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Extravehicular Mobility Unit Penetration Probability from Micrometeoroids and Orbital Debris – Revised Analytical Model and Potential Space Suit Improvements

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Abstract

The NASA Extravehicular Mobility Unit (EMU) micrometeoroid and orbital debris protection ability has recently been assessed against an updated, higher threat space environment model. The new environment was analyzed in conjunction with a revised EMU solid model using a NASA computer code. Results showed that the EMU exceeds the required mathematical Probability of having No Penetrations (PNP) of any suit pressure bladder over the remaining life of the program (2,700 projected hours of 2 person spacewalks). The success probability was calculated to be 0.94, versus a requirement of **>**0.91, for the current spacesuit's outer protective garment.

Figure 1 – NASA's EMU at work on flight STS-116, late 2006

In parallel to the probability assessment, potential improvements to the current spacesuit's outer protective garment were built and impact tested. A NASA light gas gun was used to launch projectiles at test items, at speeds of approximately 7 km per second. Test results showed that substantial garment improvements could be made, with mild material enhancements and moderate assembly development. The spacesuit's PNP would improve marginally with the tested enhancements, if they were available for immediate incorporation.

This paper discusses the results of the model assessment process and test program. These findings add confidence to the continued use of the existing NASA EMU during International Space Station (ISS) assembly and Shuttle Operations. They provide a viable avenue for improved hypervelocity impact protection for the EMU, or for future space suits.

Key Words

Extravehicular Mobility Unit, Probability of No Penetration, Micrometeoroids, Orbital Debris, Space Environment Model, Thermal and Micrometeoroid Garment

Introduction

In May of 2002, NASA completed an update to the model of Low Earth Orbit (LEO) Micrometeoroids and Orbital Debris (MMOD) and utilized it to re-assess the risk posed during the planned undertaking of ISS construction and maintenance EVAs.[1] This review concluded that the maximum acceptable EVA risk was exceeded for International Space Station operations over the life of the program. The new PNP was calculated at 0.88 versus a program requirement of >0.91. Release of these findings sent a shock wave through the EVA community that sped them on a path to understand the decrease and to scrub the detail of the 3 dimensional model describing the EMU and the computer code (called BUMPER) that calculates the hypervelocity impact exposure risk for the EMU.

Due to the level of concern for crewmember safety during the spacewalk intensive station program, potential improvements to the EMU softgoods were developed and exercised in parallel to the full analytical scrub.

NASA and its contractors expected this dual approach to ultimately validate the EMU's ability to meet MMOD safety levels in the space station environment, whether or not the initial PNP assessment proved accurate.

Background

The NASA Extravehicular Mobility Unit (EMU) is comprised of the Space Suit Assembly (SSA) and the Life Support System (LSS) that astronauts wear when performing space walks (called Extravehicular Activities, or EVAs) from the Shuttle, or from the International Space Station (ISS), see Figure 1. The EMU must protect the crewmember from the harsh external space environment, while supplying a habitable internal environment. Besides the vacuum and the thermal challenges of space, the EMU must protect crewmembers from the micrometeoroids and orbital debris known to traverse low Earth orbits. During ISS and Shuttle EVAs, these projectiles will have average intercept speeds of between 10 and 20 km per second. They range in size from miniscule dust particles to large, radar trackable fragments.

The Orbital Debris Environments Model (ORDEM) was developed by NASA and has been used in various iterations for over a decade. This model maps the fluxes of micrometeoroids and orbital debris of various sizes, versus orbital altitude and inclination. As of 2002, NASA's EMU was certified to meet its Probability of No Penetration (PNP) requirments baselined on the ORDEM 96 micrometeoroid and orbital debris model. See Figure 2 for a comparison of ORDEM 2000 and ORDEM 96). Of note is the significant increase in flux density in the 0.05 cm, critical penetration size for the EMU TMG. By definition, a critical penetration is one that will cause a pressure leak in the EMU.

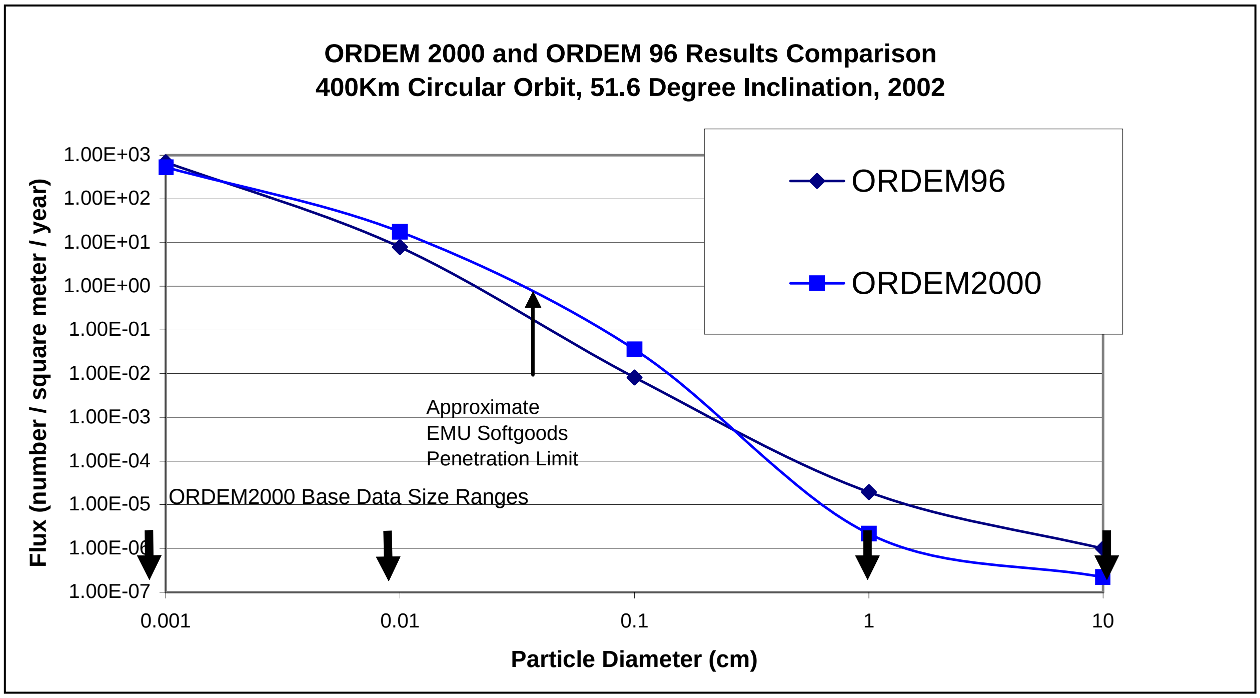

Figure 2 – Comparison of NASA Micrometeoroid and Orbital Debris Flux Models

The new model shows a significant drop in particles above the 0.5 cm size range. The flux density of this MMOD region is roughly 3 orders of magnitude less than for particles at the critical diameter for the EMU TMG though, making the decrease insignificant to the EMU's safety The "base data size ranges" shown by down arrows were points of direct comparison for both models.

