



# Entry, Descent, and Landing (EDL) Instrumentation

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**19 April 2022**

# Outline



- What is EDL Instrumentation?
- Overview of sensors used in EDL instrumentation suites
- Examples of EDL instrumentation flown on NASA missions (2012-Present)

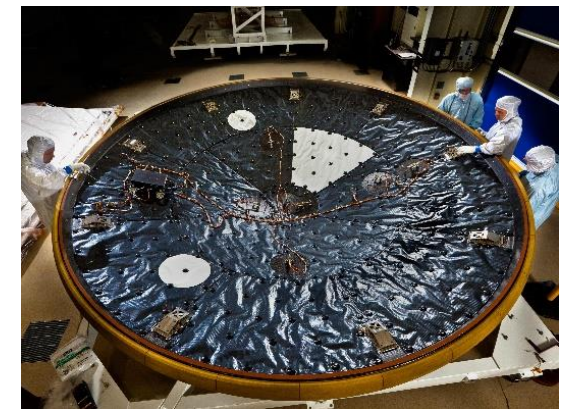
# What is EDL Instrumentation?



- For spaceflight missions involving atmospheric entry, the environment experienced by a spacecraft cannot be fully replicated on the ground
- Taking measurements in the flight environment is the “gold standard” for:
  - Validating predictive modeling tools
  - Reducing risk on future EDL missions
- EDL Instrumentation can consist of in-situ sensors embedded within the aeroshell, or remote observations
  - Focus of this presentation is on NASA in-situ sensors



*Orion EFT-1 heat shield*

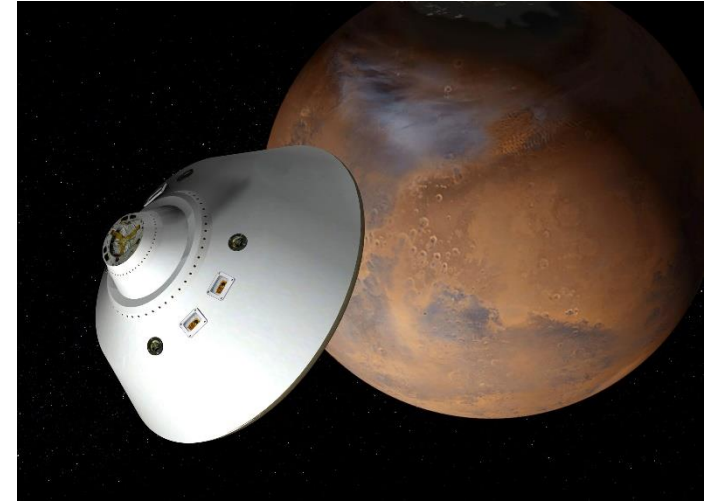


*MEDLI instrument suite*

# Benefits of EDL Instrumentation



- NASA has significant science and human exploration goals for Mars
  - Mars Sample Return Campaign
  - Artemis missions
- There is a need to increase our knowledge of how vehicle systems perform to reduce risk on future missions
  - Atmospheric Models
  - Aerothermodynamics and TPS material response models
  - Reduce TPS sizing margins
  - Entry system Aerodynamics models
  - Separate atmospheric and aerodynamic performance issues (not possible with Inertial Measurement Unit data alone)



*(Courtesy: NASA.gov)*



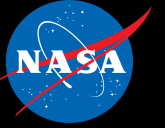
# EDL Instrumentation: Additional Context



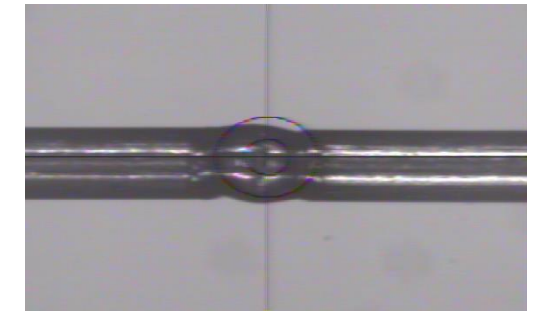
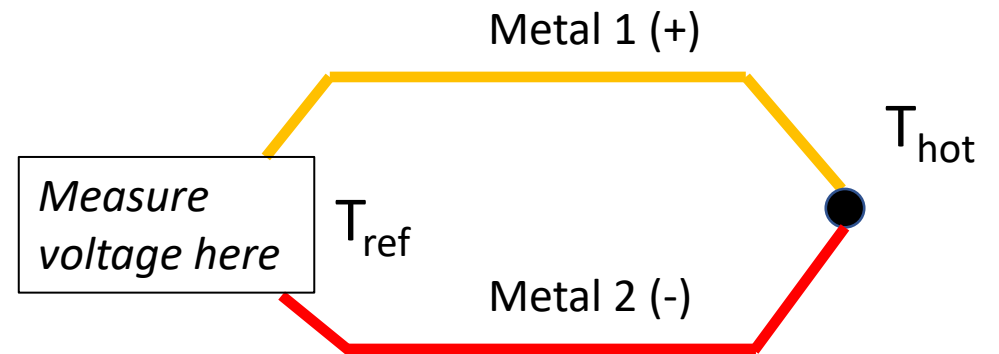
- The 2020 NASA Technology Taxonomy articulates the technology development disciplines needed to enable future space missions
  - Item TX09.4.6 covers “Instrumentation and Health Monitoring for EDL”
- NASA’s competed Discovery and New Frontiers class missions are required to propose an Engineering Science Investigation (ESI) suite
  - Dragonfly is the first New Frontiers mission to fulfill this requirement
- 2023-2032 Planetary Decadal Survey white paper on EDL Instrumentation
  - Summarizes state-of-the-art for EDL instrumentation
  - Describes current challenges and new measurements or capabilities needed for EDL instrumentation



# Thermocouples



- Operating Principle:
  - Measure temperatures difference between hot and cold junctions by measuring the voltage from Seebeck effect
  - Must be two dissimilar metals
  - ASTM E-230 and NIST provide additional details
- Used in an EDL instrumentation suite to measure heat shield and backshell TPS material temperatures during atmospheric entry
  - Infer surface heat flux
  - Characterize performance of the TPS material
  - Identify onset of transition from laminar to turbulent flow

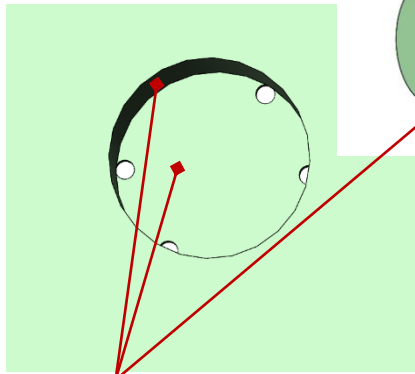


*TC bead weld ("hot junction")*

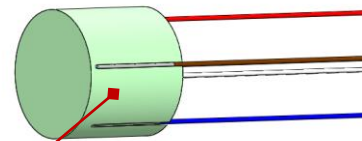
# Thermocouple Plugs



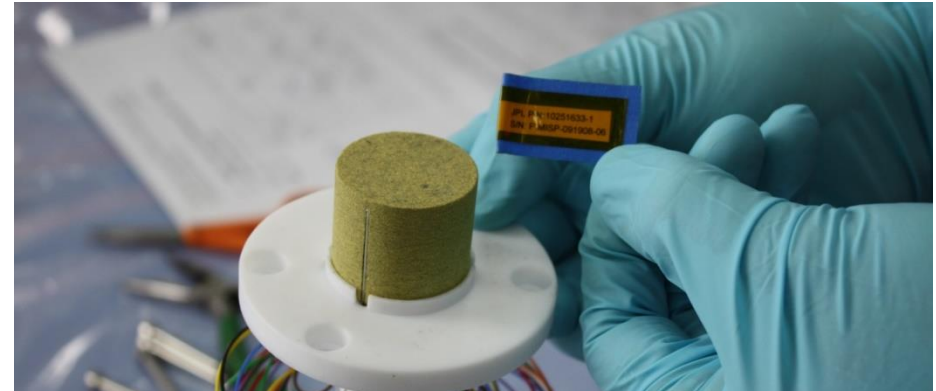
Heatshield:



