TFAWS Interdisciplinary Paper Session

Thermal Vacuum Testing Strategy And Thermal Desktop Model Correlation For The Moon To Mars Planetary Autonomous Construction Technologies (MMPACT) Robotic Terrestrial Arm

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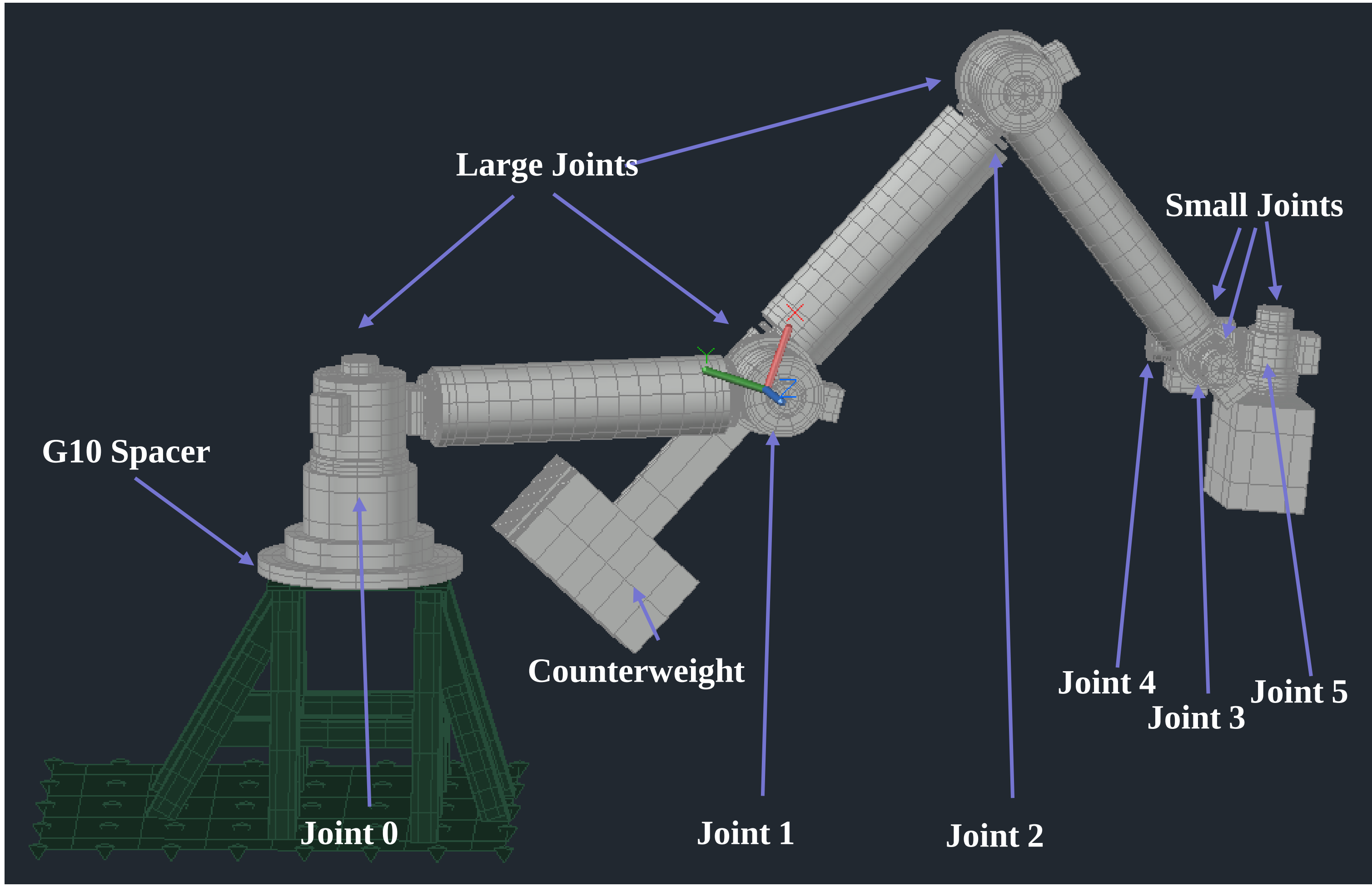
Introduction

