The Effects of Arcing Ejecta on Space Suit Materials from ISS RPCM Hot Mate/Demate During EVA

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Onboard ISS, taking systems off-line when powering down to perform servicing on Remote Power Control Modules (RPCMs) introduces operational risk. An investigation lead by the NASA Engineering and Safety Center (NESC) was performed by a multi-center team to assess the safety of performing on-orbit replacement of RPCMs without powering down. This investigation revealed the potential for molten metal particulate generation in the event of an arcing occurrence. As RPCM replacement can be performed outside ISS during an Extra Vehicular Activity (EVA), it is necessary to assess the effects of this molten metal ejecta contact with the Extravehicular Mobility Unit (EMU) Space Suit Assembly (SSA) during an arcing event.

A test was devised to mimic arcing ejecta contact with samples representing various SSA cross-sections. Four areas of the SSA were chosen for test to represent the majority of the SSA cross-sections. Testing was conducted by the University of California, Riverside that generated the molten metal particles, included varying composition, size and temperature, and dropped them onto the surface of the various SSA cross-sections.

Exposed SSA materials were then evaluated for degree of damage, penetration, and thermal conductance through the cross-section by ILC Dover. Results showed that the SSA Glove is most susceptible to damage from arcing events. This data will be used to make risk management decisions for future RPCM servicing operations. This testing also demonstrated the durability of the SSA design and materials to exposure to extreme environments.

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I. Introduction

When major International Space Station (ISS) systems, such as the central active thermal control system, are powered down for a Remote Power Controller Module (RPCM) removal and replacement (R&R) there is operational risk both during the powered down duration and when bringing the system back on line. This operational risk must be balanced with hazards to the extravehicular activity (EVA) crew if electrical mate/demate operations are conducted while the power feed to the RPCM is active.

Powered R&R are currently performed via robotic operations. The risk to an EVA crewmember performing a powered R&R has been deemed catastrophic due to the potential for molten metal generation from an electrical arc during the operation. An assessment was conducted to better characterize and evaluate the risks of electrical arc hazards to the EVA crew during possible powered RPCM R&R operations (e.g., risks of molten metal).

The assessment considered the energy released in a RPCM R&R if an arc event occurs during a short circuit scenario while the receptacle connector is exposed waiting for the replacement unit installation. The electrical arc could happen if there is a bridge, by a conductive material of the proper geometry, between the exposed 124V connector contact and a grounded surface near or within the connector. The energy in this event (560J) is bounded by the overcurrent protection profile of the upstream power distribution source called the Direct Current/Direct Current Converter Unit (DDCU). Initial calculations showed that if all the energy was concentrated into generating molten metal, the maximum amount of material generated is equivalent to 0.5 grams in a sphere of 5 mm. In reality, a portion will be molten metal and a portion will be vapor. An EMU thermal model was considered under these conditions. However, the complexity of the scenario modeled, and the uncertainty of the estimate drove the recommendation to proceed with arc testing to measure the distribution of molten metal generation.

II. Test Approach

The objective of the study was to develop a better understanding of risk for R & R of the RPCM by the crew. The testing performed as part of this investigation was designed to characterize arcing ejecta discharge and determine the effects of ejecta contact with the EMU SSA.

The EMU SSA is a modular system containing; Thermal Micrometeoroid Garments (TMG) to protect against thermal extremes, radiation and micrometeoroid and orbital debris damage to the structural and air retaining parts of the suit as well as protect against damage from contact with external surfaces; Restraints to provide shape and handle all loads reacted through the suit; and Bladders to provide for air retention and maintain pressure. The Liquid Cooling Ventilation Garment (LCVG) is worn underneath to provide cooling for crew thermal regulation and comfort.

The team determined the most critical parts susceptible to damage of the EMU as 1) TMG acreage areas, as represented by the lower arm cross-section, 2) SSA Glove finger front cross-section 3) SSA Glove finger back cross-section and 4) helmet visor and bubble material. Figures 1 through 3 show the various cross-sections.

Figure 1: Lower Arm Cross-Section

Figure 2: Glove Finger Back Cross-Section

Figure 3: Glove Finger Front Cross-Section

Two series of tests were conducted in this investigation. The first set of tests were arc tests that generated molten metal particles based on the DDCU protection profile energy, vacuum, plasma, electrodes' composition, and dimensions. Measurements from the liberated material included size, velocity, and temperature. Results were used to determine setup parameters for a second type of test; Induction Levitation Melting. The second set of tests used induction levitation to melt metals which were then dropped onto EMU materials in a controlled manner (vacuum ambient and particle temperature, and speed). Design of Experiments (DOE) was used to define test matrices for each test with the purpose of obtaining enough statistical data to find correlations among event variables (e.g., particle size, temperature and, electrodes' composition and dimensions).