During the late 1990's through the early 2000's, the space community was devoting significant resources to understanding and cataloguing the low earth orbit MMOD environment. The ORDEM 96 model relied on data from the Long Duration Exposure Facility (LDEF), the Space

Surveilance Network (SSN) catalog and the HAYSTACK radar. ORDEM 2000 was able to add new empirical information from:

- the Russian MIR space station
- EURECA (a Shuttle deployed European sattelite)
- SFU (a Japanese Space Flyer Unit, launched on an H-2 rocket and retrieved by the Shuttle on STS-72),
- the Hubble Space Telescope
- Goldstone (Pasadena, CA) and HAX (Cambridge, MA) radars
- the Shuttle (review of thermal tile and window damage)

Additionally, NASA's ORDEM 2000 incorporated more accurate mathematical models due to advances in computing ability. Based on a rigorous international peer review, ORDEM 2000 became the standard model for low Earth orbit debris and micrometeoroid flux predictions.

Discussion

A graphic representing the overall program of revising the PNP calculation for the EMU is shown in Figure 3, PNP Assessment Methodology. Genesis of the ORDEM 2000 model has been discussed as Background. A summary of the rest of the approach to PNP recalculation follows.

EMU Size and Configuration

Per the assessment plan, the EMU three-dimensional model (using I-deas® software) was reviewed to assure that it was fully consistent with the current flight configuration. The review revealed that the model had 8" longer legs than the 95th percentile male would have in the suit. Since the 95th percentile American male is the largest crew design point, this geometric deficiency was corrected. The following additional model improvements were considered:

- update the glove configuration to the Phase VI glove – a more dextrous glove
- add Cuff Checklist Band and checklist pages – spacewalk to do list
- add Wrist Mirror Band and Mirror – to see control settings
- add EVA Remote Camera Assembly (ERCA) – helmet cam
- add the Helmet Mounted Lights – work lights for night passes

- add the Mini Work Station (MWS) Base plate and Gimbal – a tool belt for spacewalks

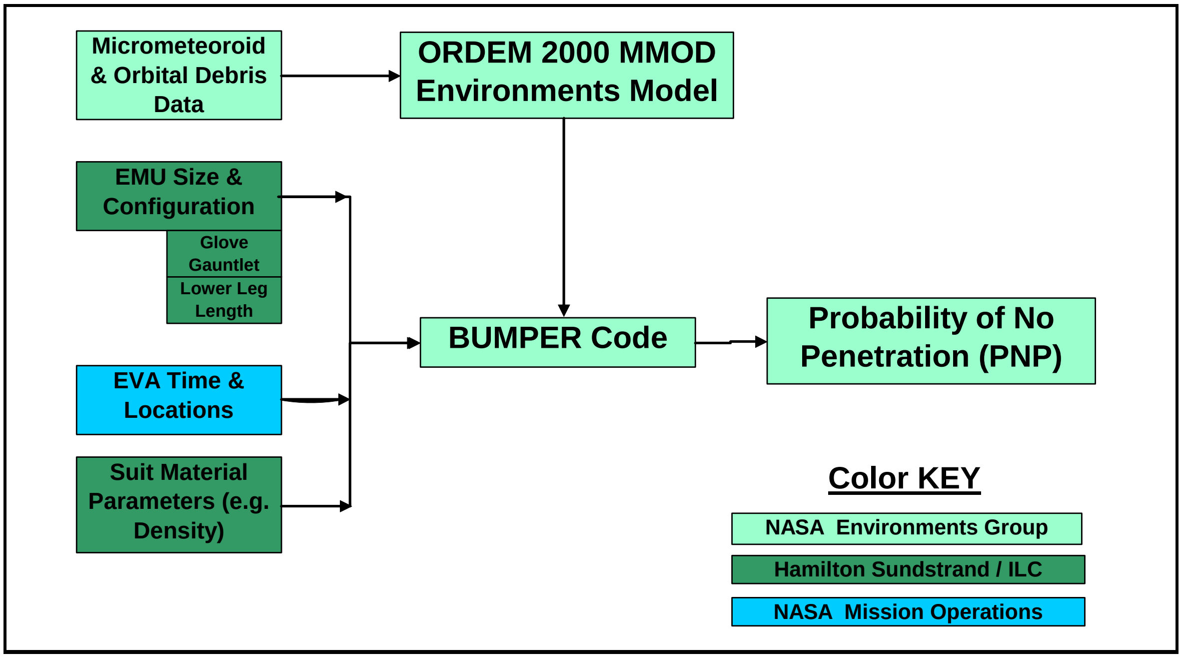

Figure 3 – Spacesuit Probability of No Penetration Assessment Methodology and Responsibilities

Of these changes, some (the Cuff Checklist Band and Pages, Wrist Mirror Band and Mirror, the remote camera, and work station and baseplate) would have little or no positive effect on the EMU's overall shielding and would further complicate an already detailed model. Their incorporation could risk model integrity and increase its run time. Thus, they were not included in the BUMPER II model, though their I-deas® surface models were developed.

The Helmet Lights and the Phase VI Gloves were included in the latest BUMPER model as each of them had an effect on impact vulnerability. The Helmet Lights marginally improve upper EMU shielding and were updated to the latest configuration, which has a somewhat larger geometry than older lights. The Phase VI Glove's revised quick disconnect location, higher up the arm, and broad design differences from the previous, 4000 Series Gloves, end up decreasing shielding slightly. This is due to the Phase VI Gloves' design being heavily focused on mobility.

Ultimately, the overall EMU I-deas® model contained well over 10,000 elements spread across 41 different material regions of the EMU, see Figure 4 – Final I-deas® Surface Mesh for EMU.

EVA Time and Locations

NASA's Mission Operations Directorate (MOD) is responsible for EVA planning and choreography. It is difficult for them to characterize the precise amount of spacewalk time that is associated with each valid work location over the course of the EMU's full 2,700-hour operational time period on the ISS. The 2,700 hour operational time is the result of 1,350 estimated EVA hours for each of two crewmembers. Final EVA choreography is worked out only a short time prior to each Shuttle mission, based on a detailed review of astronaut EVA simulations conducted underwater at the Neutral Buoyancy Lab (NBL), and in the virtual reality and air bearing floor labs at Johnson Space Center (JSC). What NASA could model, years in advance of most EVAs, were 156 combinations of planned EMU spacewalk orientations and locations on the ISS, through full build and operation. Orbiter docked and undocked conditions were included as follows: 740 Shuttle docked hours used, with the space station in a +XVV orientation and 1,960 hours used with the ISS in a -XVV orientation (see Figure 5, noting that +XVV places the +X axis of the station in the direction of travel). An even time split over the 132 locations/combinations was used as the best estimate, with both ISS and Shuttle vehicle shadowing of work sites incorporated in the model as appropriate. For conservatism, the EMU probability of no penetration had traditionally been reported without shadowing.

