# Design and Qualification of a High Temperature Multi-Layer Insulation Blanket for the Europa Clipper Mission

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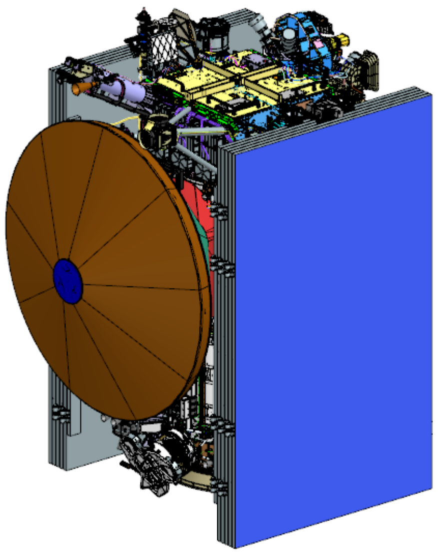
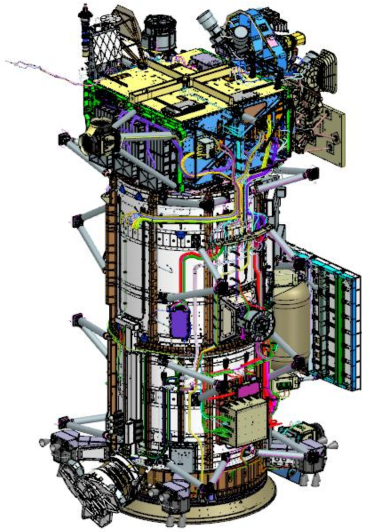
# Europa Clipper Mission Overview

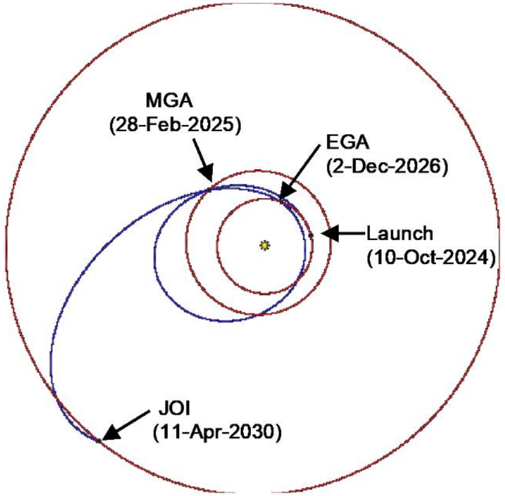
- The Europa Clipper mission is planned to launch in October 2024. The mission will study Europa, one of Jupiter's moons.
- The primary goal is to determine if Europa has conditions that could support life. There are three parts to this:
  1. Determine the thickness of the surface crust and how it interacts with the ocean underneath
  2. Investigate composition of the subsurface ocean
  3. Characterize geology
- The science instruments can generally be grouped into imagers, plasma and magnetic field, radar and gravity, and chemical analysis.
- The mission trajectory includes Mars and Earth gravity assists with a solar distance ranging from 0.82 AU to 5.6 AU. Cruise to Jupiter is about 5.5 years. The spacecraft would make about 50 flybys of Europa.



Stowed Spacecraft



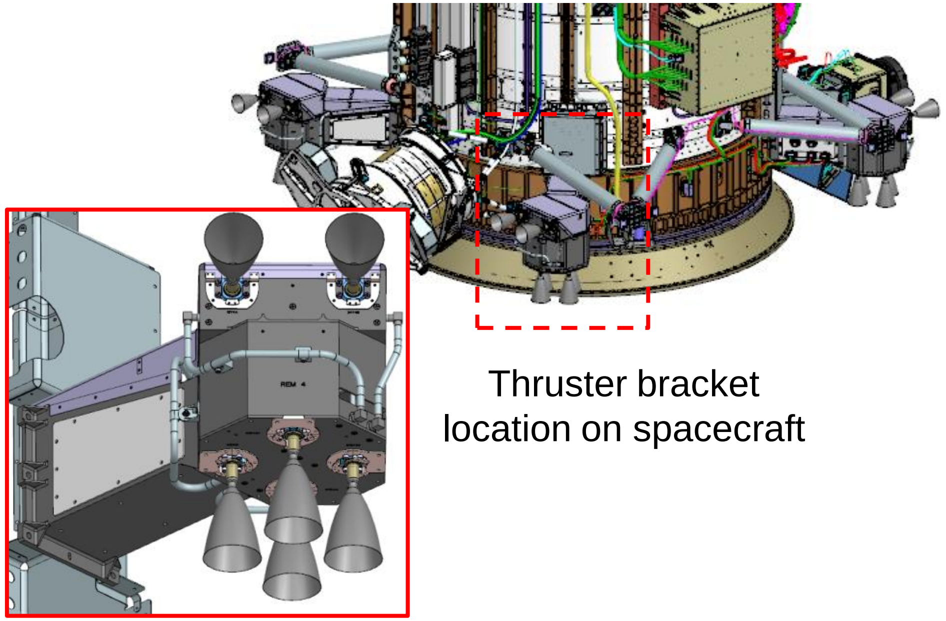
Solar arrays, high gain antenna hidden




Mission Trajectory (MEGA)

# Europa Clipper MLI Blanket Design

- **Ionizing radiation is a significant driver of material selection for Europa Clipper! External surfaces are predicted to see Grad levels of radiation over the mission lifetime.**
- MLI blankets will have tape bound and stitched edges (the typical JPL practice)
- This MLI design is robust for ground and flight and, importantly for Europa Clipper, acceptable for a radiation environment because the stitching provides a secondary mechanical attachment to keep blanket intact
- Most of the spacecraft blankets are 22 layers with a StaMet coated black Kapton outer layer (see image of coupns to right)
- Around the thruster engines, a high temperature blanket design was needed. The temperature could exceed 500 °C on the outer surface, which is too high for polyimide materials commonly used in MLI.