A. Arc Testing

Three facilities conducted arc testing: The Air Force Research Laboratory (AFRL), Marshall Space Flight Center (MSFC), and Goddard Space Flight Center (GSFC). Tests in all three locations were performed in vacuum, used the same electrode metal types, and limited the energy per the DDCU overcurrent protection profile. The arc test setups varied in the use of plasma, arc initiation method and electrode's geometry and polarity. Three metals, Copper (Cu), Aluminum (Al 6061) and Stainless Steel (SS 304), were selected for the electrodes' composition based on the materials surrounding the R&R area including potential tools at the worksite.

Two electrode categories were used among the different arc test setups. Filaments of Cu, Al and SS were used as electrodes ranging in size from 0.203mm (0.008 inches) to 2.057mm (0.081 inches) in diameter. Also, rods shaped as cone, point and polished flat surfaces were used as larger electrodes simulating tools and other materials with potential to create a bridge between the positively biased connector socket and a grounded surface.

The distribution of the generated particles ranged from dust to 2.75 mm in diameter. The smaller electrodes (filaments) produced larger particles whereas the larger electrodes produced a maximum size of 0.38 mm diameter. Since the smaller electrode size (filament) resulted in the largest particles those became the worst case for the molten metal drop test. Figure 4 ('x' for AFRL test particles and 'o' for MSFC test particles) shows the results from the arc test ejected particles in terms of their size. For the use of the filament as electrode, the experimental procedure was conservative as the filament would be expected to eject out when the arc initiates. However, they were held in place potentially allowing the smaller filaments (with their smaller radii of curvatures) to wave around in the plasma thus sustaining the arc and producing more particles at higher temperatures. The temperatures of these particles were measured to be as high as 2500 K (Figure 5) with velocities as high as 21.3 m/s (70 ft/sec), Figure 6. The cooling rate of these particles as they shoot from the arc is low enough that the particles remain above the melting point within several feet from the arc site and therefore within reach of the crew. These arc test data were used to determine conditions for the induction levitation melting tests at University of California, Riverside (UCR). Specifically, the metal test particle size distribution and temperatures to be dropped against the SSA samples. A chart showing size and number of particles generated during arcing is presented in Figure 7.

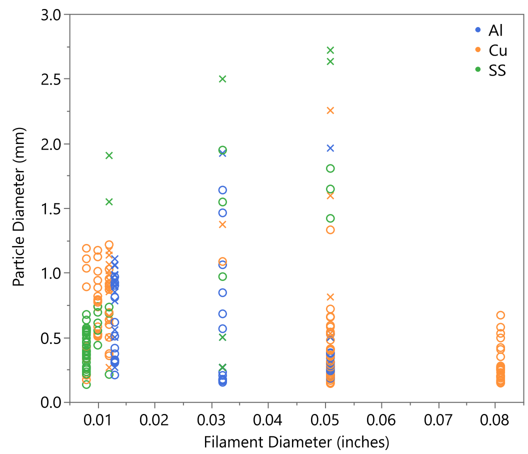

Figure 4: Measured Particle Sizes from Arc Test Ejected Molten Metal Material.

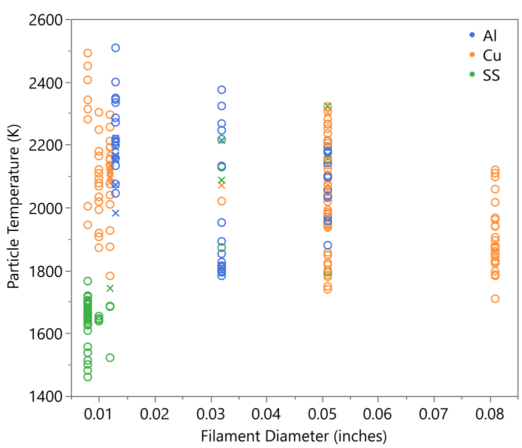

Figure 5: Measured Particle Temperatures from Arc Test Ejected Molten Metal Material