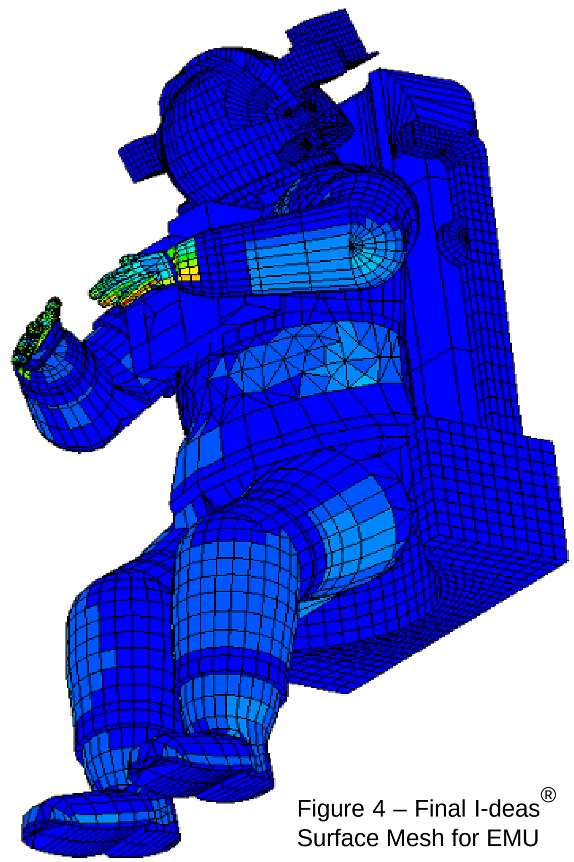

Figure 4 – Final I-deas® Surface Mesh for EMU

Suit Material Parameters

Accurate EMU material properties and lay-up geometry for the TMG and for metallic, fiberglass and polycarbonate components are critical to an accurate PNP calculation. These properties are well known and were validated in the BUMPER II code prior to this series of runs (see Figure 6 - EMU Component Breakdown).

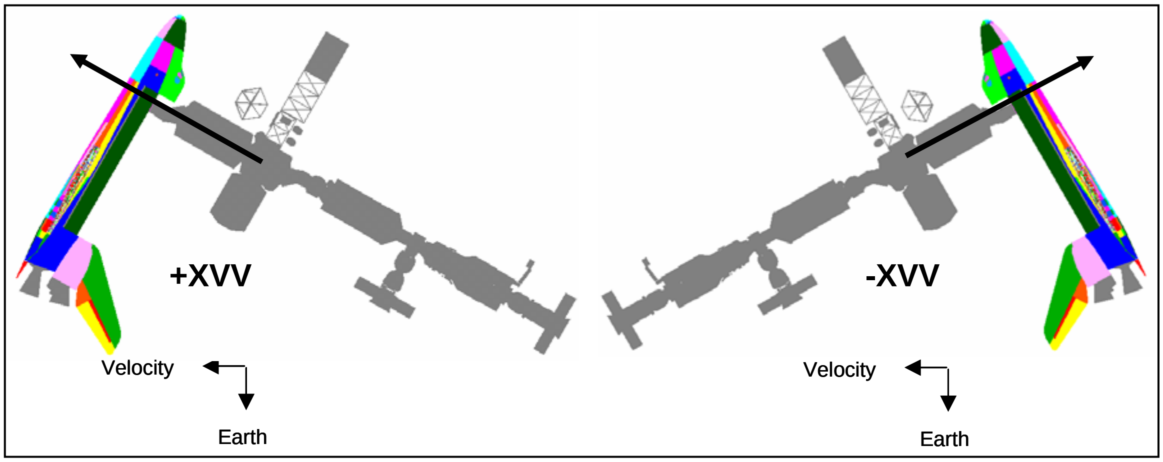

Figure 5 – ISS Orientations – Shuttle docks in +XVV and then moves to –XVV for improved vehicle shielding. Note – the EMU is used for EVAs from the ISS both with and without the Shuttle docked.

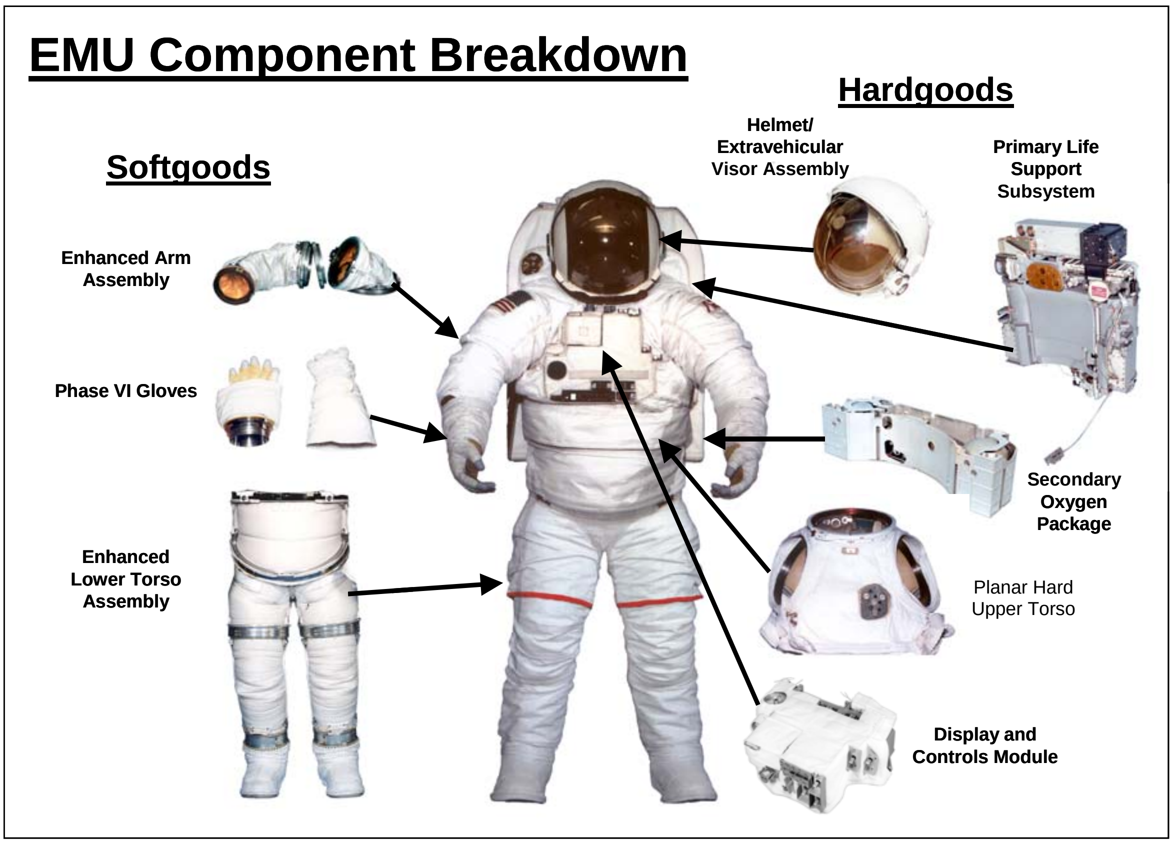

Figure 6 – Breakdown of EMU Hardgoods and Softgoods – TMG Is Removed, Except from Display and Controls Module & Hard Upper Torso

TMG Improvements

In parallel to the scrubbing of the EMU model and it's impact safety calculations, revised Thermal and Micrometeoroid Garment (TMG) constructions were developed, built and tested. Since a number of "ballistic" materials have been developed since the TMG lay-up was last modified, there were a number of candidates available to test for improvement to the TMG's ballistic limit.