Thruster bracket location on spacecraft

Europa Clipper spacecraft “standard” design test coupons

# High Temperature MLI Driving Requirements

- The mission environment, science payload, and proximity to the thruster engines contribute a number of (sometimes competing) requirements:
  - **Thermal** – temperature in flight remains below material's maximum service temperature
  - **Radiation** – remain intact after worst case TID radiation exposure
  - **iESD** – not a ESD risk to nearby victims; compliant with REASON noise budget
  - **Magnetics** – compliant to less than 1 Gauss at 1 cm
  - **Outgassing** (vacuum and radiation induced) – rate less than $5*10^{-14}$ $g/cm^2/s$
  - **FOD** – minimal particulation or shedding
  - **Propellant compatibility** – remain intact after vapor and liquid exposure to MMH and MON-3
- Each of these applies to some extent to all MLI blankets on the mission, but the thermal capability needed for the high temperature blanket is significant and what specifically drives a different approach than the rest of the spacecraft

# Outer Layer Candidate Materials

- Looking at broad material categories, there were no ready to fly solutions
- Each material had at least one kind of concern to investigate (ceramics with the environment, metallics with manufacturability)
- Development testing was needed to see what could work for flight

| Constraint | Polyimide | Ceramic Textile | Aluminum | Copper | Stainless Steel | Titanium |
|---|---|---|---|---|---|---|
| Temperature | Unacceptable | Acceptable | Would need test | Acceptable | Acceptable | Acceptable |
| Radiation | Would need test | Acceptable | Acceptable | Acceptable | Acceptable | Acceptable |
| iESD | Acceptable | Would need test | Acceptable | Acceptable | Acceptable | Acceptable |
| Magnetics | Acceptable | Acceptable | Acceptable | Acceptable | Depends | Acceptable |
| Outgassing | Acceptable | Acceptable | Acceptable | Acceptable | Acceptable | Acceptable |
| FOD | Acceptable | Would need test | Acceptable | Acceptable | Acceptable | Acceptable |
| Propellant Compatibility | Would need test | Acceptable | Acceptable | Would need test | Acceptable | Acceptable |
| Manufacturability | JPL flight heritage | JPL flight heritage | Some heritage, would need test | Would need test | Would need test | Would need test |

# Materials Testing

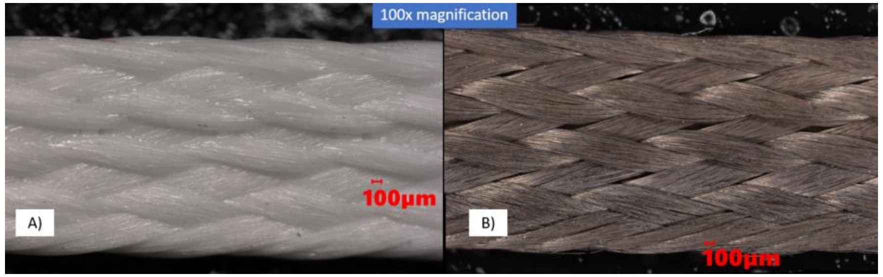
- Due to uncertainties with all of the material candidates, development testing was often done with constituent materials to evaluate compliance
  - **Thermal** – does it melt, degrade, change?
  - **Radiation** – does it survive, change?
  - **iESD** – does it discharge? If so, how often and how much?
  - **Contamination control** – does it shed fibers or outgas? Does it contain organic material?
  - **Propellant compatibility** – does it survive, degrade, change?
- Separate from the mission requirements, metallic outer layers needed study for manufacturability. More general concerns existed about how to sew the blankets, build complex geometries, and hold dimensional tolerance.
- Different lacing cord and sewing thread was introduced as well due to temperature concerns. JPL typically uses nomex lacing cord and polyester sewing thread. We changed to PTFE coated fiberglass lacing cord and PTFE coated fiberglass thread with an Inconel wire insert. These materials were also included in some tests.

