DESIGN AND QUALIFICATION OF A HIGH TEMPERATURE MULTI-LAYER INSULATION BLANKET FOR THE EUROPA CLIPPER MISSION

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ABSTRACT

The Europa Clipper mission and environment imposes several constraints on the design of multi-layer insulation (MLI) blankets that insulate the thruster engine brackets. The driving environmental constraints are material compatibility with ionizing radiation, low or no electrostatic discharge, low outgassing rates in vacuum and in the presence of ionizing radiation, not a generator of foreign object debris, magnetic cleanliness to not interfere with instrument science data, and compatibility with monomethyl hydrazine and mixed oxides of nitrogen propellants. The combination of these constraints limits the number of materials acceptable for the flight blanket design. These requirements are most driving for materials on the space-viewing side of the blanket that would experience the worst case space environment effects. Furthermore, the MLI must simultaneously survive a 0.82 AU solar load as well as infrared and plume impingement heat loads generated by the nearby thruster engines during trajectory maneuvers. Development testing was performed with constituent materials to identify materials that fully address these constraints or minimize negative impacts to the mission. Coupons of several prospective MLI layups were then fabricated for qualification to the high temperatures and a separate thermal balance test for heat loss characterization. These tests were designed to demonstrate capability to the worst case thermal environment and provide inputs for the Europa Clipper system thermal model. This paper will describe the driving requirements, the materials considered and tested for this application, the candidate high temperature MLI blanket designs, the qualification test efforts, test observations, and lessons learned.

NOMENCLATURE, ACRONYMS, ABBREVIATIONS

α	solar absorptivity
ε	infrared emissivity
ε^*	MLI blanket effective emittance
BOL	beginning of life
EOL	end of life
iESD	ionizing electrostatic discharge

FOD	foreign object debris
JPL	Jet Propulsion Laboratory
MLI	multi-layer insulation
MMH	monomethyl hydrazine
MMOD	micrometeoroid and orbital debris
MON-3	mixed oxides of nitrogen
PTFE	polytetrafluoroethylene
RDF	radiation design factor
REASON	Radar for Europa Assessment and Sounding: Ocean to Near-surface
TID	total ionizing dose
VDA	vapor deposited aluminum

INTRODUCTION

The Europa Clipper mission is planned to launch in 2024 to conduct reconnaissance of Europa, which is one of Jupiter's moons. Once the spacecraft arrives at Europa, the science instruments will begin to collect data about the moon and hopefully address some questions about this ocean world's prospects for habitability. However, the Jovian environment presents significant engineering challenges for material selection and survivability. The science payload also imposes its own constraints on material selection. As a result, some of the flight heritage and best practices developed from past flight projects have had to be reexamined or replaced altogether.

The Europa Clipper spacecraft will be nearly covered with multi-layer insulation (MLI) blankets in flight to insulate the spacecraft and conserve heater power. These blankets are crucial for thermal performance since the mission uses a solar array for power and solar flux is limited to about 50 W/m^2 during the mission's science phase at Europa. The MLI blanket construction at the Jet Propulsion Laboratory (JPL) uses tape bound edges with stitched seams. This design is robust for ground handling and flight environments. The typical JPL manufacturing techniques and the Europa Clipper specific MLI blanket designs and implementation approach for most of the spacecraft were documented in a previous paper.[1] However, there is a separate need for a high temperature blanket around the thruster engines (Figure 1). This blanket must be compliant with the same requirements as other blankets while also surviving high temperatures that result from solar and thruster engine heat loads. This is particularly true for the materials at the outermost, space-viewing layer, which experience the worst case mission environment.

This paper will outline the high temperature MLI driving requirements, material selection process, thermal analysis, and qualification of a flightworthy design.

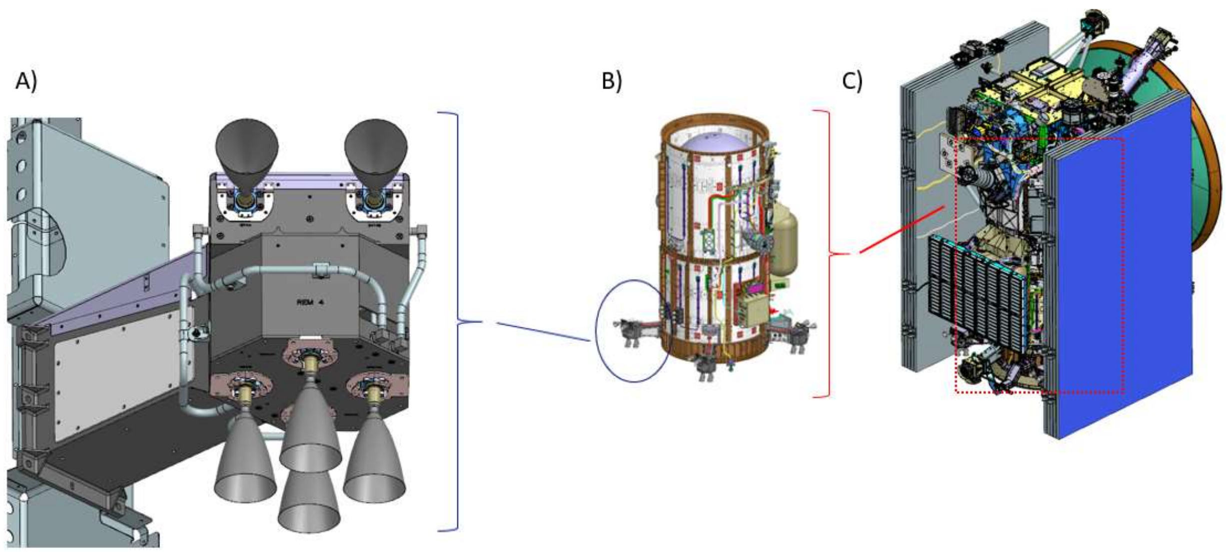


Figure 1. The aft end of the Europa Clipper spacecraft contains A) four brackets with thruster engines used for attitude control. Each rocket engine module contains six thruster engines. The octagon shape with the six engines is the location of interest for the high temperature MLI. These brackets are attached to the B) propulsion module, which is integrated with the C) Europa Clipper spacecraft.

MISSION ENVIRONMENT AND REQUIREMENTS

Natural Space Environments

Ionizing radiation is a major challenge for designing hardware to function at Jupiter. The expected radiation dose received by hardware depends on the amount of shielding between it and space, but the maximum total ionizing dose (TID) for external surfaces is estimated at over 1 Grad for the planned lifetime of the mission. The radiation dose is reduced to approximately 44 Mrad (radiation design factor (RDF) = 2) for hardware underneath a 22 layer MLI blanket (assuming a conservatively low 0.45 kg/m^2) planned for use around most of the spacecraft. Since most MLI has an unobstructed view to space, the outer layer and support materials (lacing cord, sewing thread, edge tape) must remain functional to over 1 Grad TID, while hardware inside and underneath MLI only needs to survive the Mrad TID regime.

The ionizing radiation has an additional side effect in that it can create ionizing electrostatic discharge (iESD). Electric charge can accumulate naturally on material when close to Jupiter. A discharge can occur or charge can be bled off when further away from Jupiter. Materials that are not electrically conductive can become increasingly prone to ESD until an ESD event occurs.

This can damage sensitive electronics or science instruments. Some amount of discharge may be acceptable, but the acceptable frequency and magnitude depends on the sensitivity of the victim(s). Furthermore, the Radar for Europa Assessment and Sounding: Ocean to Near-surface (REASON) instrument requires low background electrical noise to meet its science objectives. Therefore, in addition to general ESD compliance for hardware safety, as is typical on any flight project, Europa Clipper has a “noise budget” for REASON to help assess whether a material application will be acceptable. iESD analysis can be done to provide a coarse assessment for mission compliance, but material testing is often more conclusive.

The planned mission trajectory includes gravity flybys of Earth and Mars before the spacecraft reaches Jupiter. The solar distance ranges from 0.82 to 5.6 AU. At 5.6 AU, there is a maximum 9.2 hour eclipse caused by Jupiter. A trajectory control maneuver with the thruster engines is planned at 0.82 AU and imposes additional thermal loads on MLI located near the engines. Detailed thermal analysis was performed of the thruster engine area and the high temperature MLI blankets that would be covering the area. This analysis considers the worst case hot solar load at 0.82 AU and the infrared loads created by adjacent thruster engines. Thruster firing durations can be about 45 minutes at inner cruise and 6.5 hours during Jupiter orbit insertion, either of which can be long enough to approach a steady state temperature on the outer surface of the MLI. The temperature of the outer layer will be primarily a function of solar absorptivity and infrared emissivity. As will be described later, both the ratio of these two values and the infrared emissivity by itself can have significant effects on temperature.

Micrometeoroid and orbital debris (MMOD) protection is also something to consider, but it does not drive the high temperature blanket design. MMOD damage probability for the mission has been assessed using the expected MLI coverage and designs planned for flight, and a high temperature blanket design will only reduce the damage probability for the thruster brackets since some materials will be higher density and therefore offer greater shielding than that from polyimide materials. A brief discussion of the MMOD approach for Europa Clipper may be found in the aforementioned reference.

