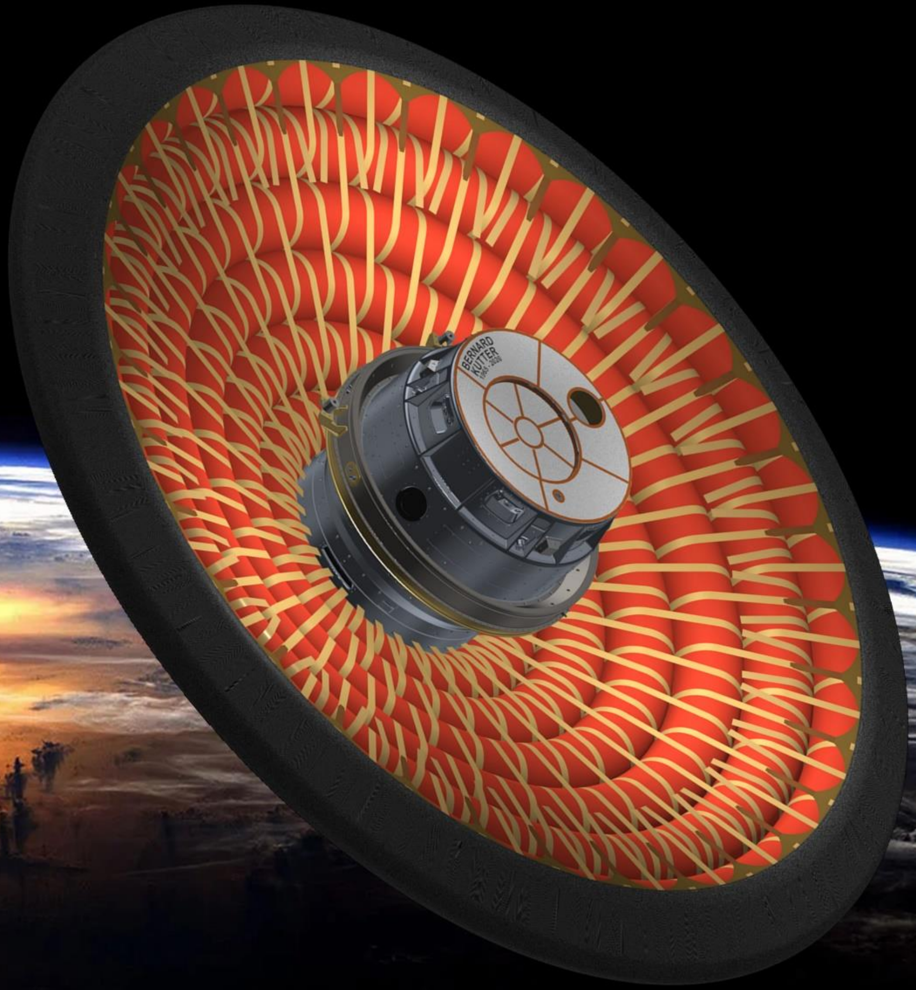
Low-Earth Orbit Flight Test
of an Inflatable Decelerator

National Aeronautics and
Space Administration

Evaluation of the LOFTID Flight Thermocouple Measurements



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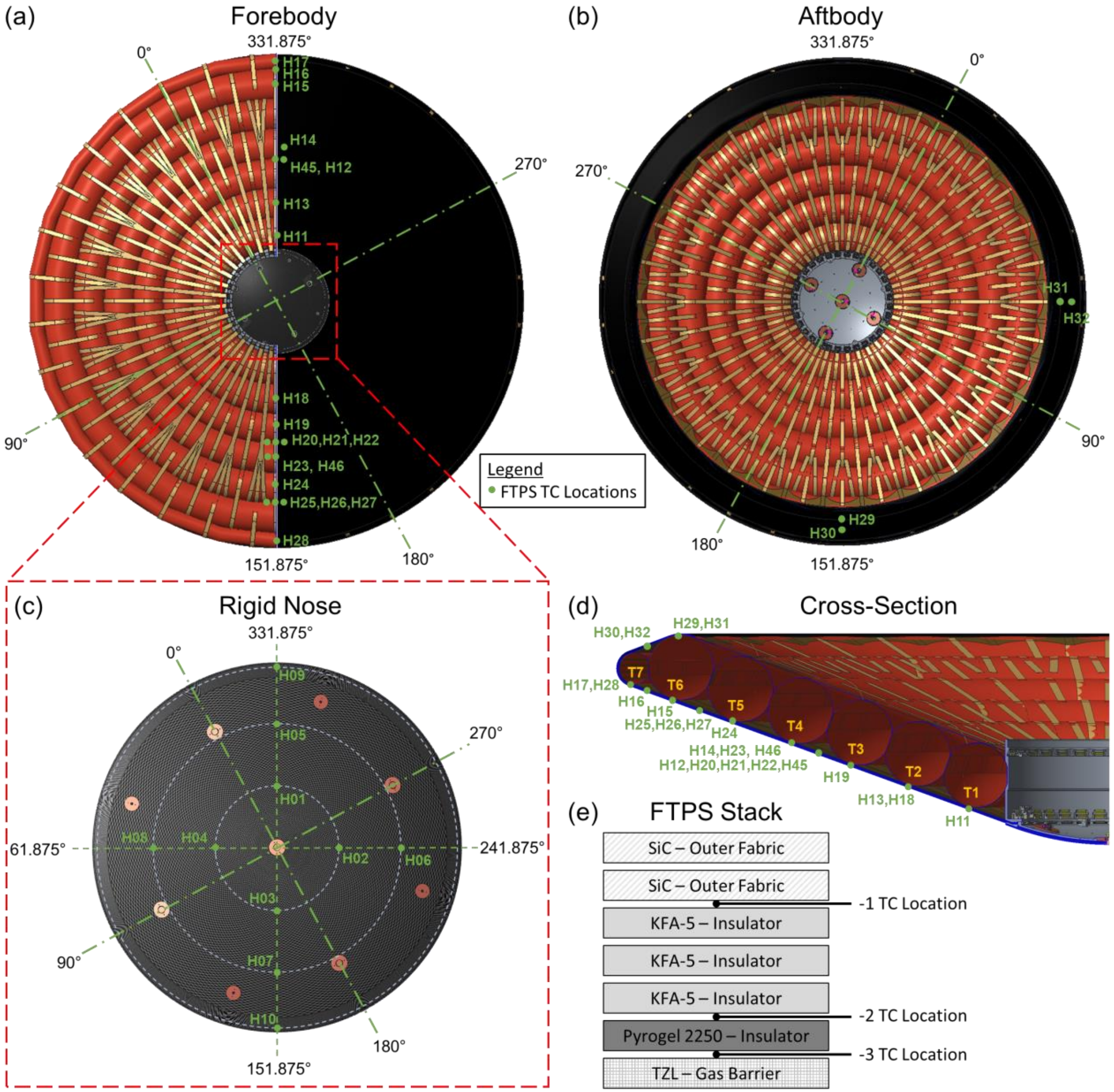
Introduction

- **The LOFTID instrumentation suite included thermocouples (TCs) integrated at various locations across the vehicle and at three depths within the Flexible Thermal Protection System (FTPS) stack**
  - 20 TCs in the FTPS on the rigid nose
  - 36 TCs in the FTPS on the deployable aeroshell
- **The accuracy of the flight TC measurements is critical for validation of the thermal models which support the ongoing effort to scale HIAD technology to diameters of 10 meters or greater**
- **Naming convention for the LOFTID FTPS TCs consists of 7 characters (e.g., LTH01-1)**

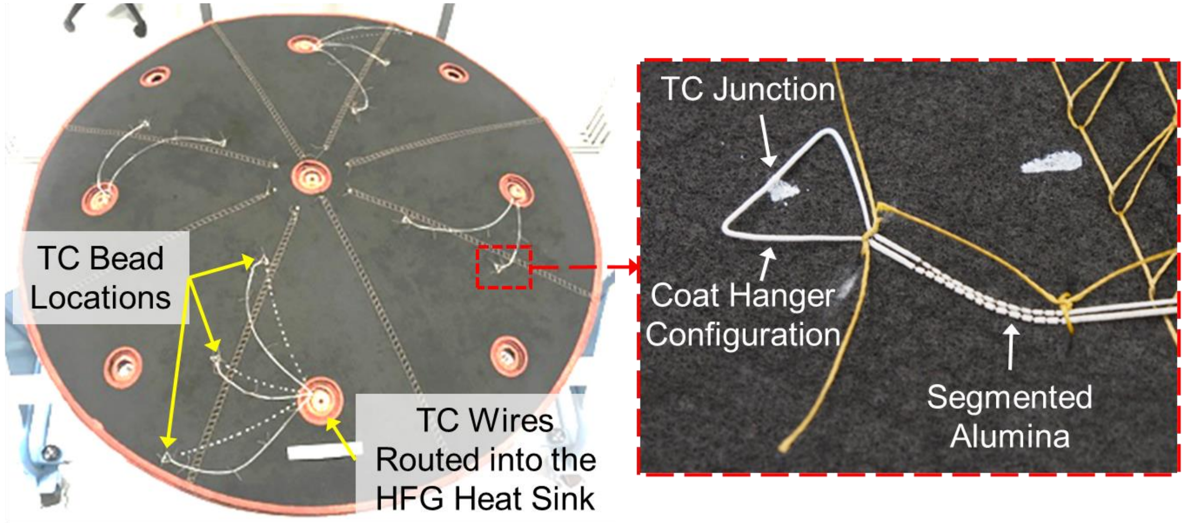
L = LOFTID
T = Thermal
H = HIAD Aeroshell
= Measurement Location on the Vehicle
- = Dash
= TC Location within the FTPS Stack



