equilibrium code used to extend the basic properties to derive pyrolysis gas properties and normalized surface recession tables
- **Material models anchored to arc jet test results over a wide range of test conditions based on recession and in-depth temperature performance**
- **All of the sizing analyses use 1-D models**
  - Some work has been completed to implement the multi-dimensional analysis capability



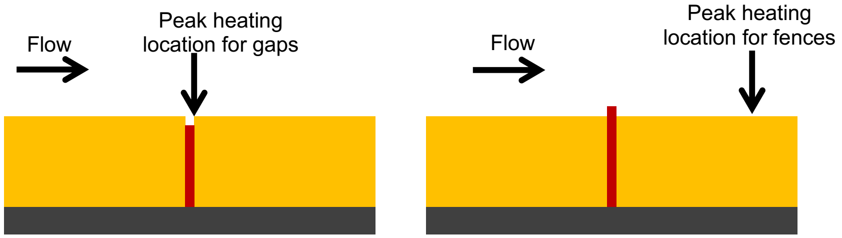


Avcoat Block System / Environment Interaction



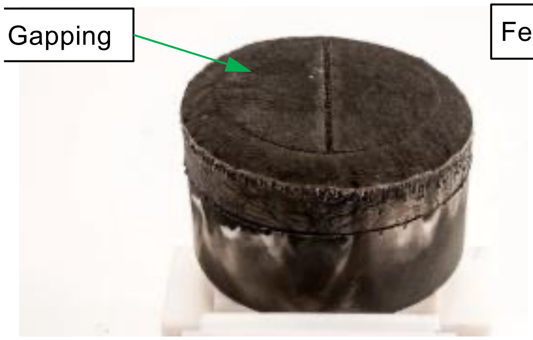
The Block System Interacts with, is affected by, and affects the Environment

- **Fencing is a highly coupled process**
  - Feature formation/type is dependent on heating
    - High heat rates produce gaps
    - Low heat rates produce fences
  - Local environment is affected by seam features
    - Heating augmentation downstream of feature
    - Peak heating different for gaps vs. fences
  - Fences can induce transition, linking downstream environments to upstream response

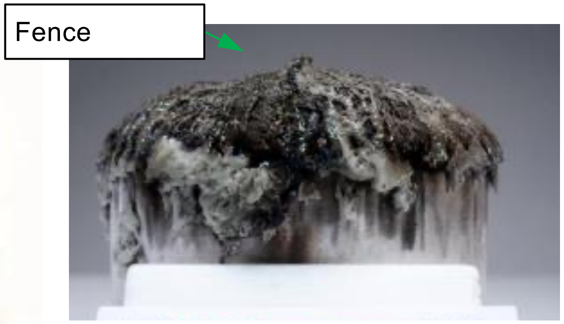


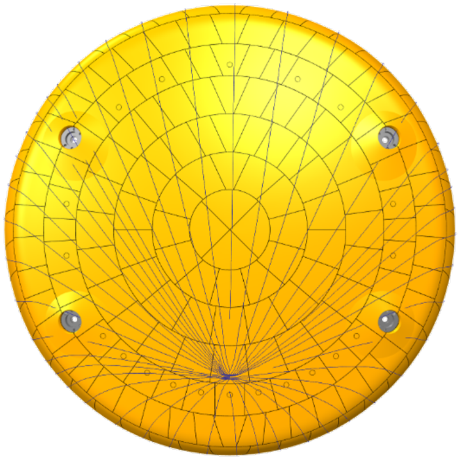
- **The peak heating location for fences and gaps occurs at different locations on the block and therefore sizing is run for both locations**
  - The worst case sizing from these 2 locations is used to size the acreage