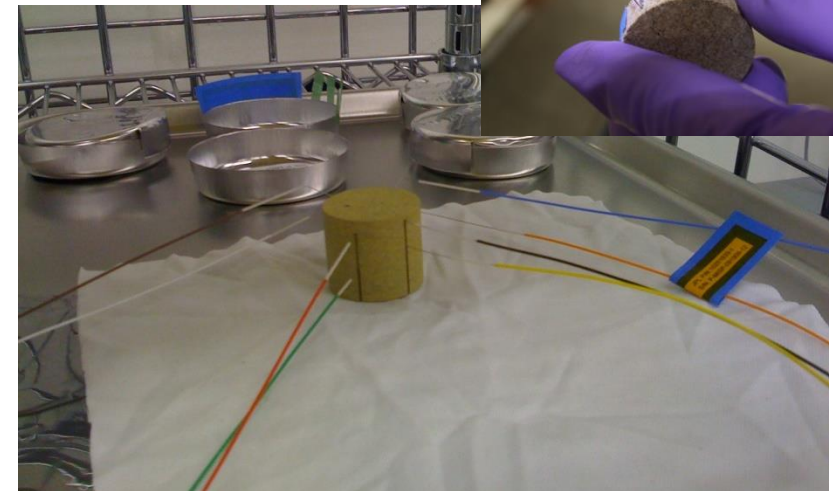
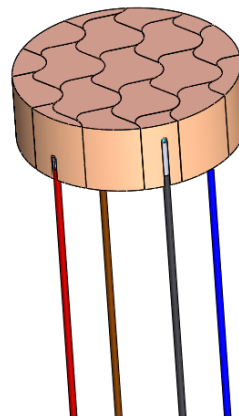
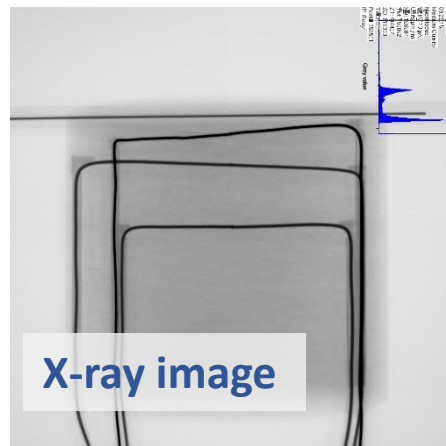
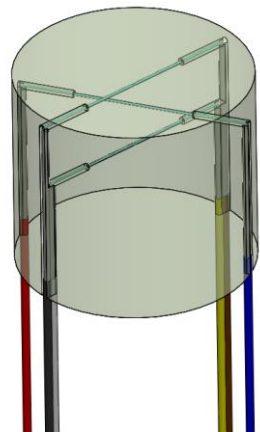
RTV-560



- HS TC plug is installed into counterbore with RTV-560 applied at the bottom face and sidewall
- Lead wires fed through the structure to route to data system



Thermocouple plug fabrication



# Pressure Transducers



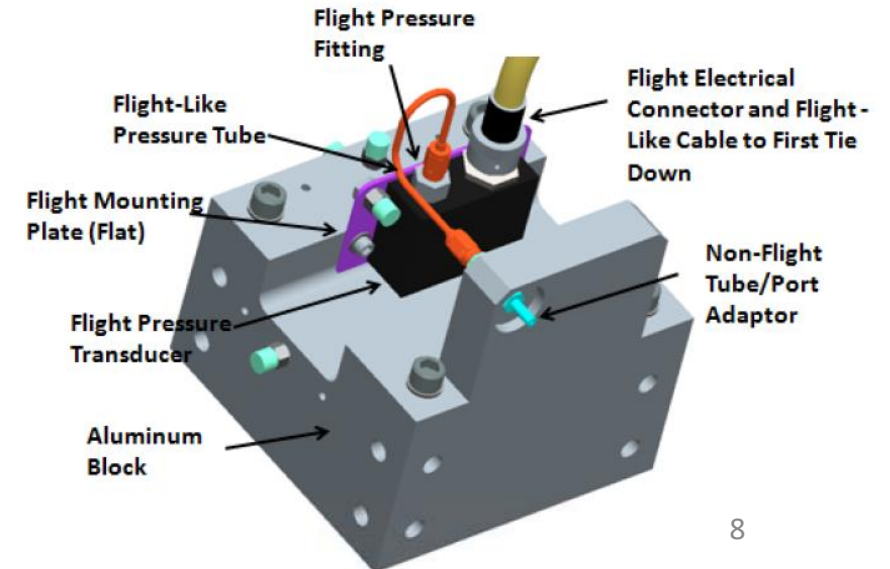
- Measure surface pressure in-situ on the heat shield or backshell of an entry vehicle
- Data are used to reconstruct freestream density and vehicle attitude
  - Angle of attack
  - Angle of sideslip
- Accommodation onto a flight aeroshell requires a hole through the TPS material and substructure
- Tubing is used to provide the pressure path to a transducer



*MEDLI2 Hypersonic and Supersonic pressure transducers installed on the Mars 2020 heat shield*

*(Courtesy: NASA/JPL-Caltech)*

*CAD image of Orion EFT-1 pressure transducer test configuration*

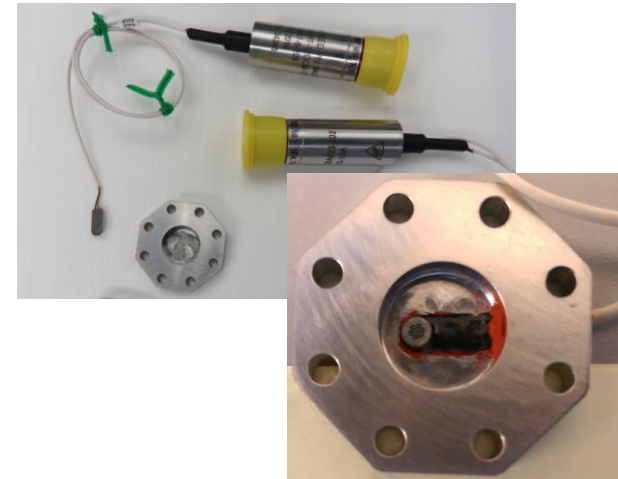


# Pressure Transducers



- Commercial and NASA built units have flown
- Various sensing technologies:
  - Piezoresistive strain gage
    - Honeywell PPT: Micromachined silicon die with piezoresistive strain gauges
    - NASA LaRC in-house design for MEDLI2
  - Variable Reluctance for very low pressure applications
    - Two variable reluctance sensors with a diaphragm in-between
    - Commercial unit for MEDLI2
- Design considerations:
  - Absolute vs differential
  - Calibration
  - Tubing and port design

