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Error Sources and Mitigation Strategies for Thermocouples Integrated in Flexible Thermal Protection System Materials

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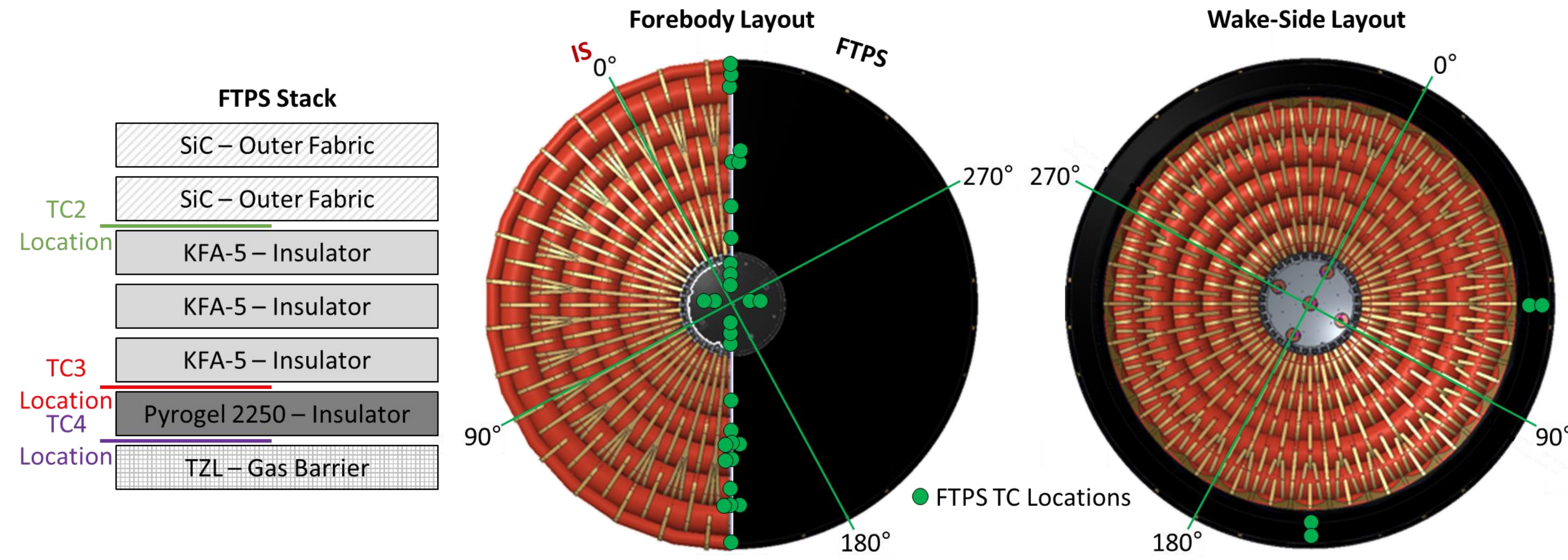
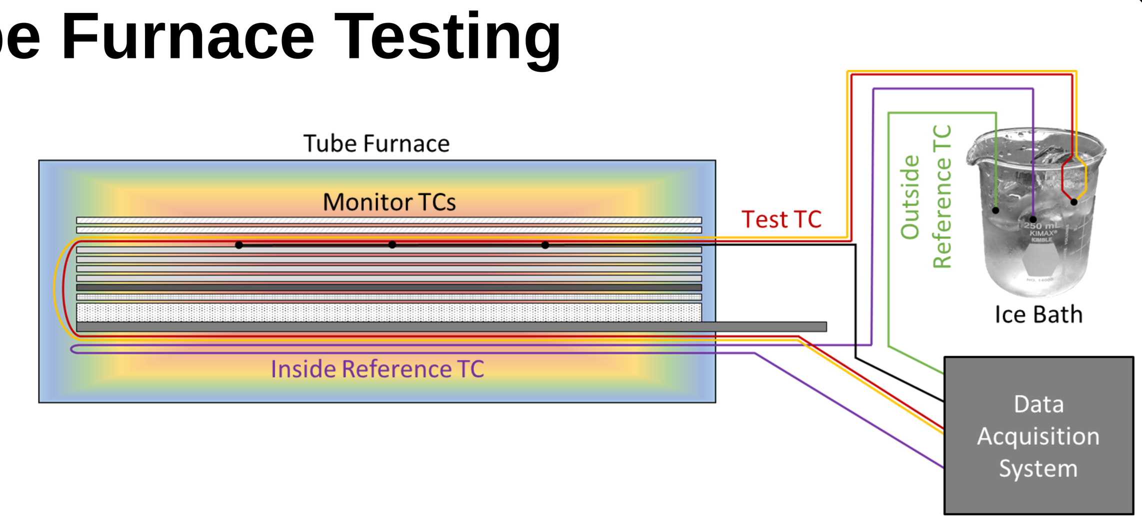
Introduction