Additional Requirements

The mission’s science payload imposes several additional material selection challenges. There are two instruments, Europa Clipper Magnetometer and Plasma Instrument Magnetic Sounding, that study magnetic field. As such, magnetic cleanliness is important to avoid contaminating their science data. The typical magnetic requirement for spacecraft MLI blankets and support hardware is 1 Gauss or lower at 1 cm distance.

In addition to magnetics, contamination control is another factor to consider. The typical requirement is for outgassing to be less than $5*10^{-14}$ g/cm^2/s at the hardware’s hottest predicted temperature during the mission’s science phase at Europa. This requirement applies when in a vacuum and also in a radiation environment, which can create additional outgassing and is a factor near Jupiter. Therefore, ideal materials would be low outgassing and also not susceptible to change in radiation. Related to this, materials should not be generators of foreign object debris (FOD) through generation of particles or fibers. Conductive FOD is of particular concern. This concern applies more to ground handling of the MLI during installation, modification, and removal since FOD generation is not expected after launch. Directional venting is another item to note for Europa Clipper, although this does not affect the high temperature MLI design since the location is further from sensitive instruments. A stitched and edge bound seam blanket construction allows venting to be controlled by design of the blanket overlap/underlap direction and features at interfaces.

Lastly, the outer materials must survive impingement of monomethyl hydrazine (MMH) and mixed oxides of nitrogen (MON-3) propellant. The thruster engines create vapor plumes and liquid droplets of propellant, either of which may cause adverse chemical reactions that degrade function.

Requirements Summary

- 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 – 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

MATERIAL SELECTION

The large number of requirements imposed on material selection eliminated some prospective materials from further consideration. As will be discussed later, polyimide materials, which are common for MLI blankets, would only be suitable in a "low temperature" portion of the blanket layup, if at all, because of the high predicted temperatures. Therefore, the outer layer and some number of internal layers in the "high temperature" portion of the blanket layup should be ceramic or metallic. Ceramic textiles would be a good choice for a high temperature, high radiation environment, but they are not electrically conductive and are prone to shedding from handling or vibration. Some metallic materials have excellent compatibility with the mission environment but pose manufacturing challenges for a soft good and have less favorable thermal optical properties. Refer to Table 1 for a summary of the initial material selection matrix. Further testing was needed for materials without relevant flight heritage, intrinsic compliance from known material properties, or existing test data.

Table 1. Summary of Driving Requirements and Starting Position for Each Candidate Material

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

MATERIAL TESTING

Short screening tests were done with materials that had possible concerns or unknowns with the Europa Clipper environment. These were intended to quickly confirm a material could be acceptable for the high temperature MLI design or determine another material may be needed.

Constituent Material Screening Tests

Thermal

Some materials were subjected to a one hour 600 °C dwell with an ambient pressure argon backfill as a thermal screening test. This was to reduce risk of finding a material failure during the later qualification test. The 600 °C temperature was derived from the worst case hot temperature prediction (described in a later section) for a layup with copper foil outer layer, which had the highest predicted temperature of the designs considered, with some added margin. Pre and post test images of the samples are included in Appendix A. The following materials were included in this test:

- Copper foil (outer layer)
- 1.8 mil copper foil with pressure sensitive adhesive (edge tape)
- Glass tissue (high temperature separator layer)
- Polytetrafluoroethylene (PTFE) coated fiberglass lacing cord
- PTFE coated fiberglass thread with Inconel wire insert (sewing thread)

Copper foil was tested but not expected to be a concern for thermal survivability. However, copper can be reactive, so thermal optical property change was of interest. The copper showed visible darkening after the testing (Figure A1). The average pre-test properties were α/ε = 0.141/0.010 (=14.1); average post-test properties were α/ε = 0.735/0.068 (=10.6). This large of a change was not expected and could be due to either the temperature exposure, impurities in the argon gas, or both. Copper is susceptible to oxidation at higher temperatures, so oxygen in the chamber may be a potential cause for the change.

Glass tissue would function as a separator layer in place of polyester netting that typically separates layers in a MLI blanket. Other than visible darkening, there were no changes noted to the glass tissue material (Figure A3). Magnified images showed the internal structure was similar after exposure (Figure A4).

Not to be forgotten, the edge tape, sewing thread, and lacing cord must also survive the same environment as the outer layer material. The backing adhesive was no longer present on the copper foil tape, indicating that the material would no longer function as a tape (Figure A2). However, the material would be stitched to the blanket with sewing thread, so the remaining copper substrate would still able to maintain the bound edges. The lacing cord was darker and more flexible (Figures A5, A6). The outer portion of the sewing thread was visibly darker and the thread was stiffer (Figure A7). However, the thread retained integrity and the Inconel wire insert was unchanged. It was expected that the PTFE coating on the lacing cord and thread would decompose at these temperatures since its melting temperature was lower than 600 °C. The thread generated some particulate contamination when handled after exposure. However, this is not a concern for the mission since the thread will not be in this condition until flight, at which point no handling will occur to create particulation. Related to the outgassing requirement, the contamination control team determined there was not a viable transport mechanism in this case to sensitive hardware to negatively impact the mission.

Radiation

Radiation testing was completed for the Europa Clipper spacecraft blankets and ground straps in a separate effort with the JPL materials and processes group. Most of the high temperature candidate materials (ceramics, metals) described earlier are robust to Grad radiation levels. However, the polyimide layers and support materials (tape, sewing thread, lacing cord) must also remain intact. 2 inch by 2 inch square coupons of various MLI layups planned for Europa Clipper were subjected to thermal cycling and up to Grad TID radiation exposure (Figure 2). The standard 22 layer blanket design was thermally cycled ten times between ambient and +204 °C, radiation dosed in multiple stages in an inert environment to reach up to Grad TID on the external layer and Mrad regime on the internal layers, and then thermally cycled ten times between ambient and -236 °C. This order of operations was intentional to replicate flight (or at least as closely as possible). No significant discrepancies affecting fit, form, or function were observed. There was some creep of the StaMet coated black Kapton tape adhesive from underneath the substrate. The adhesive adhering the nomex scrim backing reinforcement to the StaMet coated black Kapton outer layer exhibited creep as well. These may have occurred during the hot thermal cycles. These findings only apply to the standard MLI design used elsewhere on the spacecraft and not the high temperature design. Some fraying and outgassing of the lacing cord and thread was observed but the knots were retained (Figure 3). Neither of these was considered an issue for the MLI in flight.

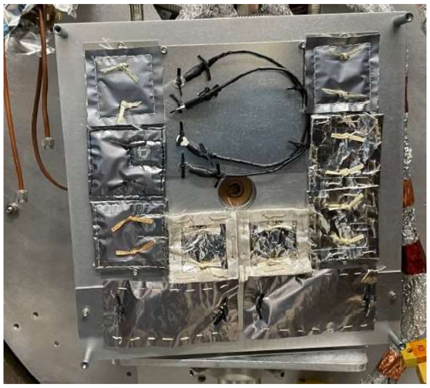


Figure 2. Radiation test setup with sample blankets and ground straps.

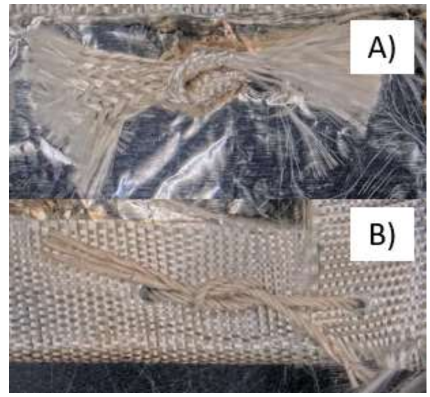


Figure 3. A) Lacing cord B) sewing thread post test images.

iESD

The lacing cord and ceramic fabric (Nextel 312 specifically) were the only non-metallic (or non-metallic coated) bulk materials considered for this high temperature blanket application. As procured, the Nextel 312 material had a bare, uncoated side (looks white in appearance) and a vapor deposited aluminum (VDA) coated side. Neither of these sides had electrical continuity when measured with a digital multimeter. Since the material was not electrically conductive, its iESD compatibility with sensitive hardware and the REASON instrument needed to be assessed. iESD testing was done with lacing cord and the uncoated and aluminized sides of Nextel 312 (Figure 4) to evaluate if they would be acceptable for the mission.

The lacing cord test resulted in an effective discharge rate of 13 ESD/sec for an assumed total length of 5000 ft. This estimate accounted for partial blockages by being covered by blankets or mechanical interfaces. This discharge rate was acceptable for REASON.