*Artemis 1 shoulder pressure transducer*



*Orion EFT-1 pressure transducer*



*MEDLI2 Supersonic transducer*

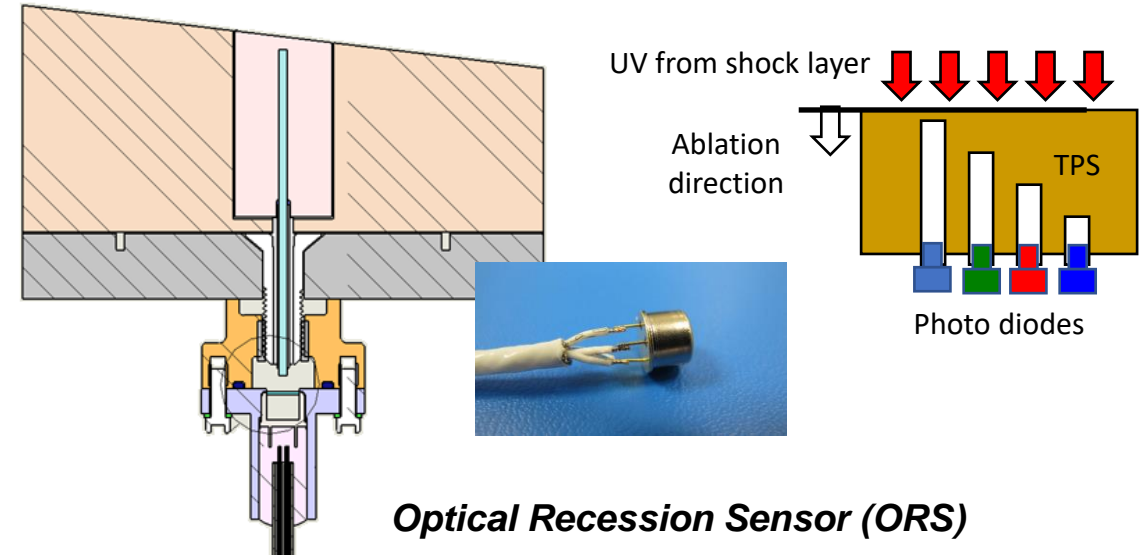


*MEDLI / MEDLI2 Hypersonic transducer*

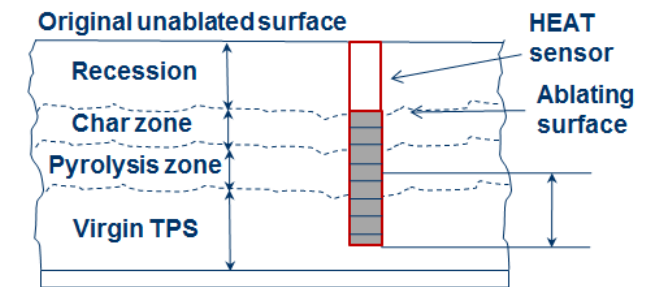
# Recession Sensors



- Optical Recession Sensor for Artemis 2
  - Blank holes at different depths are drilled in TPS
  - When the receding surface reaches the tip of blank hole, the drilled hole opens up
  - UV from shock layer is detected by the photodiode when drilled hole opens
  - Ideal response is a step function at time of opening
  - Qualified for flight on Artemis 2; will be installed on Artemis 2 heat shield later this year



- “HEAT” sensor
  - Two wires wound around a hollow Kapton tube
  - Resistance measurement is correlated to the uncharred length of the sensor
  - History:
    - Flown on MSL and Orion EFT-1
    - Evolved from NASA’s ARAD sensor



**Hollow aErothermal Ablation and Temperature (HEAT) sensor**

# Heat Flux Sensors and Radiometers



- Direct measurement of heat flux incident on a heat shield or backshell
- Thermopile is commonly used for the sensing element
- Total heat flux sensor detects combined convective and radiative heating
- Radiometers incorporate a window to block out convective heating contribution
  - If installed at the surface, deposition of TPS ablation products on a sensor's window can block or reduce the heat flux reading
  - If recessed beneath the surface, radiation from the TPS cavity can be a significant contribution of the measurement

**EFT-1 Heat shield Radiometer**



**MEDLI2 Backshell Radiometer**

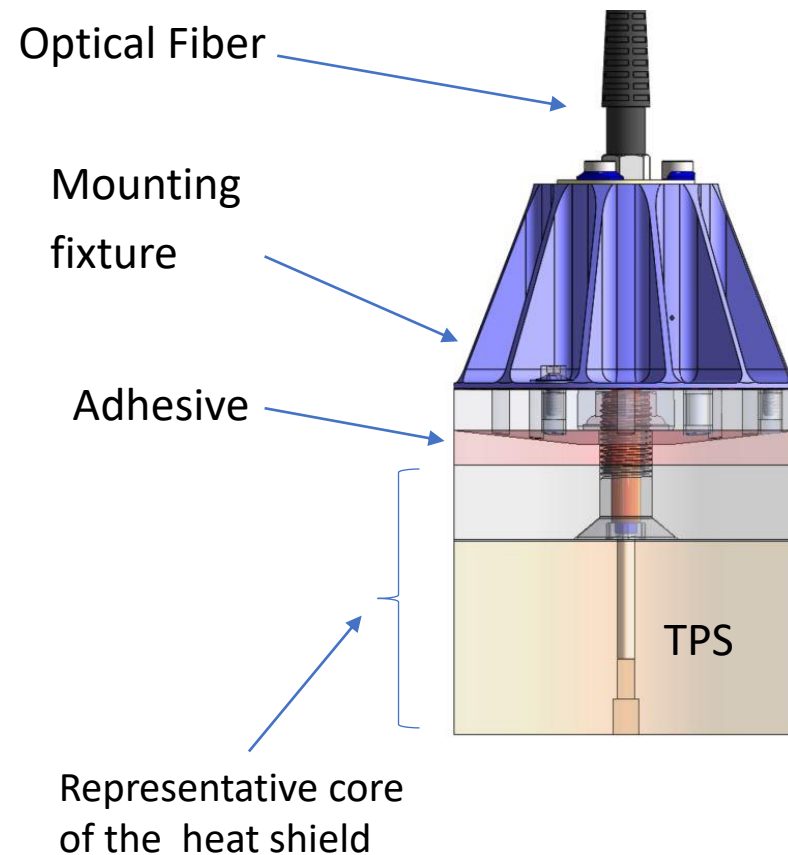


**MEDLI2 Backshell Total Heat Flux Sensor**

# Spectrometers



- Spectrometers provide wavelength information on shock layer radiation
- Artemis 2 spectrometer
  - COTS units qualified to meet environmental and functional requirements of the mission
  - Optical sub-assembly to provide light path and mounting scheme for fiber optic cable
  - Fiber optic cable is routed to housing containing two spectrometers
- Planned for flight on Artemis 3-5 missions