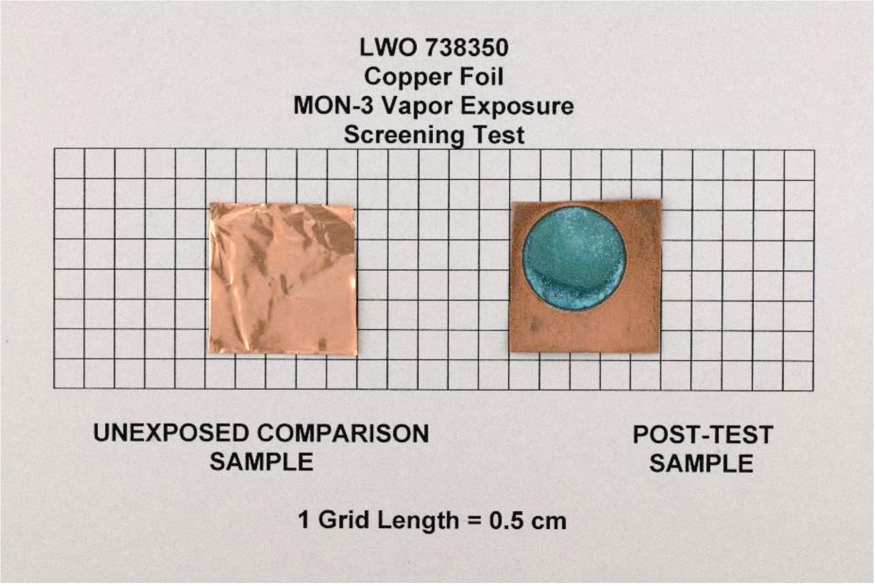
# Summarized Test Findings

- Thermal
  - Tested various materials to 600 ° C for 1 hour in argon at ambient pressure
  - Copper optical properties shifted (WAS α/ε = 0.141/0.010 = 14.1, IS α/ε = 0.735/0.068 = 10.6); could also be due to oxidation
  - Glass tissue remained intact
  - PTFE coating on lacing cord and sewing thread was lost at 600 C; the lacing cord and sewing thread fiberglass remained
- Radiation
  - Tested up to 1 Grad dose with thermal cycles between -236 and +204 ° C
  - No major changes to any of the prospective high temperature materials
- iESD
  - Bare and VDA sides of Nextel 312 discharged. VDA side had lower discharge frequency and magnitude.
- Contamination control
  - Nextel 312 consistently shed fibers when handled
  - No organics detected with Nextel 312, glass tissue separator
- Propellant compability
  - Tested various materials with MON-3 and MMH propellant – liquid and vapor cases for each
  - Copper, lacing cord, and thread reacted with MON-3 and MMH propellant but base structure remained intact. Copper formed a green corrosion layer (which was made worse when exposed to air after testing)
  - StaMet coating completely gone from Kapton when immersed in MMH liquid.

- Details on test setups and more pictures are in the paper

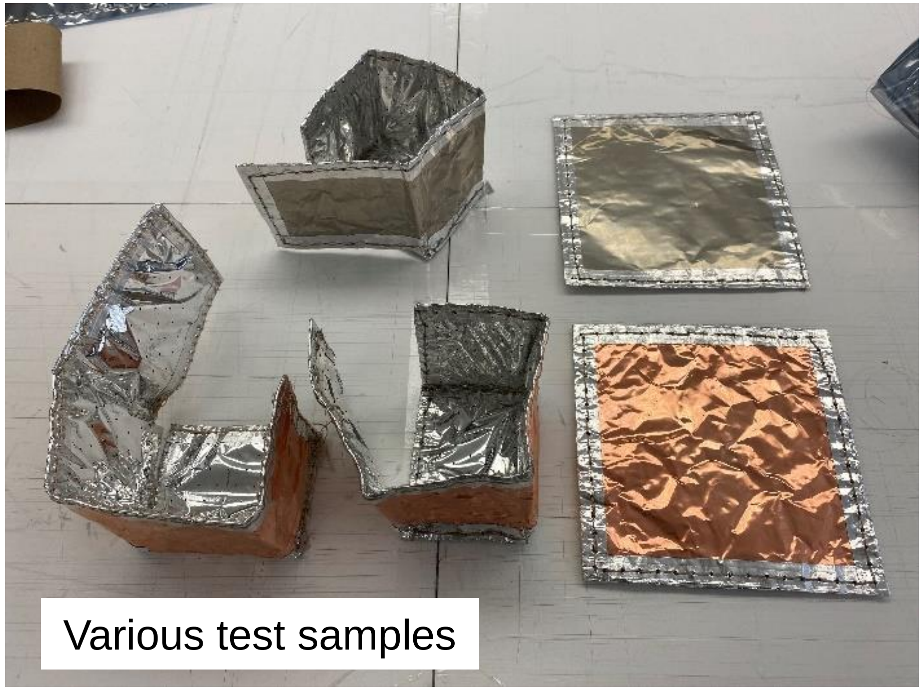
Lacing cord before and after 1 hour exposure at 600 ° C

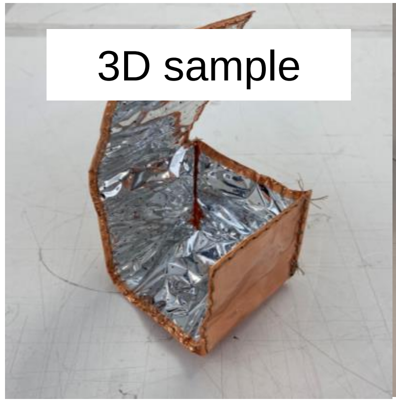


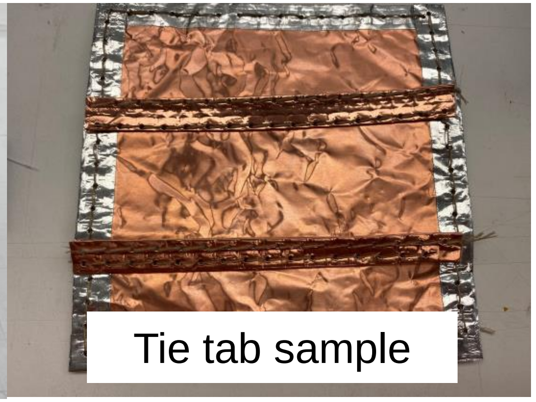



# Manufacturability

- Small 2D and 3D MLI samples were fabricated to evaluate how to work with layups containing so many metal layers, metal outer layers, and the fiberglass/Inconel sewing thread
- Sewing thread broke frequently at first; adjustments were needed on sewing machine tension.  Running thread through isopropyl alcohol on a cleanroom wipe also seemed to help.
- Coupons demonstrated there were no showstoppers, but it would be more difficult to fabricate with these materials than with polyimide materials
- Blankets tended to get smaller over time in-plane (due to creasing) and held a shape if bent