The TMG is the outer, multilayered fabric that covers the majority of the EMU. In areas where it is backed up by hardgoods it is primarily present for spacesuit thermal control. However, in zones of softgoods only, it forms the primary protective barrier to micrometeoroid and orbital debris penetration.

The TMG has a fairly consistent lay-up on the EMU. In the Arms and Lower Torso, TMG and Restraint layers are as shown in Figures 7 & 8 – Baseline Lay-up and TMG Layers. The white outer layer that is most visible to the observer is a Teflon impregnated Orthofabric.

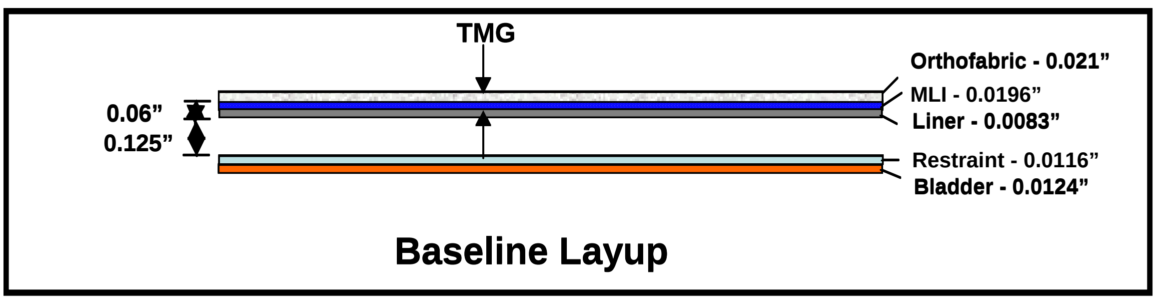

Figure 7 – Baseline EMU TMG and Restraint Lay-ups and Thicknesses – 0.125" gap is typical, due to fabric fit geometry and bunching

It's rugged, durable and damage resistant. Under that are 5 layers of aluminized mylar, separated by a non-woven scrim (together called MLI or Multi-Layer Insulation). These layers form a high performance thermal insulation for the EMU when evacuated. Below the MLI is the liner layer which is comprised of Neoprene coated nylon ripstop. It's a slip layer, designed to minimize abrasion with the pressurized restraint layer below it. These layers constitute the TMG.

On average, there is about an eighth inch gap between the TMG liner and the restraint layers, though no physical attempt is made to maintain this gap. The Restraint layer, made of dacron is

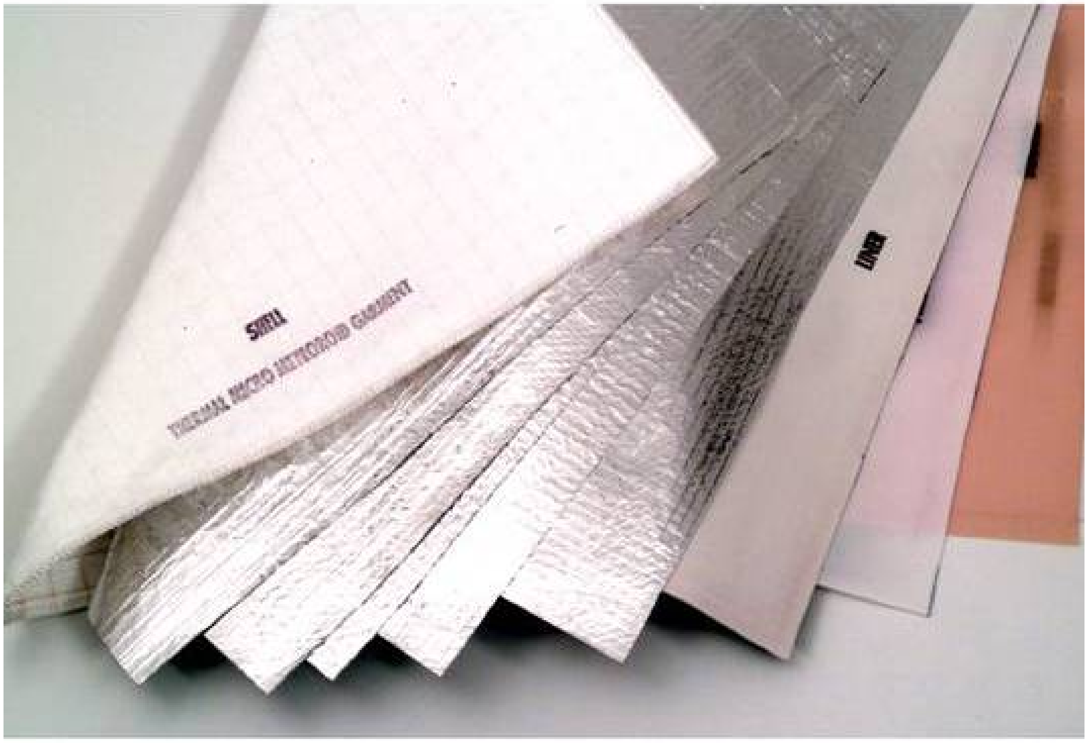

Figure 8 – Thermal and Micrometeoroid Garment Layers

next. This layer bears the primary hoop stress loads from the pressurized suit. Lastly, we have the Bladder layer. This is the pressure sealing layer of the EMU arms and lower torso. It's made from urethane/nylon laminate.

The TMG/Restraint system defines a Whipple shield arrangement for the crewmember's Arms, Lower Torso and Legs. The outer Orthofabric induces the majority of the shock pulse that will break up an impinging particle and cause formation of an expanding plasma jet. The MLI and Liner layers aid particle break up and add some spacing, allowing the plasma jet to begin to spread radially. Lastly, the plasma jet traverses the Liner/Restraint gap and impinges on the Restraint and Bladder layers. Any particle impact that caused debris to be visible on a plexiglass witness plate under the Bladder, or caused the Bladder layer to fail a 2 psi leakage test constituted a "Failed" test.