*Images of Artemis 2 spectrometer housing (development unit)* 12

# Data Acquisition Systems (DAS)

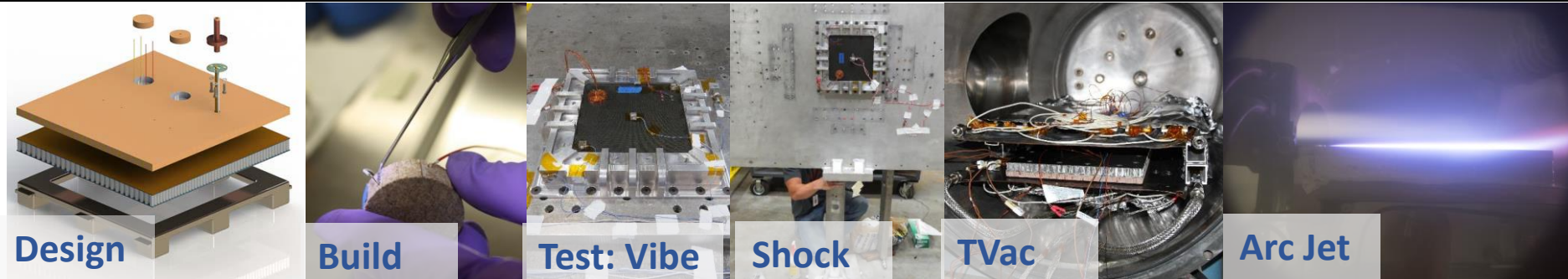


- Destinations such as Mars, Venus, and Titan pose many challenges for EDL data acquisition systems, including radiation, environmental loads, and volume constraints.
- It is not always possible to tie into the main mission's avionics system.
  - Separate, dedicated DAS for the EDL Instrumentation is often required
- High cost associated with qualifying a standalone DAS for spaceflight
  - Custom design
  - Electrical and mechanical interfaces
  - Qualification testing to meet temperature (often colder than  $-100\text{ }^{\circ}\text{C}$ ) and dynamic load requirements
- The high cost prohibits smaller mission classes such as Discovery and New Frontiers from using MEDLI-like systems, therefore limiting the EDL science that can be conducted by NASA.



***MEDLI2 Support System Electronics (SSE)***

# Making a Sensor “Spaceflight ready”



- **Development Environmental Testing**
  - To gain insight into design compatibility or functionality in expected environments
- **Do No Harm Testing**
  - Must prove via test that the addition of instrumentation will not cause harm to the overall mission
  - Typically integrated into an assembly to mimic flight-like installation and interfaces
- **Qualification (“Qual”) Testing**
  - Performed on dedicated Qualification Models of flight hardware (which is not intended to fly) in order to qualify the hardware design for the maximum expected flight environment plus margin, including margin on environmental duration or cycles.
- **Flight Acceptance / Protoflight Testing**
  - Protoflight or Flight Acceptance testing is performed on instrumentation which is intended to be flown. This testing verifies workmanship of the as-built sensor providing confidence in flight operation.
- **Unique Challenges to Space Missions:**
  - Extreme Low Temperatures During Long Cruise Phase
  - Maintaining Calibration of Sensors
  - Contamination Control and Planetary Protection

# Accommodation onto Flight Aeroshell



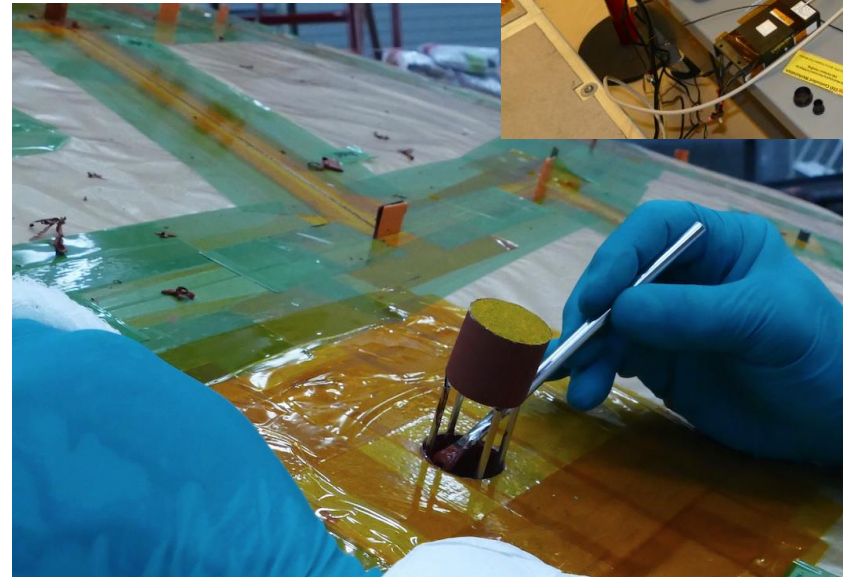
- Mounting and installation
- Mechanical and electrical interfaces
- Assembly, Integration, and Test (AI&T)



***MEDLI2 pressure transducer installation***

19 April 2022

(Courtesy: NASA/JPL-Caltech)



***MEDLI2 thermocouple plug installation***

(Courtesy: NASA/JPL-Caltech)

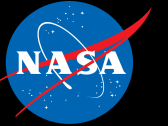
***MEDLI2 Post-Delivery  
functional testing***



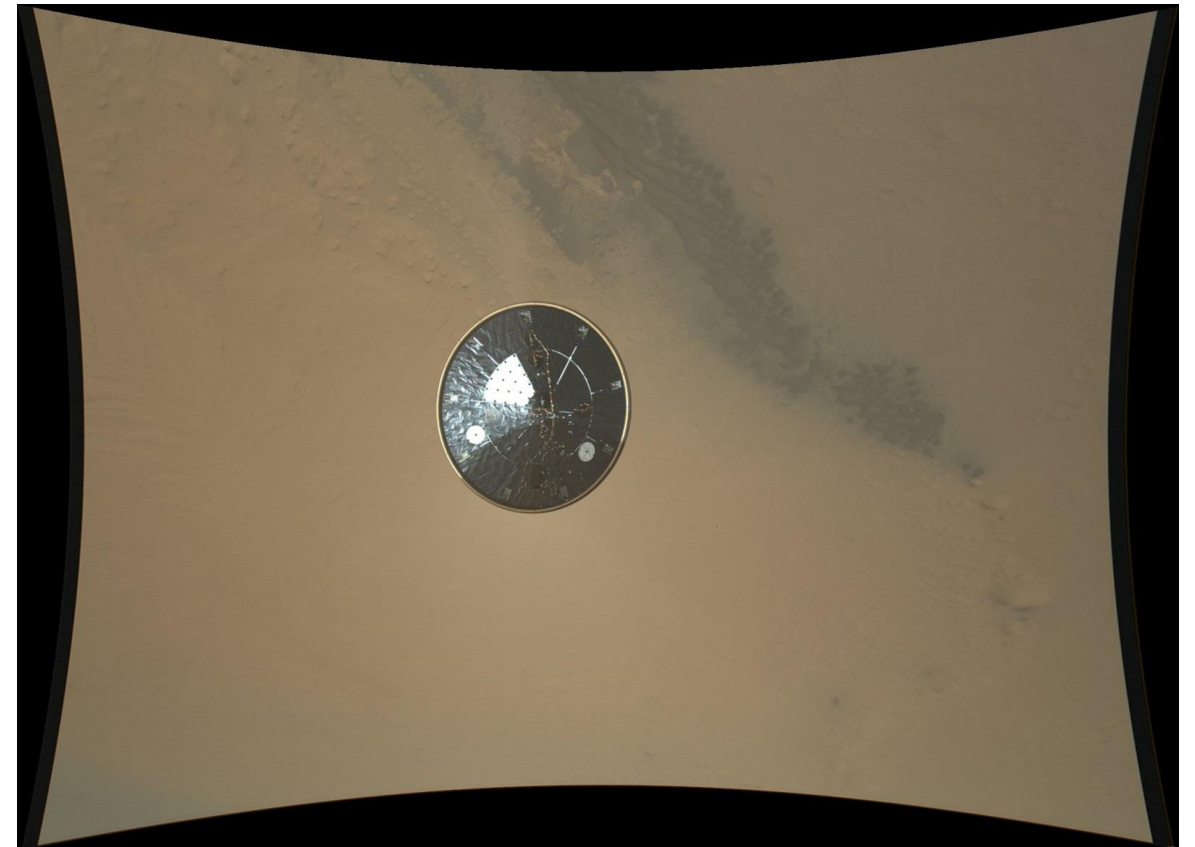
# NASA Flight Missions with EDL Instrumentation