Various test samples


3D sample

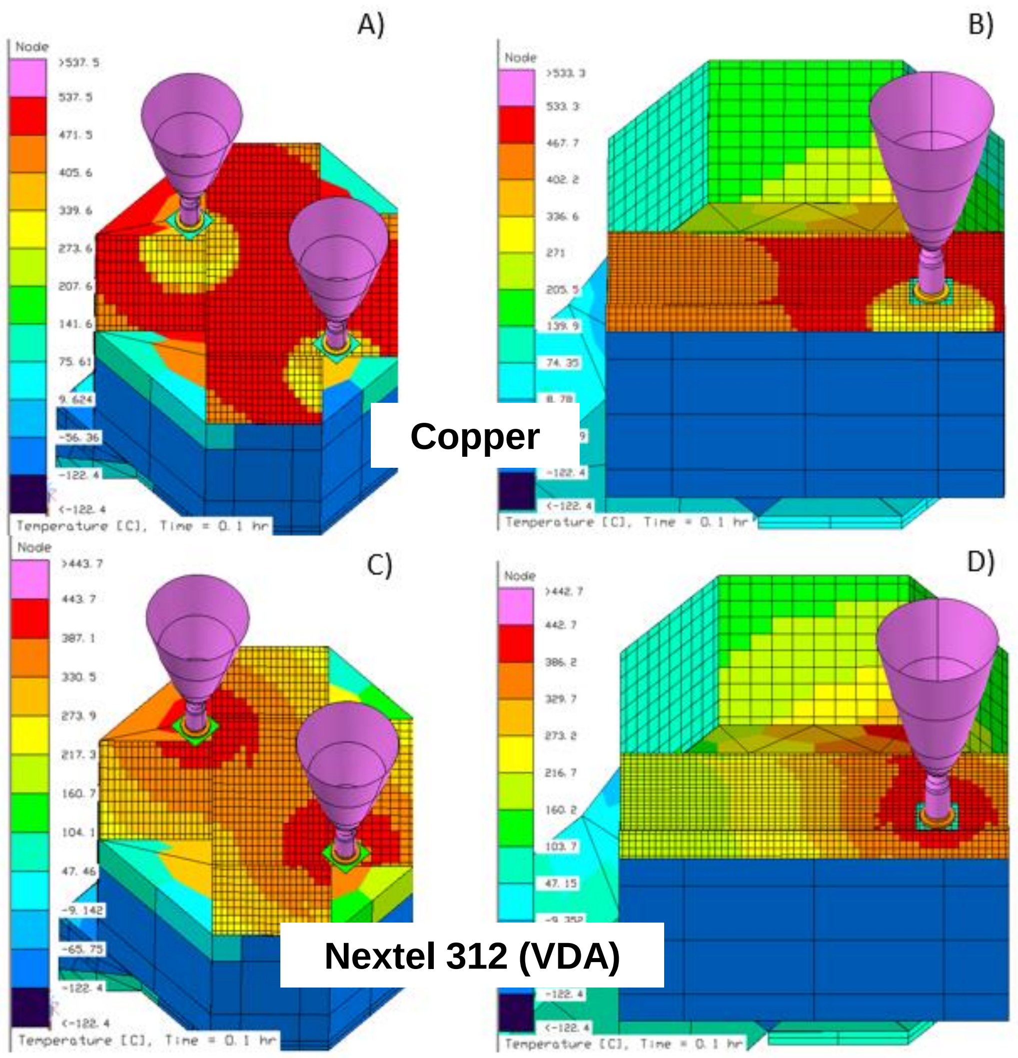

Tie tab sample

# Detailed Thermal Analysis

- Thermal analysis was done in two parts
  1. Find the worst case hot outer layer temperature
  2. Find internal layer temperatures (setting outer layer as a boundary temperature)
- All assumptions for first objective were biased to worst case hot conditions
  – Worst case hot solar flux, operating thruster engines (prime side on, backup side off), and thruster engine plume impingement for heat loads
  – Mechanical structure temperature set to maximum allowable flight temperature
  – MLI performance, ε*, set to a best case (lowest value) to approach adiabatic boundary
  – MLI nodes were arithmetic nodes (no mass); nodes at contiguous faces were not merged
- Selected Nextel 312 (bare and VDA sides viewing space), titanium, and copper as outer layers to focus on. Also included StaMet coated black Kapton (the outer material on other Clipper blankets) and aluminum as reference.