On other areas of the EMU where the TMG is backed up by hardgoods, the ballistic limits are substantially higher, so lay-ups including hard goods were not tested. The EMU Phase VI Gloves, however, have a reduced TMG to maintain high mobility. As critical as mobility is to the mission and noting the relatively small area of the gloves, the glove TMG was not examined for improvement at this time.

Highlights of this test effort include: a) completion of two rounds of hypervelocity impact testing with down selection of the best candidates for mobility areas, b) concept iteration and manufacturing of three mock-up leg TMGs for test and c) functional performance testing of the TMG mock-ups built into legs. A performance comparison of the mock-ups to the current flight Leg TMG was also completed.

The initial round of hypervelocity testing was reported on in JSC 63077[11]. During this round of tests, conducted in mid to late 2004, 51 test lay-ups were impacted at the White Sands Test Facility (WSTF) using a 17 caliber, 2 stage light gas gun.

In support of the second round of hypervelocity impact testing, carried out in May and June of 2005, ILC and JSC's Hypervelocity Impact Test Facility (HITF) produced 90 test articles for evaluation. This testing was completed at White Sands and is reported on in JSC 63093[12]. Various lay-up configurations, impact angles, projectile sizes and velocities were evaluated.

Results

Probability of No Penetration Recalculation

NASA's BUMPER II computer code brings together the following elements to calculate EMU exposures at different sites and integrates those inputs to arrive at a Probability of No Penetration over 2,700 operational hours of two crewmember ISS spacewalk time:

- information from the NASA ORDEM environments model for the space station orbit,
- I-deas® software based geometric data from the EMU and the space station, and
- EMU area lay-up ballistic limits, based on impact tests

Figure 9 shows a sample graphical representation of the I-deas® based geometric attitude information for a specific planned EVA.

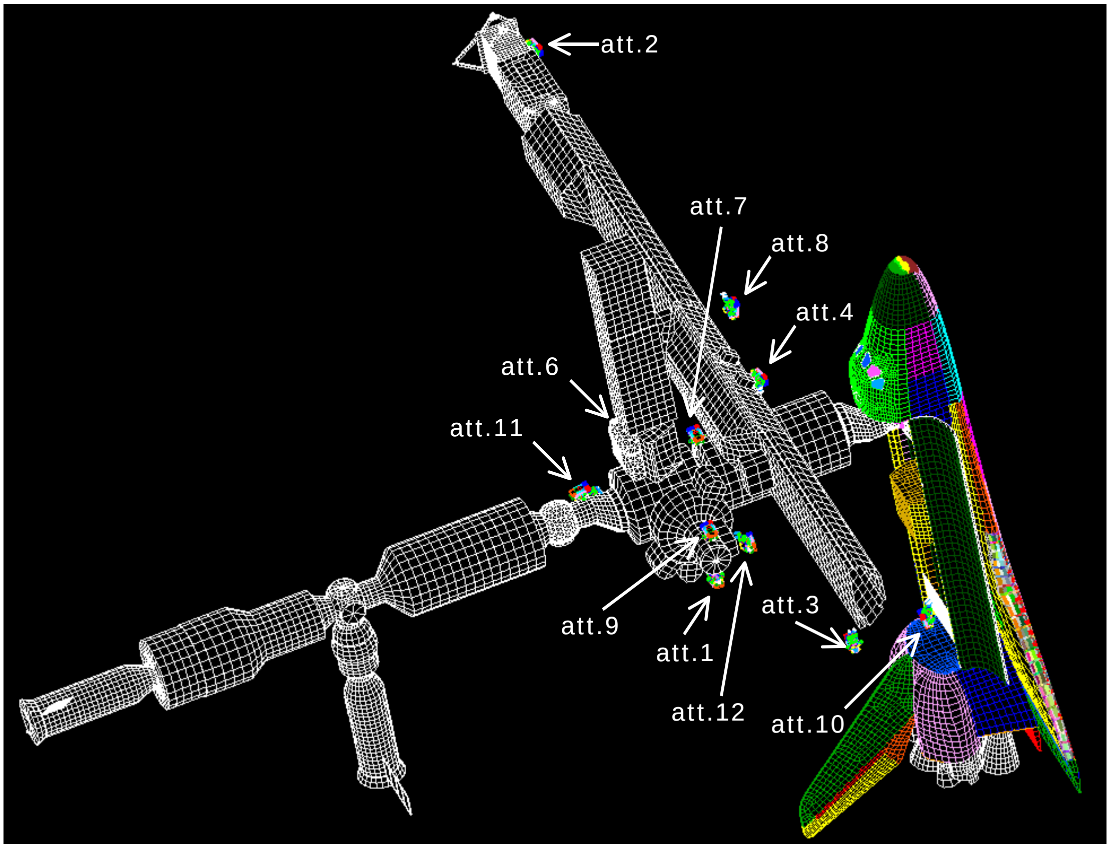

Figure 9 – BUMPER II 3 Dimensional Model of ISS with Docked Shuttle, Showing EVA Crew Attitudes and Locations

A substantial effort was required on the part of the NASA environments team to calculate the various PNP cases. A total of 3,744 runs were made, with each run consisting of exercising the BUMPER II code several times. To make the 3,744 runs, BUMPER II was invoked 7,512 times and required the use of 266 finite element models. Results of the case runs follow:

- EMU without Shuttle and ISS shadowing; PNP = 94.1% (see Figure 10)
- EMU with Shuttle and ISS shadowing; PNP = 97.1%
- EMU with enhanced protective garment and invoking Shuttle and ISS shadowing; PNP = 98.1% (see Figure 11)

These PNPs can be compared to the requirement of 91% PNP over 2,700 hours of 2 person EVA[6]. Whether considering Shuttle and space station shadowing or not, the safety requirement is met. A selectively enhanced TMG improves PNP by a seemingly small 1%. However, if those enhancements were available for immediate incorporation, they would reduce the chances of a penetration from 1 in 35 (97.1%), to 1 in 52 (98.1%), a substantial improvement in safety .