- 2012 - Present Day
- Planned

# MEDLI (2012)

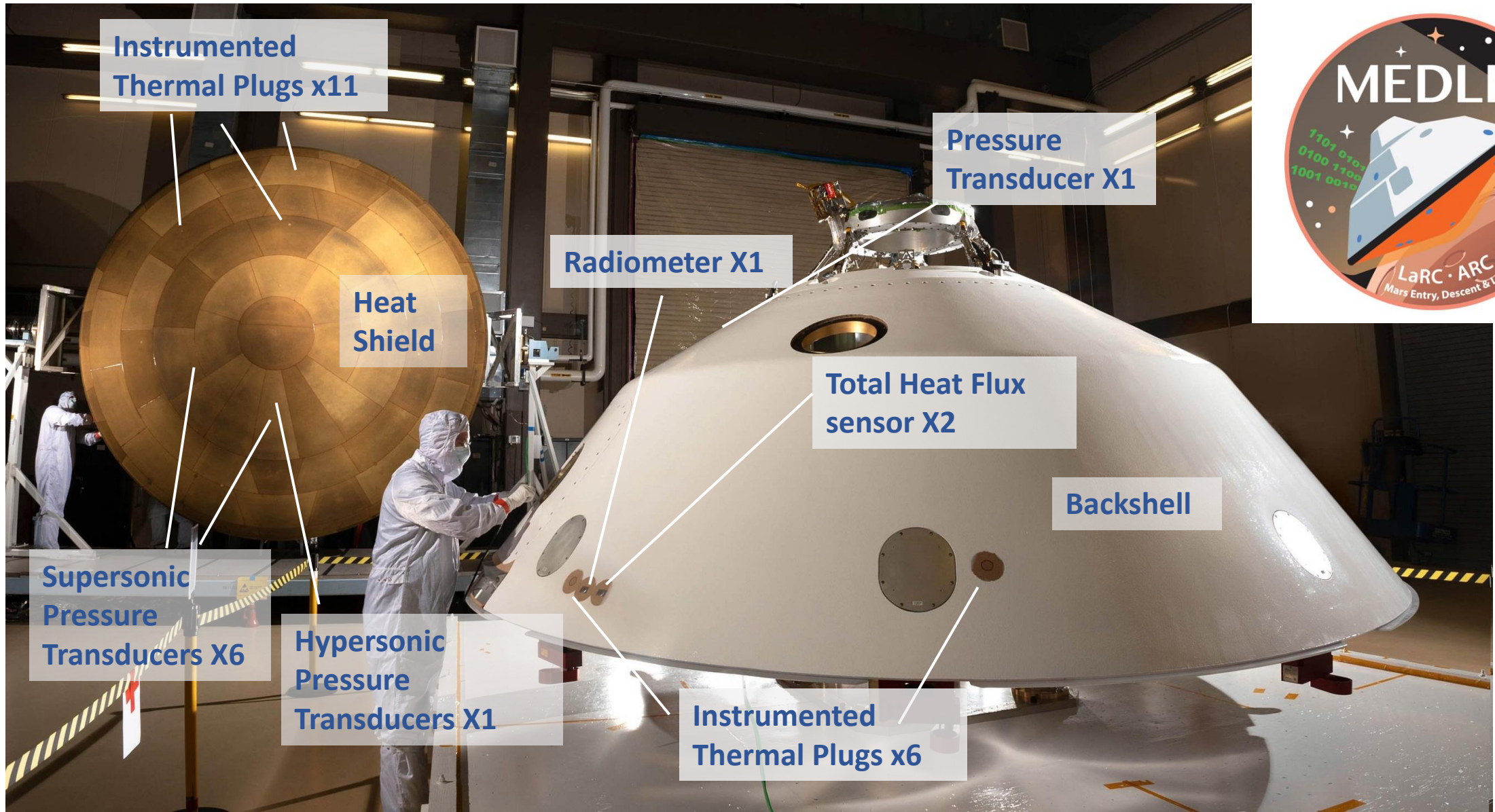


- Instruments:
  - 7 heat shield TC plugs
  - 7 hypersonic range pressure transducers
  - 1 Support System Electronics box
- Measured Pressure
  - Confirmed spacecraft aerodynamics
  - Independently measured attitude
  - Determined density profile
  - Determined wind component
- Measured Temperature and Ablation
  - Verified heating levels on spacecraft surface
  - Determined maximum total material ablation
  - Validated material response at Mars conditions



***View of the Mars Science Laboratory heat shield acquired by the Mars Descent Imager (known as "MARDI")***

# MEDLI2 (2021)



Instrumented Thermal Plugs x11

Pressure Transducer X1

Radiometer X1

Heat Shield

Total Heat Flux sensor X2

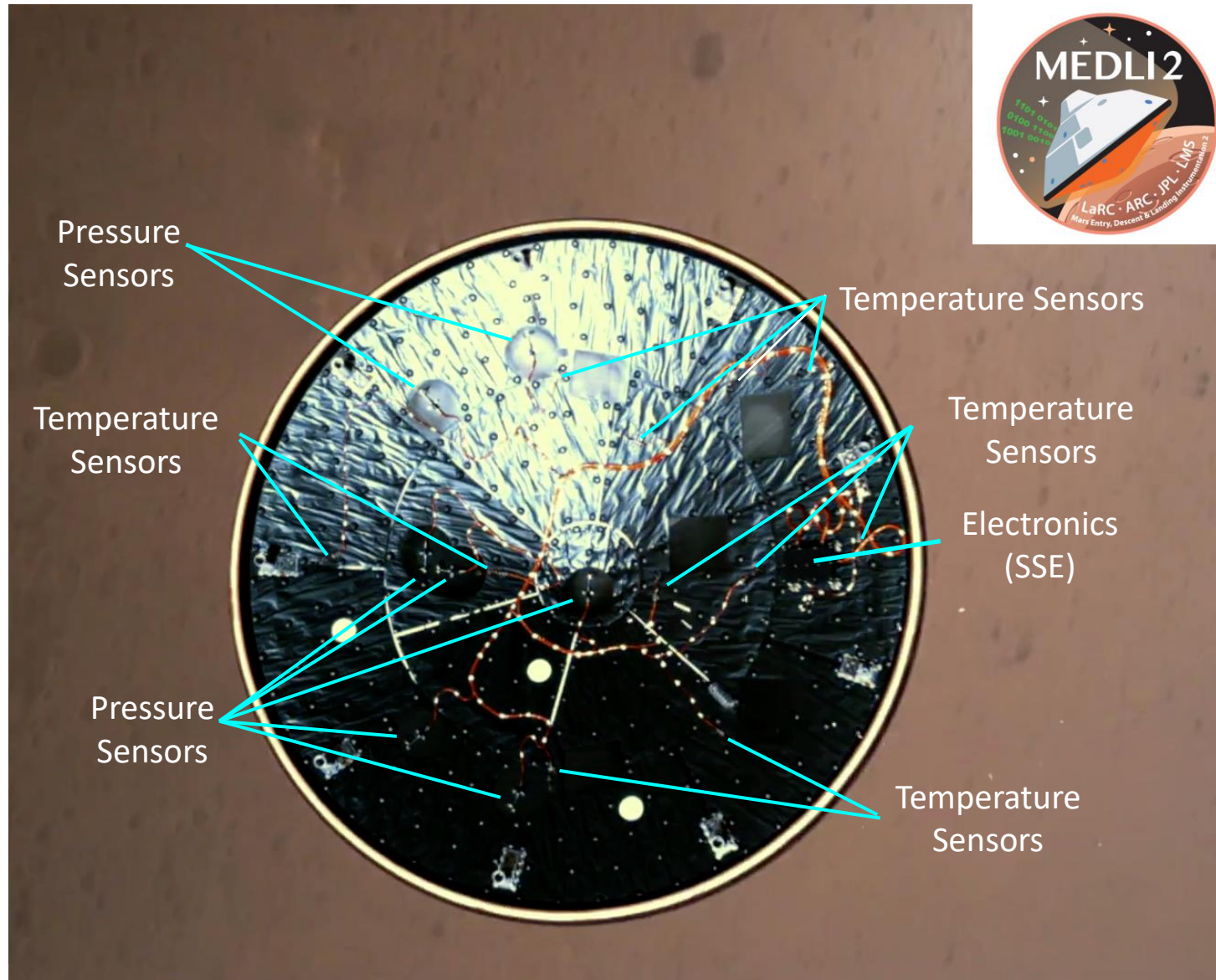
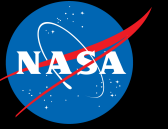
Backshell