The first test with Nextel 312 was done at NASA Marshall Spaceflight Center with the aluminized side facing space (Figure 4A). After exposing the material to 60 keV on target, 0.5 nA/cm^2, and temperature around -160 °C for ten hours, the discharge rate was about 0.16 arc/sec for a 4 inch by 4 inch sample and 0.46 arc/sec for a 8.5 inch by 8.5 inch sample. The largest arc was 110 mA for the 4 inch by 4 inch sample and 440 mA for the 8.5 inch by 8.5 inch sample through 50 Ohm. The discharge rate and magnitude scaled roughly linearly with area. After correcting for sample rate limitations and the background noise environment and then extrapolating the results to a worst case max area usage of 1.2 m^2 in flight, the predicted discharge rate was 57 arc/sec, which was acceptable for the REASON noise budget given the

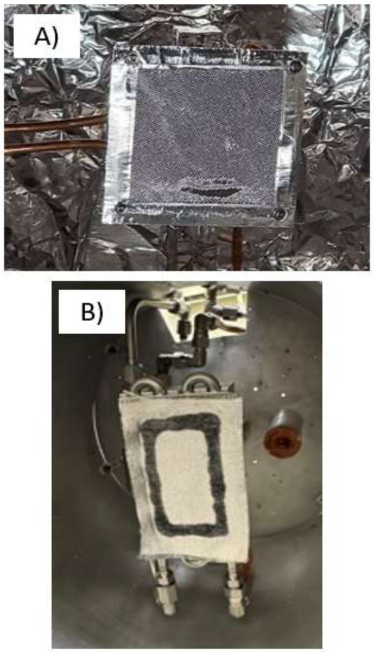


Figure 4. Nextel 312 iESD testing A) with aluminized side B) uncoated side.

other known discharge sources on the mission. The discharge magnitude was also acceptable since all nearby electronic hardware would be rated to at least human body model class 2 and wire harness would be wrapped with copper tape.

The second test was done later on at JPL with the uncoated side (Figure 4B). The setup was intended to be similar to Marshall's and the conditions were 60 keV on target, 0.58 nA/cm^2, and temperature around -90 °C for ten hours (temperature was a limiting factor on this setup). The discharge rate was about 0.36 arc/sec for a 3.5 inch by 6 inch sample. The largest arc was 76 V through 50 Ohm. Assuming the results scaled linearly with area like the previous test and applying correction factors, the predicted discharge rate for 1.2 m^2 of surface area in flight was 24 arc/sec with a maximum arc of 9300 V through 50 Ohm, which resulted in human body model class 3B. This result was more concerning than that for the aluminized side, so if Nextel 312 were to be used, the preference for iESD was for the aluminized side to face space.

Contamination Control

The second concern about the Nextel 312 material, and only the Nextel 312, was its tendency to shed fibers when handled. To quantify this impact, an agitation test was performed with both a single piece of material and a piece sewn into a blanket as an outer layer. The agitation tests generated fibers about 1-2 cm long. Additionally, the handling produced small particulate observed on nearby witness plates. This confirmed a need to limit particle shedding if the material were to be used in the flight blankets. A mitigation strategy for this is to use a cleanroom vacuum during installation of the blankets and add a temporary ESD safe, thin film cover over the blankets afterwards to prevent generating or migrating any new particulate. The high temperature blankets only need to be exposed for spacecraft thermal vacuum testing and launch, which reduces the amount of handling time and chance for particulation. Another mitigation is to use a different material edge tape to prevent or contain any fibers on the edges.

Analytical chemistry testing of the Nextel 312 and glass tissue separators revealed no significant levels of organic materials or sizing agents. Trace amounts of aliphatic hydrocarbon and ester residues were detected, but amounts were below 0.1 µg/cm^2.

Propellant Compatibility

Due to the high temperature blanket's proximity to the thruster engines, it is possible for MMH or MON-3 propellant vapor or liquid to impinge on the outer surface. To assess the impact of this, small material samples were subjected to vapor immersion, liquid immersion, and liquid drip tests for several hours each at the White Sands Test Facility. The materials of greatest interest were the copper, sewing thread, and lacing cord. StaMet coated black Kapton was included since it would be used elsewhere on the spacecraft, but it was only relevant for the standard MLI blankets located elsewhere on the spacecraft.

MON-3 generally produced more noticeable changes than MMH (Figure 5). MON-3 liquid led to delamination or dissolving of the PTFE coatings for lacing cord and thread. The colors also changed. However, neither outcome was considered detrimental to the function for the MLI blanket since the lacing cord and thread would each be mechanically bound to the MLI in some way to keep them in place in flight. The intrinsic structure of the lacing cord and thread also remained. MON-3 vapor created a loose, green corrosion layer on copper. This effect mostly happened after the sample was in air for several hours. The corrosion was much less evident immediately after the MON-3 exposure, so the worst case result was not fully flight like.

MMH was more impactful to StaMet coated black Kapton (Figure 6). The liquid exposure led to full removal of the StaMet germanium coating from the black Kapton substrate. This was not surprising since the StaMet coating was only about 60 Angstroms thick, but it did reveal that the material would function thermally like black Kapton (higher solar absorptivity) if it were used in this application.

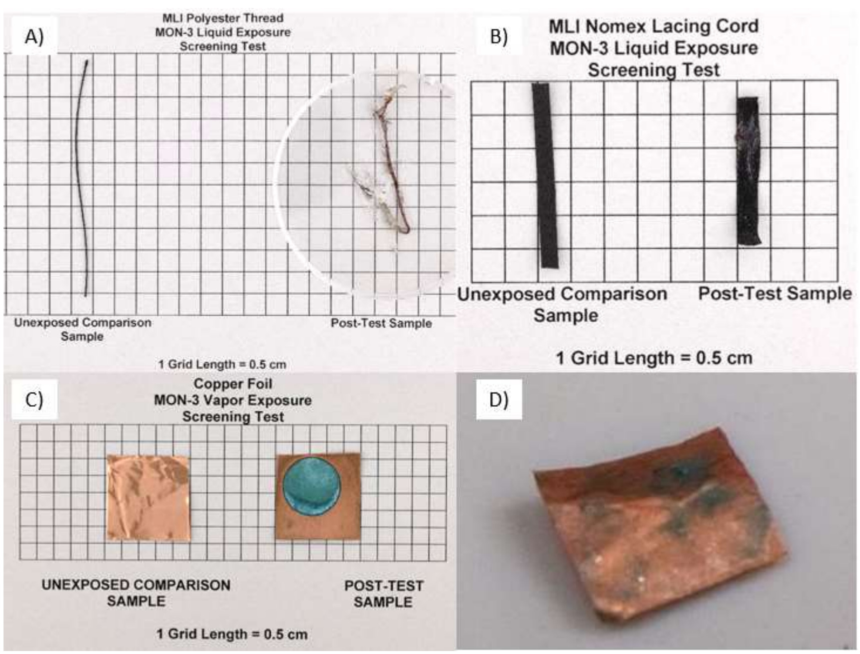


Figure 5. Results of MON-3 exposure for A) sewing thread B) lacing cord C) copper foil D) copper foil after 4 hour MON-3 vapor exposure but before air exposure (therefore green corrosion not yet evident).

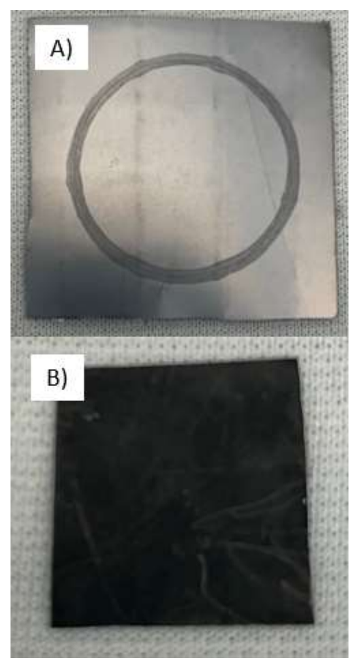


Figure 6. Results of MMH exposure for StaMet coated black Kapton A) in vapor B) in liquid.

Manufacturability

Environmental compliance aside, a design is not valuable if it cannot be manufactured. JPL has fabricated small, high temperature "patch" MLI with aluminum internal layers but never blankets with metallic outer layers. Small scale manufacturing tests were created as proofs of concept. Key concerns to address were sewability of the thread, likelihood of tear propagation, and suitability for a three dimensional shape. These proofs of concept (Figure 7) provided some early validation that such a design could be manufactured with minimal change to existing process. One immediate observation was that the metal layers tended to form and maintain creases. If a blanket were folded, the blanket held that shape. If the blanket were folded again to a different position, the blanket held that new shape. Tearing was not observed in the foil itself but was observed sometimes around holes created for lacing cord. An additional issue related to the creasing, especially for the copper outer layer samples, was that material tended to contract in-plane. This could lead to dimensional tolerancing issues on larger blankets that have cutouts or features in them. On a three dimensional blanket sample with 12 inch length, 0.75 inches of length was lost due to contraction of the material caused by handling.

The tension of the sewing machine was adjusted from what was typically used for blankets with polyester thread. Lightly lubricating the thread with isopropyl alcohol or ethyl alcohol was also helpful. Both of these were intended to keep the thread from breaking. Punching the lacing holes was harder as expected and effort seemed proportional to the number of metal foil layers in the layup.

Figure 7. Small scale manufacturing samples with copper and stainless steel foil outer layers and PTFE coated fiberglass/Inconel sewing thread.

DETAILED THERMAL ANALYSIS

Outer Layer Modeling

A geometric thermal model was created of one bracket with the thruster engines and MLI to determine the maximum temperature prediction for the outer layer MLI material. Assumptions were chosen to produce a conservative, worst case hot analysis.