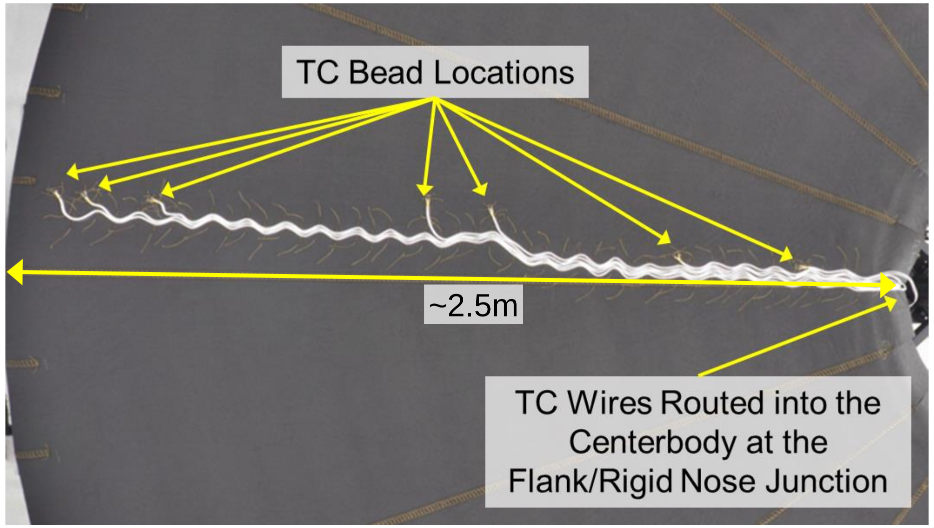
Thermocouple Routing

- **Rigid Nose**
  - TCs were routed from the measurement location through the heat flux gage heat sink to get into the centerbody and connect to the Aeroshell Data Acquisition Unit (ADAU)
  - Alumina insulation on the SiC/KFA (-1) TCs was segmented to allow the TC to bend
    - The segmented regions were covered with a ceramic braid insulation to mitigate the direct contact between the TC leads and electrically conductive materials
    - The resistance between the TC leads and the metallic structure of the rigid nose was the ideal open loop response for only four of the ten SiC/KFA (-1) TCs
- **Deployable Aeroshell**
  - TCs were routed within the same layer that they were monitoring the temperature back to the rigid nose and into the ADAU in the vehicle centerbody
  - Eliminated the need to put holes in the FTPS layers to allow the TCs to travel through-the-thickness
  - TC leads were routed for an appreciable distance through a region that exposed them to thermal gradients and temperatures that exceeded the predicted temperature at the intended measurement location

(a) Rigid Nose



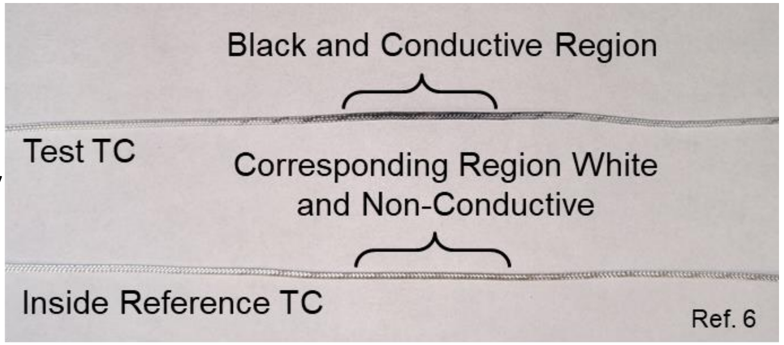
(b) Deployable Aeroshell

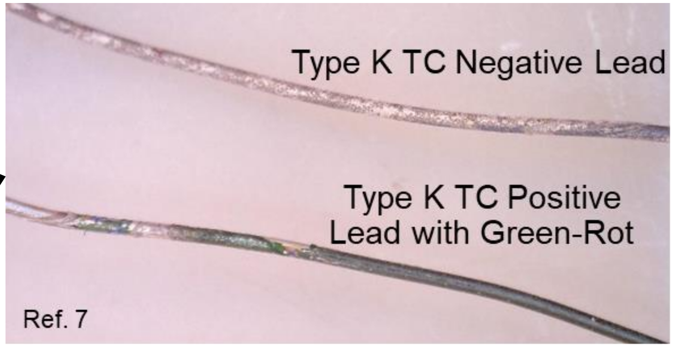


Thermocouple Uncertainty Reduction Recap

- **Pre-flight TC measurement uncertainty reduction testing via a series of tube furnace tests and arc jet test revealed four major issues:**

	Issue	Mitigation Strategy
1	Carbon deposits on the TC insulation electrically shorting the TC leads	Add a mica tape wrap on each individual TC lead
2	Glass braid TC insulation melting resulting in electrical shorting	Use Nextel 312 ceramic braid TC insulation
3	Type K TC wire melting resulting in loss of measurement	Use Type R TCs which have a higher temperature limit
4	Green-rot of Type K TC wire resulting in erroneous measurements	Use Type N TCs which are less susceptible to green-rot





- **Different TC types and TC insulations were used at each location within the LOFTID FTPS to simultaneously meet temperature measurement requirements and packing requirements**

LOFTID FTPS TCs

FTPS Location	TC Type	TC Insulation
Nose, -1	Type R	Alumina
Nose, -2	Type N	Mica/Ceramic
Nose, -3	Type K	Mica/Glass
Deployable Aeroshell, -1	Type N	Mica/Ceramic
Deployable Aeroshell, -2	Type K	Mica/Glass
Deployable Aeroshell, -3	Type K	Mica/Glass
Aftbody, -1	Type N	Mica/Ceramic

- **For further details see:**

Ref. 6: Miller, R.A., et al., AIAA JSR, Vol. 60, No. 2, 2023, pp. 591-600.
Ref. 7: Miller, R.A., et al., AIAA JSR, Vol. 60, No. 4, 2023, pp. 1043-1354.

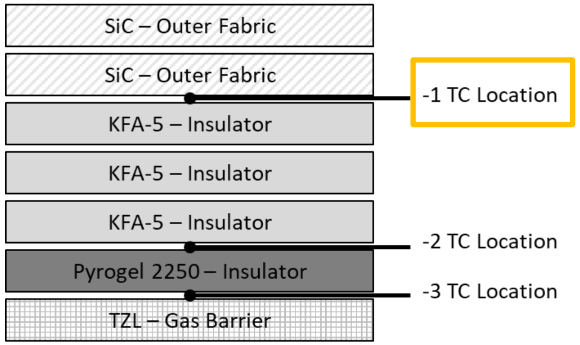
Overview of How the Data Will be Presented

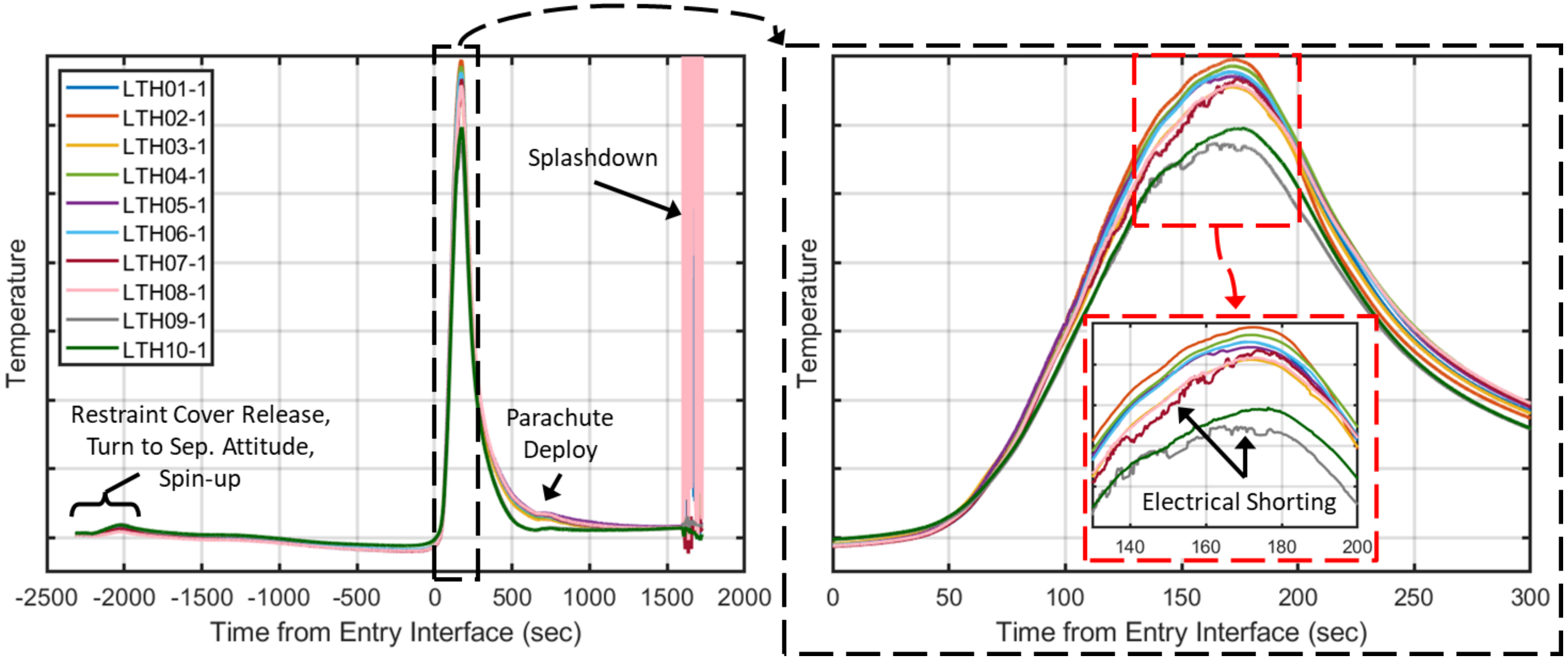
General Observations Pertinent to All TCs

- All TCs were measuring in-kind with each other prior to entry
- Small changes in slope prior to entry align with mission events such as restraint cover release, the Centaur turning to the LOFTID separation attitude, and spin-up
- Small changes in slope are seen at the time of the parachute deployment
- Splashdown is evident in every TC measurement. The noisy and/or open-loop response at splashdown likely due to TC insulation not being watertight.