- The flexible thermal protection system (FTPS) on NASA's Low-Earth Orbit Flight Test of an Inflatable Decelerator (LOFTID) vehicle will be instrumented with thermocouples (TCs) to measure the in-depth thermal response during entry into Earth's atmosphere. Accurate flight temperature measurements are critical for verifying vehicle performance and reducing thermal model uncertainties.
- The TC leads are routed from the measurement location to the data acquisition system within the same FTPS layer that they are monitoring the temperature. This approach eliminates the need to put holes in the FTPS layers. However, the insulated TC leads are exposed to high temperatures and large thermal gradients.
- The baseline TCs were commercially available 30 AWG Type K TCs with a binder impregnated glass braid insulation. The glass braid is rated to a maximum continuous use temperature of 482°C. LOFTID's heat pulse will be on the order of minutes and the maximum predicted temperature beneath the outermost FTPS layers is 1350°C.



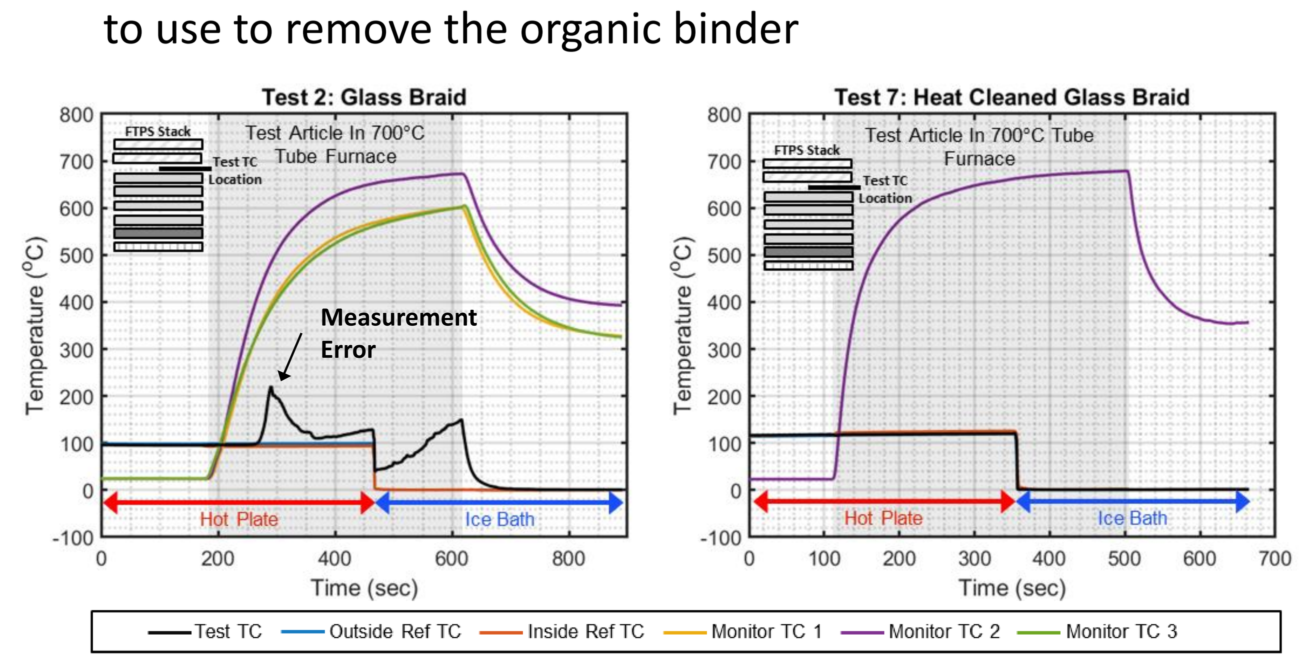
Tube Furnace Testing

- Tube furnace testing was conducted to determine if the baseline TCs routed through FTPS samples would provide accurate measurements at flight-relevant temperatures.
- **Problem:** Large measurement errors occurred beginning at approximately 400°C due to the presence of conductive char on the TC insulation creating an electrical short between the TC leads.



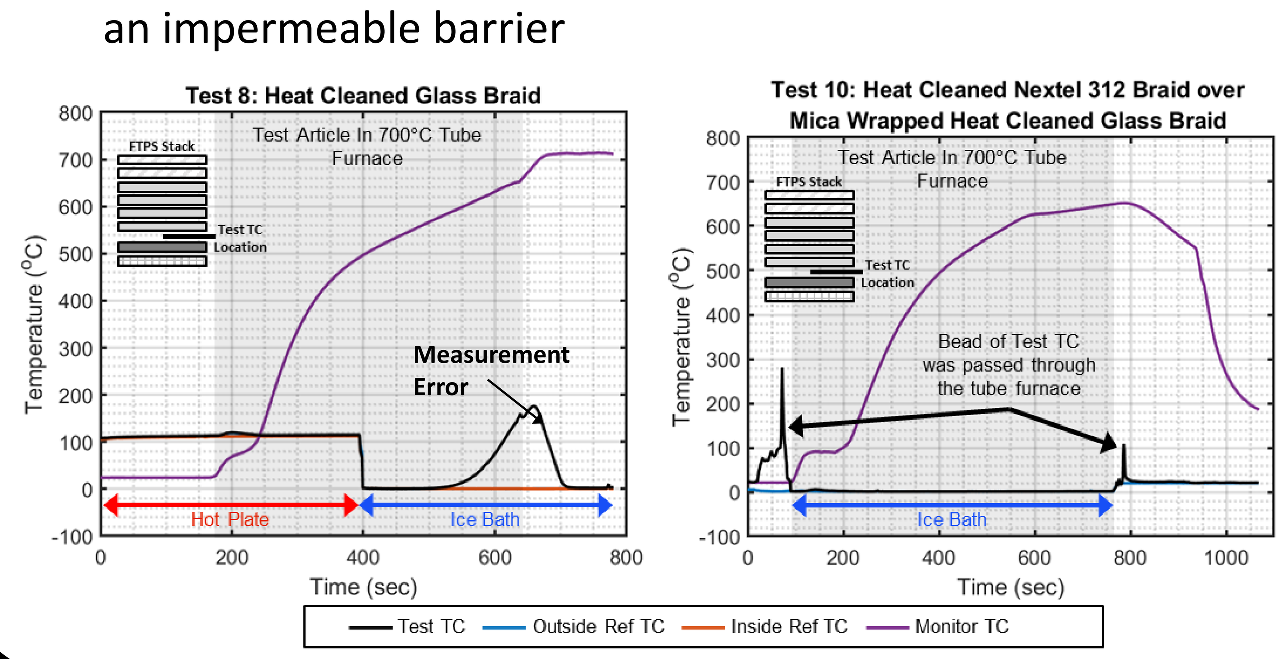
➢ **Error Source #1:** Carbonization of organic binder, sizing, or processing agents on TC insulation in a high-temperature, low-oxygen environment