# Outer Layer Thermal Analysis Results

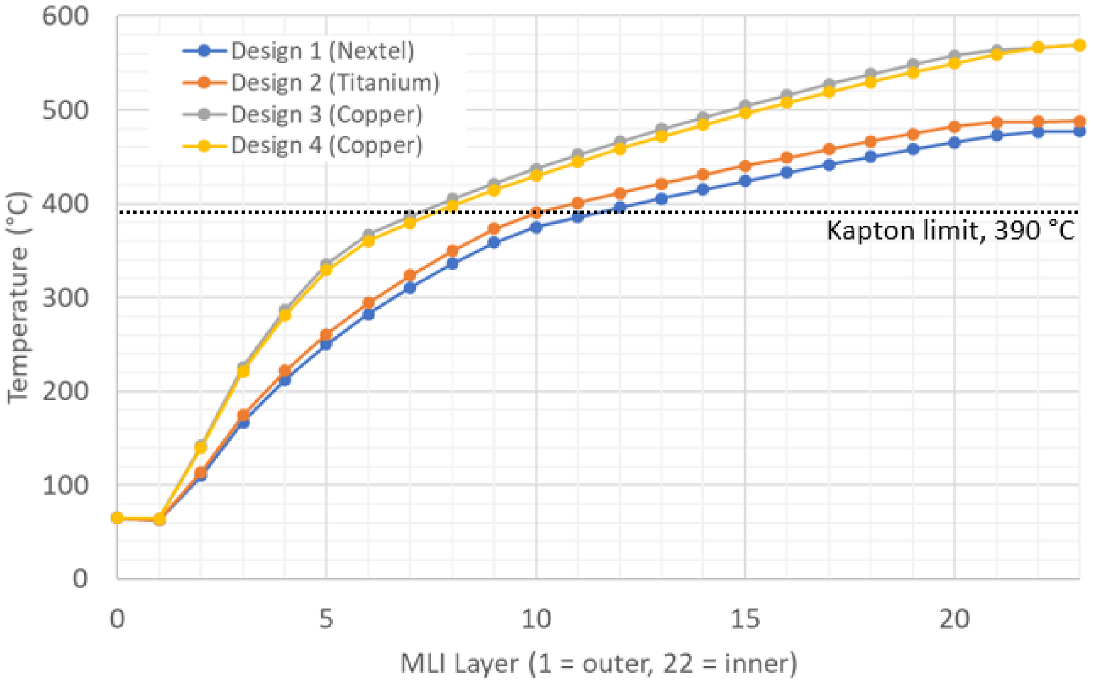
- Nextel 312 and titanium had similar temperature predictions ~ 450 ° C
- Copper (EOL) was predicted at 538 ° C
- Max temperature for low α/ε materials was near the thruster nozzle due to IR dominance. Max for high α/ε was away from the nozzle (in the sun) due to solar dominance.
- For reference, StaMet coated black Kapton was predicted at 447 ° C, which exceeded 390 ° C limit




| Outer Layer Material | α | ε | α/ε | Max Prediction (°C) | Max Service Temperature (°C) |
|---|---|---|---|---|---|
| Nextel 312, uncoated side viewing space | 0.50 | 0.82 | 0.6 | 447 | 1100 (660 for aluminization) |
| Nextel 312, aluminized side viewing space | 0.37 | 0.46 | 0.8 | 444 | 1100 (660 for aluminization) |
| Titanium | 0.51 | 0.22 | 2.3 | 463 | 1670 |
| Copper, BOL | 0.15 | 0.01 | 15.0 | 395 | 1085 |
| Copper, EOL | 0.74 | 0.07 | 10.6 | 538 | 1085 |
| StaMet coated black kapton | 0.60 | 0.85 | 0.7 | 447 | 390 |
| Aluminum 1235 | 0.20 | 0.04 | 5.0 | 431 | 645 |

# Internal Layer Thermal Analysis Results

- With the outer layer temperature known, the temperature was set as a boundary condition to determine the internal layer temperatures for several proposed blanket layups
- Four different blanket layups were proposed at this point for thermal qualification testing. Outer layer material was the key difference. We tested one with Nextel (VDA side to space), one with titanium, and two with copper (full details in backup).
- Goal was to generate pre-test temperature predictions of all layers and also determine where Kapton could start to be used in the layup (since it is lighter, better performing, and easiest to manufacture with).
- 34 ° C margin added to prediction to set qualification temperature
  - 20 ° C allowable to qual standard margin
  - 10 ° C additional margin
  - 4 ° C type K thermocouple uncertainty
- 34 ° C was used in a similar way to determine safe allowable temperature to use (< 356 ° C) for locating the Kapton layers