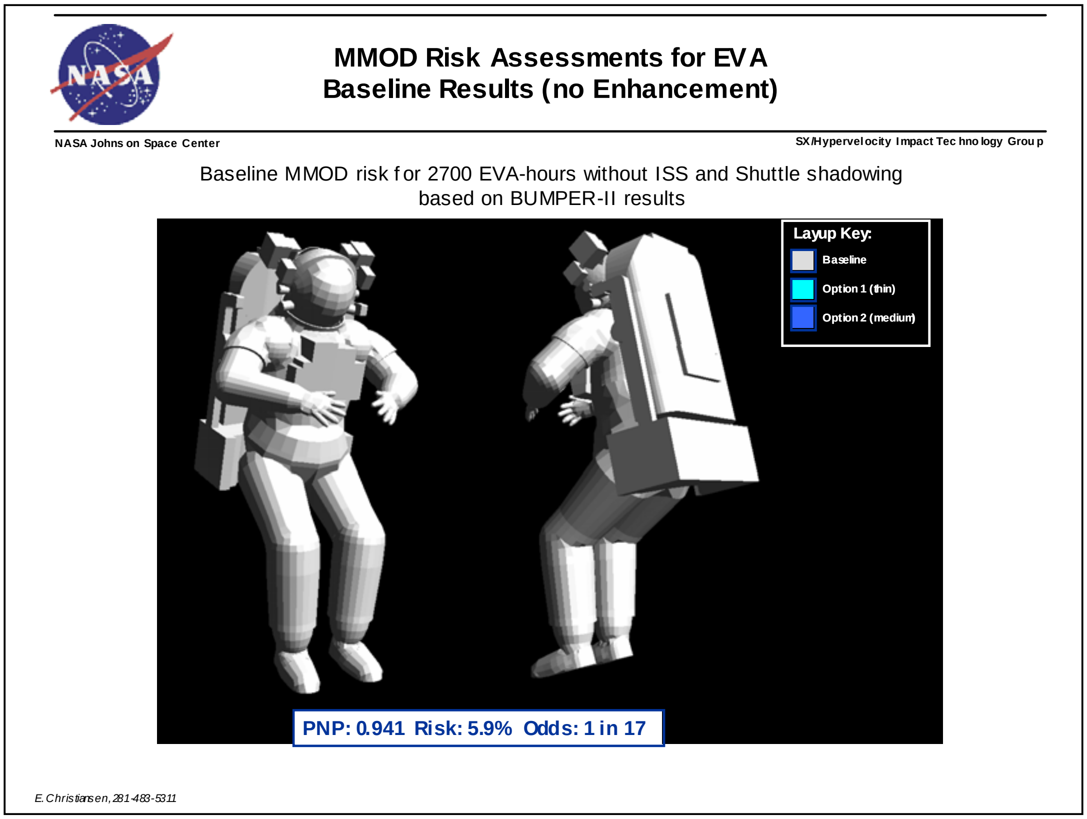

Figure 10 – Recalculated Probability of No Penetration, Including ISS and Shuttle Shadowing and Baseline TMG

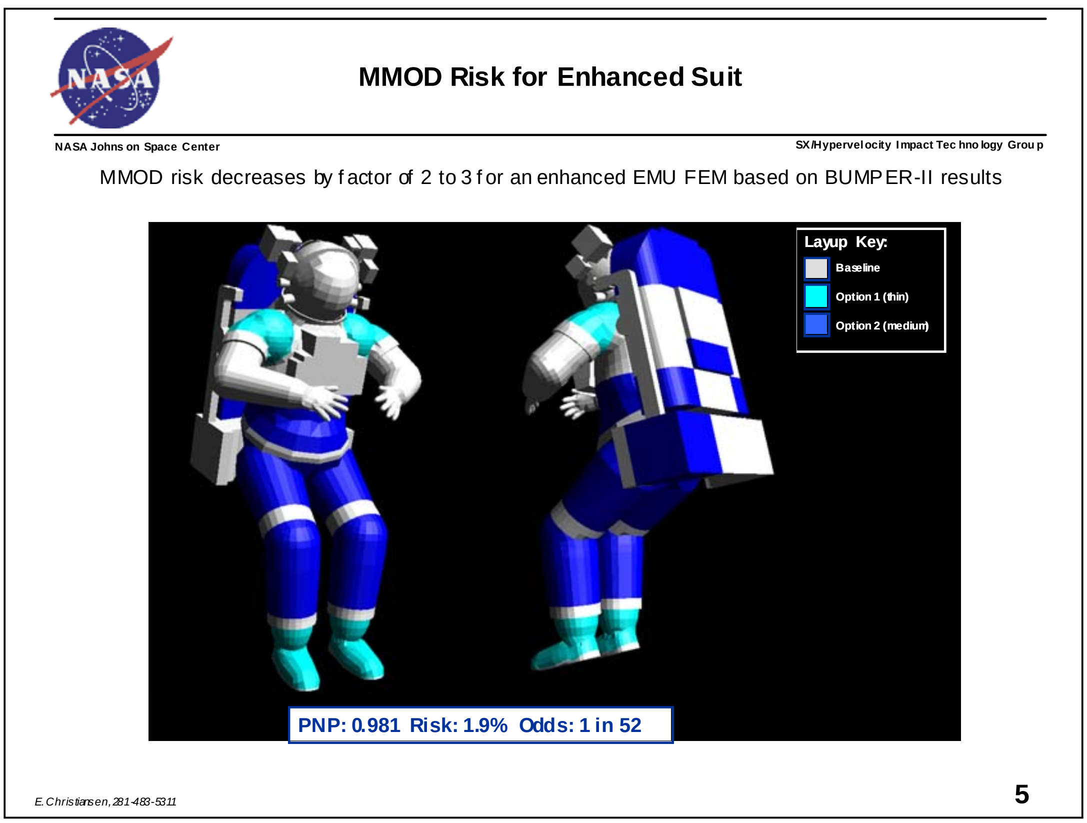

Figure 11 – Recalculated Probability of No Penetration, Including Enhanced TMG Locations **and** ISS and Shuttle Shadowing

Round 1 of Lay-up Impact Testing [11]

This round of impact testing confirmed the failure parameters for several candidate TMG materials and lay-up configurations using aluminum spherical projectiles in the 0.5 to 1.5mm diameter range. Impact velocity was approximately 6.8 km/s for this test phase. Velocity vectors normal to the test sample plane (0º) and at 45º to the sample plane were tested.

To validate the test set-up and equipment used, a set of baseline TMG impact tests were conducted. These were followed by absorber layer tests, substituting cloths made from Spectra 1000, silicone coated Kevlar, silicone coated Nextel, silicone coated Vectran, Neoprene coated Nylon and some of these fabrics without silicone coating. After the Absorber tests, a series of spacer tests were performed using Primaloft (a continuous filament Polyester insulation) and a urethane Open Cell Foam (OCF) as spacer layers. Table 1 shows the results of this testing. Any impact that just penetrated the pressure bladder, either visually or verified by post-test leak check was considered "at the ballistic limit" for the layup.

Finally, a number of tests were conducted with promising combinations of absorber and spacer materials. The end result of this testing is that no candidate absorber layer exceeded the capability of Neoprene Coated Nylon (NCN), already used for the Liner layer. Thus, neoprene coated nylon became the absorber of choice.

Open Cell Foam (OCF) was selected as the best spacer material. The OCF tended to disperse the plasma jet energy over a wider area than the the Primaloft Spacer. Additionally, a breakdown of the Primaloft can be expected within the temperature range of planned hot spacewalks. This breakdown would cause the Primaloft to lose it's loft over time, decreasing impact resistance. Various lay-ups using these materials were evaluated in Round 2 as an optimization exercise.