High Heat flux

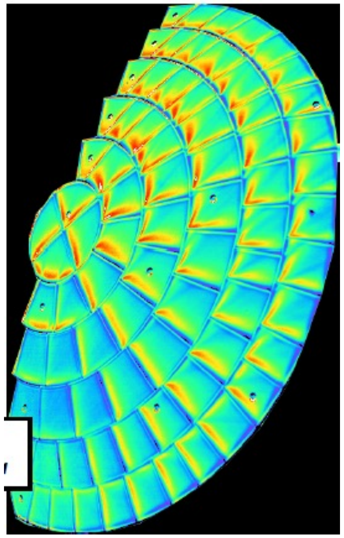


Low-med Heat flux



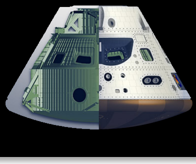


Streamline Overlay

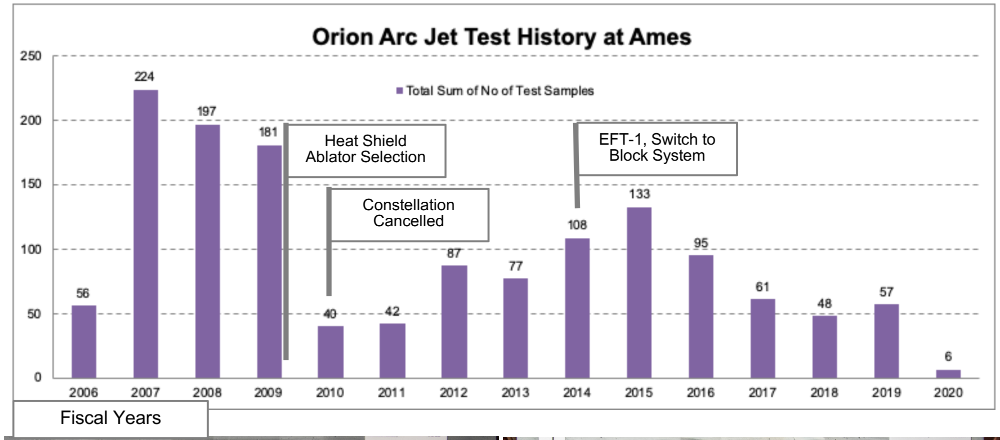


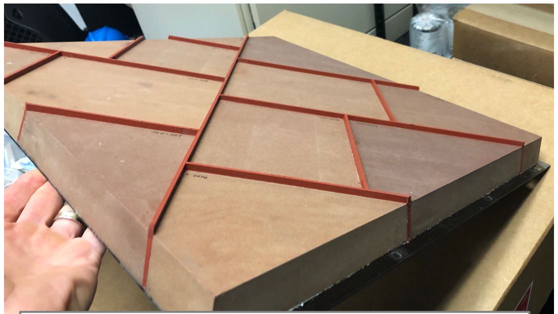
Wind Tunnel Tes

Orion Arc Jet Test Summary

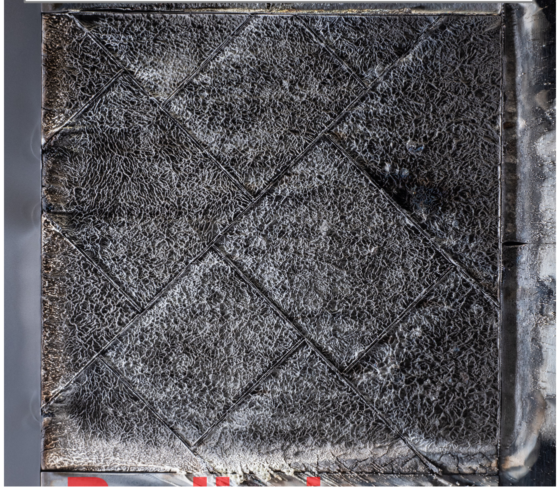


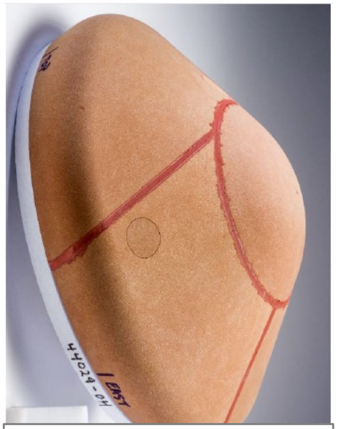
- **Since 2006, Orion has completed > 1,420 arc jet tests at NASA Ames Research Center**
  - Does not include arc jet tests at NASA JSC and the Arnold Engineering Development Center (AEDC) in Tennessee - another ~200 tests