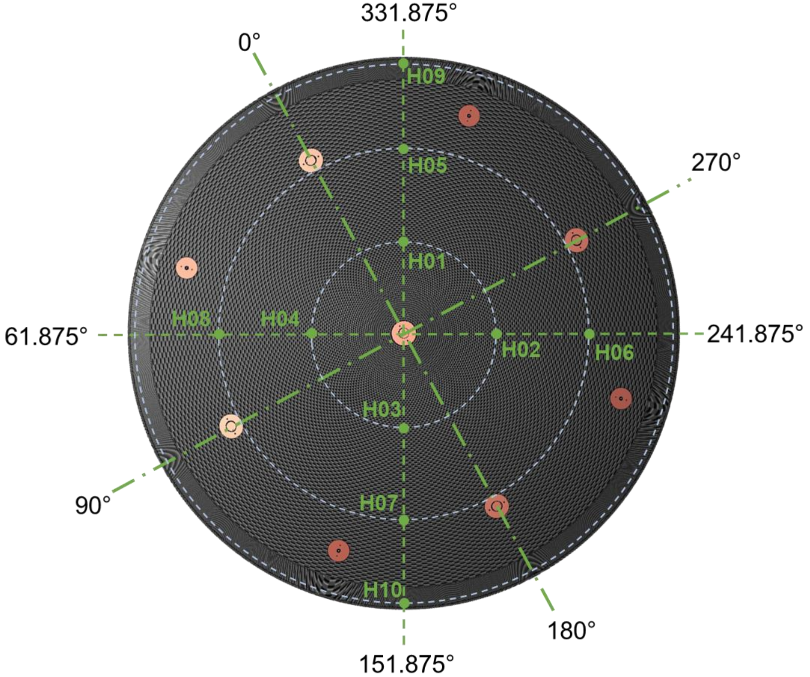
FTPS Location	TC Type	TC Insulation
Nose, -1	Type R	Alumina

FTPS Stack





Rigid Nose



Rigid Nose TCs: SiC/KFA (-1)

FTPS Location	TC Type	TC Insulation
Nose, -1	Type R	Alumina

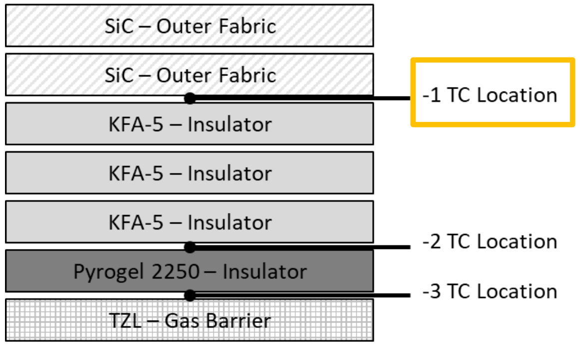
Erroneous Measurements

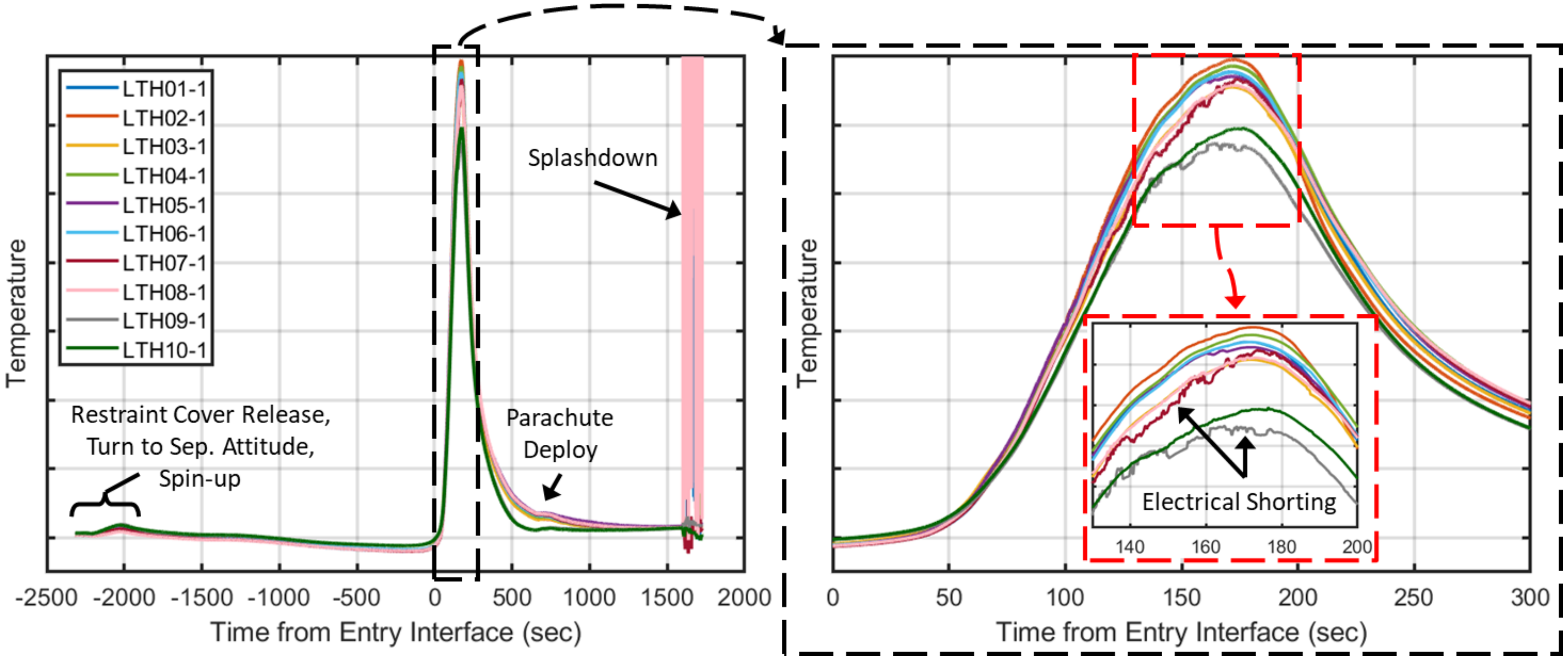
- LTH07-1 (dark red line) and LTH09-1 (gray line) became noisy near peak heating
  - Likely due to electrical shorting at the segmented alumina TC insulation
  - Error is assumed to be minimal since the TCs with the noisy response measured in-kind with the other TCs at the same circumferential location

Future Work

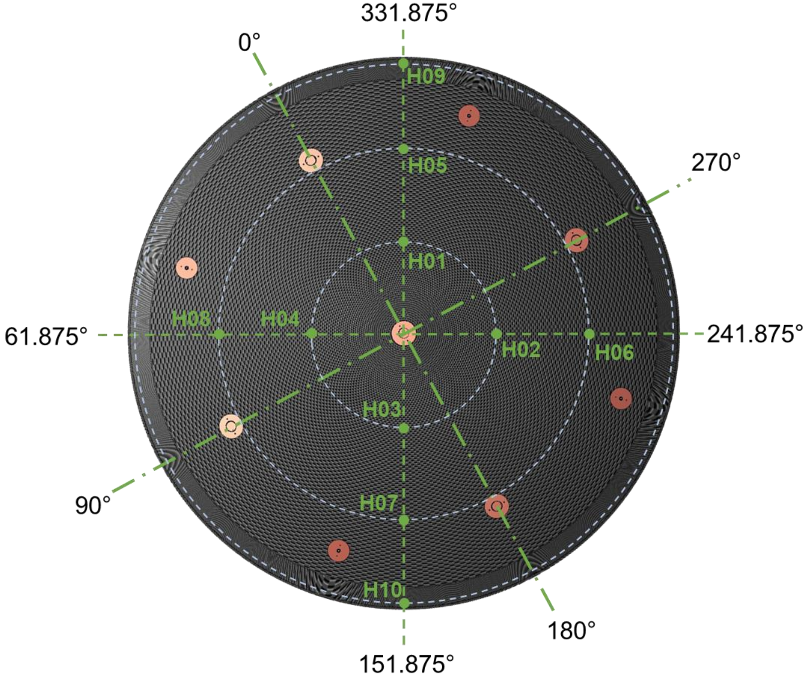
- For future missions, the segmented alumina sections should be removed or covered over to eliminate the possibility of electrical shorting