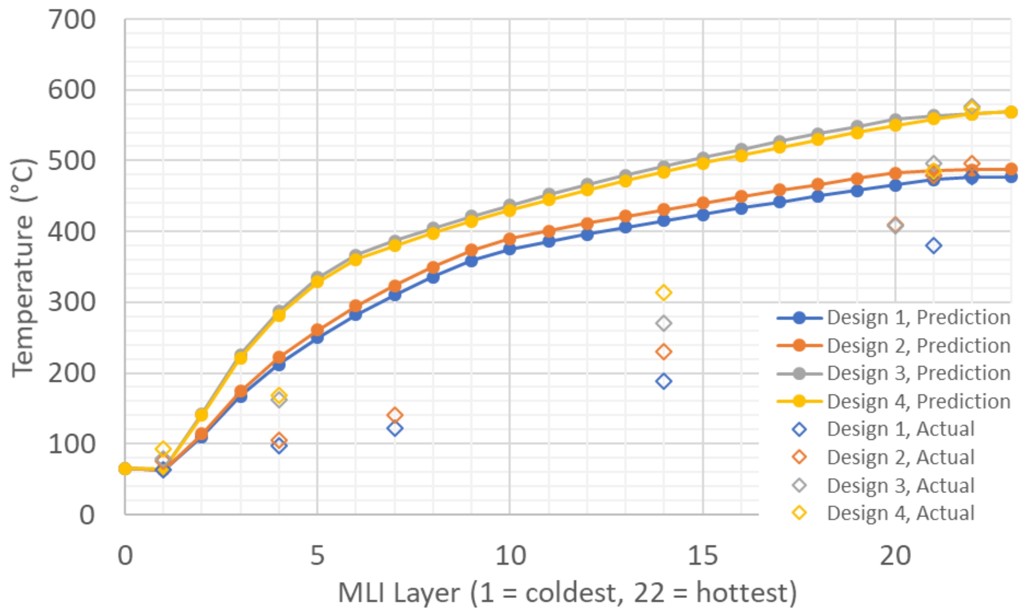


# Thermal Qualification Testing

- Three tests were created
  - Two cases for hot testing and one case for thermal performance
  - The Cassini project performed a similar test campaign with its high temperature MLI
- Hot Case – *Survivability (objective 1)*
  - First Hot Case (solar)
    - Solar simulator operating at 0.82 AU, 2033 W/m$^2$ (worst case hot closest solar approach)
    - Heat exchanger boundary operating at +65 ° C (max AFT of mechanical structure in flight)
    - Shroud flooded with liquid nitrogen, -180 to -200 ° C
  - Second Hot Case (IR)
    - Ceramic heater operating at worst case hot predicted temperature for the layup in flight with 34 ° C margin added
    - Heater surrounded by MLI blanket
    - Shroud heated to +65 ° C (max AFT of host structure in flight)
- Cold Case – *Thermal Performance (objective 2)*
  - Shroud flooded with liquid nitrogen, -180 ° C to -200 ° C
  - Temperature controlled aluminum plate at 0 ° C (min AFT of host structure in flight)

# Thermal Qualification Test Results

- Measured temperatures in solar testing were close to prediction for the Nextel and titanium outer layer design; copper was colder by over 100 ° C
- All of the materials survived the hot qualification testing
  - Some local darkening was observed with lacing cord, sewing thread, glass tissue, and Nextel similar to what was seen in the 600 ° C development test. This darkening was not concerning since the base materials remained intact.
- Measured temperatures inside the blanket were colder than predicted
  - Optical properties were conservative to produce minimal thermal isolation so that temperatures would be biased hotter
  - Nextel was used as the first internal layer in the titanium design and one of the copper designs to try and create a larger thermal gradient (Nextel is a low thermal conductivity material). Comparing temperatures of the copper designs (one with, one without Nextel), the Nextel may have produced the intended effect. This potential insulation capability of the Nextel was not modeled.
  - The glass tissue separators between aluminum layers were not modeled (thinking the glass was high ε relative to aluminum and also translucent), so they may have provided additional insulation.



# Lessons Learned

- Design
  - Starting the high temperature MLI design earlier would have been helpful. By the time this effort started in earnest (~2020), the flight hardware and thrusters were already being built and integrated. If starting earlier (circa 2018 or earlier), perhaps a thruster shield could have been implemented around the thruster nozzle and a standard MLI design could have been used. High temperature thermal control coating is another strategy.
  - Making an all metal blanket would have been one way to meet requirements but manufacturing was not really feasible for flight and mass was an order of magnitude larger than that for an all Kapton blanket
- Testing
  - Development testing was valuable (essential) for material selection and risk assessment
  - No issues with stainless steel insulated type K thermocouples and ceramic heater in qual testing; heater outgassed though at high temperatures so not advised for hardware needing to stay clean
- Manufacturing
  - Metal layers tended to form creases, they held shape when bent, and lacing holes were prone to tearing or “mushrooming”
  - Adjust tension on sewing machine and test it on sample layup until thread runs smoothly
  - Creases led to reduction in area over time and tolerance can be difficult to maintain. On a 12 inch 3D coupon, we measured a 0.75 inch loss of side length later on.

# Conclusions

- Summary
  - The four different designs tested in the thermal qualification tests each passed, so conceivably any of the four could be used at the expected temperatures
  - Preference from thermal is to fly Nextel 312 (VDA side facing space) as the design for flight to eliminate manufacturing concerns about metal outer layers and have the most temperature margin to material limits
  - JPL has flown small 2D high temperature patches (image to right) with Nextel 312 (bare side facing space) on the SWOT mission and similar predecessor missions
- Work to go
  - Contamination control is completing transport analysis to assess Nextel 312 impact on mission and if there is any credible risk.  May implement a metal foil edge tape as an additional mitigation for fiber generation on the edges.
  - Refine thermal analysis to see if high temperature MLI surface area can be reduced to just locally around the thruster engines.  This would help reduce CC and iESD impacts.
  - Incorporate performance data from cold case thermal testing into the system thermal model

High temperature MLI patch with Nextel 312 flown on AMR-SWOT

# Acknowledgments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- JPL materials and processes (Guido Canzona, Jonathan Ho, Teri Juarez, Scott Lin, Nora Low, Andrew Nuss), contamination control (Daniel Fugett), the natural space environments group (Allen Andersen, James Chinn, Wousik Kim), and the analytical chemistry lab (Jerami Mennella). iESD testing of VDA Nextel 312 was done by NASA Marshall Spaceflight Center (Todd Schneider, Jason Vaughn, Ken Wright). Propellant compatibility testing was done by NASA White Sands Test Facility (Mark McClure, Neil Paz).