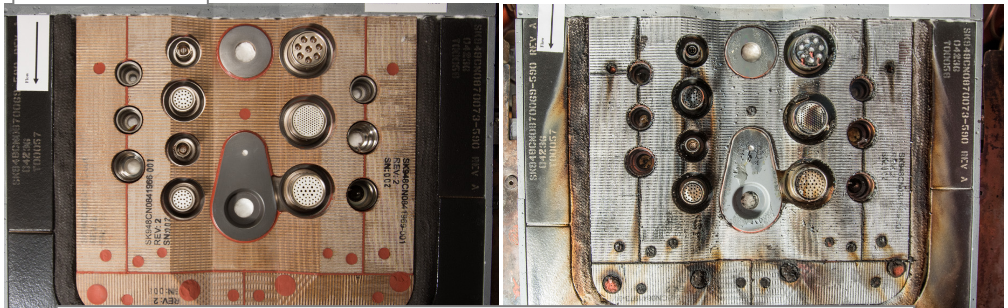


Heat Shield Avcoat Block/Seam Array in Combined Convective/Radiant Heating





Heat Shield Seam Evaluations in High Heating Environments

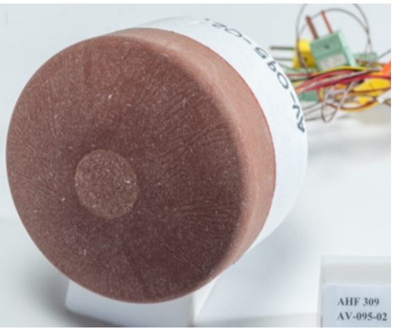


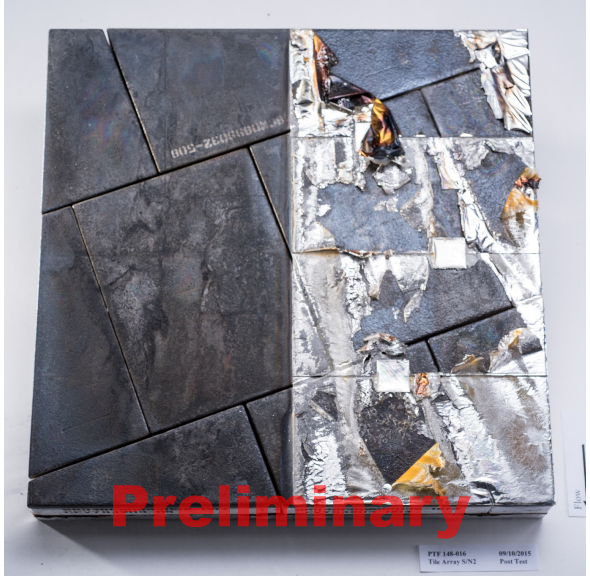
Crew Module/Service Module Umbilical Performance Validation

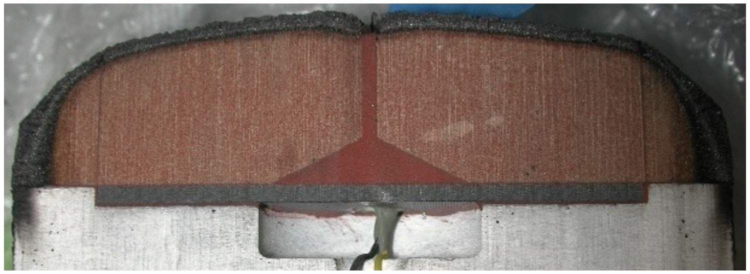
Crew Module Recovery Mechanism Hot Functional Testing

Arc Jet Testing - Why Do We Do It?

- **Material System Selection - what material systems will the spacecraft use?**
  - Orion selected Avcoat from amongst five different candidates, supported by arc jet testing
- **System Design - how will the Thermal Protection System (TPS) materials be installed on the spacecraft?**
  - Orion back shell tile and heat shield Avcoat block seam solutions were subject to arc jet testing
  - Surface coatings and thermal treatments were characterized in the arc jet
- **Material Qualification - are the materials being manufactured in a consistent way?**
  - Avcoat vendor changes and production line re-start events were accepted with the support of arc jet testing
- **Spacecraft Sustaining Engineering - is the system continuing to operate as expected?**
  - EFT-1 and Artemis-1 performance is confirmed with post-flight arc jet testing