FTPS Stack





Rigid Nose



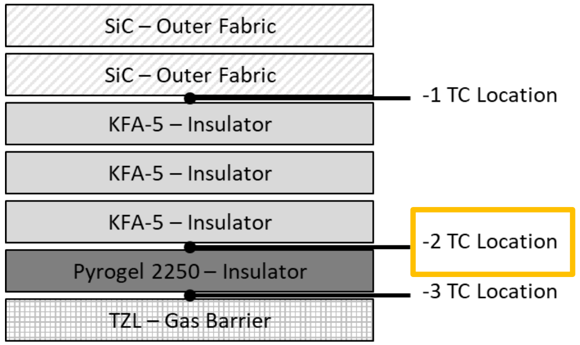
Rigid Nose TCs: KFA/2250 (-2)

General Observations

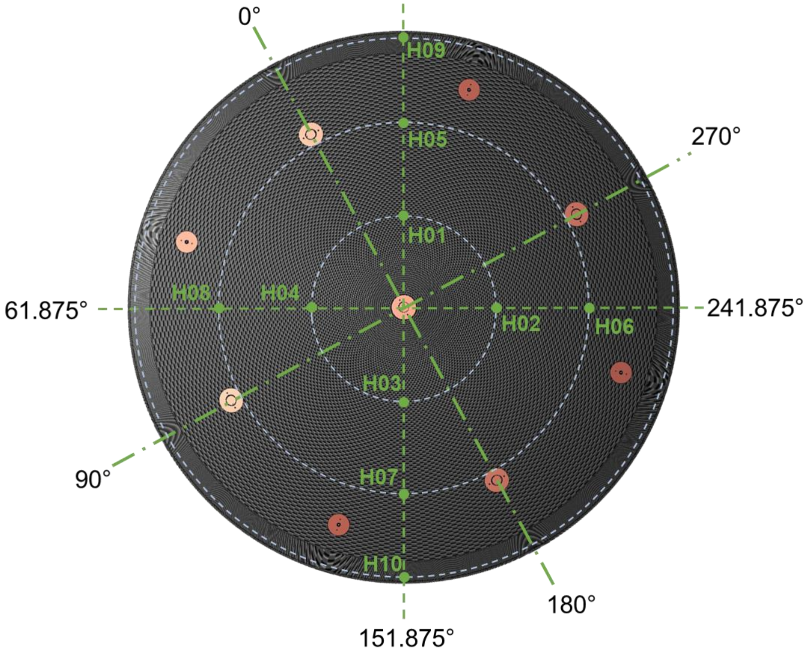
- LTH03-2 (yellow line) displayed a change in slope near the peak measured temperature.
  - Does not appear to be due to electrical shorting and does not easily correlate with other mission events.
  - Could be due to poor or varying thermal contact between the TC and the FTPS, but the precise cause is unknown.
- Type N TCs with mica/ceramic insulation performed as expected

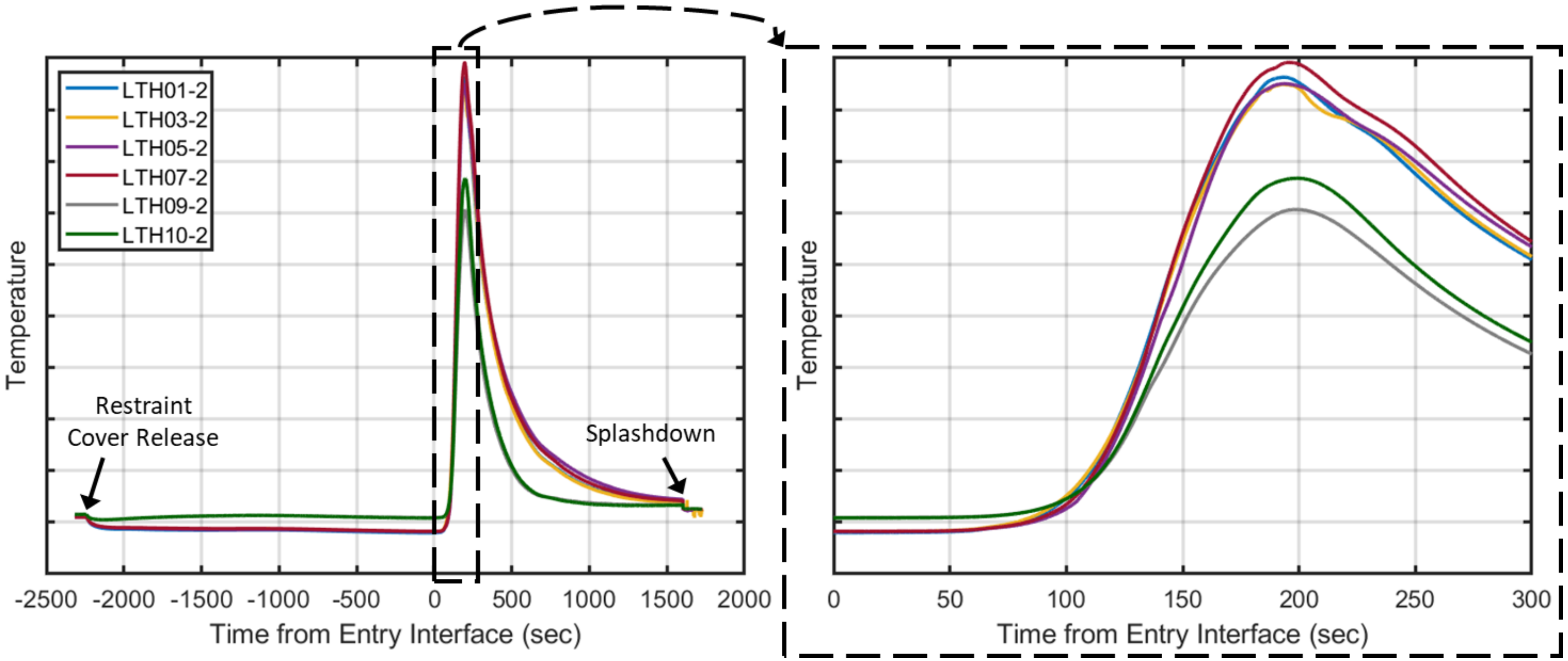
FTPS Location	TC Type	TC Insulation
Nose, -2	Type N	Mica/Ceramic

FTPS Stack



Rigid Nose





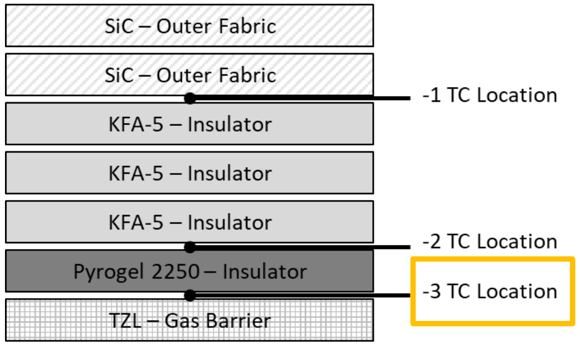
Rigid Nose TCs: 2250/TZL (-3)