Thermal model assumptions:

- 0.82 AU worst case hot solar flux (2103 W/m^2 per environmental requirements document)
- Thruster engine (prime side on, redundant side off) operates through one firing cycle
- Solar angle varies (~ten degrees off normal from surface was found to be worst)

- 35 W/m^2 (includes a factor of two uncertainty factor) incident heat flux from thruster engine plumes
- Mechanical structure temperature set to maximum allowable flight temperature (+65 °C)
- MLI performance, ε*, set to a best case (lowest value) of 0.01 to maximize temperature gradient from hardware to outer layer and approach an adiabatic boundary condition
- MLI nodes were arithmetic nodes (no mass); nodes at contiguous faces were not merged

The analysis was performed with several different outer layer materials. The materials that became the focus of further study at this point because of the large temperature margins to hardware capability were Nextel 312, titanium (unalloyed), and copper (unalloyed). Cases with uncoated and aluminized Nextel 312 viewing space were each modeled. StaMet coated black Kapton, which is the outer material used for most of Europa Clipper's blankets, and aluminum (alloy 1235) were also included for reference but not seriously considered because of the lower (or negative) temperature margins. The analysis was performed separately for the MLI on the axial and roll engine sides in case there was a difference in temperature. The incident solar angle was varied to determine if temperature could increase for a spacecraft attitude that would only occur during a trajectory control maneuver or attitude fault. Ten degrees from normal to the MLI resulted in the maximum temperature and a temperature about 20 °C higher than that when sun was normal to the MLI. The maximum temperature predictions and margins for the outer layer are reported in Table 2 below.

Table 2. Worst Case Hot Temperature Predictions by Material

Outer Layer Material	α	ε	α/ε	Optical Property Source	Axial Engine Side Max Predicted Temperature (°C)	Roll Engine Side Max Predicted Temperature (°C)	Max Service Temperature (°C)
Nextel 312, uncoated side viewing space	0.50	0.82	0.6	Measured	444	447	1100 (660 for aluminization)
Nextel 312, aluminized side viewing space	0.37	0.46	0.8	Measured	444	443	1100 (660 for aluminization)
Titanium	0.51	0.22	2.3	Measured	463	455	1670
Copper, BOL	0.15	0.01	15.0	Measured	395	393	1085
Copper, EOL	0.74	0.07	10.6	Measured after 600 °C exposure	538	533	1085
StaMet coated black kapton	0.60	0.85	0.7	Measured, spec sheet	447	447	390
Aluminum 1235	0.20	0.04	5.0	Spacecraft Thermal Control Handbook	431	426	645

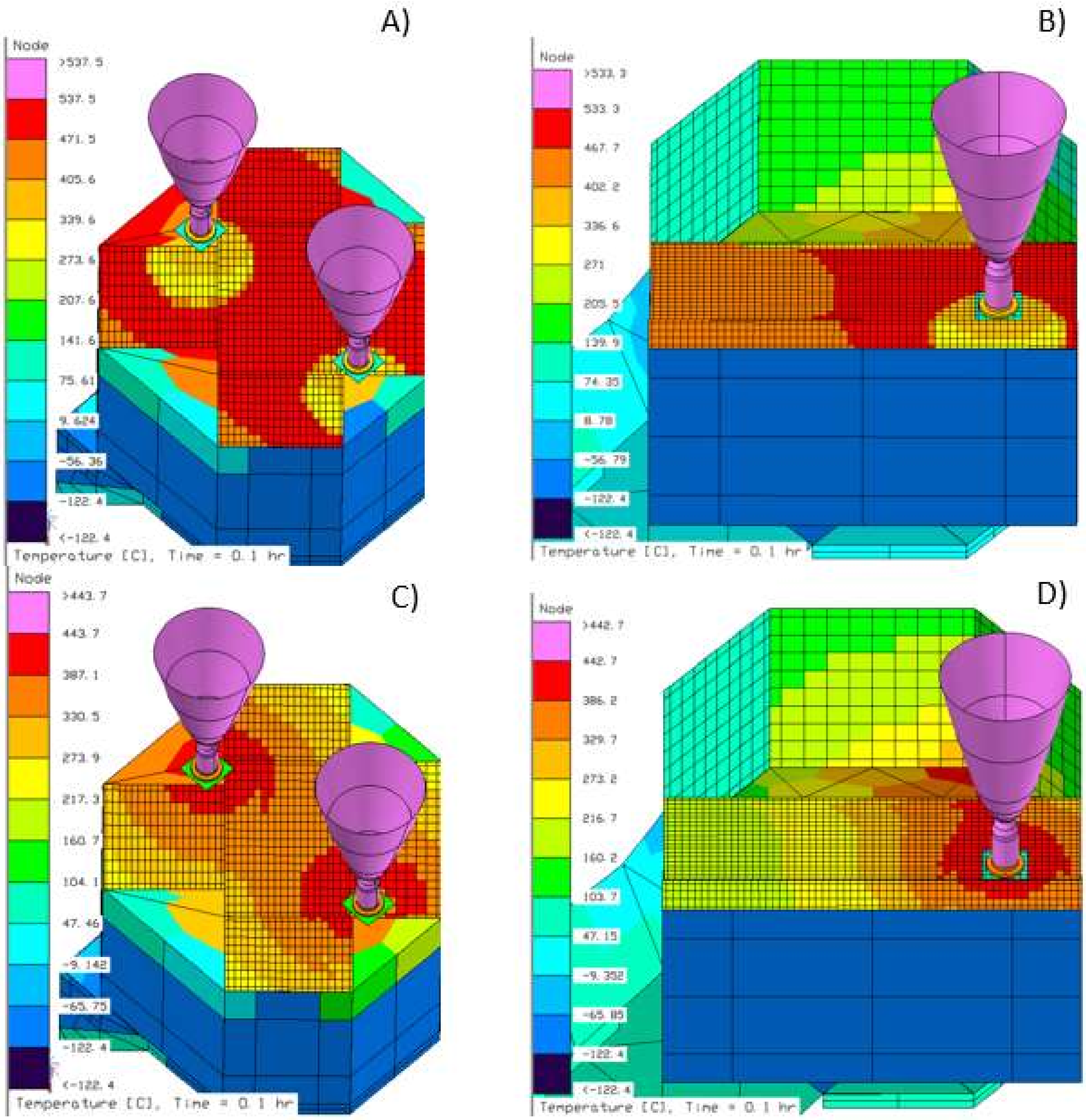


Figure 8. Worst case hot temperature predictions for A) copper outer layer, axial side B) copper outer layer, roll side C) aluminized Nextel 312, axial side D) aluminized Nextel 312, roll side. For copper (α/ε = 10.6), the nozzle shadow created a local cold spot since solar was the driving heat load. However, for aluminized Nextel 312 (α/ε = 0.8), the area around the nozzle was hottest since the nozzle IR was the driving heat load.

The worst case hot temperature predictions were 447, 463, and 538 °C for Nextel 312 (uncoated), titanium, and copper (end of life (EOL)) respectively. The difference in temperatures between roll and axial engine faces was only a few degrees Celsius for each material. A specularity of 0.7 was also included as a sensitivity case (more applicable to metals) but only increased the temperatures by at most 2 °C. This seemed logical since the structure was primarily flat, convex surfaces with minimal opportunity for reflection to create hot spots. Interestingly, the location of the hottest temperature on the MLI varied based on the optical properties. For Nextel 312 and titanium, which have lower α/ε, the hot spot was next to the thruster nozzle since the absorbed IR heat from the nozzle was higher than the absorbed solar heat. However, for copper, which has a higher α/ε and a particularly low ε, the temperature distribution was mostly uniform except for the annulus in the nozzle's shaded area since the absorbed solar heat was higher than the absorbed IR heat from the nozzle (Figure 8).

<u>Internal Layer Modeling</u>

At this point, an educated guess on the flight high temperature MLI layup was needed. The outer layer temperature prediction is an important starting point since it will be the highest of any in the blanket, but predictions of internal layer temperatures must be made to avoid damaging any vulnerable materials in the rest of the layup. A material cannot be located where temperatures will be above its melting point or the material (and possibly the blanket) will be compromised. Although the outer layer material could also be used for the internal layers, this would increase the blanket mass, thickness, and implementation complexity compared to materials used in a typical blanket. Aluminum foil was chosen as the "high temperature" internal layer and embossed VDA Kapton as the "low temperature" internal layer. Aluminum and Kapton are attractive for blanket construction due to JPL flight heritage, lower mass, and low infrared emissivity, which improves thermal performance (lower ε^*) of the blanket. Temperature predictions were made using both a three dimensional thermal model and hand calculations. The outer layer was set as a boundary temperature from the previous section plus some margin and the hardware was set to the max AFT (+65 °C). The total margin added to model predictions was 34 °C. This included 20 °C margin from allowable to qualification limits, 10 °C margin for hardware capability, and 4 °C for uncertainty in type K thermocouple readings expected at the target test temperatures. Then the temperatures of all layers were plotted and compared with the limit for Kapton (390 °C) to see where materials could be used in the layup with positive temperature margin remaining to the hardware capability (Figure 9).