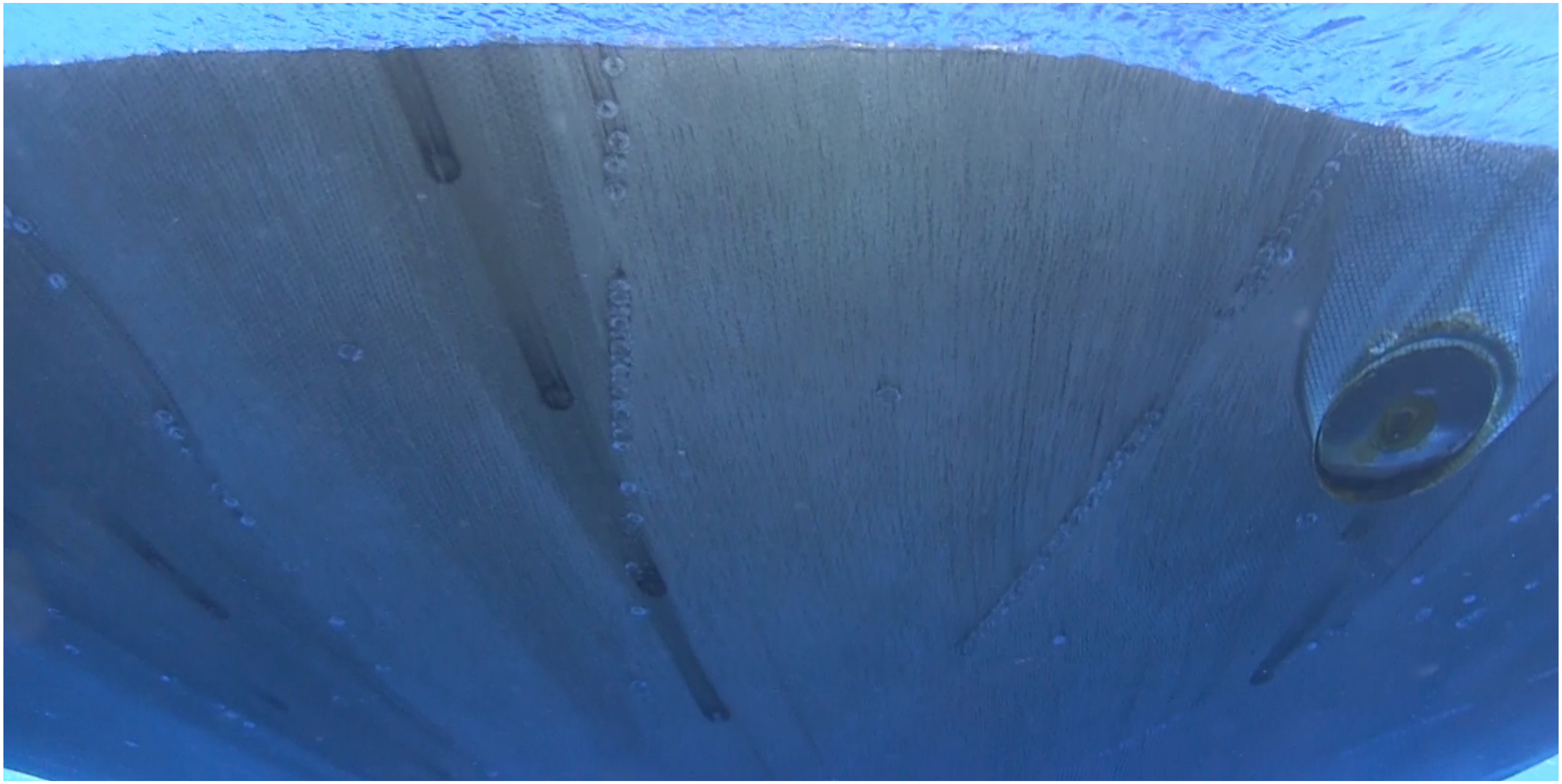


Arc Jet Testing is No Substitute for Flying!

- **EFT-1 Recovery:**
- **Horse collar and tow line attached to CM**
- **CM towed to USS Anchorage**
- **Reeled into well deck, which was then drained**