- TVAC testing strategy for a large-scale robotic arm system
  - Diagram of arm shown in Thermal Desktop (TD)
  - Arm stretched to its fullest extent is roughly 15.5 feet long
  - Test was planned with the manufacturer, ICON



Test Challenges

- Scale
  - Required dozens of thermocouples (TCs) and yards of TC wires back out to the chamber pass-through
- Movement
  - TCs can become detached in TVAC even while stationary, let alone with possible lateral forces to help them “wiggle” free
- Modeling goals vs test goals
  - The test primary objectives were:
    - Operational rehearsal of next test
    - Verify arm system capability in TVAC
    - Verify the arm actuators’ heater control boards (HCBs), heaters, and resistance temperature detectors (RTDs) in TVAC
  - Collecting TC data in support of thermal model development was a secondary objective and not required for a successful test

Test Method

- Functional check of the arm movement during different thermal environments
  - First check done before pumping down the vacuum chamber, and following done in TVAC conditions as listed below

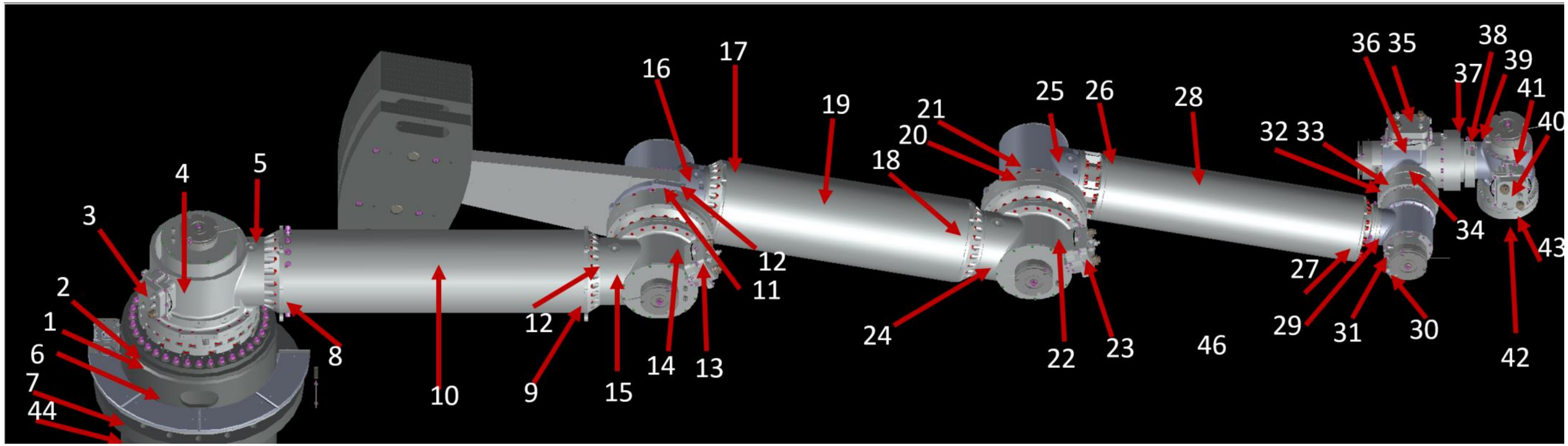
Test Case	Pressure	Heater Set Point	Chamber Set Point
Ambient	Ambient	-	-
Ambient TVAC	<1e-5Torr	-	-
Hot	<1e-5Torr	57°C	-
Cold	<1e-5Torr	0°C	-170°C

Test Configuration

- Test performed in MSFC's V-20 chamber, which has a test article area of 17' by 22'
  - Shroud is painted Catalac Black (α=0.96, ε=0.88)
  - Shroud can be flooded with LN2 and held at an average of -170° C
- Arm was installed via a loading cart sliding into and out of the chamber
- Arm was mounted to a pedestal manufactured for the test that could bolt onto the grate flooring of the cart
  - Connection from the arm to the pedestal was done with a custom G10 thermal spacer between the bolted connection to thermally isolate the arm