Round 2 of Lay-up Impact Testing [12]

The results of the Round 2 testing showed that creating additional standoff (gap) between the Orthofabric on the outside of the TMG and the inner layers was a valid avenue to ballistic limit

Ballistic Limit Test Results						
Test Results WITH Spacer						
Test Config.	New Layer	Angle	Impact Velocity	Al Projectile Dia. (mm)	Pass/Fail	Notes
Baseline		0	6.97	0.5	Pass	
Baseline		0	6.71	0.6	Pass	@ Ballistic Limit
Baseline		0	6.76	1.25	Fail	
Baseline		45	6.78	0.7	Fail	
Baseline		45	6.72	0.8	Fail	
Spacer 1	2 layers of Primaloft in between MLI and NCN	0	6.95	0.8	Pass	
Spacer 1		0	7.26	1	Fail	
Spacer 1		0	6.68	1.2	Fail	
Spacer 1		45	6.63	1	Pass	
Spacer 1		45	6.76	1.2	Pass	
Spacer 3	2 layers of Open Cell Foam in between MLI and NCN	0	6.44	1	Pass	
Spacer 3		0	7.12	1	Pass	
Spacer 3		0	6.79	1.2	Fail	BL
Spacer 3		45	6.65	1.2	Fail	BL
Spacer 3		45	6.75	1.5	Fail	
Absorber 1	2 layers of Coated Vectran surrounding OCF	0	6.82	1.25	Fail	BL
Absorber 1		0	6.75	1.5	Fail	
Absorber 1		45	6.68	1.3	Pass	
Absorber 1		45	6.86	1.3	Pass	BL
Absorber 2	2 layers of Sprectra surrounding OCF	0	6.72	1.25	Fail	BL
Absorber 2		0	6.7	1.5	Fail	
Absorber 2		45	6.66	1.3	Fail	
Absorber 3	2 layers of Coated Kevlar surrounding OCF	0	6.67	1.25	Fail	
Absorber 3		0	6.61	1.42	Fail	
Absorber 3		0	6.65	1.5	Fail	
Absorber 3		45	6.76	1.3	Pass	
Absorber 4	2 layers of Coated Nextel surrounding OCF	0	6.85	1.25	Pass	
Absorber 4		0	6.72	1.3	Fail	BL
Absorber 4		0	6.65	1.5	Fail	
Absorber 4		45	6.75	1.3	Pass	
Absorber 5	2 layers of Coated Nylon surrounding OCF	0	6.75	1.25	Fail	BL
Absorber 5		0	6.7	1.42	Fail	
Absorber 5		0	6.81	1.5	Fail	
Absorber 5		45	6.8	1.3	Fail	

Table 1 – Round 1 of Spacesuit Protective Garment Layup Impact Test Results [11]

improvements. Results showed that sandwiching the open cell foam layer between two neoprene coated nylon layers substantially raised the ballistic limit of the TMG (80% better, minimum). This lay-up was labeled “medium”. An additional lay-up that simply added another absorber layer (neoprene coated nylon) also showed some improvement in ballistic limit (53% better, minimum vs. the baseline TMG). This lay-up was labeled “thin 2”; it could be useful for high flex areas of the TMG where minimal joint torque is desirable. The ballistic limits for these lay-ups were utilized in the “enhanced suit” PNP calculations run in the BUMPER II computer model. Each lay-up would be used selectively in an enhanced TMG. See Figure 12 for a schematic of these lay-ups for comparison to the baseline TMG in Figure 7. Also view Figure 11 for the locations that the layups were modeled for on the EMU.

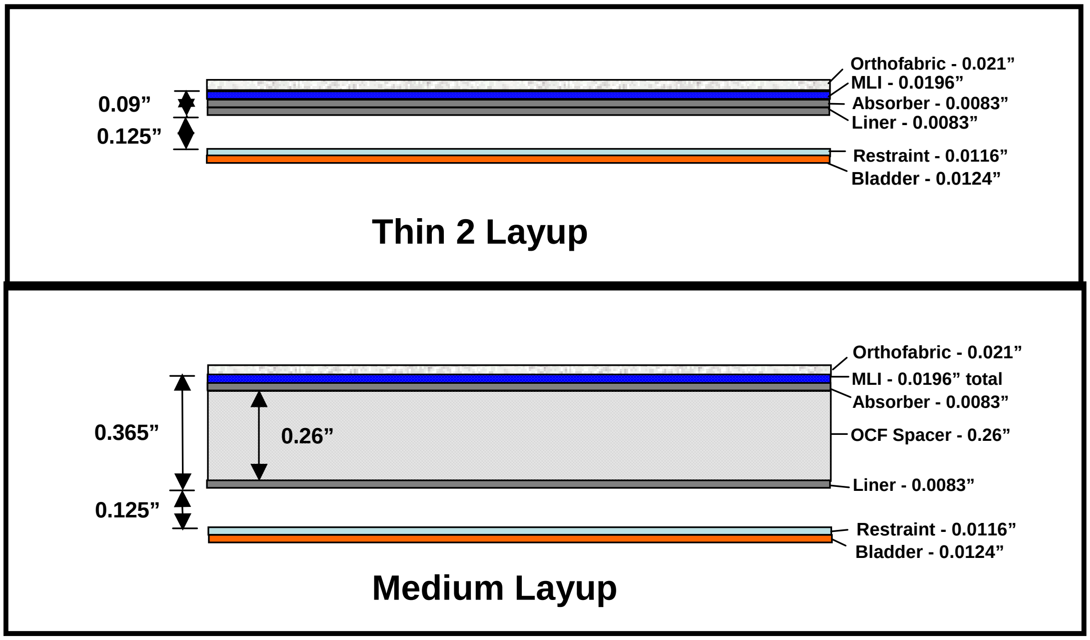

Figure 12 – Down Selected Lay-ups: Thin 2 (Adds 1 Absorber Layer) and Medium (Adds 1 Absorber Layer and 1 Open Cell Foam Layer)

Leg TMG Build and Test [12]

The next step in the evaluation was for ILC to integrate the “medium” lay-up concept into a viable TMG. The lower leg TMG was chosen for testing and 13 different manufacturing concepts were investigated. Three concepts were selected to become full-sized mock-ups. Each of the three selected concepts had a different method of assembling the layers. In one, the Open Cell Foam (OCF) was allowed to float freely between absorber and liner layers. In another the OCF pieces were intermittently stitched (tacked) to the liner peripherally. In the third lay-up, the OCF was bonded peripherally to the liner.

These new TMG concepts proved to be heavier than the existing leg TMG (+46% average). The manufacturing method of one of the concepts was most similar to the way existing TMGs are made, keeping the OCF as a separate layer in the lay-up. This manufacturing concept was deemed “best”, though all three concepts built were slated for torque testing.