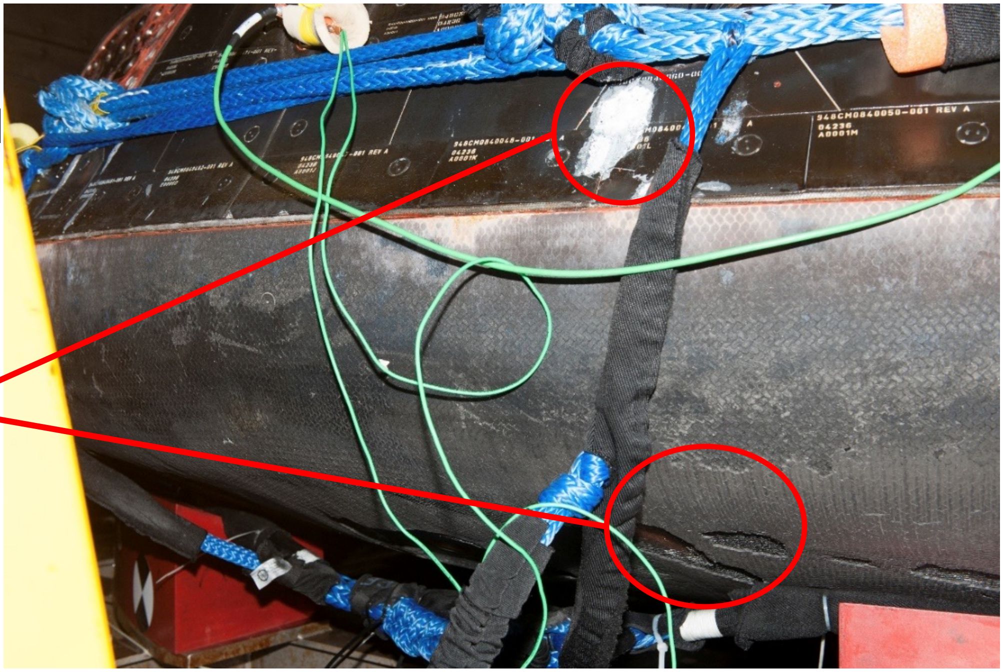
Recovery Ops

Underwater Photo of Heat Shield Taken by Diver



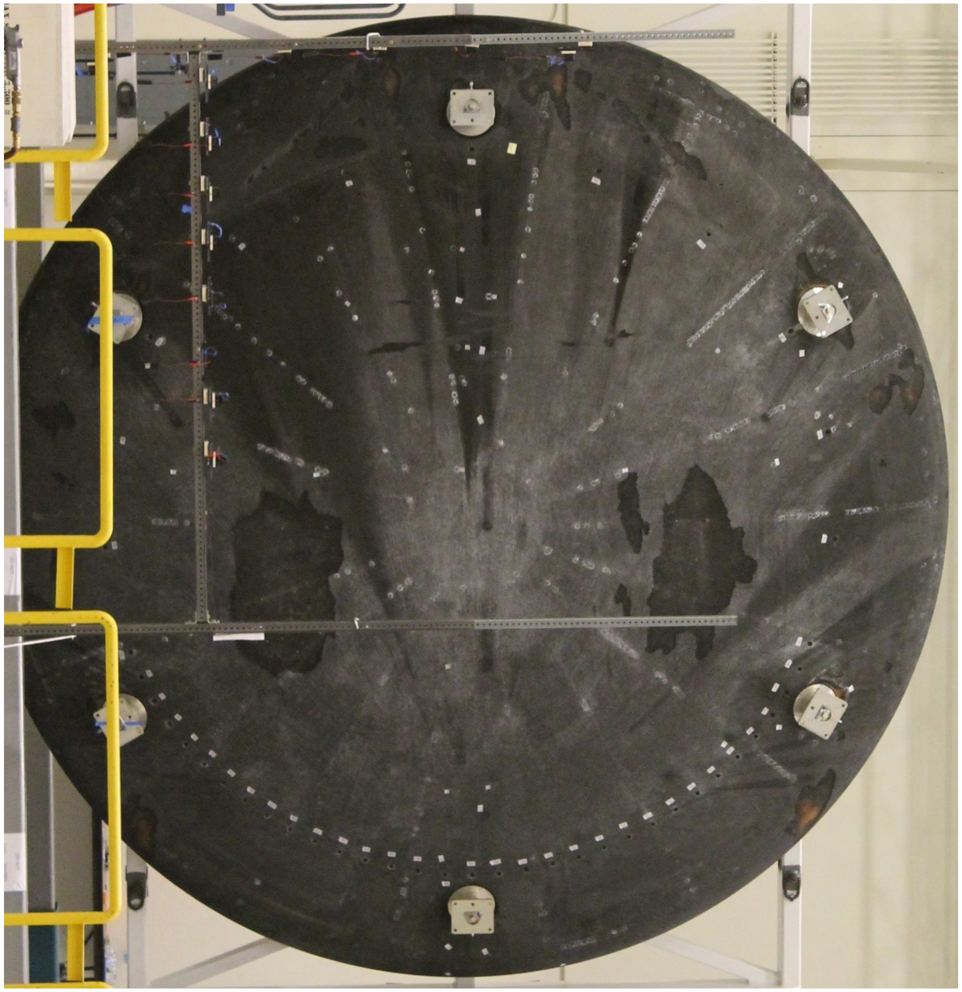
Inspection of CM in the Well Deck

Charring of RTV on Umbilical Panel

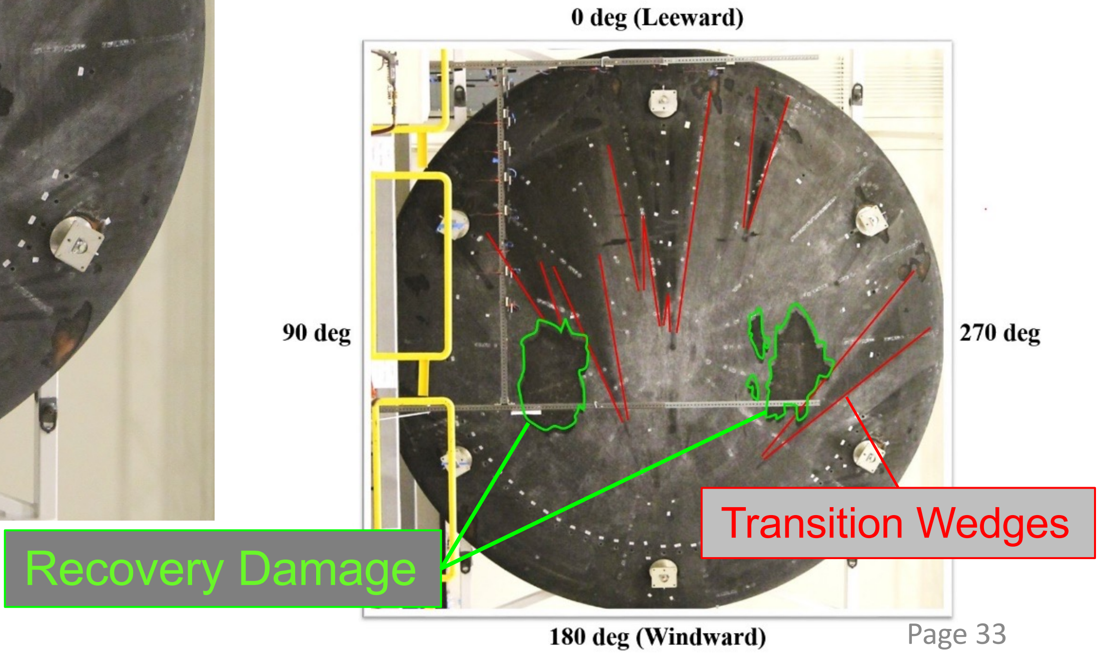


Surface Damage to Tiles and Avcoat® from Recovery Horse Collar