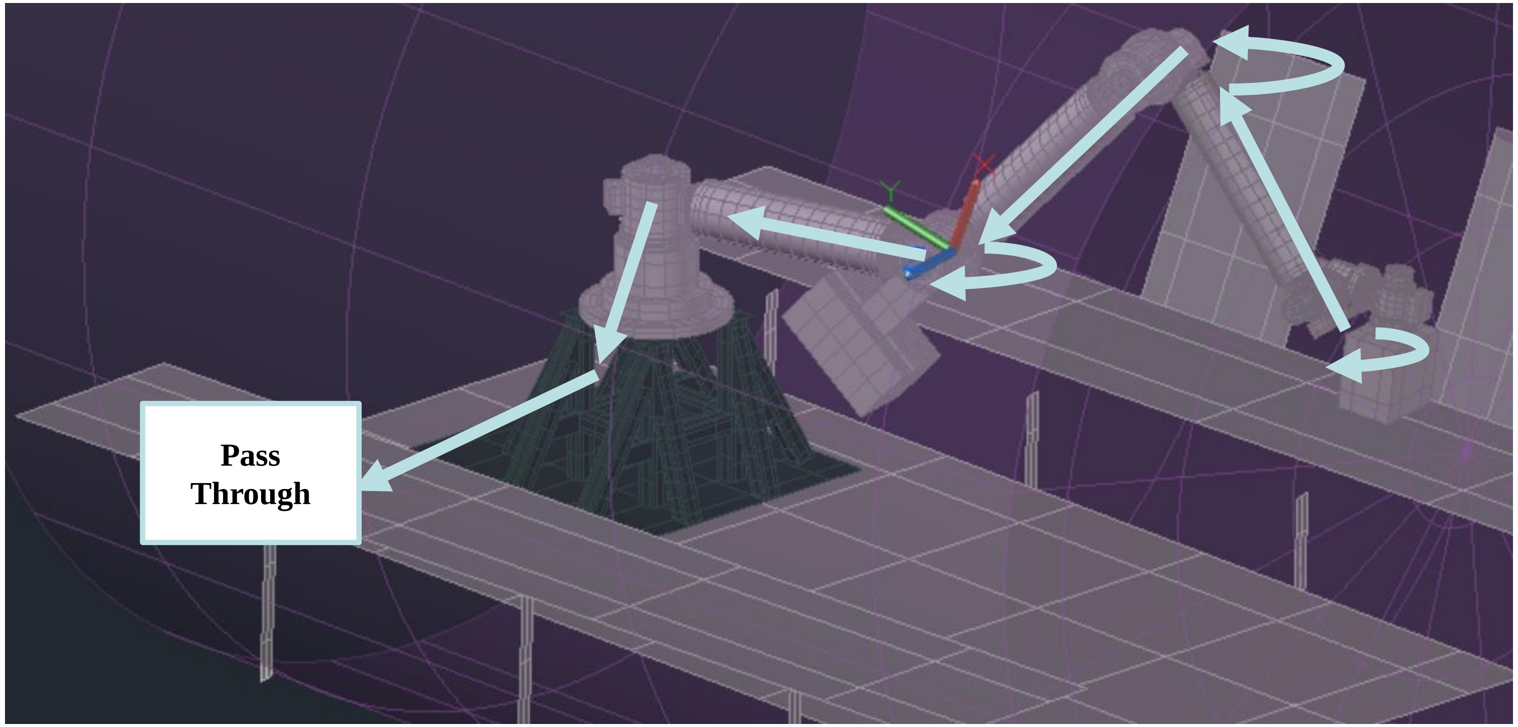
Thermocouple Installation

- 44 TCs were installed to measure each side of all mechanical and rotational joints, as well as the midpoint of each arm beam