Four different material layups (Table 3) were considered for this analysis and the thermal qualification testing that followed. MLI development testing data from the Cassini project[2] was helpful to compare initial predictions for the same assumptions before changing the assumptions to Clipper's prospective blanket designs. Emissivity values for any new materials were taken from specification sheets (Table 4). Some manual iteration was needed on the number of aluminum and Kapton layers to achieve a safe predicted temperature on the Kapton layers. Kapton was predicted to be safely below its service temperature by the 14^{th} layer in the Nextel and titanium outer layer designs. However, Kapton was predicted to be safe only starting with the 17^{th} layer in the two different copper outer layer designs because of the higher 538 °C max temperature prediction. Nextel was used as the first internal layer in two of the designs with the hope of it acting as a thermal insulator due to its greater thickness and lower thermal conductivity relative to the other materials.

Table 3. MLI Layups Created for Thermal Qualification Testing

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

Table 4. Additional Thermal Optical Properties Used for Internal Layer Analysis

Material	α	ε	α/ε	Source	Max Rated Temperature (°C)
Embossed VDA Kapton	0.14	0.02	7.0	Specification sheet	390
VDA Kapton	0.14	0.03	4.7	Specification sheet	390

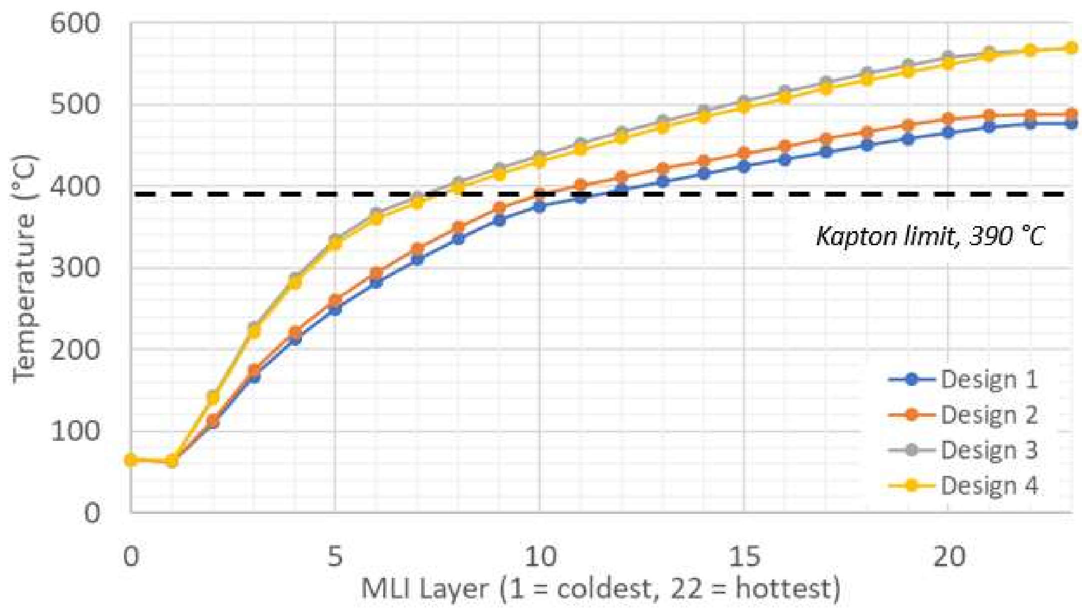


Figure 9. Predicted temperatures for worst case hot IR qualification test (described later).

THERMAL QUALIFICATION TESTING

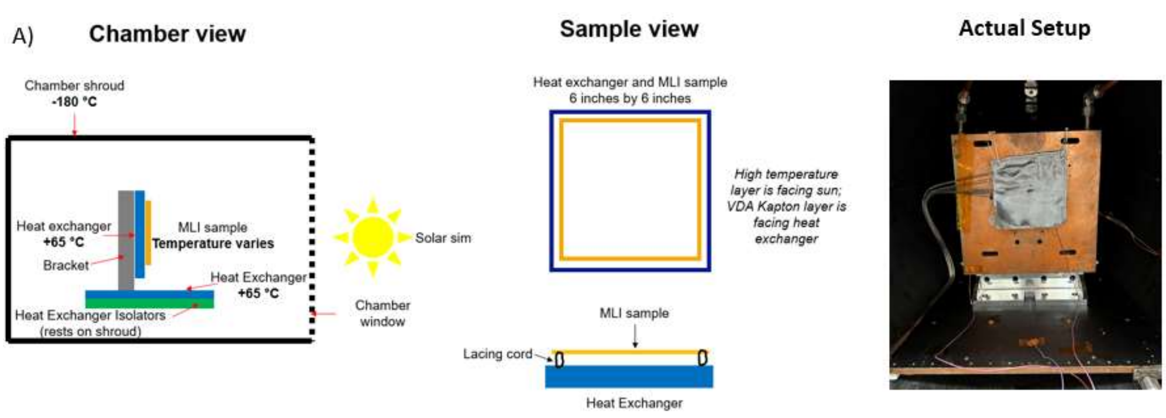
Once prospective layups were determined by material selection and thermal analysis, a final thermal qualification test of at least one flight like blanket layup was needed. The primary goal of the testing was to demonstrate a layup could survive the worst case mission environment. A secondary goal was to characterize the thermal performance to quantify any potential change in predicted spacecraft heater power in cold cases.

Survivability

An ideal test would replicate flight with simultaneous solar and thruster engine heat loads, but this was not practical. Therefore, two types of survivability tests were defined. The first was a solar test with the worst case hot mission solar flux. Without the effect of a firing thruster engine, this would not represent the true worst case hot. However, this test provided an opportunity to isolate any effects specific to solar heating. Samples were placed in a thermal vacuum chamber with a solar transparent window and mounted to a heat exchanger. The heat exchanger provided the hardware boundary condition of +65 °C. The chamber shroud was flooded with liquid nitrogen to reach a temperature around -180 °C to mimic space. Lastly, a solar simulator produced an average 2033 W/m^2 incident solar flux over the test area. Prior to testing, a 6 inch by 6 inch square mapping of the solar flux was made with a Kendall radiometer to find the power supply settings that produced the appropriate flux over the target test area. Each MLI sample was about 6 inches by 6 inches and unsewn at a corner to allow thermocouples to be installed and routed out of the sample. One cycle from ambient to the final steady state temperature was performed.

The second test was performed with a ceramic, high temperature heater wrapped with a three dimensional blanket. The heater power was controlled open loop to produce the worst case hot predicted temperature on the high temperature layer with some additional margin for qualification purposes. 34 °C margin from the internal layer analysis was used again. The heater and MLI test sample were suspended in the chamber with stainless steel wire to mitigate conduction effects and avoid compressing layers on the heater lest it affect the temperature gradient through the blanket. The shroud was controlled to +65 °C. The solar simulator was no longer present. This test represented the true worst case hot (although achieved artificially) for survivability. Each MLI sample was about 12 inches by 12 inches by 4 inches with the bottom edge unsewn to allow thermocouples to be installed and routed out of the sample. One cycle from ambient to the final steady state temperature was performed.

Type K thermocouples with stainless steel insulation were used for both tests. The thermocouples were taped (copper tape for copper layers and aluminum tape for Nextel 312, titanium, aluminum, and VDA Kapton layers) onto the center and edge of blanket layers and lacing cord was tied around the end of the thermocouple and through the tape as a secondary mechanical attachment since the tape adhesive would fail at high temperatures. Thermocouples were always located wherever the material changed. For example, with design 1, there were thermocouples on the hottest layer (Nextel 312), layer 1 (aluminum), layer 14 (embossed Kapton), and the coldest layer (Kapton) since those would be the hottest of their kind and most susceptible to damage. A thermocouple was also placed in the centermost aluminum layer and centermost Kapton layer (e.g. layers 8 and 17 for design 1) to provide more data on the temperature gradient through the blanket.



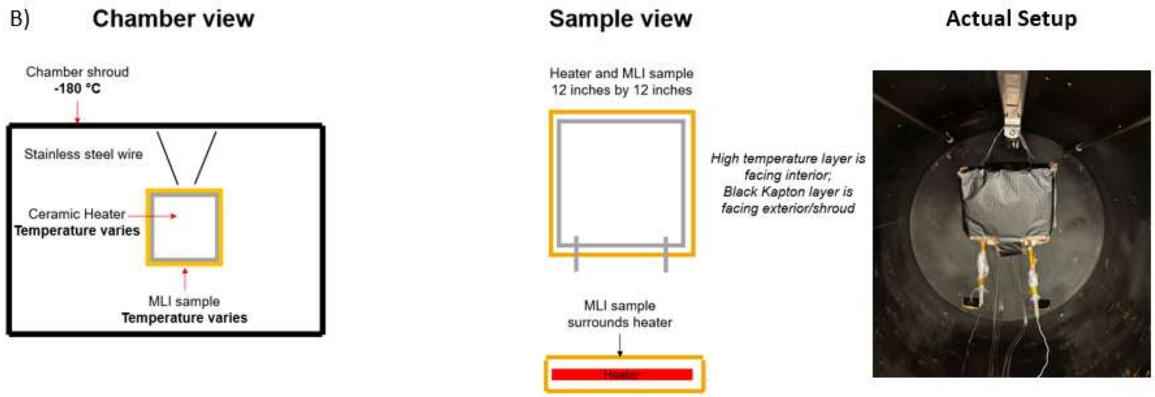


Figure 10. Test setup schematics for the A) solar B) IR thermal qualification tests

<u>Thermal Performance Characterization</u>

The performance test was designed to quantify the blanket's thermal performance in a representative cold environment. Although this could also be considered somewhat of a cold case survivability test, there was no concern about material survivability with the cold case temperatures. The polyimide materials, lacing cord, and sewing thread were already tested in the thermal cycling portion (as cold as -236 °C) of the radiation testing. Five samples were made this time – the same four designs from before as well as the baseline spacecraft MLI design as a control case for comparison. The blanket samples were 12 inch by 12 inch when wrapped around a square, temperature controlled aluminum plate with film heaters. In this configuration, all heat (except parasitic heat loss via heater and thermocouple wires) necessarily left through the MLI blanket. Like the IR test, the plate was suspended from a chamber railing with stainless steel wire for conductive isolation. Although the actual results (the MLI ε^* value) would not be necessarily applicable to the flight MLI geometry, this test would determine qualitatively how the high temperature designs compared to the baseline design. The performance testing is being completed at time of writing.