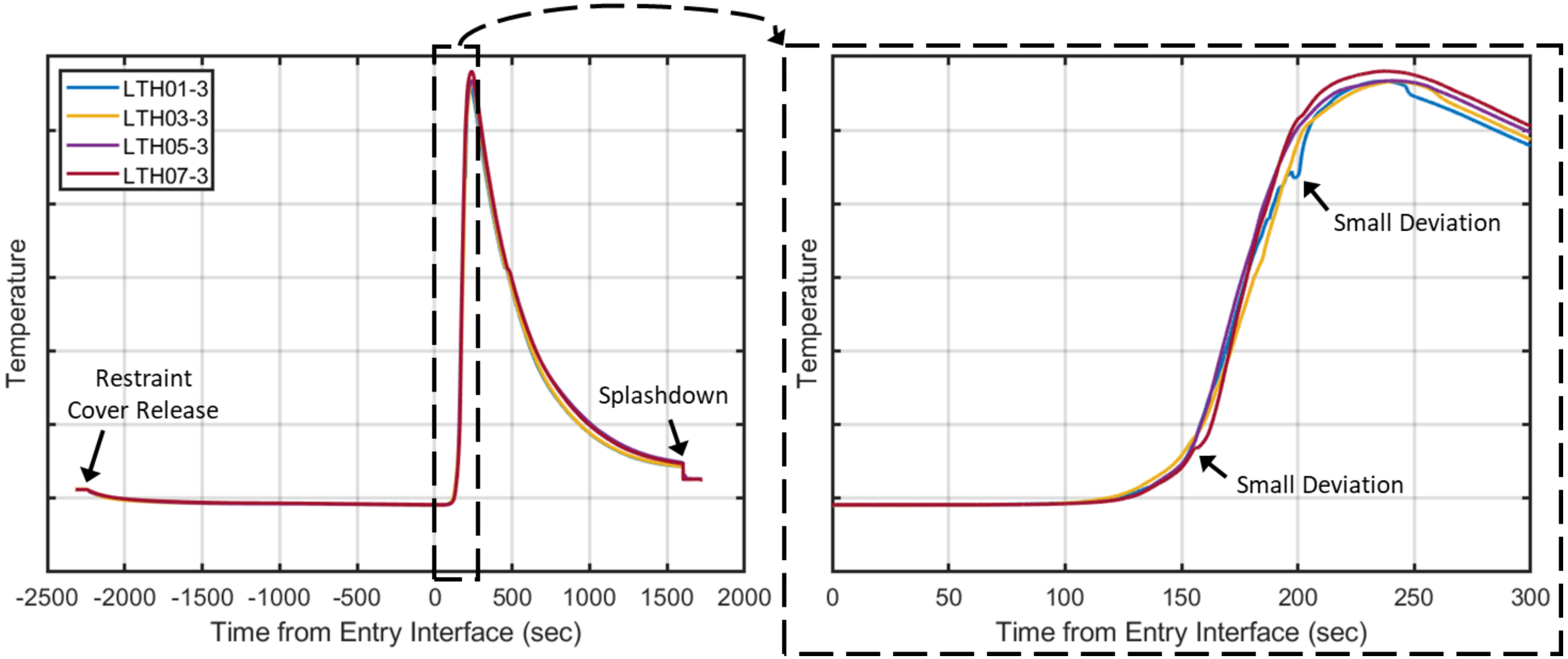
General Observations

- LTH01-3 (blue line) and LTH07-3 (dark red line) display some small deviations, but otherwise measured in-kind with the other TCs
  - These small deviations do not appear to be due to electrical shorting and they do not easily correlate with other mission events.
  - These small deviations could be due to poor or varying thermal contact between the TC and the FTPS, but their precise cause is unknown.
- Type K TCs with mica/glass insulation performed as expected

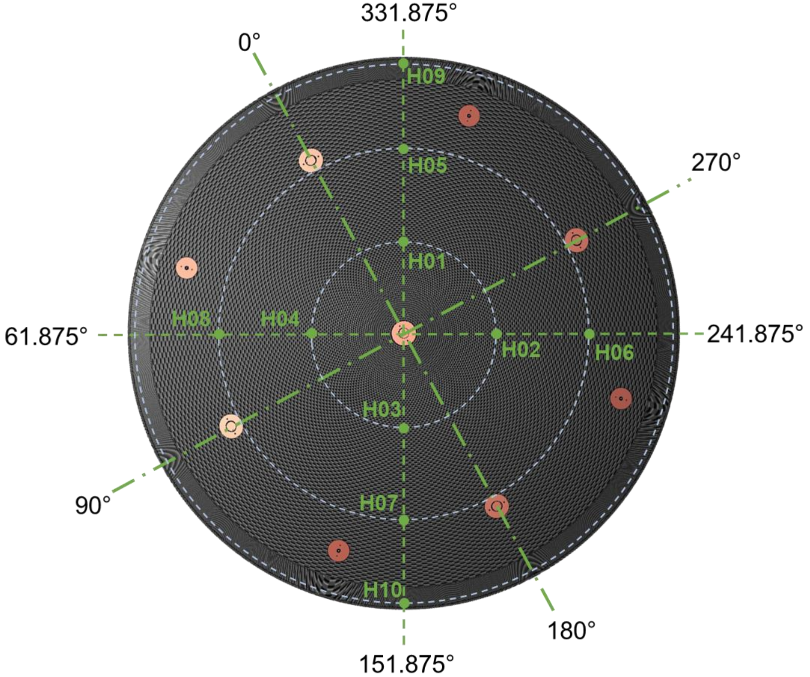
FTPS Location	TC Type	TC Insulation
Nose, -3	Type K	Mica/Glass

FTPS Stack





Rigid Nose

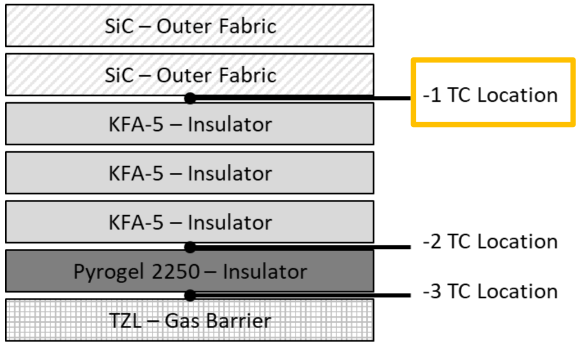


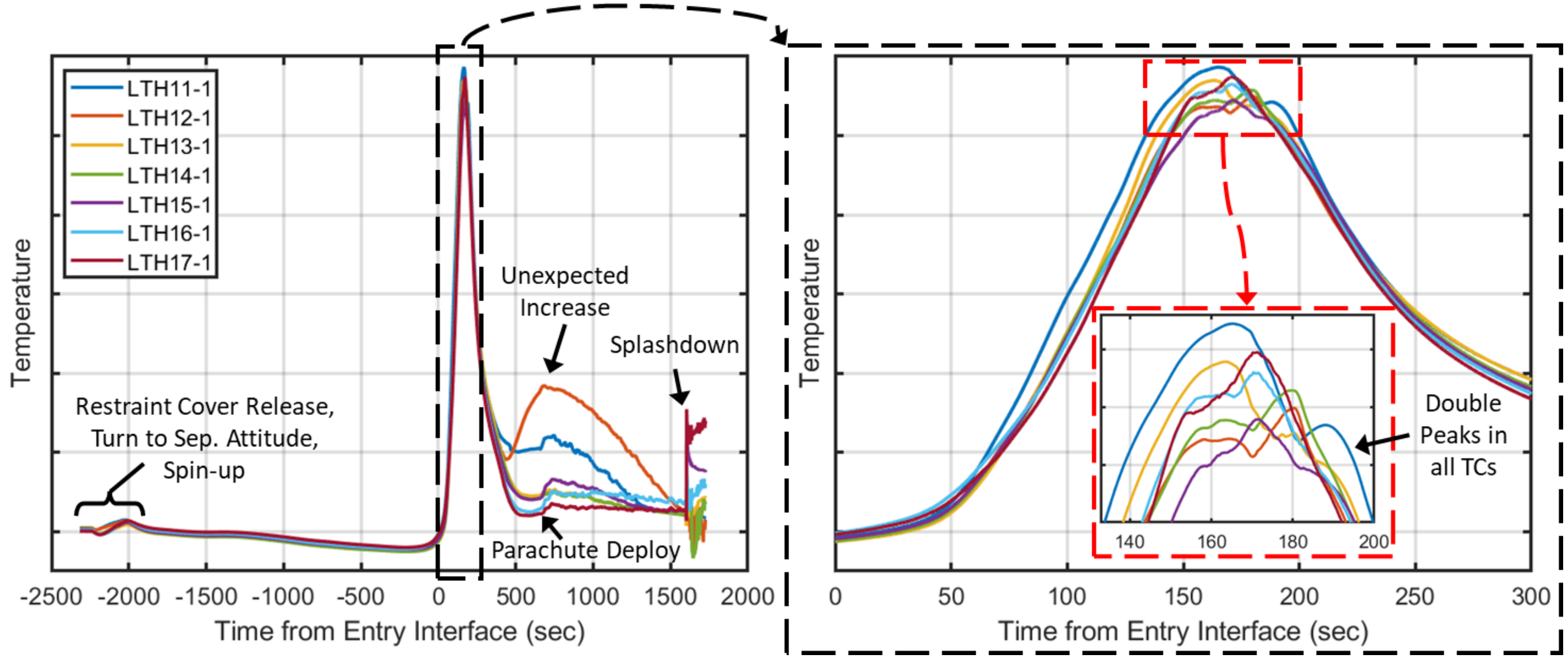
Deployable Aeroshell TCs: SiC/KFA (-1) 331.875° Radial

- **General Observations**
  - All TCs include a double peak at peak heating which could be the transition to turbulence
    - Second peak occurs closest to the shoulder first (LTH17-1, LTH16-1, and LTH15-1), then in the mid-flank (LTH14-1, LTH13-1, and LTH12-1), and lastly closest to the rigid nose (LTH11-1).
- **Anomalous Measurements**
  - LTH12-1 (orange line) measured a large and unexpected increase in temperature after the heat pulse
- **Future Work**
  - Continue to investigate unexpected increase in temperature after the heat pulse. Was this caused by TC measurement error (i.e., electrical shorting and/or green-rot) or a physical phenomena (i.e., FTPS smoldering or plasma surface charging)?