Heat Shield Flight Performance

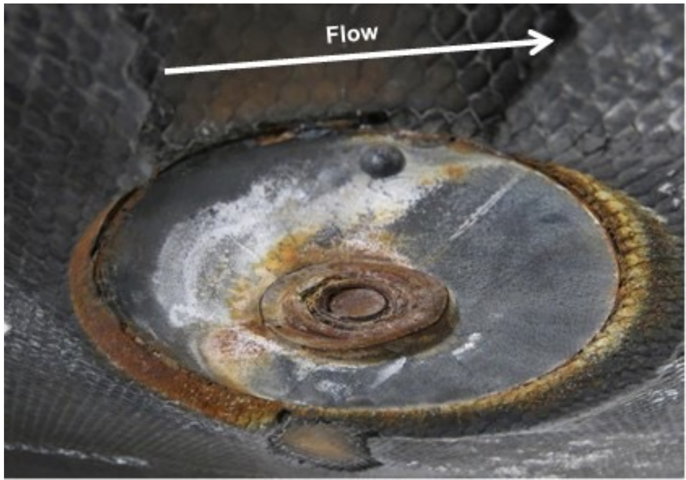


- Overall, heat shield in excellent condition post-flight
- Uniform char formed on Avcoat®, with minimal recession
- Recession patterns downstream of compression pads
- Transition wedges evident, some natural and some appearing to emanate from DFI plugs