Supersonic Pressure Transducers X6

Hypersonic Pressure Transducers X1

Instrumented Thermal Plugs x6

# MEDLI2 Hardware on the Mars 2020 Heatshield!



***This view is from the Rover Descent Camera about 5 to 6 seconds after Heat Shield Release. The entry vehicle is about 4 km AGL and moving at about Mach 0.6.***

***All MEDLI2 sensors worked perfectly and returned data! Several papers have been published.***

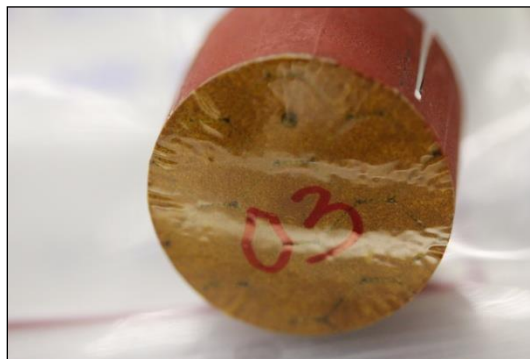
# Orion Exploration Flight Test-1



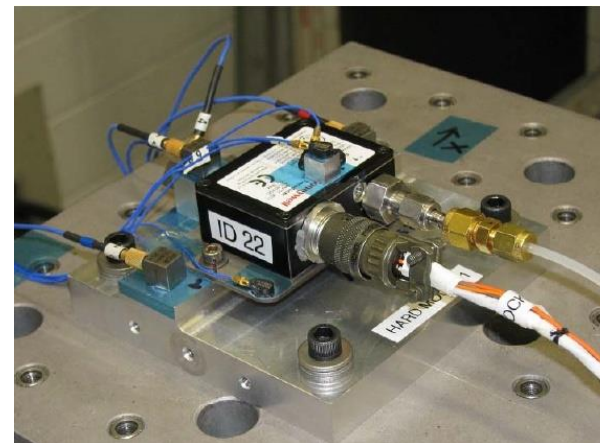
- Heat Shield GFE Instruments:
  - 34 Thermocouple Plugs
  - 9 Flush Air Data Systems (pressure transducers)
  - 2 Radiometers
- Successfully flown in Dec. 2014 – all sensors returned valuable flight data!
- TPS samples were extracted and instruments recovered in 2015