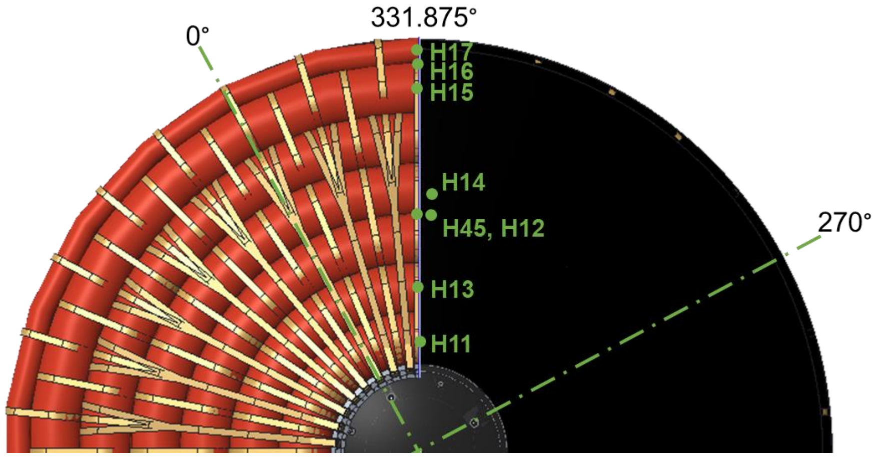
FTPS Location	TC Type	TC Insulation
Deployable, -1	Type N	Mica/Ceramic

FTPS Stack





Deployable Aeroshell

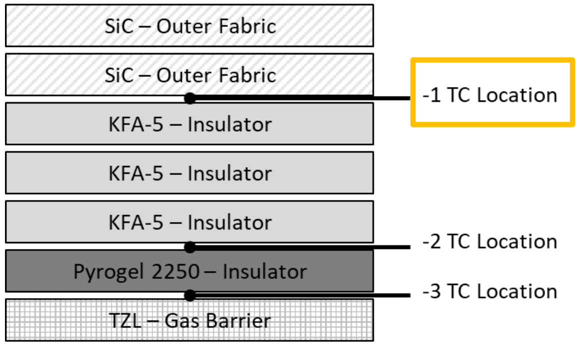


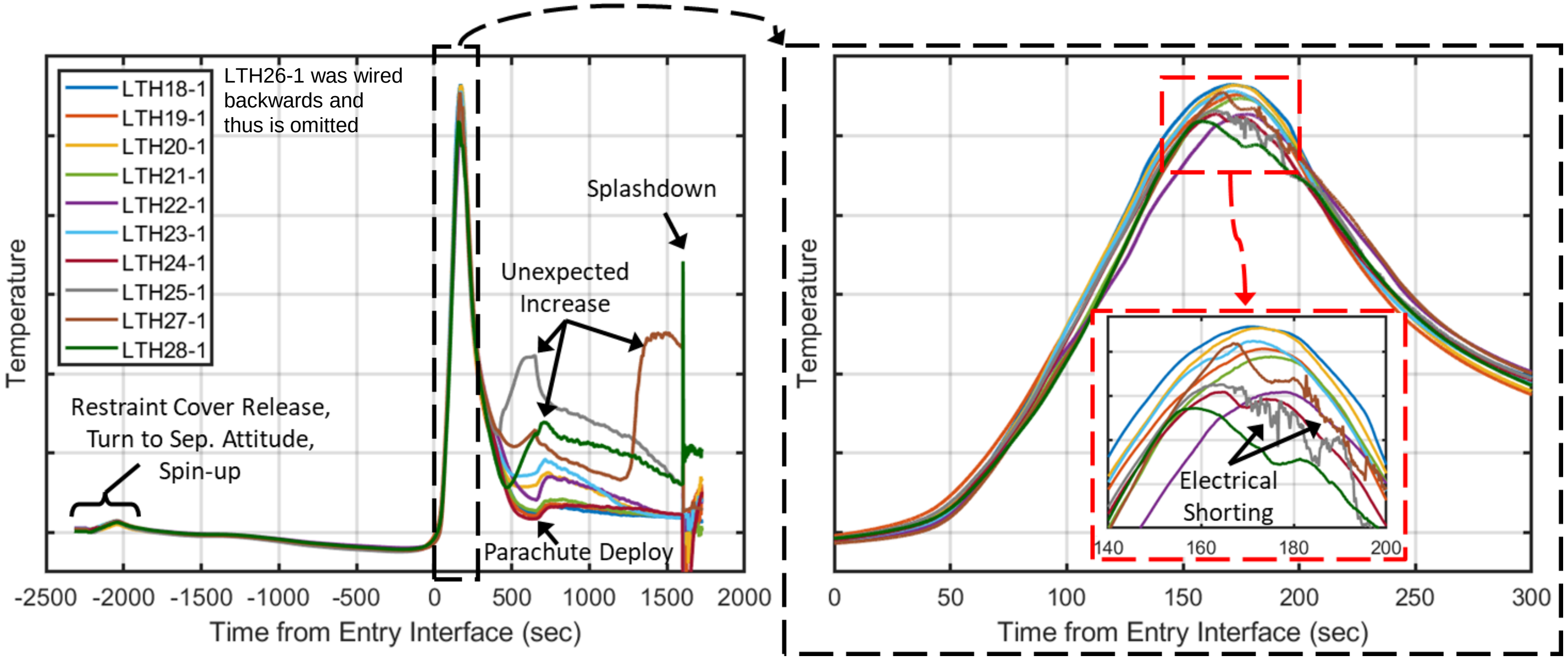
Deployable Aeroshell TCs: SiC/KFA (-1) 151.875° Radial

- **Erroneous Measurements**
  - LTH25-1 (gray line) and LTH27-1 (brown line) become noisy at peak heating
    - These two TCs are near the shoulder and have long wire runs to get to the centerbody. The mica tape wrap could have been damaged during packing since the shoulder experiences excessive handling and point loading during packing.
- **Anomalous Measurements**
  - LTH25-1, LTH27-1, and LTH28-1 (dark green line) have large and unexpected increases in temperature after the heat pulse
- **Future Work**
  - Continue to investigate unexpected increase in temperature after the heat pulse.

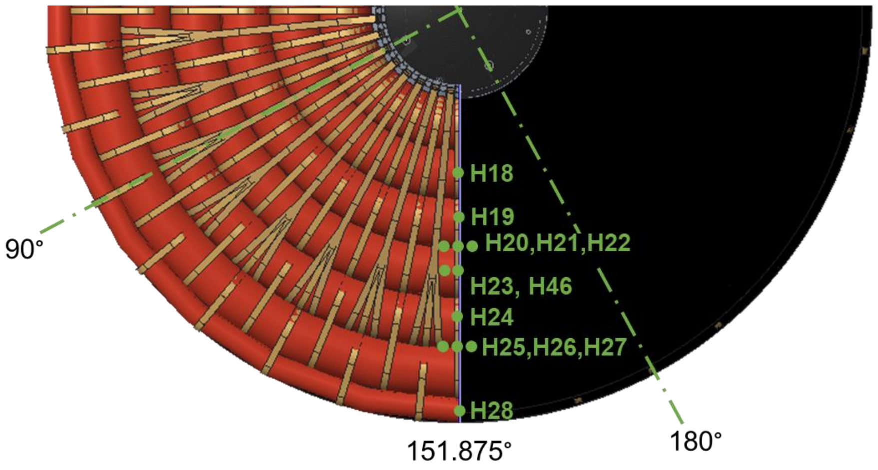
FTPS Location	TC Type	TC Insulation
Deployable, -1	Type N	Mica/Ceramic

FTPS Stack





Deployable Aeroshell

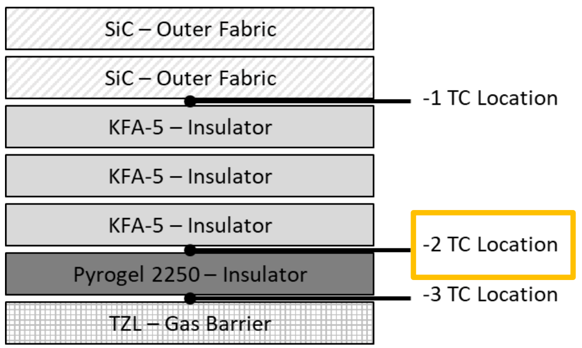


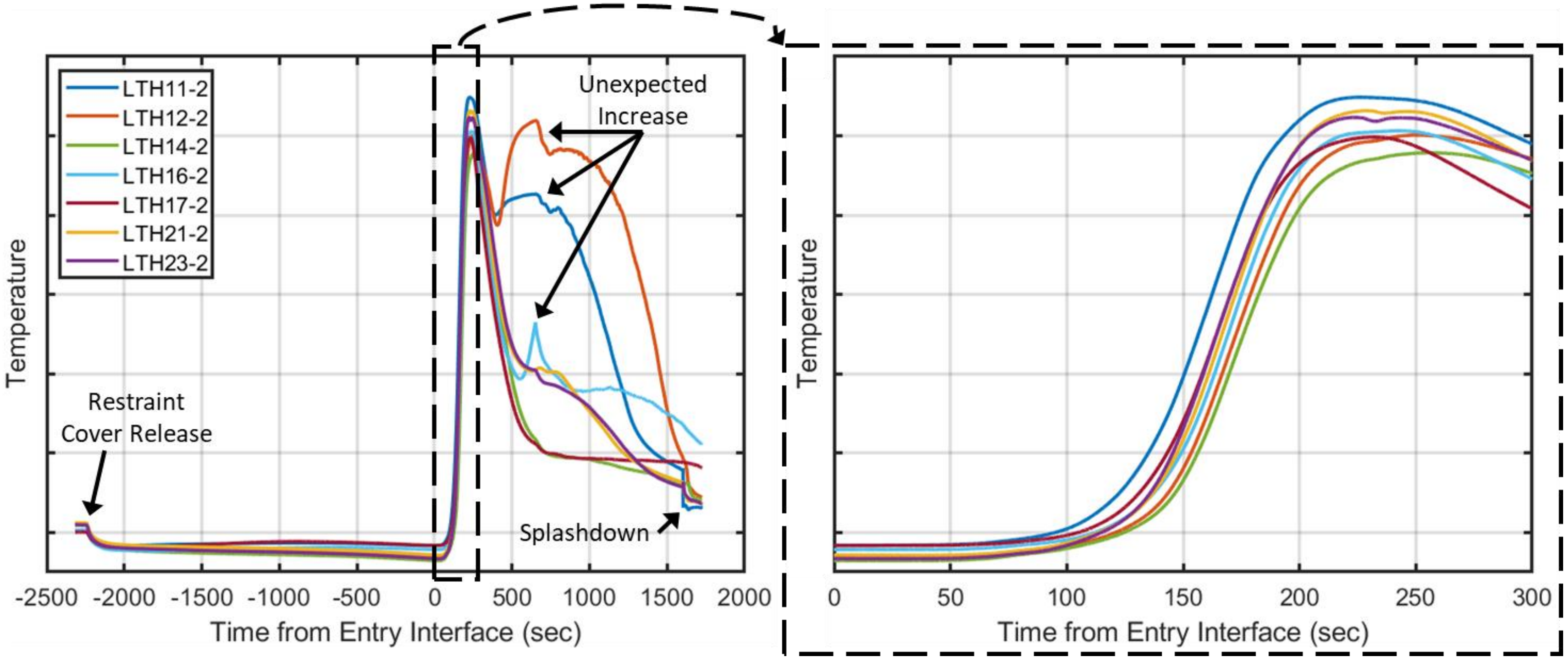
Deployable Aeroshell TCs: KFA/2250 (-2)