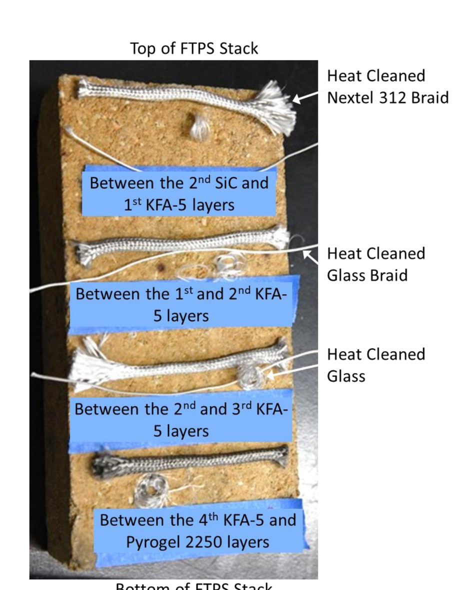
✓ **Mitigation Strategy #1:** Heat clean the TC insulation in an oxygen-rich environment prior to use to remove the organic binder



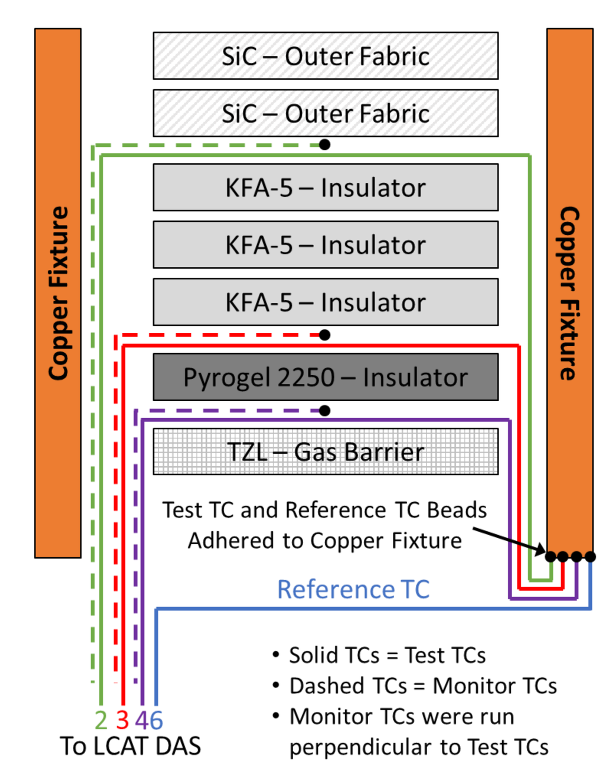
➢ **Error Source #2:** Char from FTPS decomposition permeates braided TC insulation

✓ **Mitigation Strategy #2:** Add a mica tape wrap around each individual TC lead to provide an impermeable barrier





Arc Jet Testing



- Tube furnace test results were substantiated in a more flight-like environment at Boeing's Large Core Arc Tunnel (LCAT). Three additional error sources were found.

➢ **Error Source #3:** Glass TC insulation melts, resulting in electrical shorting of the TC through contact between TC leads or the electrically conductive FTPS materials