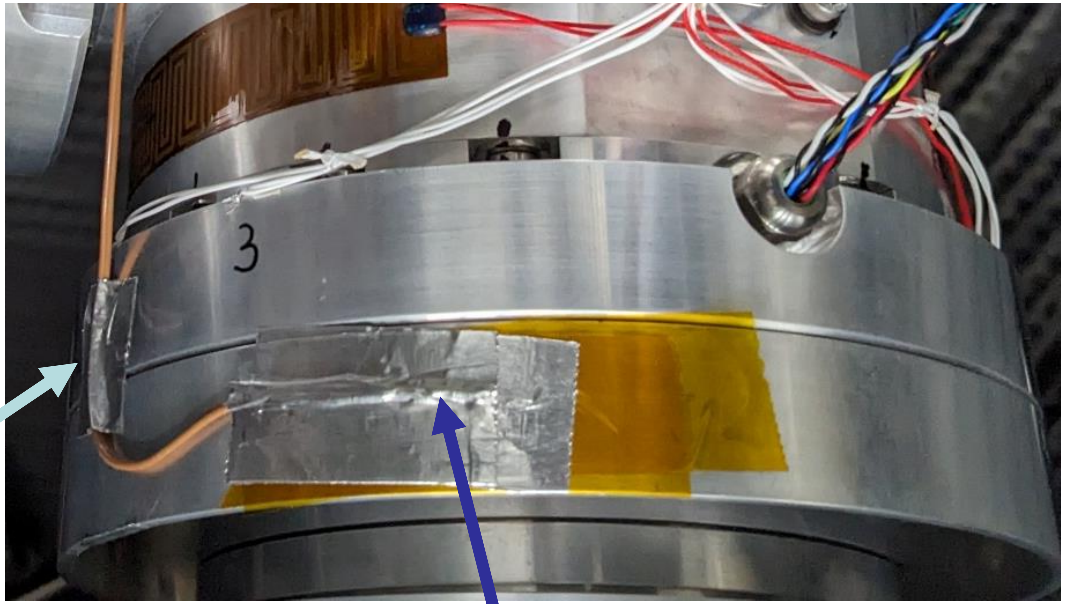
Thermocouple Installation (cont.)

- TCs routed from point of install back down the length of the arm to the chamber wall pass-through with slack at joints
  - Followed the power and control wiring already installed to avoid interfering with the arm operations



Thermocouple Installation (cont.)

- First, a layer of Kapton tape was applied to electrically isolate the TCs from the arm
- The TC was placed and another layer of Kapton tape was applied on top of the bead
- The final layer of aluminum tape was applied and scraped down to minimize air bubbles that could cause lifting
- Another piece of aluminum tape was applied a few inches from the TC to provide strain relief from any jostling from either the routing of the remainder of the wire or the arm movement during test