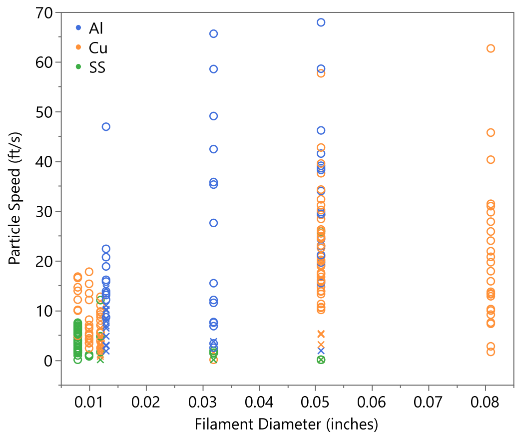

Figure 6: Measured Particle Velocities from Arc Test Ejected Molten Metal Material.

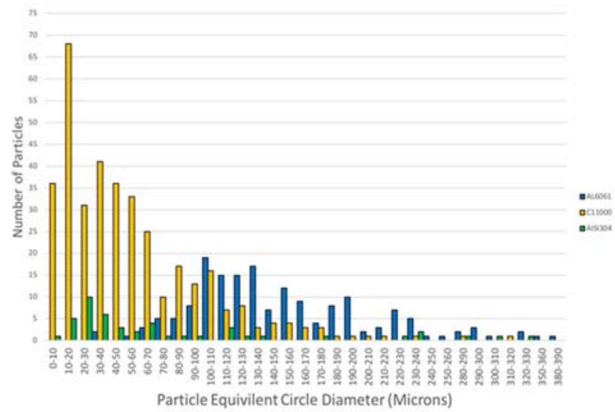

Figure 7: Measured Size and Number of Particles from Arc Test Ejected Molten Metal Material

B. Levitation Testing

The use of electromagnetic levitation is recorded as early as 1923, where induction coils were used to achieve levitation of conducting materials [1]. High frequency current produces an alternating magnetic field inside of an induction coil, which thereby induces eddy currents in the conducting material that are 180° out of phase with the applied field. This results in the material heating up as well as the creation of an opposing magnetic flux that moves the sample to the weaker part of the magnetic field. Levitation is achieved when the lifting force is equal to the weight of the sample. Modern day levitation experiments are typically conducted inside of a quartz tube that is placed inside of the water-cooled windings of an induction coil. [2]. This way a cover gas such as argon or helium can be used to prevent oxidation of the metallic sample that is being heated/melted. The water cooling prevents the coils from melting during the process. Figure 8 shows a picture of a glowing hot piece of metal levitating in a magnetic field produced by the induction coil.

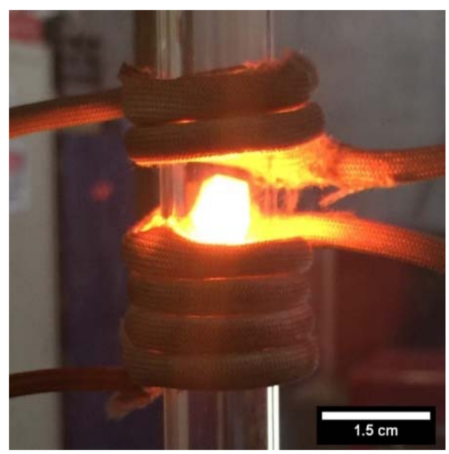

Figure 8: Hot Metal Levitating in a Magnetic Field

For the levitation testing ILC Dover fabricated material samples of the three cross-sections (reference Figures 1, 2 and 3 above) and provided polycarbonate to represent the helmet and visor applications.

Testing facilities and equipment were developed to meet the following test objectives:

1) Achieve electromagnetic levitation of aluminum, copper, and stainless steel in vacuum to systematically drop these molten and superheated particles onto the SSA material samples in a controlled fashion.
2) Measure the heat transfer from the top of the sample (where the molten metal came into contact) to the back of the sample (astronaut side).
3) Determine the drop temperature of the superheated particles prior to dropping onto the EMU.
4) Determine the particle size distribution such that correlations to EMU damage can be assessed.