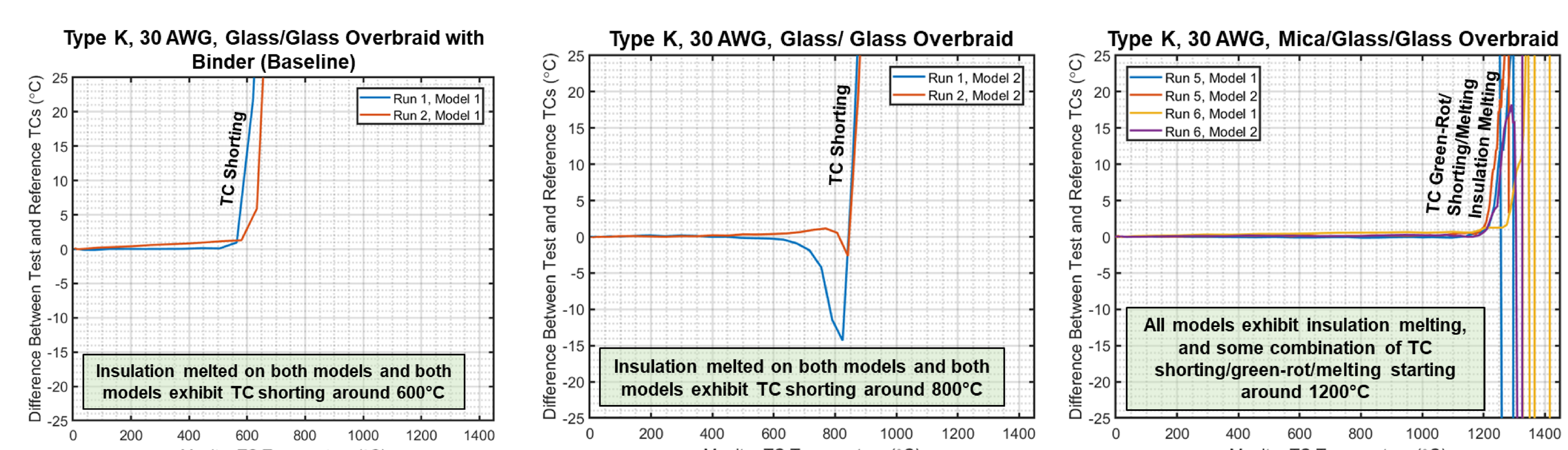
✓ **Mitigation Strategy #3:** Use ceramic TC insulation which has a higher melting temperature

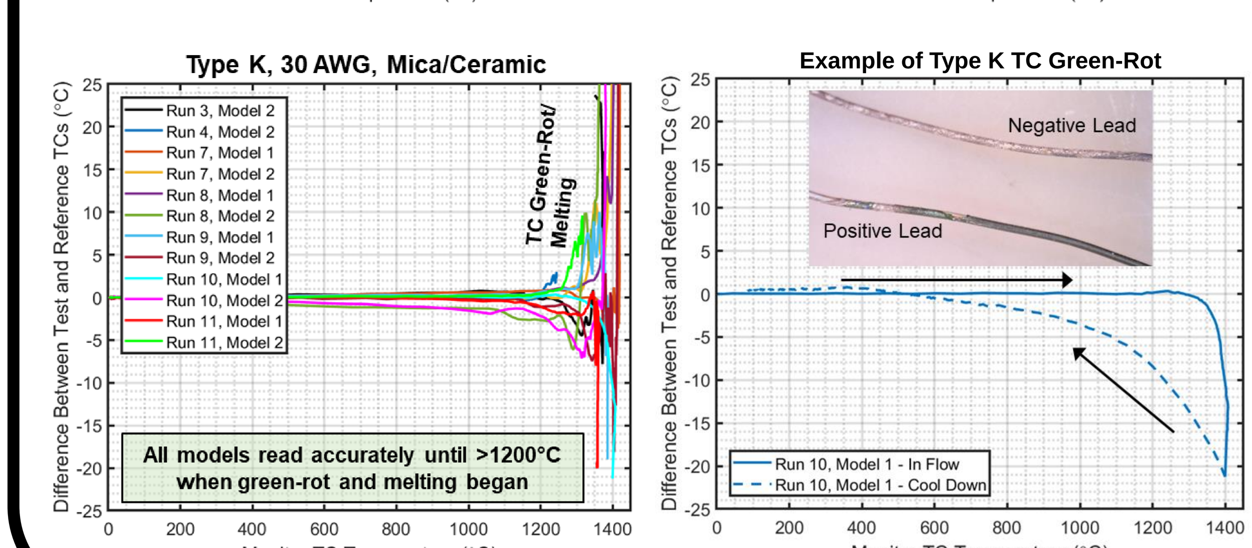
➢ **Error Source #4:** TC wire melts, resulting in a noisy or open-loop TC response