Strain relief

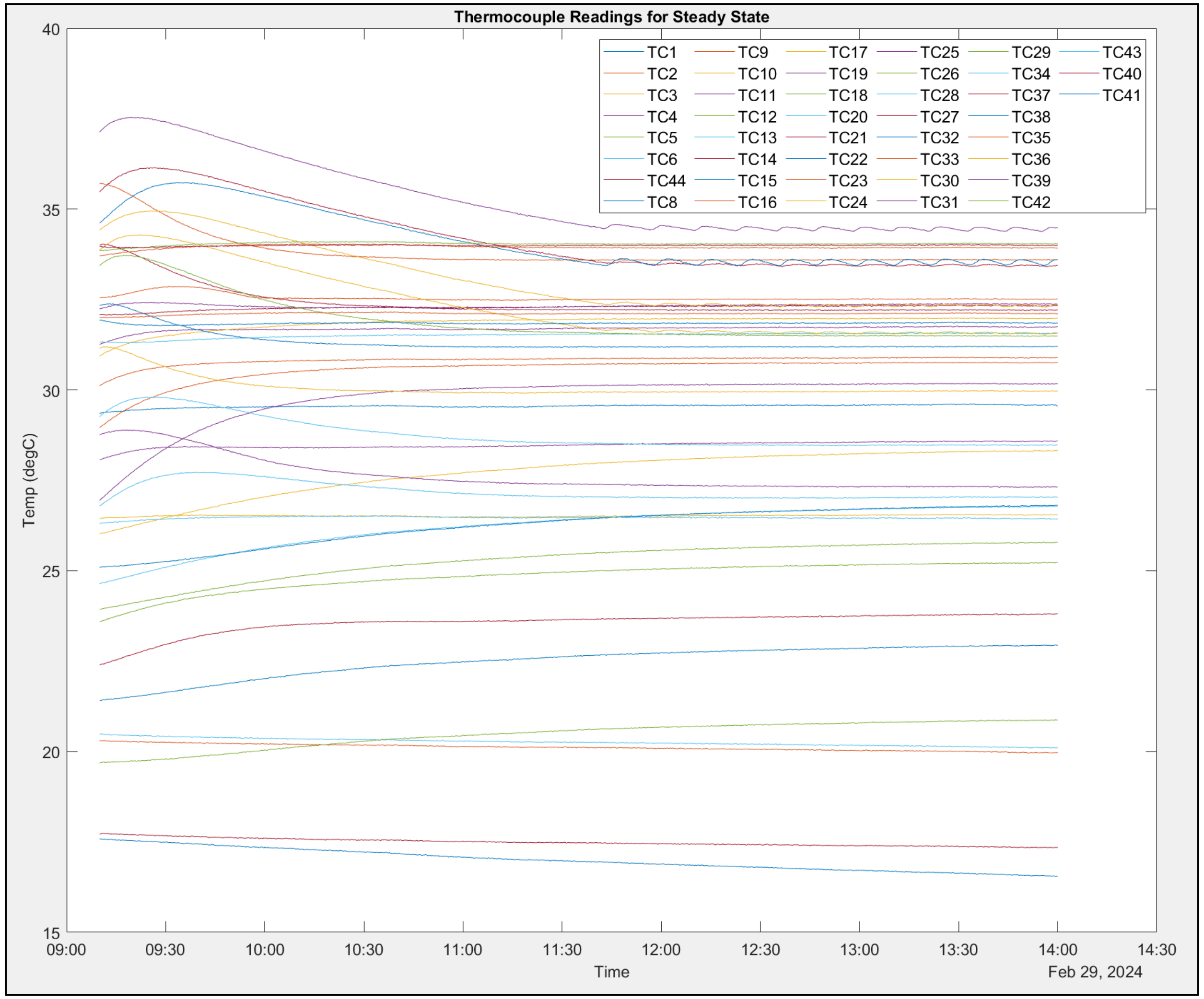
TC bead

Thermocouple Installation (cont.)

- An issue came up during the pre-test movement check not in vacuum with the installation
- Adding the TC wiring down the length of the arm made the wire bundles much stiffer
- This meant the smaller joints, where the wire bundles were navigating tighter curves, did not have sufficient slack to allow the full joint rotation
- Issue corrected by removing the TC wires from the larger bundle and bundling separately with a larger amount of slack

Thermal Steady State

- During the test, an opportunity came about to attempt thermal steady state
- Conditions:
  - Heaters set to maintain 35° C
  - Motor power to arm turned off
  - Thermal steady state defined as < = 0.01° C / hour
- Thermal steady state was achieved after six hours



Initial Thermal Model

- Primitive shapes in Thermal Desktop (TD) used for the arm, chamber, and pedestal
- Relevant initial model parameters shown below
  - G10 spacer interface between the pedestal and the arm represented as G10 material properties for that area
  - Emissivity was for an initial assumption of bare aluminum 6061
  - Large and small joint thermal resistance refer to the sealed ball bearing connection between sides of the joint and was determined by component TVAC testing at ICON’s facility

Parameter	Initial Value
Emissivity (ε)	0.2
G10 spacer interface contact coefficient	0.014884 W/in^2/K
Large joint thermal resistance	0.524 K/W
Small joint thermal resistance	1.19 K/W

Thermal Model Correlation

- Steady state TD case
  - Current data for each heater was used to determine the heater power input for the model
  - TC measurements of the chamber walls used to set the boundary node conditions of the chamber
- Started with the temperatures at the pedestal and arm attachment
  - The TCs on either side of the G10 spacer were closer in temperature than the same points in the model, implying there is a higher rate of heat transfer across that interface than modeled

G10 Spacer Interface

- Because this connection must support the moment of a 15.5' long arm, each bolt has a 2" diameter and there are 20 bolts
- The scale of the bolts makes it possible for non-negligible heat transfer paths
- The calculations on the right determine the heat flux for both the bolts and the G10 spacer, and then combine them per the proportional area of each material in the interface
- Another lesson learned for large-scale thermal testing

Constants

$$Abolt := \pi \cdot (1\ in)^2$$

$$lBolt := 0.5\ in$$

$$kAl := 4.5\ \frac{W}{in \cdot K}$$

$$G10g := 0.293\ \frac{W}{m \cdot K}$$

Thermal Conductivity (k*A/l)