1. Original Levitation Test Set-up

The electromagnetic levitation setup at UCR was used in conjunction with an ultra-high vacuum chamber such that levitation experiments could be conducted in a vacuum as opposed to the traditional argon/helium cover gas method. This chamber/levitation apparatus was named the Heating & Electromagnetic Levitation of Metals for EMU Testing (HELMET) Chamber. A picture of the HELMET chamber is presented in Figure 9, where the top portion consists of the traditional induction coil setup with a quartz tube, leading down into a vacuum chamber where the molten and superheated metal particles (herein referred to as "particles") can impact the sample.

Figure 9: The HELMET Chamber at UCR.

The HELMET chamber contained various vacuum flanges, which allowed for versatility in data acquisition. Temperatures were measured on the backside of the samples using an infrared camera mounted in front of an IR transparent viewport. For calibration of the temperature measurements, thermocouples were used in conjunction with infrared (IR) camera measurements. For molten metal temperature measurement, two pyrometers were used in the setup. A small GoPro video camera was used to capture the impact of the particles onto the EMU material.

To generate the particles, rods of aluminum and copper were cut into specific lengths based on the desired mass of the molten metal droplet. When melted, the surface tension produced a spherical molten metal particle. During the melting point drop temperature tests for these alloys, pyrometer signal loss would occur due to heavy vapor deposition onto the quartz tube during levitation. In these cases, melting of the particles was visually confirmed when the cylindrical shape of the particle turned into a sphere and was dropped out of levitation immediately after.

SSA cross-section samples were placed in an aluminum holder that extended towards the center of the vacuum chamber and allowed the particles to contact the samples straight on. As the experiments progressed, the aluminum sample holder was modified to prevent cooling of the particles when coming into contact with the aluminum frame. In addition, an insulated hopper was added to prevent the particles from splashing outside of the areas of interest. Figure 10 depicts a particle impact with this test set-up.

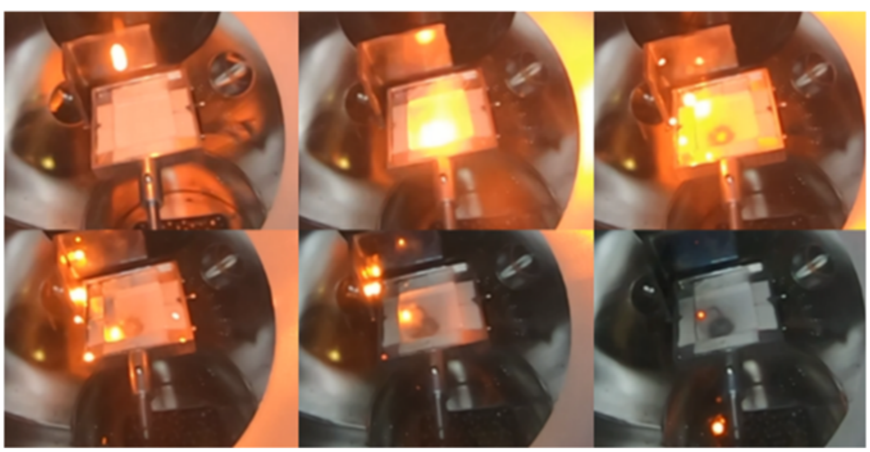

Figure 10: Particle Impact with the Original Test Sample Set Up (left to right)

2. **Particle Break Up Test Set-up**

Arc testing, performed to characterize arcing ejecta, demonstrated the need to control particle size. In order to achieve a wider distribution of smaller particle sizes the test set-up was modified such that the larger particle would not be dropped directly onto the sample but would first go through a refractory strainer crucible and then be trapped on top of the samples by an insulated ceramic mesh (see Figure 11). This way a larger distribution of smaller particles could come into contact with the material during a single experiment. Also, as part of the test modifications, stainless steel was eliminated as a test variable due to testing difficulties. Thermally insulating refractory ceramic was used to minimize heat transfer from the particles.

Figure 11: Particle Impact with the Particle Break-up Test Design (left to right)

During testing using the original test set up, it was observed that the particle would always bounce away from the initial impact site with metal vapor deposited on the EMU sample. In the Arm, Glove Finger Back, and Glove Finger Front materials the collision produced more of a bounce than the polycarbonate, resulting in an approximate 1- to 2-inch jump up from the surface of the material. The particle would then travel back down to the material due to the force of gravity, at much slower speeds, and either break-up upon re-impact or after several or more bounces and impacts. The polycarbonate material did not produce as much of a bouncing effect on the material; however, the particles still bounced away from the initial impact site. Many of the polycarbonate experiments resulted in a transverse spreading of the particle into several smaller particles similar to a billiard ball collision in all directions as opposed to a bouncing-ball upward motion.