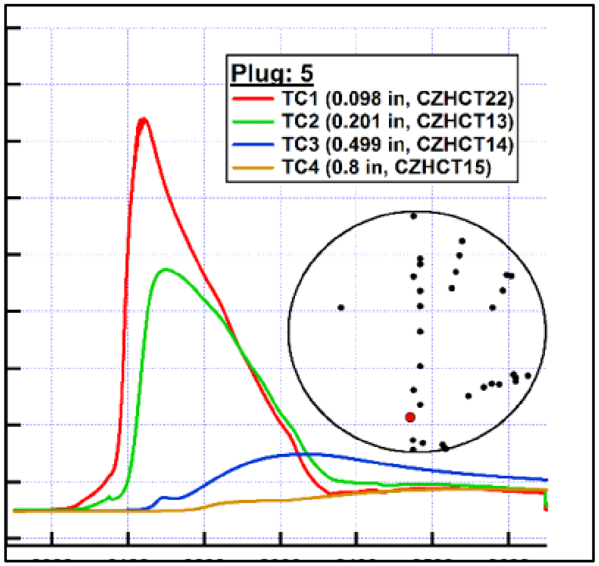


Heat Shield Flight Performance

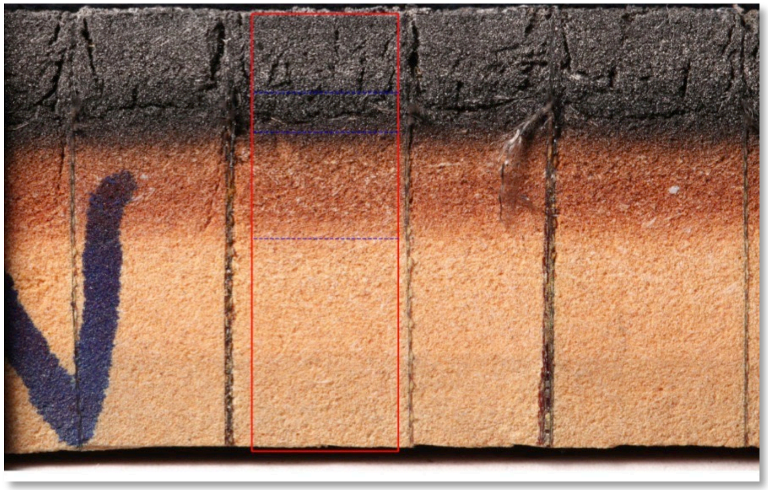
Compression Pad Post-Splashdown



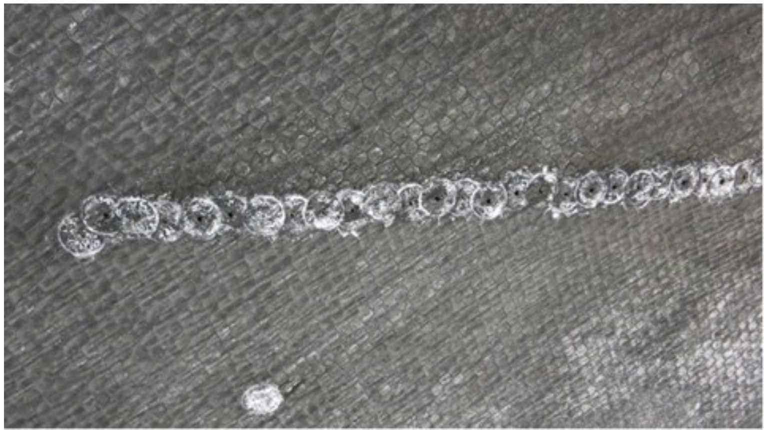
Instrumentation Data Near Stagnation Point