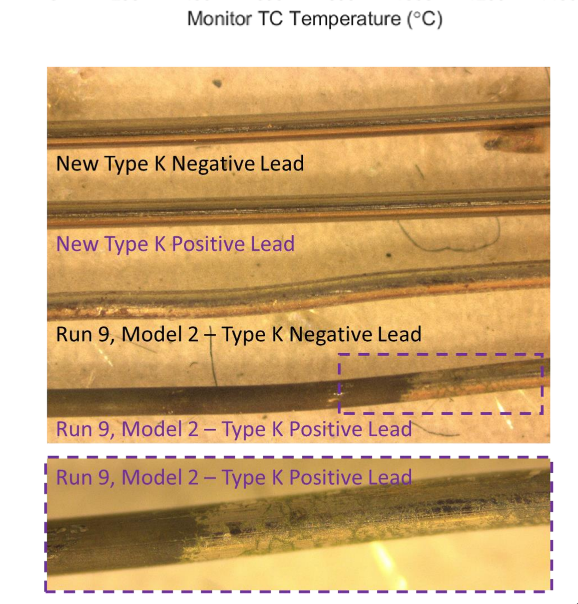
✓ **Mitigation Strategy #4:** Use larger wire diameter to provide additional thermal mass or use different TC materials. Maximum wire diameter is limited since the TCs cannot damage the FTPS during packing.

➢ **Error Source #5:** Green-rot of Type K TC wire. In high-temperature low-oxygen atmospheres, preferential oxidation of the chromium in the positive lead of Type K TCs occurs resulting in a green patina and large calibration errors.

✓ **Mitigation Strategy #5:** Use Type N TCs which were designed to mitigate green-rot







Results Summary – Error Sources and Mitigation Strategies

	Error Source	Error Onset Temperature	Contributing Factors	Mitigation Strategies	Mitigated Use Temperature
#1	Carbonization of organic TC insulation materials	~350-600°C depending on oxygen content and temp. ramp rate	High temp., low oxygen environment	Heat clean TCs in an oxygen-rich environment prior to use to remove organic materials	~800-900°C, application dependent
#2	FTPS decomposition products permeating braided TC insulation	~800°C depending on oxygen content and temp. ramp rate	High temp., low oxygen environment	Wrap mica tape around each individual TC lead to provide barrier	Mica tape wrap reported use temperature ~1150°C
#3	Glass TC insulation melting	e-glass: ~830-916°C	High temp.	Use ceramic TC insulation	Nextel 312: 1200°C continuous use temperature
#4	TC wire melting	Type K: 1427°C (chromel) 1399°C (alumel)	High temp., wire diameter	Use larger wire diameter to provide additional thermal mass	Other TC materials should be used to achieve higher temperature operation
#5	TC wire green-rot	Error first observed: ~1300°C Literature: 815-1040°C Higher observed temp. potentially due to fast temp. ramp rate	High temp., reducing or vacuum environment, wire diameter	Type N TCs which were designed to be less susceptible to green-rot	Other TC Types should be used to achieve higher temperature operation

Key Findings

- Five error sources for TCs integrated in FTPS materials were identified and mitigation strategies were presented.
- For LOFTID, different locations in the FTPS stack require different TC configurations to meet temperature and packing requirements.
- The testing presented here was designed to allow TC measurement error to be easily identified. In flight, it could be very difficult to distinguish between an accurate measurement and an erroneous one.
- The failure modes and mitigations identified in this study should be considered in the design of any future system utilizing TCs to make FTPS temperature measurements.

Acknowledgments

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