Testing showed that the smaller particles from these tests may have been hot enough to contribute to the heat observed by the IR camera on the backside of the material. Unfortunately, there is no way to accurately determine the temperature contributions pertaining to the specific particle sizes present on the topside of the material. Therefore, a conservative approach was taken for assessing the maximum backside temperature by only plotting the largest particle that was generated in the experiment. Although smaller particles may collectively generate the heat observed on the backside of the material, the largest particle present is likely the most contributing body to the heat transfer and therefore can be referred to as a conservative upper limit threshold particle size for the temperatures observed. That is, if the largest particle were by itself, it would either transfer the maximum amount of heat that was observed in the IR recording or slightly less. The largest particle vs. backside temperature graph is pictured in Figure 12, for the particle break up method.

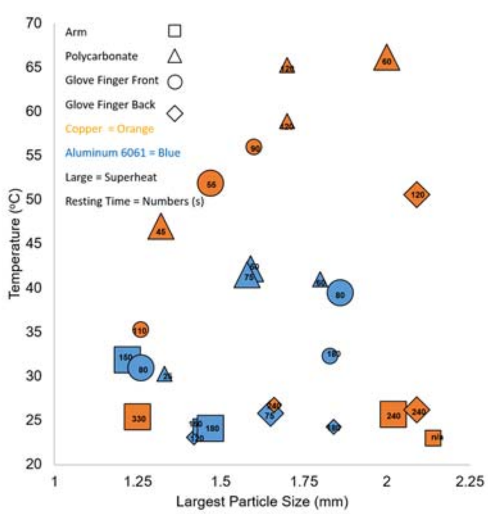

Fig. 12: Backside Temperature vs. Largest Particle Size (Particle Break-up Method).

III. Test and Sample Analysis

Criteria

Criteria was established for four categories of impact: slight, moderate, severe, and catastrophic. The criteria were based on 1) the amount of damage to the fabrics and how far the damage penetrated; 2) whether or not the particle contact caused fusing of layers and what layers were fused; and 3) the highest temperature recorded on the backside (crew side) of the sample. Table 1 depicts the test sample inspection criteria established for each of the cross-sections.

Testing which exposed TMG shell materials to ejecta during the arc ejection characterization phase of the task showed that incidental contact with ejecta resulted in minor yarn damage to the TMG shell fabrics but that metal vapor was deposited on the material surface (reference Figure 13). In these tests, material was hung in the vicinity of expected arc locations. The ejecta tended to bounce off immediately and therefore extended contact was not experienced.

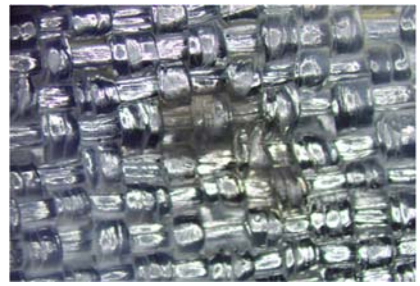

Figure 13: Metal Vapor Deposition on TMG Shell Material (20X)

The levitation testing was designed to promote extended direct contact of the particles with the samples since folds and creases in the fabric could trap the particles. This testing showed several results:

1) that the molten metal particles could seep through the yarn interstices of fabrics, deposit as droplets on the backside and cause damage to underlying areas.
2) that fabrics made from more temperature resistant materials did not always display damage although more temperature sensitive materials underneath was damaged, limiting inspection capability
3) that the Glove finger back cross-section was the most susceptible to damage
4) that there was a temperature gradient through the bladder material
5) that molten metal particles within the expected size range of arcing ejecta (less than or equal to the 2.75 mm) can cause catastrophic and/or severe damage
6) and additionally, with respect to the visor, no particles completely penetrated a single layer of polycarbonate.

A. Polycarbonate Testing

For ease of testing, the polycarbonate testing was performed with a single layer representing the protective visor. If testing produced complete penetration or rupture of the single layer, then the set-up would be modified to include a second layer to represent the helmet. Testing showed that the particles generated in the original test set-up were large enough to cause significant damage with penetrations up to 90% through the sample. All the particles generated for the particle break up method caused damage but did not penetrate more than approximately 30% through the material. In addition to localized melting, the material did experience crazing and bubbling, particularly for samples tested using the original method. None of the samples completely penetrated the polycarbonate. A tested polycarbonate sample is shown in figure 14. The moderate rating assigned to the samples were based on the damage being on the protective visor and not to the helmet bubble. However, there are small areas at the lever where the helmet bubble is exposed (not protected by the protective visor) and damage to the helmet bubble would be considered catastrophic since it is the pressure barrier.