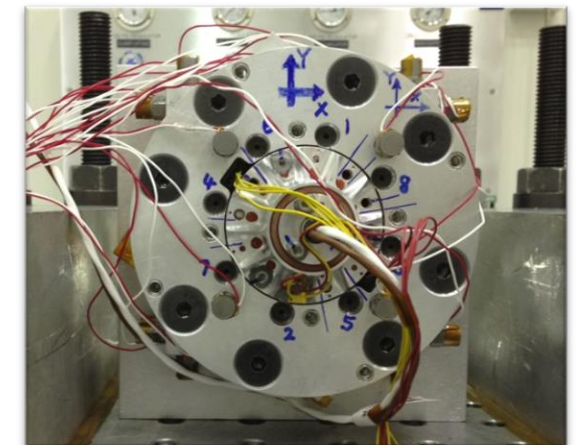
*Heat Shield Installed*



*Instrumented Plug before installation*

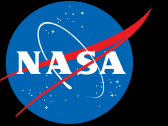


*FADS Testing*

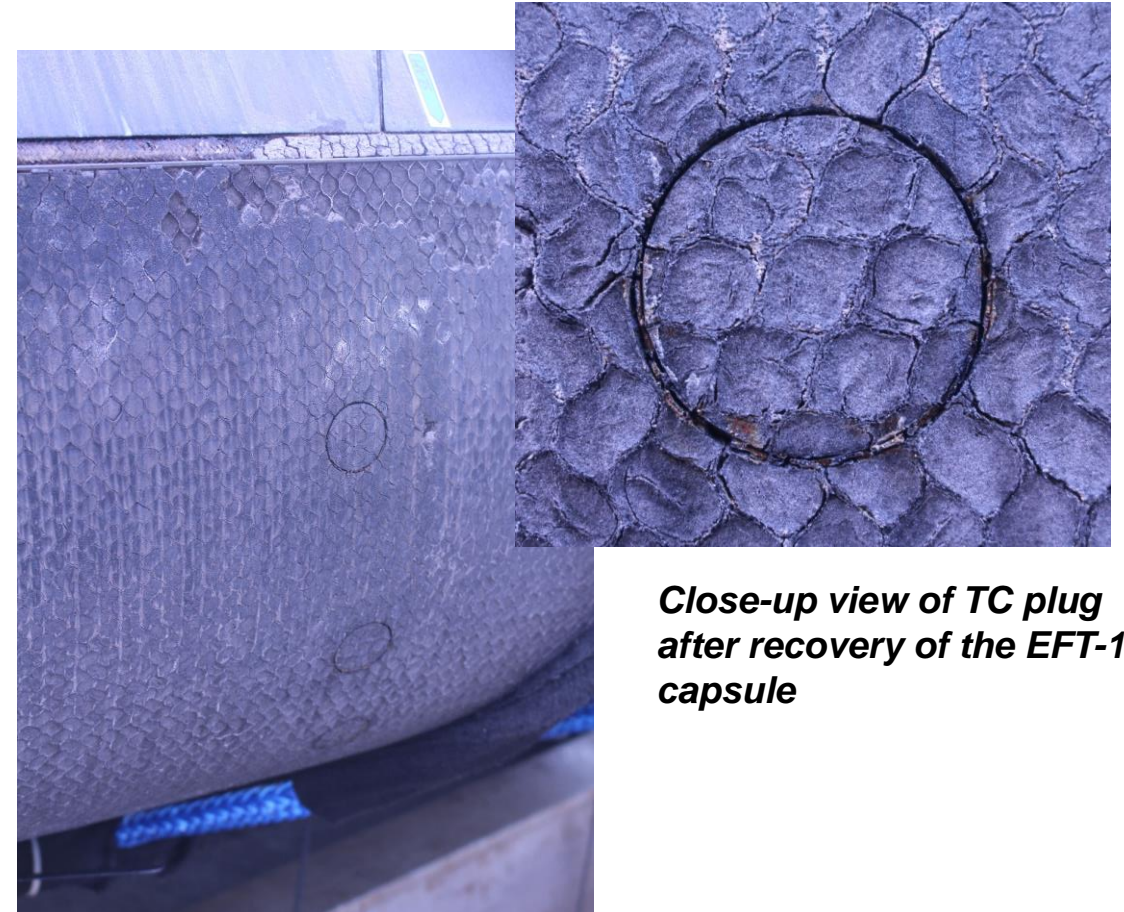


*Radiometer Testing*

# Orion EFT-1 Post-Flight Photos



**Post-Flight EFT-1 heat shield at  
NASA Marshall Space Flight Center**



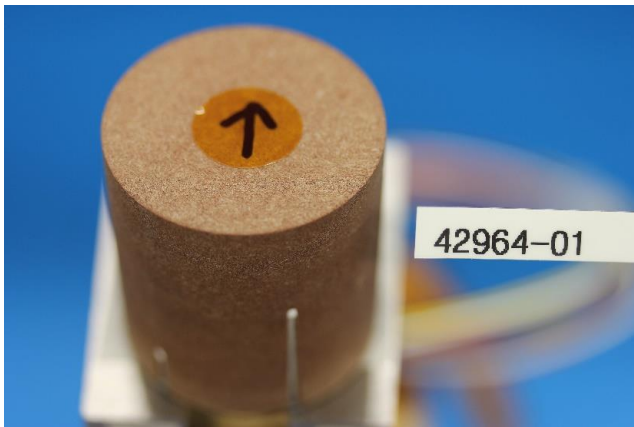
***Close-up view of TC plug  
after recovery of the EFT-1  
capsule***

***Image of EFT-1 heat shield shoulder upon recovery from  
water landing***

# Artemis 1 (Uncrewed)



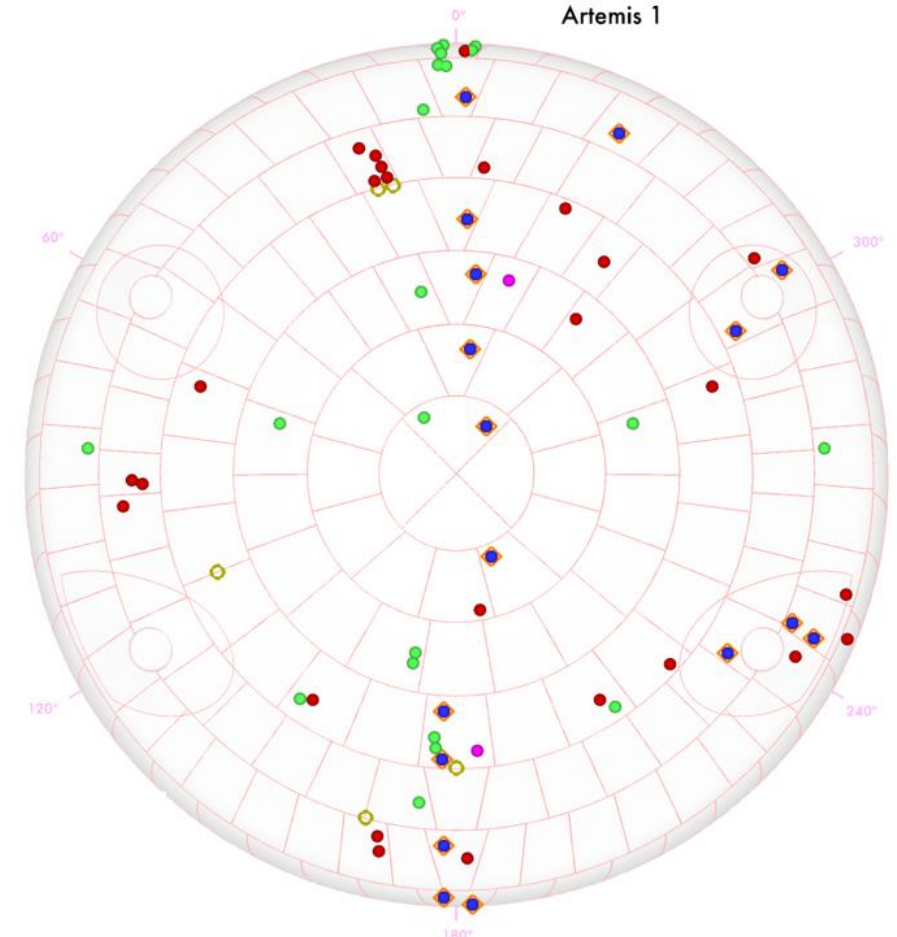
- Sensors will support flight test objectives:
  - Determine the aerodynamic environment
  - Determine aerothermodynamic environments and TPS performance
- Instruments:
  - 43 TC plugs
  - 2 Radiometers
  - 14 FADS acreage pressure transducers
  - 7 shoulder pressure transducers



Heat shield thermocouple plug



Heat shield radiometer



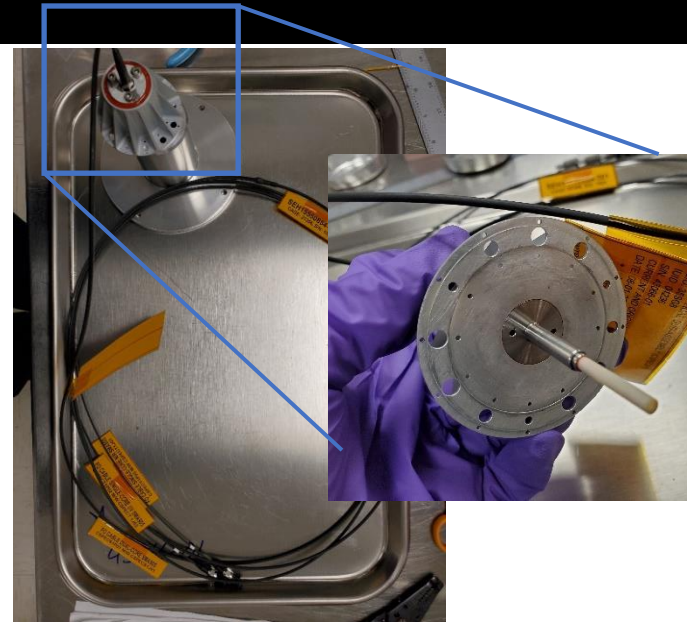
### Sensor Type Legend

- 4-TC Plug
- 2-TC Plug (Regular & Fence)
- Radiometer
- FADS / Pressure
- Bondline TC
- Seam TC

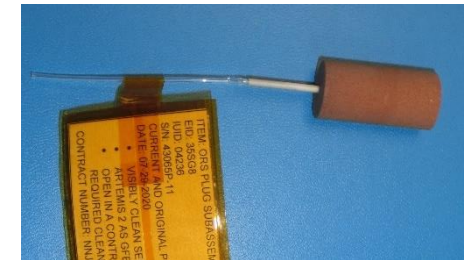
# Artemis 2 (Astronaut crew onboard)