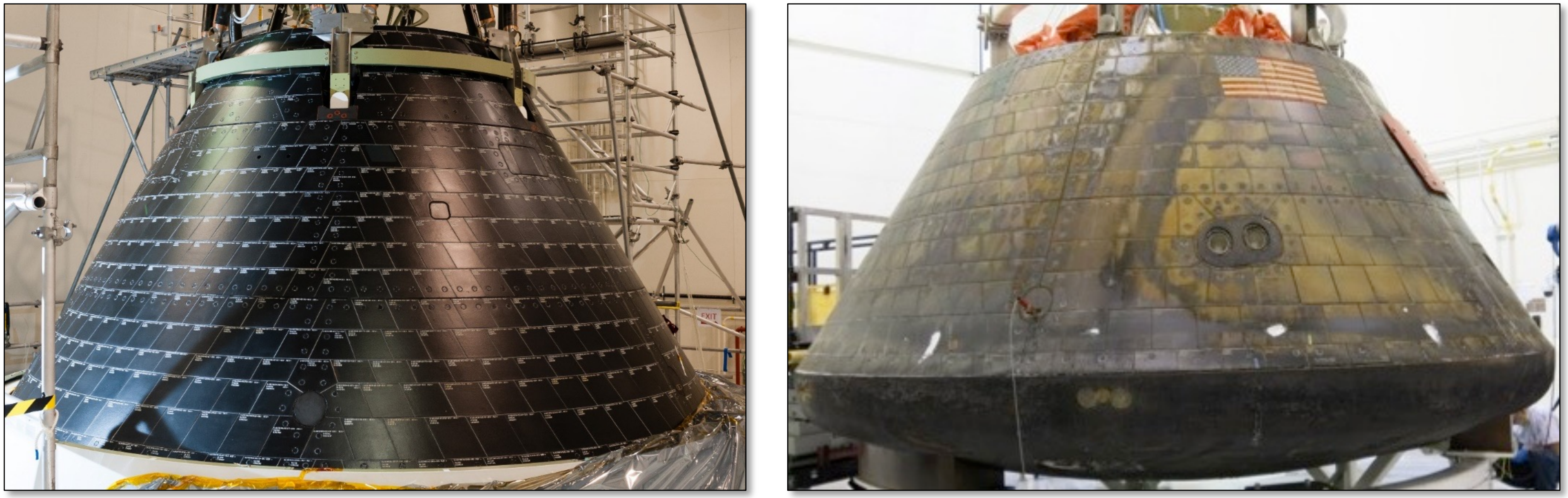
Avcoat® Cross-section



Crack Repair Plugs

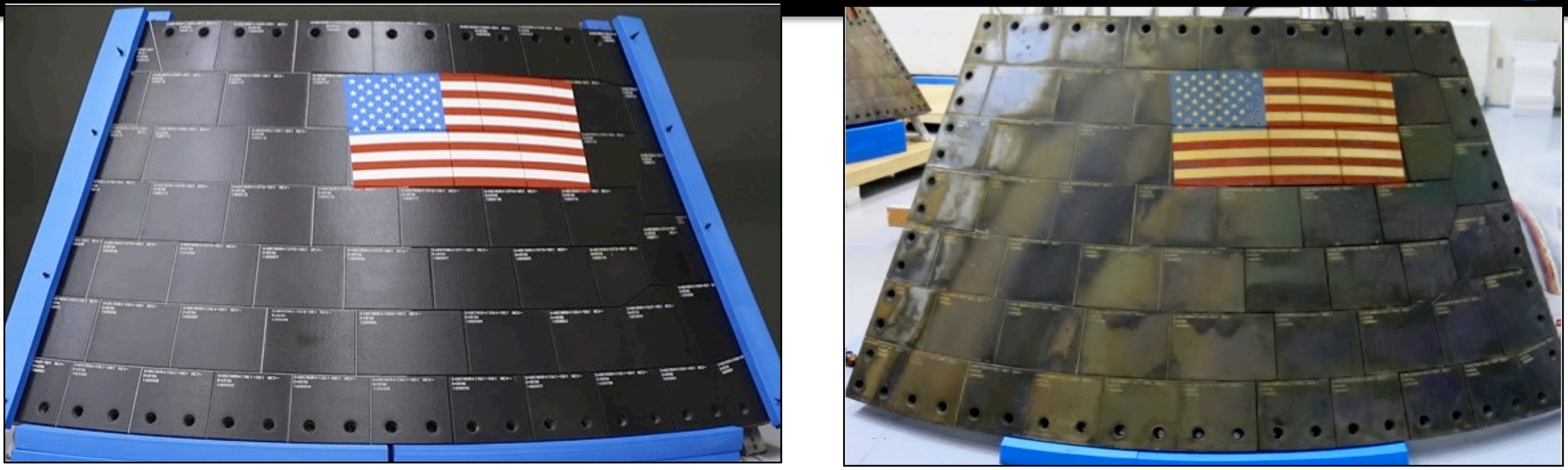


Back Shell Flight Performance



- TPS performed as expected
- Tile surfaces discolored from deposition of heat shield ablation products
- No evidence of flow past any of the numerous back shell TPS penetrations
- Forward bay cover was not recovered. However, there was no evidence of thermal damage/flow on the underlying components and structure
- FRSI on the docking hatch (apex) was not charred; silicone coating was discolored

Back Shell Flight Performance



Panel I – Pre-Flight and Post-Flight

Thruster Thermal Barriers

FRSI on Docking Hatch

Conclusion

- **Aerosciences and TPS are hand-in-hand disciplines**
  - Each feeds back to the other in iterative ways
- **While the EFT-1 flight test provided a vast amount of certification evidence, the Artemis 1 flight test in the coming months will be critical to the Program’s ability to transition to crewed flights**