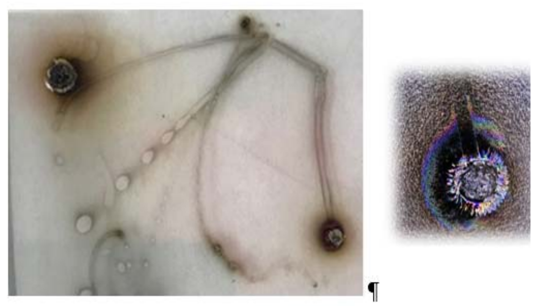

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Figure 14: Polycarbonate Test Sample (20x and 50X respectively)

Table I: Inspection Criteria for Levitation Testing

	Slight Impact	Moderate Impact	Severe Impact	Catastrophic Impact
Most Likely Resulting Action on Orbit	*No effect to mission or continued use*	*Continue EVA but do not re-use hardware*	*Terminate EVA and do not re-use hardware*	*Abort EVA/Loss of crew*
Lower Arm Cross-Section	Discoloration on TMG shell fabric surface with no penetration	Damage to shell fabric (only partial penetration) and evidence of heat damage to underlying layers of MLI but not TMG liner fabric	Damage to all or most layers of the TMG but no evidence of damage or heat transfer to restraint fabric or bladder material	Damage to all or any amount of materials within the TMG with damage or evidence of significant heat transfer to restraint and/or bladder materials
	Backside temperature does not exceed crew skin comfort temperatures	Backside temperature >crew skin comfort but less than bladder softening temperature	Backside temperature approaching bladder softening temperatures but less than melting temperature	Backside temperature greater than bladder melting temperatire
	Blocking = <1 on any layer	Blocking <2 any layer	Blocking >2 but <4 on any layer except restraint to bladder (must be <2)	Blocking >2 on restraint/bladder layer or 4 on any layers
Phase VI Glove Finger Back Cross-Section	Discoloration on TMG shell fabric surface with no penetration	Damage to shell fabric (only partial penetration) and evidence of heat damage to underlying layers of MLI but not TMG liner fabric	Damage to all or most layers of the TMG but no evidence of damage or heat transfer to restraint fabric or bladder material	Damage to all or any amount of materials within the TMG with damage or evidence of significant heat transfer to restraint and/or bladder materials
	Backside temperature does not exceed crew skin comfort temperatures	Backside temperature >crew skin comfort but less than bladder softening temperature	Backside temperature approaching bladder softening temperatures but less than melting temperature	Backside temperature greater than bladder melting temperatire
	Blocking = <1 on any layer	Blocking <2 any layer	Blocking >2 but <4 on any layer except restraint to bladder (must be <2)	Blocking >2 on restraint/bladder layer or 4 on any layers
Phase VI Glove Finger Front Cross-Section	Discoloration on TMG palm material surface with no penetration	Discoloration and partial damage to TMG palm material but no complete yarn breaks	Damage to TMG palm material resulting in at least 1 complete yarn break but no damage or evidence of significant heat transfer to underlying restraint or bladder materials	Damage to TMG palm with damage or evidence of significnat heat transfer to restraint fabric and/or bladder material
	Backside temperature does not exceed crew skin comfort temperatures	Backside temperature >crew skin comfort but less than bladder softening temperature	Backside temperature approaching bladder softening temperatures but less than melting temperature	Backside temperature greater than bladder melting temperatire
	Blocking = <1 on any layer	Blocking <2 any layer	Blocking >2 but <4 on restraint to TMG palm layer but <2 on restraint to bladder layer	Blocking >2 on restraint/bladder layer or 4 on restraint to TMG palm layer
EVVA Protective Visor/Helmet Cross-Section	Discoloration with no penetration of polycarbonate	Partial penetration of polycarbonate but no through hole	Penetration of polycarbonate but no evidence of damage or significant heat transfer to underlying second layer of polycarbonate	Any evidence of damage or significant heat transfer to second layer of polycarbonate
	Backside temperature does not exceed nominal visor temperatures	Backside temperature exceeds nominal visor temperatures but is less than polycarbonate softening temperature	Backside temperature approaching polycarbonate softening temperatures but less than melting temperature	Backside temperature greater than polycarbonate melting temperatire