$$boltQ := kAl \cdot \frac{Abolt}{lBolt} = 28.274\ \frac{W}{K}$$

$$boltQ'' := \frac{kAl}{lBolt} = 9\ \frac{W}{in^2 \cdot K}$$

these are per bolt

$$G10Q := G10g \cdot \frac{268.138\ in^2}{0.5\ in} = 3.991\ \frac{W}{K}$$

$$G10Q'' := \frac{G10g}{0.5\ in} = 0.015\ \frac{W}{in^2 \cdot K}$$

Proportional effect of bolts on surface

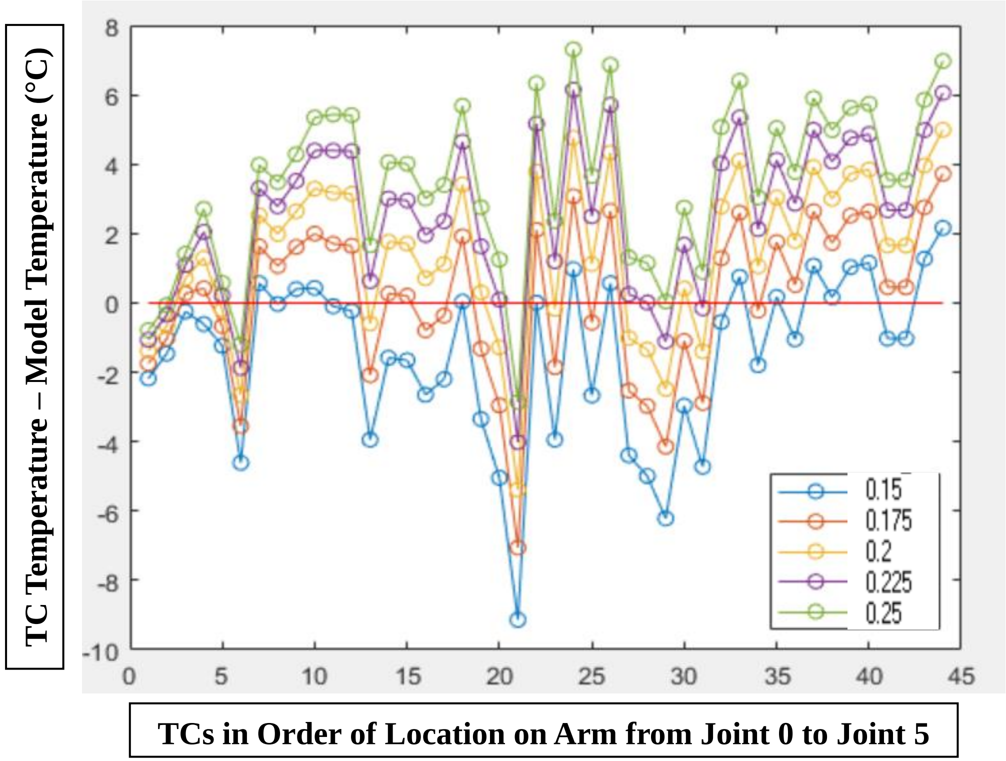
$$fraction := \frac{Abolt \cdot 20}{268.138\ in^2} = 0.234$$

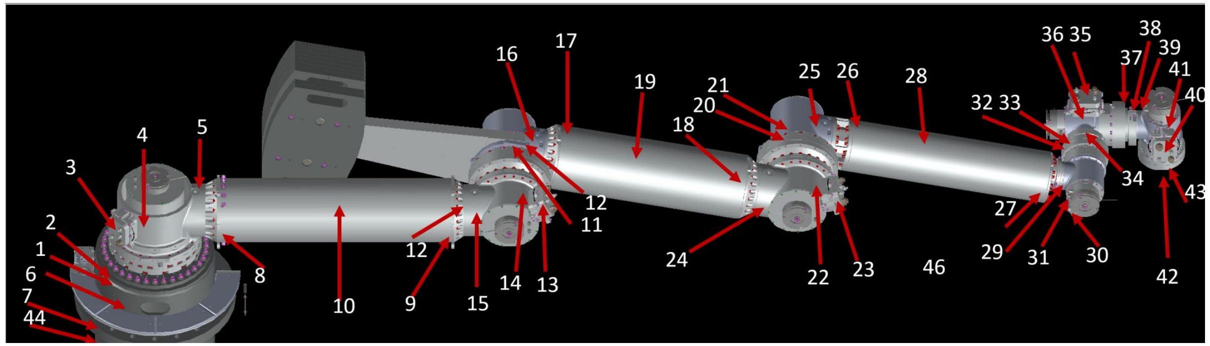
this is the fraction of the total surface area the total bolt diameters take up

$$Gave := fraction \cdot boltQ'' + \frac{1}{fraction} \cdot G10Q'' = 2.172\ \frac{W}{in^2\ K}$$