# Questions?

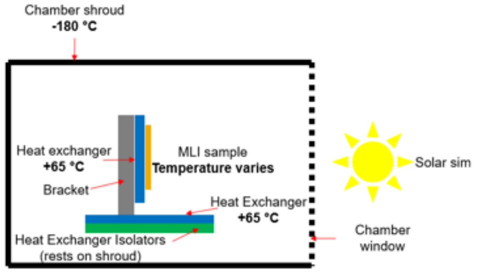
# Backup

# Thermal Qualification Test Setups

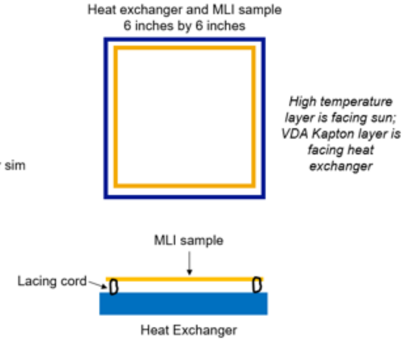
## Hot Survivability Testing

### Solar

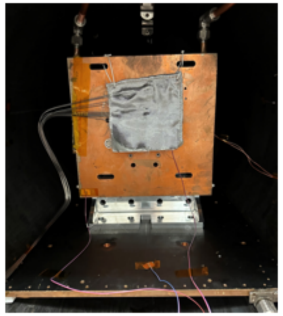
A) **Chamber view**




**Sample view**

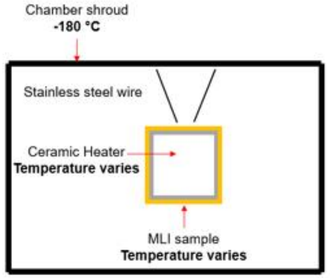



**Actual Setup**

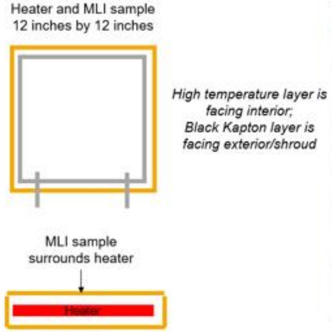


### IR

B) **Chamber view**



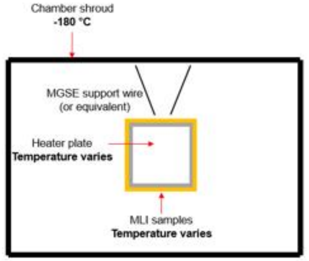

**Sample view**



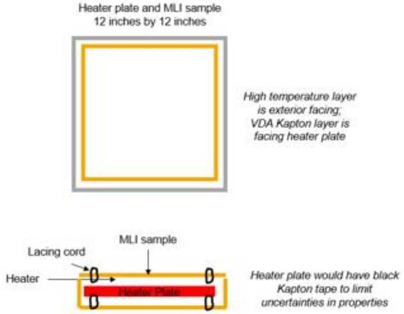

**Actual Setup**

## Cold Performance Testing

**Chamber view**



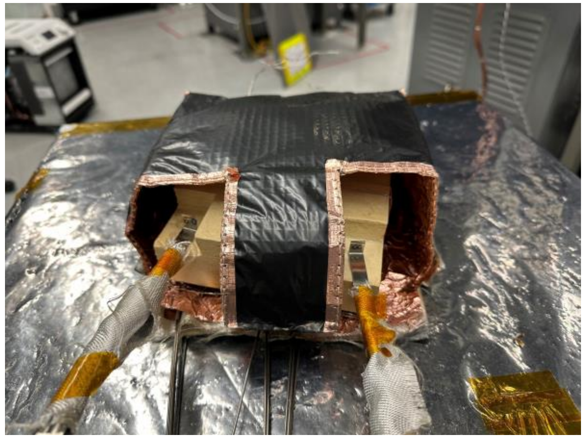

**Sample view**



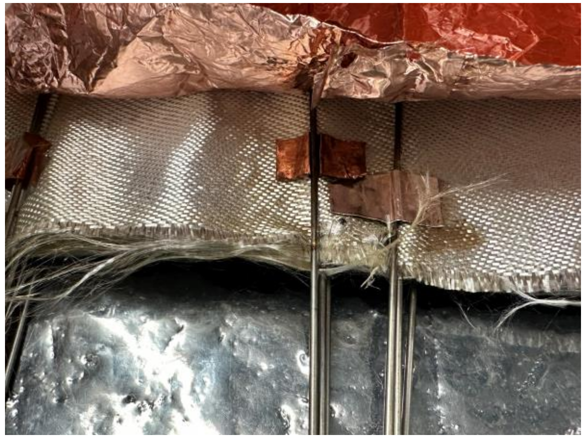

**Actual Setup**

# Thermal Qualification Testing Pictures

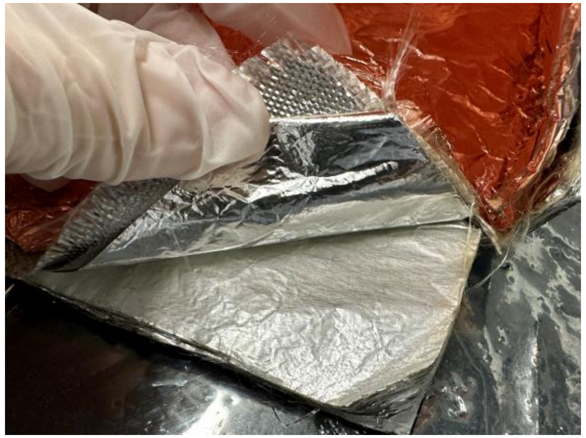
Sample installed
around heater



Nextel 312



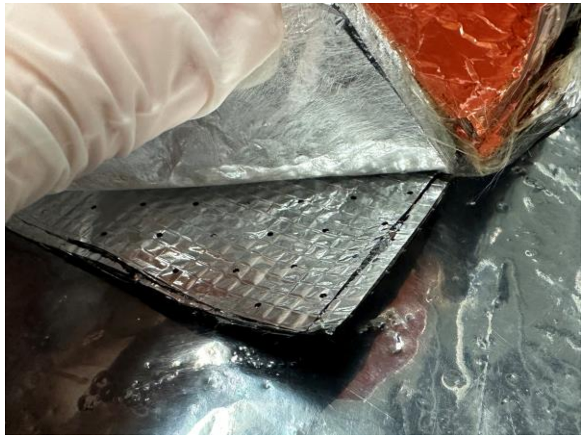
Aluminum, glass tissue
separator layers



Copper Foil

Lacing Cord

Embossed Kapton



# Thermal Qualification Test Layups

- Blanket layers
  - **Design 1** = 1x Nextel 312 (VDA side facing space), 13x aluminum foil with glass tissue separators, 7x embossed VDA Kapton, 1x VDA Kapton
  - **Design 2** = 1x titanium foil, 1x Nextel 312 (white side facing space), 12x aluminum foil with glass tissue separators, 7x embossed VDA Kapton, 1x VDA Kapton
  - **Design 3** = 1x copper foil, 1x Nextel 312 (white side facing space), 15x aluminum foil with glass tissue separators, 4x embossed VDA Kapton, 1x VDA Kapton
  - **Design 4** = 1x copper foil, 16x aluminum foil with glass tissue separators, 4x embossed VDA Kapton, 1x VDA Kapton
- Support materials
  - PTFE coated fiberglass with Inconel insert sewing thread
  - PTFE coated fiberglass lacing cord
  - Copper tape for edge binding of designs 3, 4 (designs 1 and 2 wrapped the outer layer material around the edge instead and no tape was used)

| Location | Design 1 | Design 2 | Design 3 | Design 4 |
|---|---|---|---|---|
| Outer layer | Nextel (VDA to space) | Titanium Foil | Copper Foil | Copper foil |
| Separator | Glass tissue | None | None | Glass tissue |
| Layer 1 | Aluminum foil | Nextel (white to space) | Nextel (white to space) | Aluminum foil |
| Separator | Glass tissue | Glass tissue | Glass tissue | Glass tissue |
| Layer 2 | Aluminum foil | Aluminum foil | Aluminum foil | Aluminum foil |
| Separator | Glass tissue | Glass tissue | Glass tissue | Glass tissue |
| Layer 3 | Aluminum foil | Aluminum foil | Aluminum foil | Aluminum foil |
| Separator | Glass tissue | Glass tissue | Glass tissue | Glass tissue |
| Layer 4 | Aluminum foil | Aluminum foil | Aluminum foil | Aluminum foil |
| Separator | Glass tissue | Glass tissue | Glass tissue | Glass tissue |