B. Lower Arm Cross-Section Testing

This testing showed that the molten metal could seep in between the yarn interstices of the TMG shell fabric where it would solidify as small balls of material on the backside of the fabric. This was verified to occur during the initial impact. This caused damage to the first layer of MLI and in some instances also the second layer. However, yarn damage to the TMG shell was rarely seen from the initial impact. Figures 15 shows the metal balls created from the seepage and the resulting damage to the MLI. This testing also showed catastrophic damage to the restraint material within the arcing ejecta size range that did not correspond to exterior material damage. This indicates that damage severity may not be able to be determined by inspections of the hardware without disassembly.

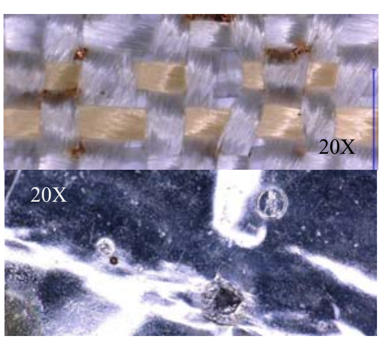

Figure 15: TMG Shell Molten Metal Seepage and MLI Damage

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C. Glove Finger Back Testing

Testing showed that this cross-section was the most susceptible to damage from arcing ejecta. Of the samples tested most showed at least severe damage. One of the notable observations from the testing was that the bladder material had a significant thermal gradient and although the face side of the bladder film showed thermal deformation, the temperature measured on the backside of the film was significantly lower than the softening temperature of the material. This information suggests that thermal damage could not be detected or assessed using crew sensory feedback. Burn through of the TMG shell material, a lighter fabric than the lower arm TMG shell material, was common. MLI material damage was also readily evident but there were several instances of significant restraint fabric damage with some thermal deformation noted to bladder material. Figure 16 shows an example of the damage resulting from ejecta contact

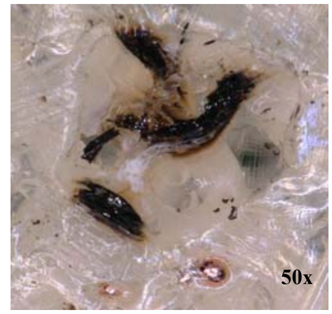

Figure 17: Entrapped Ejecta and Damage to TMG Palm Material

D. Glove Finger Front Testing

While larger particles (greater than 3 mm) showed significant damage to the materials in the finger front cross-section, particles in the arcing ejecta size range showed considerably less damage in comparison to the finger back. The TMG palm material contains a light coating of silicone rubber that provided insulation and prevented molten metal seepage, imparting thermal protection to the underlying materials. As shown in Figure 17, the thermal damage did not extend beyond the silicone coating.

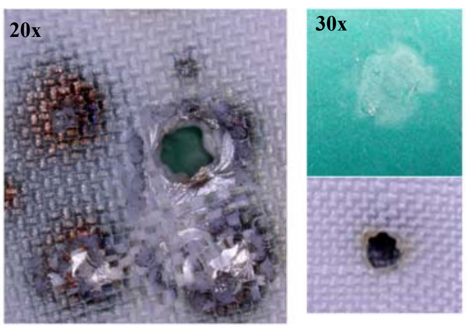

Figure 16: Burn Through Damage to Glove Finger Back TMG Shell and Restraint Materials with Thermal

20x

IV. Levitation Test Results Discussion

The testing was designed with much conservatism. Among the conservatisms of the testing the most significant was that the molten metal particles were dropped onto horizontal sample surfaces and were made to maintain contact. The arcing testing performed to characterize the ejecta showed that the ejecta tended to bounce off the material surfaces rather than adhering or maintaining contact. Prolonged contact could occur however, if the particle were trapped in a fold or crease.

The glove finger front test data demonstrated that the silicone coating provided significant protection from thermal damage to the underlying materials. The test samples did not contain the silicone pads that cover a significant portion of the palm acreage, with small breaks in between the pads to allow flexing. This is another significant conservatism in the test. However, during EVA silicone coating can be removed through wear leaving the open structure of the palm material vulnerable to penetration

This testing did not account for suit pressurization as the samples were clamped in a sample holder without tension. During pressurization the bladder and restraint are in intimate contact, which would increase thermal conductance between the restraint and bladder materials. In addition, the TMG, while designed to be unloaded can be put into compression which would also increase thermal conductivity through the cross-section. Since materials were not loaded damage tolerance was also not considered. To account for this any damage to the restraint or bladder materials were considered catastrophic.