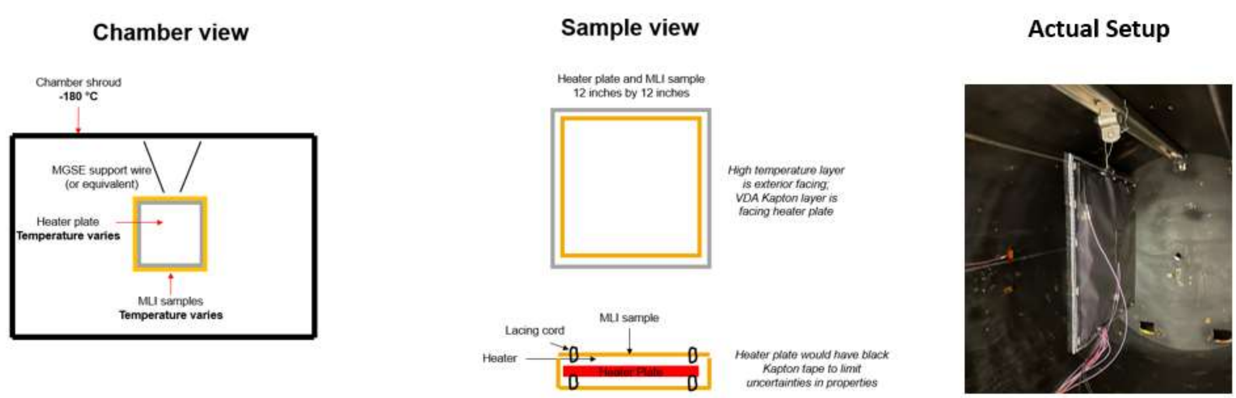


Figure 11. Test setup schematic for performance test

<u>Test Results and Findings</u>

The maximum temperatures measured in solar testing were 149, 241, and 273 °C for Nextel 312 (VDA side facing space), titanium, and copper respectively. With the optical properties in Table 2, the first two cases compare well with predictions of 147 and 267 °C. However, the copper temperature was predicted at 389 °C for BOL and 584 °C for EOL, both of which were significantly higher than the measured temperature. The copper was not visibly oxidized following this test, which could explain some difference but not the full amount. Another possibility is that creases formed in the copper reduced the absorbed solar load because of changes to the average optical properties or the solar flux no longer being uniformly normal to the surface.

There were no significant changes to materials after the solar and IR tests and no negative impacts to fit, form, or function. Like the 600 °C exposure test described earlier, the lacing cord and glass tissue separators were sometimes darker in local areas. This was more applicable to the two designs with copper that were heated to 572 °C at the copper layer. The metal, ceramic, and Kapton layers remained intact with no signs of degradation for all four designs (Figure 12). Therefore, any of the four blanket designs would be acceptable thermally for the intended flight application.

The measured temperatures inside of the blanket were lower than the model predictions (Figure 13). This was most apparent with layer 1 (the first internal layer). The temperature difference between layer 1 and the hottest layer was up to 100 °C whereas modeling predicted

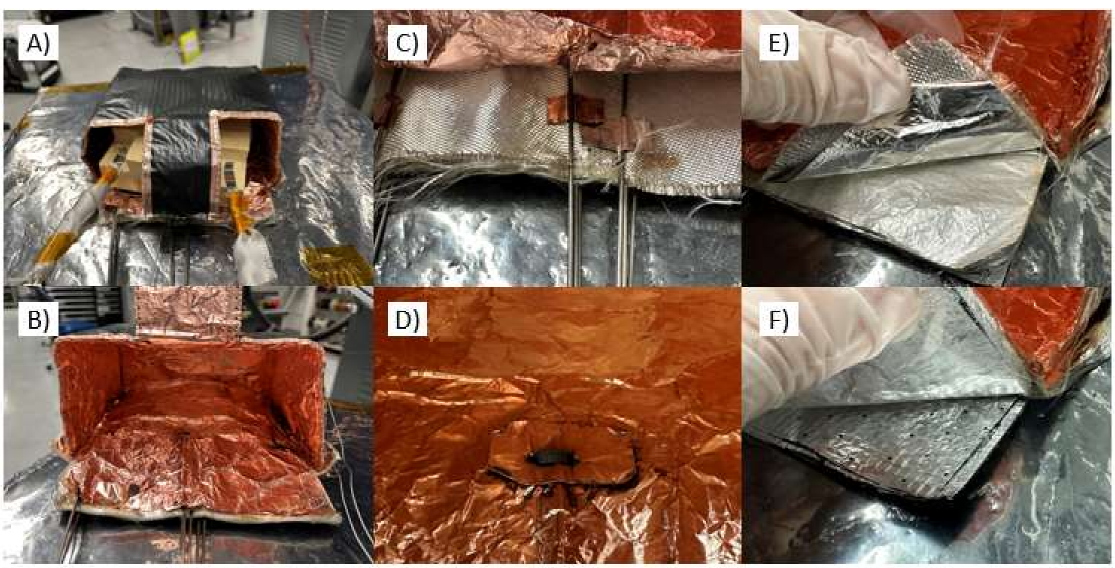


Figure 12. Post test images of copper foil outer layer blanket design 3. A) the overall blanket B) the copper layer remained unchanged C) Nextel 312 (layer 1) had some local darkening near tape D) lacing cord was notably darker near the center of the blanket E) the first aluminum foil layer (layer 2) and glass tissue separator remained unchanged F) the first Kapton layer (layer 17) remained unchanged.

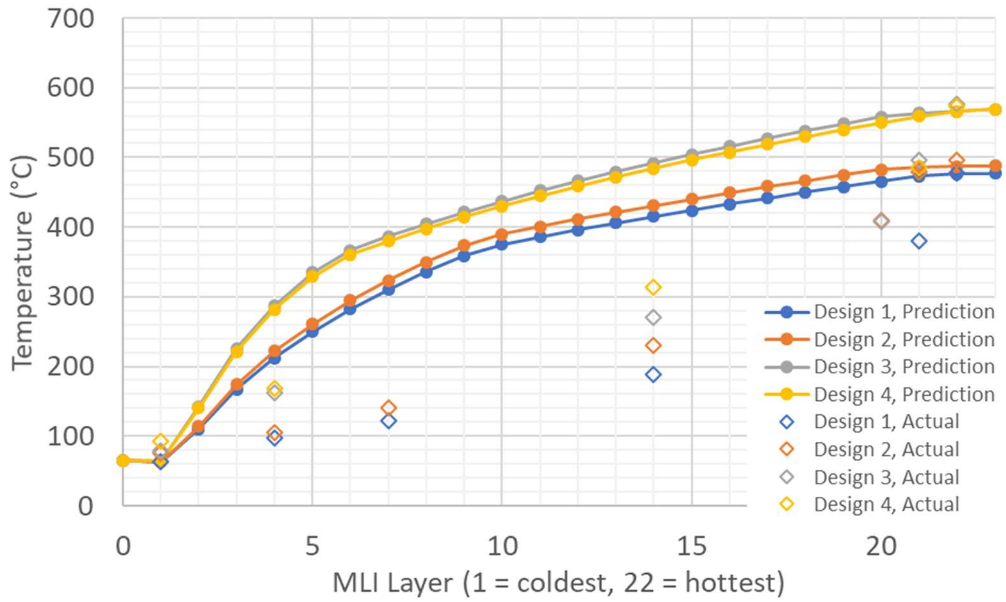


Figure 13. Predicted vs actual temperature distribution within the four blanket designs evaluated in the IR testing.

a difference closer to 5 °C. While this is a favorable finding for the survivability of the blanket, a mechanism for the outcome is not clear. Possible contributing factors are lower emissivity of either or both layers than what was modeled, emissivity changing at higher temperature, and lower conduction through seams than what was modeled. Using Nextel 312 as an internal layer in two of the designs may have contributed to this larger than predicted temperature gradient, which was hypothesized before testing because of its greater thickness and lower thermal conductivity. The only differences between designs 3 and 4 were in the first internal layer (Nextel 312 for design 3 and aluminum foil for design 4). The temperatures of the 8th internal layer (the next one instrumented for both samples) were 270 and 313 °C for designs 3 and 4 respectively. Therefore, the Nextel may have been influential in creating a roughly 40 °C decrease in temperature in part of the layup given the other variables were the same.