Emissivity

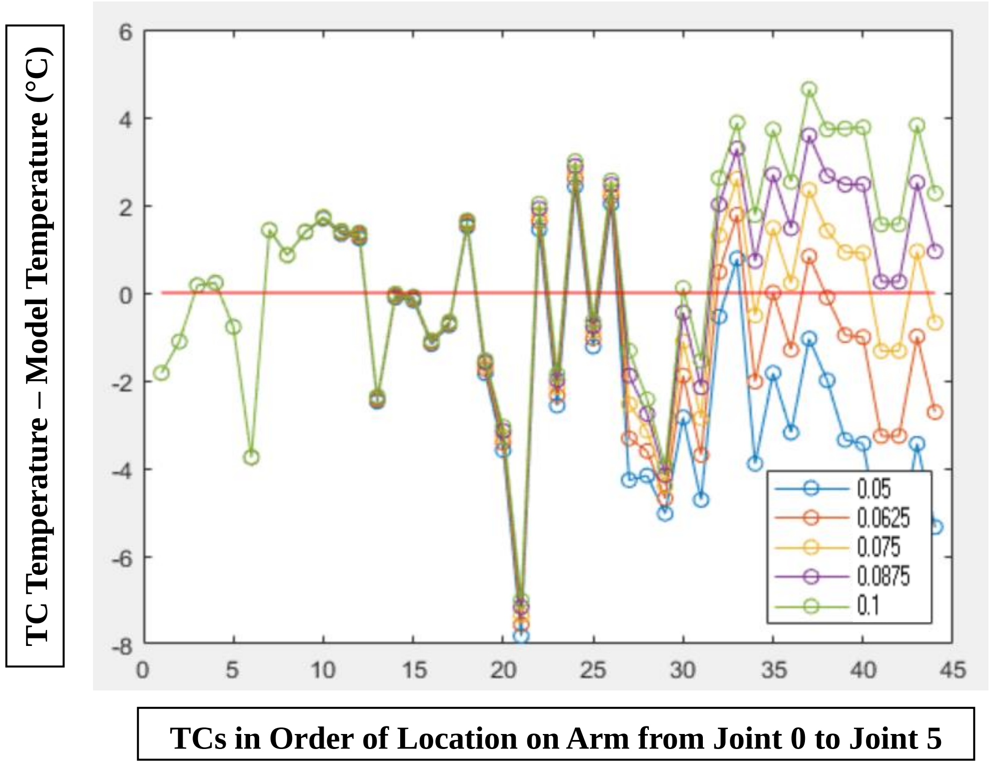
- Plotted the delta between the TC value and the model value in linear order down the arm to look for a temperature gradient
  - The closer the values are, the closer to zero each data point is
- Trade study of emissivity values to determine best fit
  - ε = 0.15 to 0.25
  - ε = 0.175 was chosen as the best fit, which is reasonable the emissivity is slightly lower than bare metal, given the cables and routing trays attached to the surface of the arm





Emissivity (cont.)

- However, the small joints at the end of the arm (joint 3-5) fit best with the lowest examined value, 0.15
- A trade study varying only the emissivity on those joints showed a value of ε = 0.00625 as the best fit
  - Proportionally more of the surface area is blocked by cabling with the smaller joints



Final Thermal Model

Parameter	Initial Value	Final Value
Emissivity (ε) of small joints (joints 3-5)	0.2	0.0625
Emissivity (ε) of the remainder of the arm	0.2	0.175
G10 spacer interface contact coefficient	0.014884 W/in^2/K	2.172 W/in^2/K
Large joint thermal resistance	0.524 K/W	0.524 K/W
Small joint thermal resistance	1.19 K/W	1.19 K/W

Conclusions

- Scale and motion of test article presented challenges uncommon to MSFC's ES20 division
  - TC cable routing for avoiding motion interference
  - Strain relief of TCs
  - Heat transfer path through large-scale attachment point despite G10 thermal spacer
- Model correlation completed, but limited
  - Correlating to only one test case can mask inaccuracies that would be revealed if the model had to find a best fit between two different cases
  - Transient test data unsuitable for model correlation, as the arm was never starting motion at a known or steady state
- Future recommendations
  - Additional steady state thermal testing or controlled transient testing

Acknowledgements / Questions

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- Questions?