Contact with the arcing ejecta frequently resulted in metal vapor deposition on the surface. While this is an indicator denoting ejecta contact, it was not always present. In addition, testing showed that underlying material damage could not be predicted by the extent of damage to the outermost material. Therefore, criteria for EVA continuation and or continued use of the suit could not rely on inspection. In addition, the extent of deposition observed on some material surfaces could have impact to thermal emissivity characteristics of the SSA resulting in inability for continued use although underlying material damage did not occur.

The testing performed allowed for the characterization of arcing ejecta and resulting damage to the SSA from contact. The ejecta particle size together with the sample analysis was used to determine the smallest particles resulting in each cross-sections damage rating (see Table II).

Table II: Smallest Particle Causing Damage

Impact Rating		Moderate Impact	Severe Impact	Catastrophic Impact
Most Likely Resulting Action on Orbit	*Material*	*Continue EVA but do not re-use hardware*	*Terminate EVA and do not re-use hardware*	*Abort EVA/Loss of crew*
Lower Arm Cross-Section	**Stainless Steel**			1.7 mm
	Copper	1.1 mm		2.8 mm
	Aluminum	1.1 mm		
Phase VI Glove Finger Back Cross-Section	**Stainless Steel**			
	Copper		0.8 mm	2.1 mm
	Aluminum	0.8 mm	1.7 mm	
Phase VI Glove Finger Front Cross-Section	**Stainless Steel**			
	Copper	1.0 mm		3.1 mm
	Aluminum			4.0 mm
EVVA Protective Visor/Helmet Cross-Section	**Stainless Steel**	2.7 mm		
	Copper	0.5 mm		
	Aluminum	0.4 mm		

V. Conclusions

The testing and analyses performed by the NASA Engineering & Safety Center (NESC) provided the necessary data to allow the International Space Station (ISS) program to make a well-informed risk trade of conducting a hot mate/demate of a Remote Power Controller Module (RPCM). While the risk to the EVA crewmember resulting from molten metal damage to the suit could be catastrophic, the probability of generating an arc is low due to the geometry of the RPCM connections. Additionally, a first order assessment of the likelihood of severe to catastrophic suit damage during this activity was shown to be relatively low even with the assumption that an arc was generated.

A detailed review of the findings by the ISS Safety Review Panel (SRP) identified operational controls that would need to be implemented in order to facilitate an RPCM hot mate/demate. These operational controls will be documented in an ISS integrated hazard report and include both cautions and warnings to be included in the EVA procedures, as well as inspections of the worksite for damaged wire ties or other foreign object debris that could cause a hazard. Additionally, the SRP recommended the development of a program level non-conformance report (NCR) to document risk acceptance for certain ISS Critical Contingency EVAs (CCEs). CCEs are those EVA repairs that are considered critical to the survival of the ISS. The NCR will serve to document the findings of the NESC assessment and allow a risk trade to be done on a case by case basis for other RPCM replacements.

It will also describe the criteria the program will use to evaluate the relative risk between powering down an RPCM for EVA replacement versus the risk to the EVA crewmember resulting from suit damage due to molten metal. Because the low probability of critical or catastrophic damage to the suit, the SRP determined the risk to be acceptable for a CCE task. For other RPCM replacement tasks, the program will need to weigh the relative risk of powering down ISS hardware for that particular scenario against the risk to the crew.

If the program opts to perform an RPCM replacement without powering down the hardware, EVA planners in the Flight Operations Directorate will ensure the procedures for that task include the operational mitigations recommended in the NCR. Cautions and warnings to the crew would be added to the EVA procedures to mitigate the risk of causing an arc that could result in molten metal.

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References:

1. O. Muck, "Levitation of Solid or Molten Conductors," *Pat. 42204*, vol. Germany, no. Oct. 30, 1923.
2. E. C. Ethridge, P. A. Curreri, J. Theiss, and G. J. Abbaschian, "Technique for the efficient and reproducible fabrication of electromagnetic levitation coils," *Rev. Sci. Instrum.*, vol. 55, no. 11, pp. 1859–1861, 1984, doi: 10.1063/1.1137680.