LESSONS LEARNED

This section contains a few lessons learned from the design and testing of these blankets.

- Alternative design solutions – this paper describes the evolution in design and testing of a MLI blanket for thermal control. A natural question to ask is why a MLI blanket solution was pursued at all given the significant resources required to qualify it. Other thermal solutions, such as thruster shields or thermal control coatings of the bracket, could be viable options on this or other missions. These may significantly reduce implementation complexity for the overall thermal control of the thruster area. With an appropriate thruster shield, perhaps a standard, low temperature MLI design may have been suitable.

A high temperature coating could eliminate the need for a blanket entirely albeit at the expense of higher heater power. The primary reason that neither approach was adopted is due to not identifying the need for high temperature insulation until after the mechanical design of the thruster bracket had been completed and an underappreciation for the number of analyses and tests to qualify such a blanket. The thruster engines and support brackets were among the first locations on the Europa Clipper spacecraft to finalize a mechanical design and build flight hardware. It was not until several years later that the Europa Clipper environmental challenges associated with high temperature MLI blankets were fully appreciated and the detailed temperature predictions were made. In design cases with a large number of requirements or environmental unknowns, it may be helpful to accelerate development in case a simple or flight heritage solution is not identified right away.

- Development testing – short development tests with constituent materials were invaluable for making quick progress on material screening. Although many of the outcomes were positive, there were cases in which potential risks (e.g. reactivity of copper, discharge differences for Nextel 312) were identified if a material were to be used for flight. Similarly, manufacturing issues were identified with the metal materials immediately when making small scale samples. These proved to be workable problems with iteration but may have led us to pursue other options or fabrication techniques in greater detail otherwise.
- Manufacturing findings – these high temperature blankets showed some signs of shape memory. If a blanket were intentionally creased somewhere other than the seams, it would tend to hold the shape. This type of rigidity and shape memory with blankets is uncommon in JPL's blanket experience since blankets are typically constructed of polyimide or mylar films. This could be a helpful property in certain applications but was not seen as such for Europa Clipper. An additional finding was that the metal layers made it harder to meet dimensional tolerance for flight hardware. For an all copper foil blanket made to a one to one scale model of the thruster bracket, 0.75 inches of 12 inches length was lost due to small creases and folds in the material. As the metal folds, it tends to contract the area – this does not occur for polyimide films. Setting up the sewing machine proved to be an important factor for not breaking the thread repeatedly while sewing. Finding an appropriate tension and lubricating the thread (with contamination control approved solvents) greatly reduced the chance of breaking the thread.
- Overdesigning for environmental compliance – at one point, a sample blanket was constructed of only copper layers. This addressed requirements with the fewest concerns and mitigations but carried implementation risks and the mass per area was over ten times higher than typical. In situations with little or no resource constraints or small area usage, the easiest solution may be to simply overdesign the blanket if manufacturing is not an issue.
- Instrumentation – the stainless steel insulated type K thermocouples worked well throughout the test campaign. Of the 80 different thermocouples that were in use (some multiple times), only one failed (the one on the ceramic heater) and it was after three tests. Since the wire length was intentionally long to ensure it reached the chamber

feedthrough, it did need some gradual back and forth bends to reduce the length since it cannot be coiled like polymeric insulation wires. Using a ceramic heater to produce the elevated temperatures also worked well and there were no thermal issues in testing. However, the heater did produce significant outgassing (particularly for the two copper design cases that were tested to higher temperatures) that required cleaning after testing. Such a heater may not be suitable for applications where cleanliness is important.

CONCLUSIONS

The Europa Clipper mission environment and science payload imposes a number of constraints on MLI blanket design. Due to the high predicted temperatures, the thruster bracket region of the spacecraft demands a different type of solution than the baseline MLI planned for use around the Europa Clipper spacecraft. Several different high temperature MLI blanket materials and layups were tested and qualified for the upcoming Europa Clipper mission. The tested outer layer materials included Nextel 312 (VDA side viewing space), titanium, and copper. Each of these blankets used aluminum foil and glass tissue separators for a "high temperature" portion of the blanket and embossed VDA Kapton for the "low temperature" portion of the blanket. PTFE coated fiberglass lacing cord and sewing thread (with Inconel wire insert) were also introduced for added temperature capability over heritage materials. There was no observation from the thermal qualification tests that negatively impact fit, form, or function of the blanket for flight. The intent of the thermal subsystem is to fly the design with the Nextel 312 (VDA side viewing space) outer layer since it eliminates residual concerns about manufacturability with metal outer layers and has the lowest predicted temperature in flight (therefore the most margin) of the designs that were qualified. Some contamination control analysis work remains to confirm that any potential shedding of Nextel fibers does not present a mission risk.

Further thermal analysis may be done to optimize the locations where the high temperature MLI is needed. A small 2D patch around the thruster engines may be sufficient if the high temperature on the MLI is very localized (as was seen with Nextel 312 and titanium). This high temperature patch approach has been implemented on several JPL flight projects where solar light can be concentrated on a small area in off-nominal attitudes. The most recent of these is the Advanced Microwave Radiometer instrument on the Surface Water Ocean Topography mission (Figure 14), which used a Nextel 312 outer layer (bare side viewing space) followed by aluminum and glass tissue separators for the first half of the blanket layup.

Figure 14. High temperature MLI patch flown on AMR-SWOT.

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REFERENCES

1. Schmidt, T., Hua, J., Tseng, H., Duran, M., Bhandari, P., Mehoke, D., Iyer, K. (2020). Detailed Design Process of MLI Blankets for the Europa Clipper Mission. International Conference on Environmental Systems.

2. Lin, E., Stultz, J. (1995). Cassini MLI Blankets High-Temperature Exposure Tests. Aerospace Sciences Meeting and Exhibit.

APPENDIX A

This appendix includes images of various materials before and after a 600 °C temperature exposure. The primary objective of this test was to screen materials to determine if they could remain intact and suitable for their function in flight or if alternative materials or implementation would be needed. All materials were exposed to 600 °C in an oven for 1 hour with an ambient pressure Argon gas backfill.

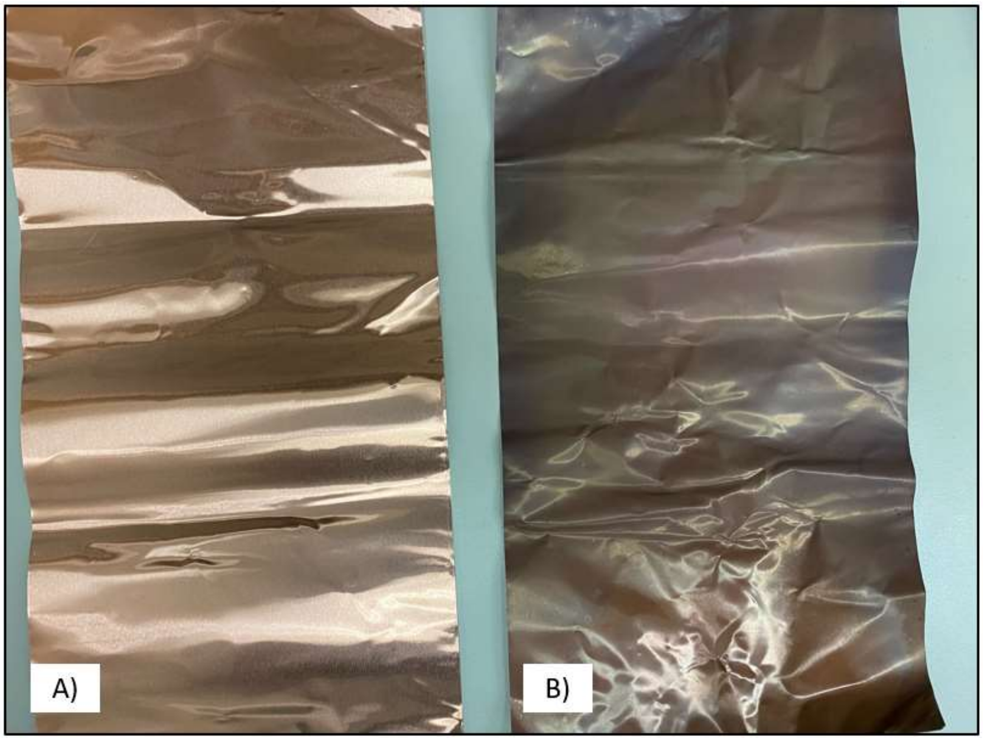

Figure A1. Copper foil A) pre test B) post test.

Figure A2. Copper tape A) pre test B) post test.