- **Anomalous Measurements**
  - LTH11-2 (blue line), LTH12-2 (orange line), and LTH16-2 (light blue line) had large and unexpected increases in temperature after the heat pulse
    - These TCs were Type K, so could be due to green-rot, but this is unlikely since the peak measured temperatures were less than the green-rot on-set temperatures reported in literature
    - The TC insulation could have lost integrity thus resulting in electrical shorting, but this also seems unlikely based on examination of TCs post-arc jet testing
- **Future Work**
  - Continue to investigate unexpected increase in temperature after the heat pulse.

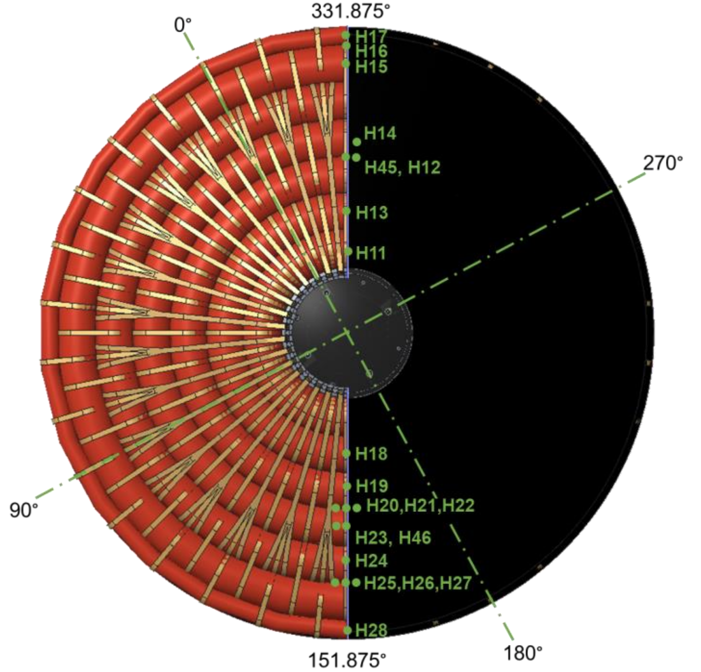
FTPS Location	TC Type	TC Insulation
Deployable, -2	Type K	Mica/Glass

FTPS Stack





Deployable Aeroshell

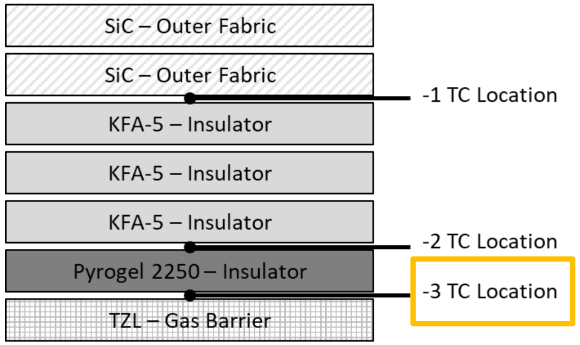


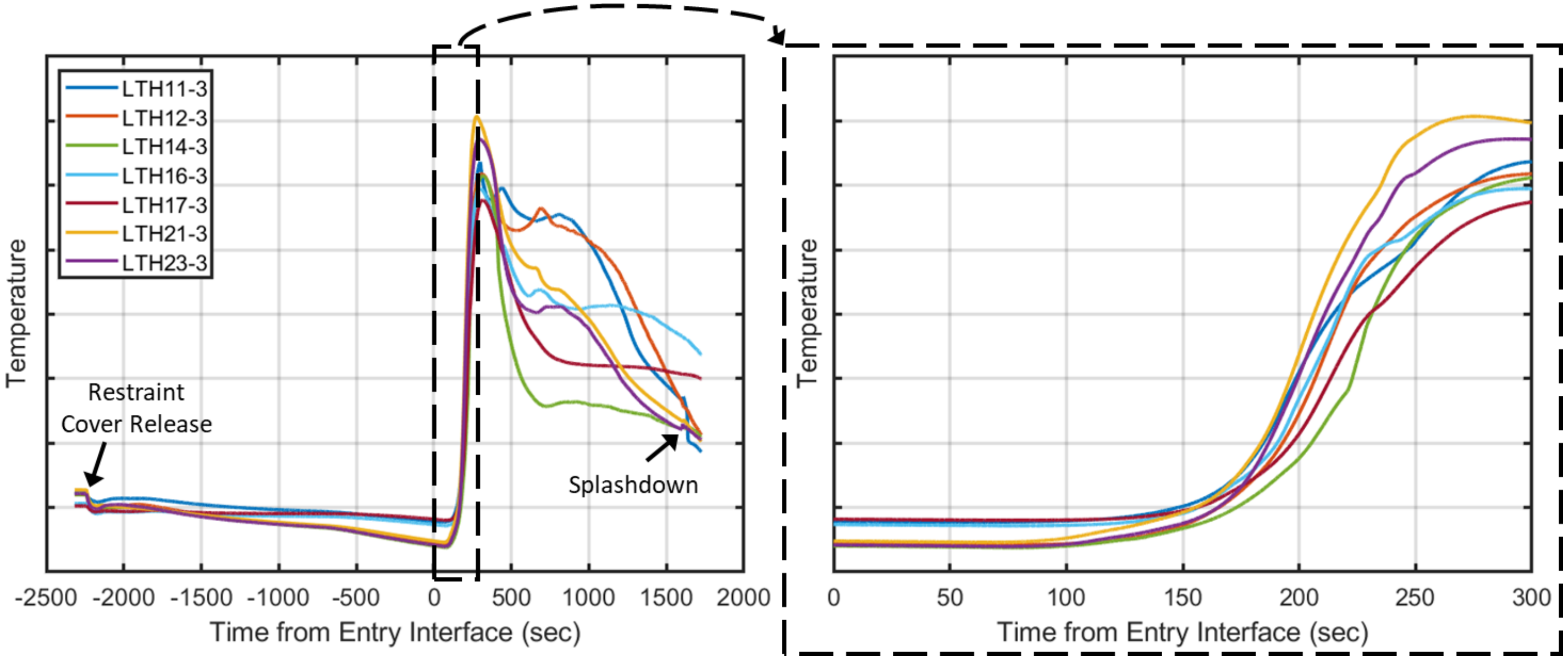
Deployable Aeroshell TCs: 2250/TZL (-3)

- **General Observations**
  - Several TCs (LTH11-3, LTH12-3, LTH16-3, LTH21-3, and LTH23-3) have a wavy response after peak heating rather than the expected smoothly decreasing response
    - Measurements are assumed to be accurate since the measured temperatures were not high enough to cause electrical shorting, green-rot, or any other known issue.
  - TCs at the -3 location which have a wavy response are at the same locations on the aeroshell as the TCs at the -1 and -2 locations which had unexpected increases in temperature
    - Indicates that something is universally affecting all TCs at the same location on the aeroshell, but there is not a trend with location across the aeroshell (inboard vs outboard, torus tangent vs valley)
- **Future Work**
  - The cause of this is unknown and will be investigated further as future work