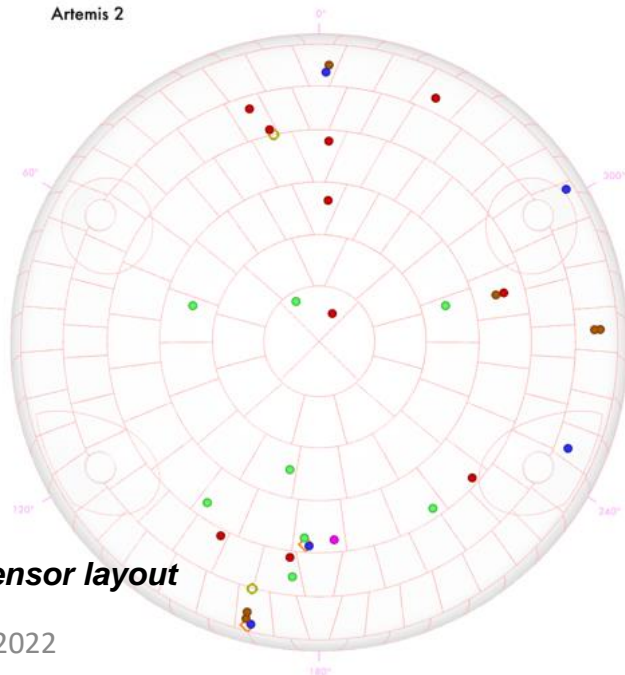
- Heat Shield GFE Sensors:
  - 15 TC plugs
  - 2 Radiometers
  - 8 FADS pressure transducers
  - 6 Optical Recession Sensors
- Backshell GFE Sensor:
  - 1 Radiometer



**Artemis 2 Heat Shield Spectrometer Optical Sub-assembly**



**Artemis 2 Heat Shield Optical Recession Sensor (ORS) – plug and diode housing**

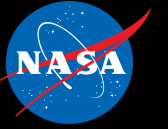


**Artemis 2 Backshell Radiometer**



**Artemis 2 Heat Shield Thermocouple (TC) plug**

# Dragonfly Entry Aerosciences Measurements (DrEAM) – Titan Entry in early 2030s

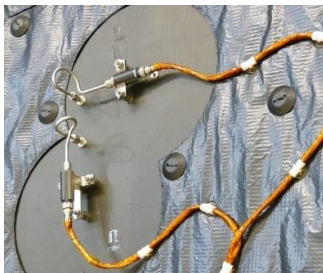


- **Dragonfly Sensors for Thermal Reconstruction (DragSTR)**
  - In-depth thermocouples to reconstruct the aerothermal environment and understand the material response of the Thermal Protection System (TPS)



*(Thermal plugs used for MEDLI2)*

- **Dragonfly Atmospheric Flight Transducers (DrAFT)**
  - Surface pressures on heatshield to understand flow and dynamics



*(Pressure transducers used for MEDLI2)*

- **COmbined Sensor System for Titan Atmosphere (COSSTA)**
  - Backshell sensors for radiative & total heat flux, pressure and temperature. Main focus is to understand radiative heating from CN.



*(Aerothermal sensors used for ExoMars)*

- **Data Acquisition System (DAS)**
  - DLR is also providing the data acquisition system for all the DrEAM instruments

*(DAS box used for ExoMars)*



# EDL Instrumentation Future Needs

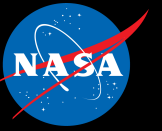


Physical Parameter	Sensor	Sensor Accuracy and/or Resolution	Type of TPS		
			Rigid Ablator	Flexible	Woven
TPS In-Depth Temperature	Thermocouple	$\pm 50^{\circ}\text{C}$ at $1,260^{\circ}\text{C}$	●	◐	●
	Fiber Optic Sensing System	$\pm 5^{\circ}\text{C}$ at $350^{\circ}\text{C}$	●	◐	●
Total heat flux	Thermopile or Schmidt-Boelter sensor	$\pm 1 \text{ W/cm}^2$ at $15 \text{ W/cm}^2$	●	●	●
Radiative heat flux	Radiometer	$\pm 1 \text{ W/cm}^2$ at $15 \text{ W/cm}^2$ (excluding effects of TPS)	●	✖	●
	Spectrometer	1 nm spectral resolution	◐	✖	●
TPS Surface Pressure	Pressure transducer	$\pm 1\%$ forebody at 34 kPa $\pm 4 \text{ Pa}$ aftbody at 680 Pa	●	✖	●
TPS Recession	Recession sensor (e.g., optical)	$\pm 0.1 \text{ cm}$ at $400 \text{ W/cm}^2$	◐	✖	●
TPS Surface Shear Stress	Under development	(To be determined)	✖	✖	✖

**Legend:**

- = Flight proven, fully capable sensor
- ◐ = Flight qualified and/or scheduled on upcoming missions
- = Potentially capable (development and/or qualification needed)
- ✖ = No existing measurement capability; sensor R&D necessary

*Future work is needed to advance the state-of-the-art towards a goal of having flight-proven sensors across the board*

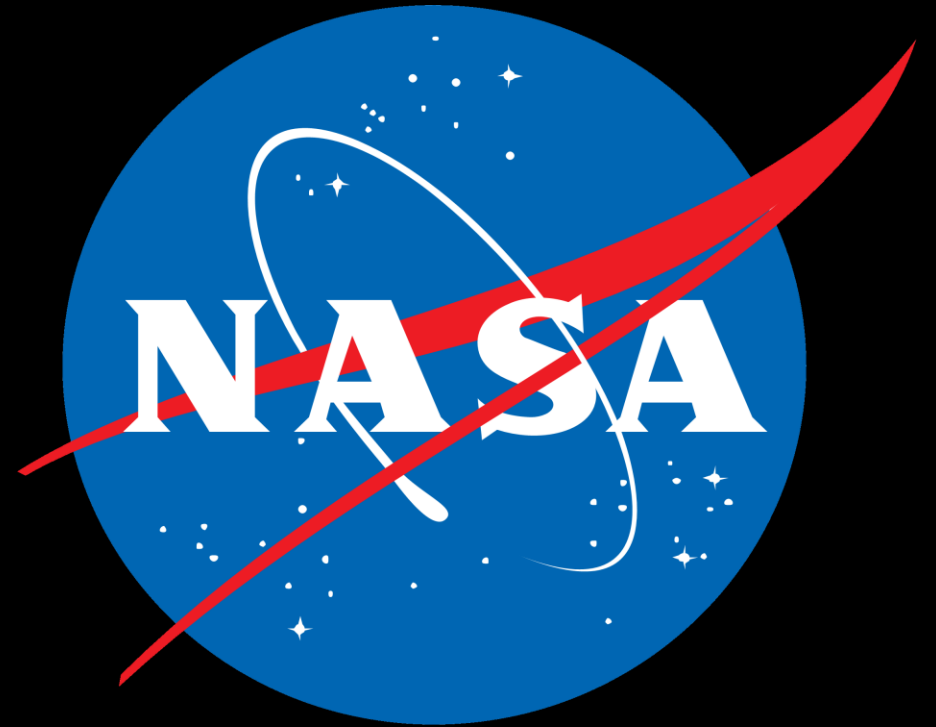


# Questions?

The EDL instrumentation technologies presented herein are available for tech transfer from NASA.

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Ames Research Center  
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