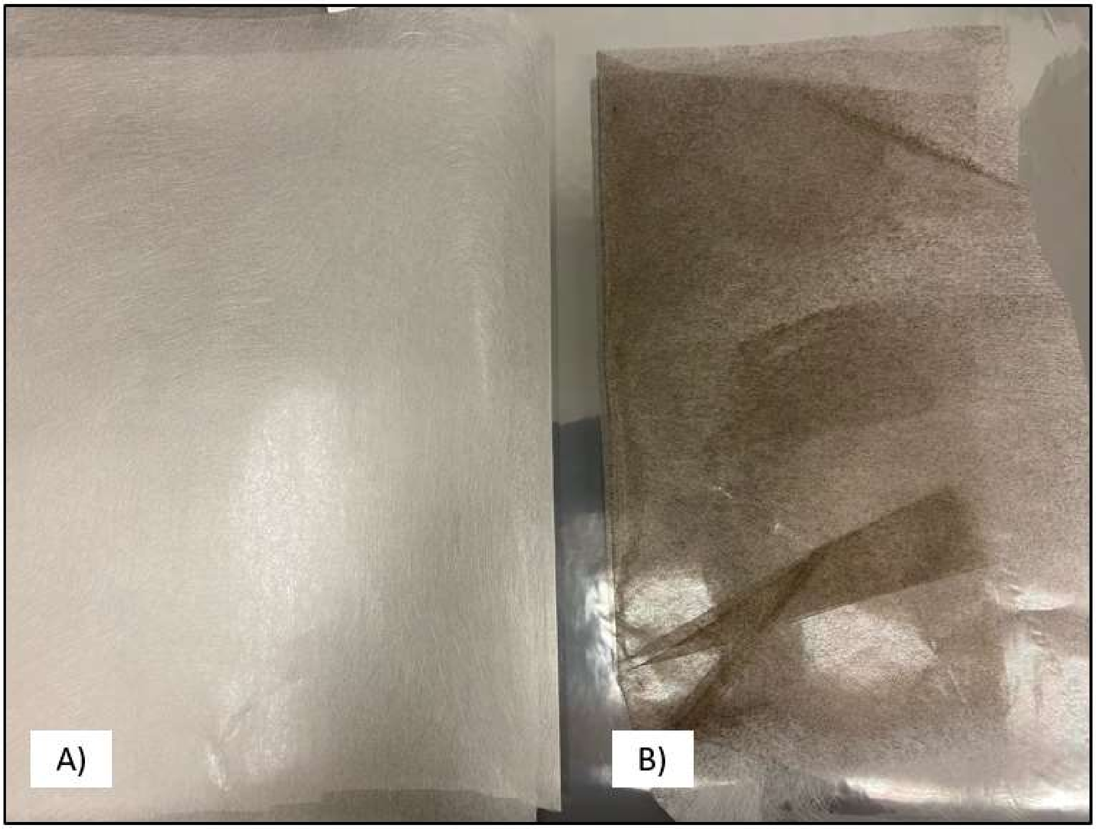

Figure A3. Glass tissue separator A) pre test B) post test.

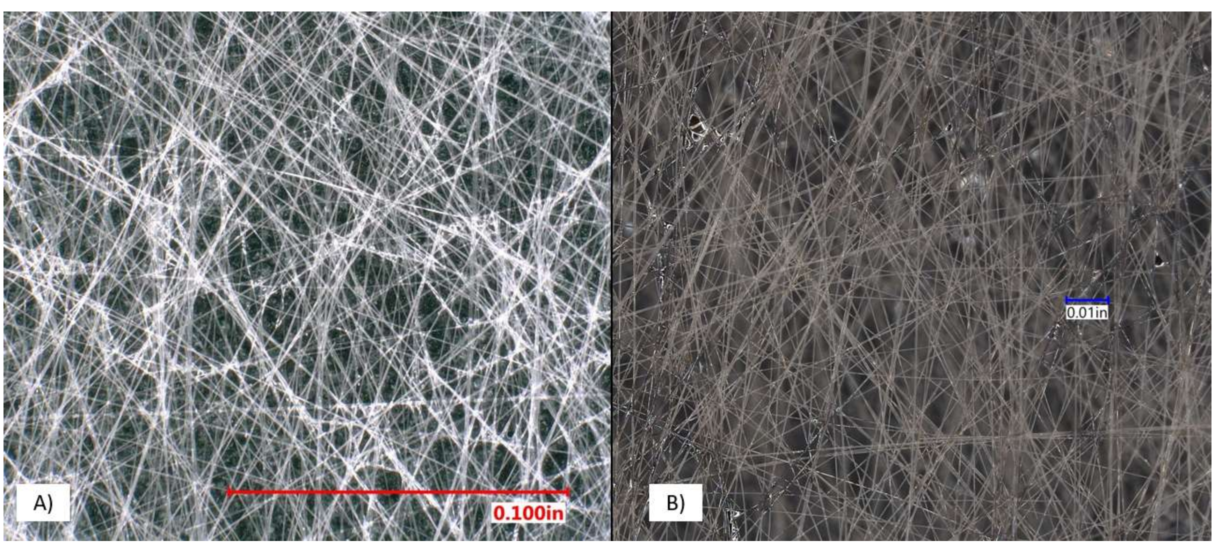

Figure A4. Glass tissue separator magnified A) pre test B) post test.

Figure A5. Lacing cord A) pre test B) post test.

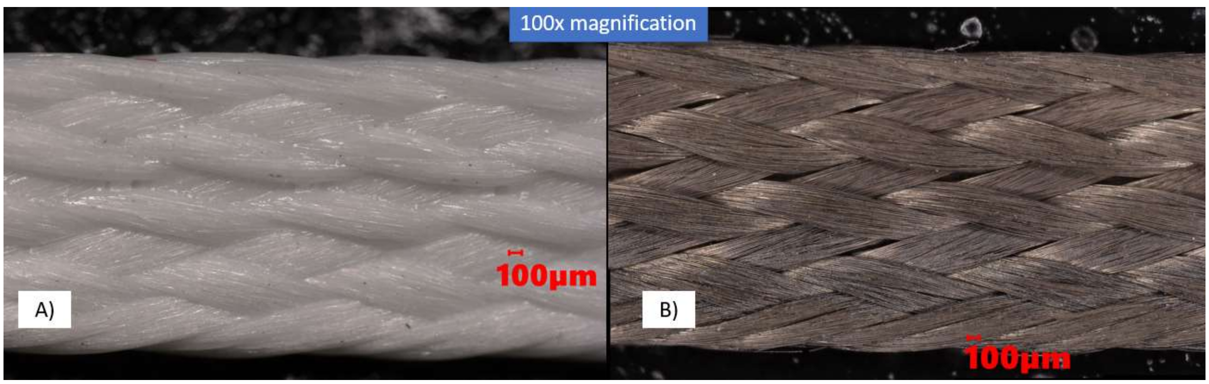

Figure A6. Lacing cord magnified A) pre test B) post test.

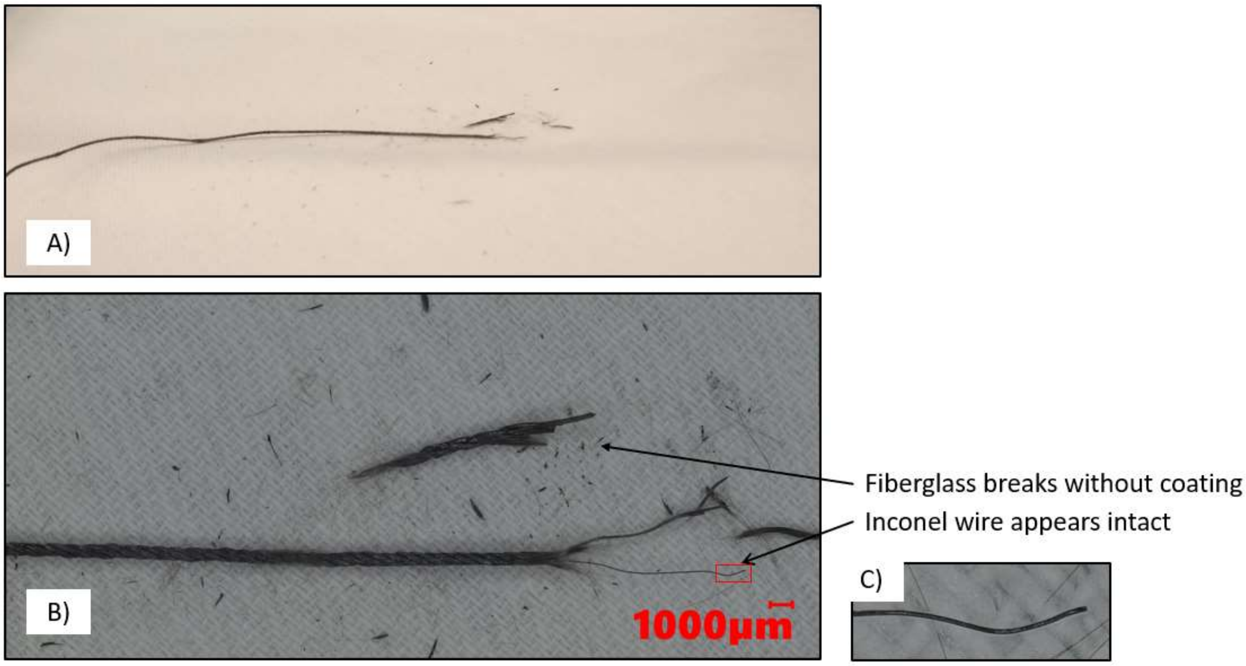

Figure A7. Sewing thread A) post test B) magnified post test C) Inconel wire insert magnified post test.