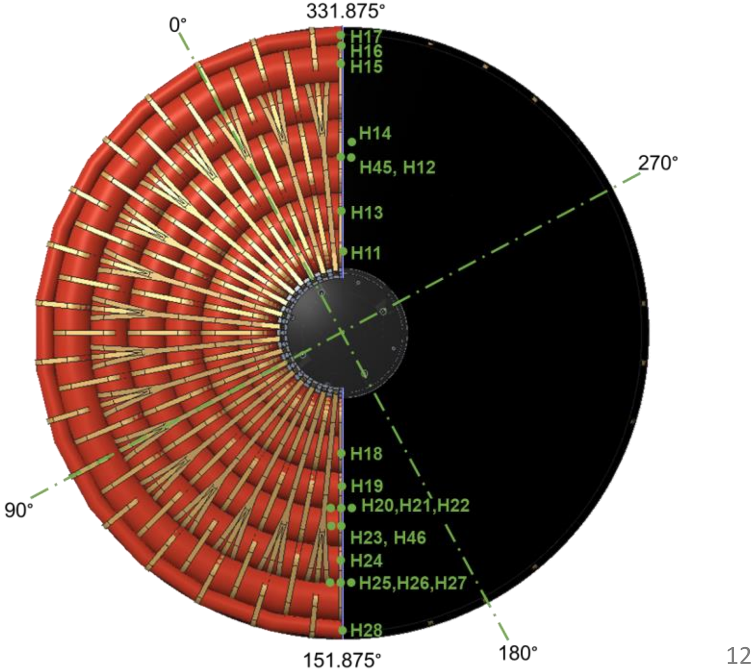
FTPS Location	TC Type	TC Insulation
Deployable, -3	Type K	Mica/Glass

FTPS Stack





Deployable Aeroshell

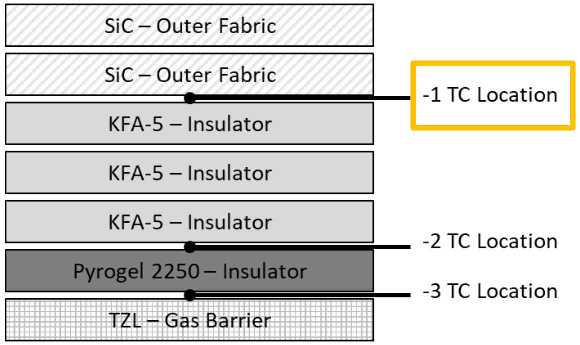


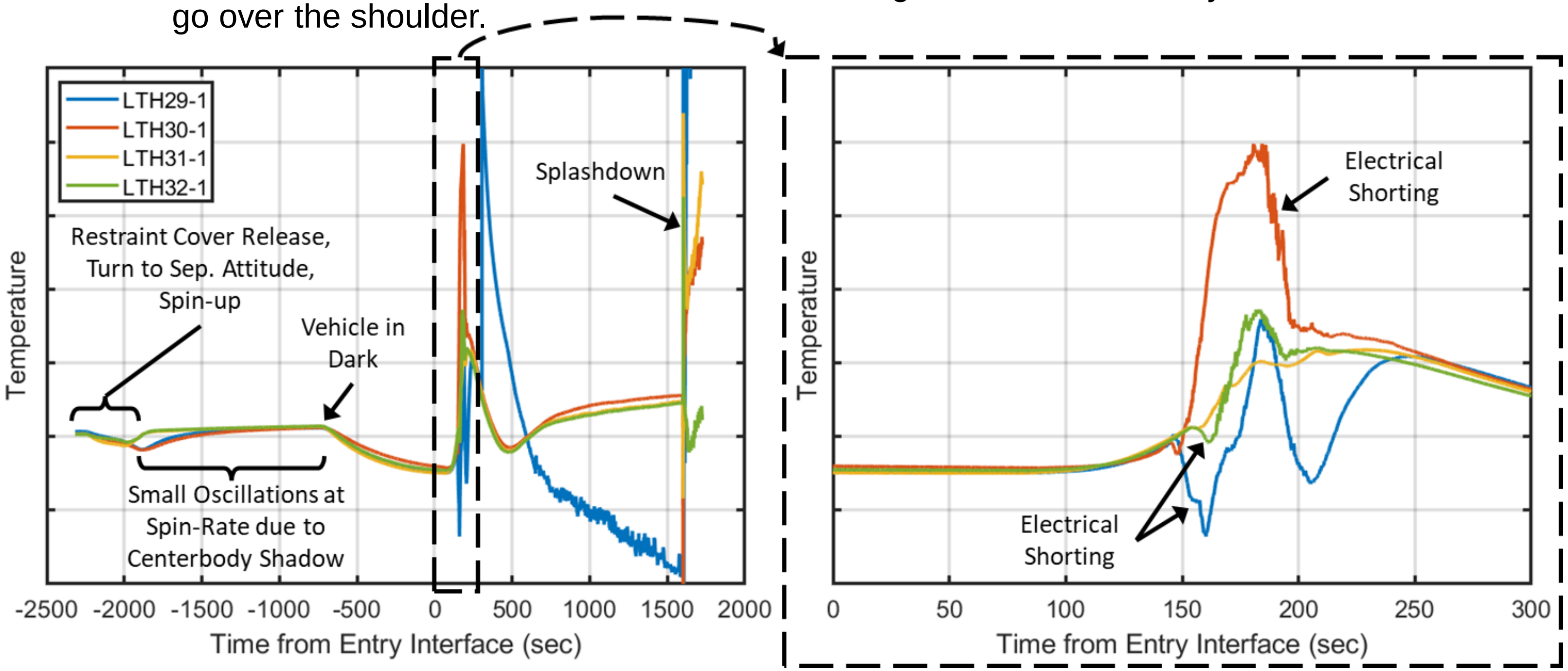
Aftbody FTPS TCs

- **General Observations**
  - Small oscillations are seen after the start of spin-up that correlate with the shadow of the centerbody seen in the camera pod videos rotating around the aftbody of the vehicle at the planned spin rate of ~18°/sec
  - Small oscillations end once the vehicle is in the dark and the measured temperature decreases until entry
- **Erroneous Measurements**
  - All TCs experienced electrical shorting during the heat pulse
    - TCs were routed over the shoulder within the same layer that they were monitoring the temperature back to the rigid nose
    - The ceramic insulation and mica wrap were likely damaged during packing since the shoulder experiences excessive handling and point loading during packing
    - The length of the TC lead wires were exposed to high temperatures on the forebody resulting in electrical shorting
- **Future Work**
  - Future missions should consider alternate routing schemes for aftbody FTPS TCs to eliminate the need to go over the shoulder.

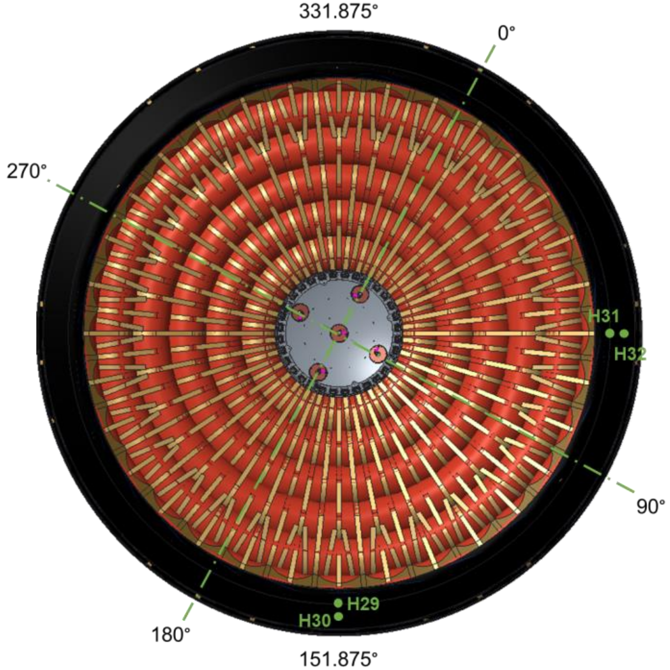
FTPS Location	TC Type	TC Insulation
Aftbody, -1	Type N	Mica/Ceramic

FTPS Stack





Aftbody



Conclusions and Future Work

- The extensive ground-test campaign that was conducted prior to flight to inform the selection of the LOFTID flight FTPS TCs was proven to be highly valuable and resulted in a **rich flight data set**.
  - In addition to measuring the in-depth temperature during the entry heat pulse, other mission events such as restraint cover release, spin-up, parachute deploy, and splashdown were seen in the TC data.
- While most of the flight FTPS TCs provided **accurate temperature measurements**, a few of the TCs still exhibited electrical shorting or other anomalous behavior.
- The TC data will continue to be examined to understand the causes of the anomalous behavior and ways to further mitigate erroneous TC measurements will be investigated for future HIAD missions.

Thank you!
Questions?

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LOFTID Flight TC Data Summary

FTPS Location	TC Type	TC Insulation	Flight TC Data Summary
Nose, -1	Type R	Alumina	2 of 10 TCs had noisy measurements at peak heating consistent with electrical shorting due to segmented alumina TC insulation. Segmented alumina should not be used in the future.
Nose, -2	Type N	Mica/Ceramic	6 of 6 TCs performed as expected
Nose, -3	Type K	Mica/Glass	4 of 4 TCs performed as expected
Deployable Aeroshell, -1	Type N	Mica/Ceramic	2 of 17 TCs had noisy measurements at peak heating consistent with electrical shorting 4 of 17 TCs had an unexpected increase in temperature after the heat pulse
Deployable Aeroshell, -2	Type K	Mica/Glass	3 of 7 TCs had an unexpected increase in temperature after the heat pulse
Deployable Aeroshell, -3	Type K	Mica/Glass	5 of 7 TCs had a wavy response after peak heating. The measurements are assumed to be accurate, but the cause is unknown.
Aftbody, -1	Type N	Mica/Ceramic	All 4 TCs suffered from electrical shorting during the heat pulse. Alternate routing schemes which eliminate the need to go over the shoulder should be considered in the future.