| Layer 5 | Aluminum foil | Aluminum foil | Aluminum foil | Aluminum foil |
| Separator | Glass tissue | Glass tissue | Glass tissue | Glass tissue |
| Layer 6 | Aluminum foil | Aluminum foil | Aluminum foil | Aluminum foil |
| Separator | Glass tissue | Glass tissue | Glass tissue | Glass tissue |
| Layer 7 | Aluminum foil | Aluminum foil | Aluminum foil | Aluminum foil |
| Separator | Glass tissue | Glass tissue | Glass tissue | Glass tissue |
| Layer 8 | Aluminum foil | Aluminum foil | Aluminum foil | Aluminum foil |
| Separator | Glass tissue | Glass tissue | Glass tissue | Glass tissue |
| Layer 9 | Aluminum foil | Aluminum foil | Aluminum foil | Aluminum foil |
| Separator | Glass tissue | Glass tissue | Glass tissue | Glass tissue |
| Layer 10 | Aluminum foil | Aluminum foil | Aluminum foil | Aluminum foil |
| Separator | Glass tissue | Glass tissue | Glass tissue | Glass tissue |
| Layer 11 | Aluminum foil | Aluminum foil | Aluminum foil | Aluminum foil |
| Separator | Glass tissue | Glass tissue | Glass tissue | Glass tissue |
| Layer 12 | Aluminum foil | Aluminum foil | Aluminum foil | Aluminum foil |
| Separator | Glass tissue | Glass tissue | Glass tissue | Glass tissue |
| Layer 13 | Aluminum foil | Aluminum foil | Aluminum foil | Aluminum foil |
| Separator | Glass tissue | Glass tissue | Glass tissue | Glass tissue |
| Layer 14 | Embossed VDA kapton | Embossed VDA kapton | Aluminum foil | Aluminum foil |
| Separator | None | None | Glass tissue | Glass tissue |
| Layer 15 | Embossed VDA kapton | Embossed VDA kapton | Aluminum foil | Aluminum foil |
| Separator | None | None | Glass tissue | Glass tissue |
| Layer 16 | Embossed VDA kapton | Embossed VDA kapton | Aluminum foil | Aluminum foil |
| Separator | None | None | Glass tissue | Glass tissue |
| Layer 17 | Embossed VDA kapton | Embossed VDA kapton | Embossed VDA kapton | Embossed VDA kapton |
| Separator | None | None | None | None |
| Layer 18 | Embossed VDA kapton | Embossed VDA kapton | Embossed VDA kapton | Embossed VDA kapton |
| Separator | None | None | None | None |
| Layer 19 | Embossed VDA kapton | Embossed VDA kapton | Embossed VDA kapton | Embossed VDA kapton |
| Separator | None | None | None | None |
| Layer 20 | Embossed VDA kapton | Embossed VDA kapton | Embossed VDA kapton | Embossed VDA kapton |
| Separator | None | None | None | None |
| Inner Layer | VDA Kapton | VDA Kapton | VDA Kapton | VDA Kapton |
| Thread | Inconel + Fiberglass | Inconel + Fiberglass | Inconel + Fiberglass | Inconel + Fiberglass |
| Lacing cord | Fiberglass | Fiberglass | Fiberglass | Fiberglass |
| Edge Tape | N/A, Nextel wraparound | N/A, Titanium wraparound | Copper tape | Copper tape |