All three “medium” concepts were successfully integrated with a lower leg, and pressurized, knee joint torque testing was completed at ILC. Two ranges of knee flexion and extension were analyzed at a constant, slow rate of angular velocity. For the 55° test, peak torque for the test unit vs. the baseline leg increased by 18% and with a 75° degree test, peak torque went up by 35%. Still, this level is well below the Leg specification maximum torque requirement. Further, all three concepts behaved in a tight performance window. See sample data for the 55° test in Figure 13.

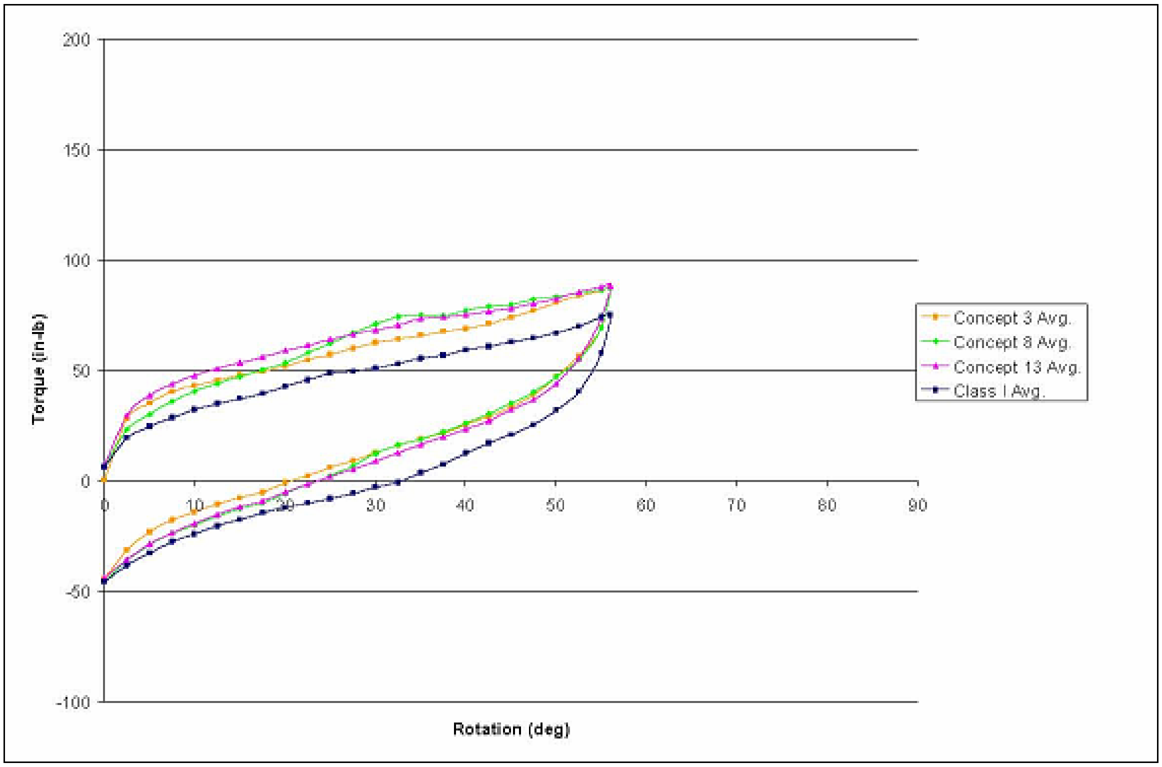

Figure 13 – Leg TMG Concept Torque Test, vs. Class 1 Flight Hardware Baseline, 55° Bend Angle

Summary and Conclusions

A highly successful program was executed by NASA and the spacesuit contractor community to

- reassess the modeling inputs that impact the Probability of No Penetration (PNP) of the current Extravehicular Mobility Unit (EMU)
- recalculate the PNP for baseline and modified outer protective garments
- test new Thermal and Micrometeoroid Garment (TMG) candidates to improve ballistic limits

- manufacture and test a small number of down-selected TMG constructions to assess their performance and technology readiness

The overall program yielded an improved PNP analysis code that incorporates the new space environment model and more accurately represents the EMU, it's possible spacewalk locations on the International Space Station (ISS) and the protective shadowing provided by the ISS and Shuttle. Refinements to the ballistic limit equations used in the analysis were also incorporated. This model iteration shows that the present EMU, with its current protective garment, meets the requirements for crewmember protection over the full 2,700 hours of projected International Space Station Extravehicular Activity (EVA). The current reported PNP is 0.94, which exceeds the 0.91 requirement.

Thus, from a pure requirements standpoint, there is no need to enhance the TMG for MMOD protection. But, using an analytical mindset, the improvement from a shielded PNP of 97.1% (baseline) to 98.1% (enhanced) is substantial. It would reduce the chance of a penetration of the pressure bladder from 1 in 35, to 1 in 52 over the 2,700 projected EVA hours if the revised TMGs could be deployed today. Another way to think of this is that enhancing the TMG with the recommended configuration reduces the chances of an MMOD penetration by about 35%! Thus, improving the hypervelocity impact resistance of the TMG would be a significant benefit to spacewalking astronauts.

Further, should a TMG with improved Micrometeoroid and Orbital Debris (MMOD) resistance be requested, an improved leg has been designed, built and tested via down-selection from many candidate lay-ups. Incorporation of this "medium" concept TMG into select areas of the EMU would provide substantive gains in the PNP and improved safety for EVA astronauts. Incorporation of the improved TMG would be at low technical risk due to the knowledge gained through this assessment. As an example, a 1% overall PNP improvement could be realized by selectively incorporating the "thin 2" and the "medium" lay-ups in the EMU Thermal and Micrometeoroid Garment. This technology improvement could apply to the EMU, or to any future EVA suit that must operate in a micrometeoroid and orbital debris environment.

Recommendations

Current NASA planning will have the space environments model, ORDEM 2000, updated in the 2007 time frame and that a separate Meteoroid Environment Model will also be issued in 2008. The authors have recommended that any hazard increases due to the environmental reassessment be rapidly evaluated by the EVA community and that any changes to the risk be assessed at that time.

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Acronym and Definition List

BUMPER – (now BUMPER II) a NASA computer code that calculates the PNP of an orbiting body in LEO

CM - EVA Crew Member

EMU – Extravehicular Mobility Unit

ERCA - EMU Remote Camera Assembly (an EMU helmet mounted camera system)

EVA - Extra-Vehicular Activity

Hardgoods – Polycarbonate, fiberglass and metallic elements of the EMU, usually covered by TMG

HITF - Hypervelocity Impact Test Facility

HS (HS SLS) - Hamilton Sundstrand, Space, Land & Sea Systems (Windsor Locks, CT)

I-deas® – a commercially available, solid modeling software

ILC - ILC, Incorporated (Dover DE, or Houston, TX)

ISS – International Space Station

JSC - NASA Johnson Space Center (Houston, TX)

TMG - Thermal and Micrometeoroid Garment of the EMU, the outer garment that forms the primary MMOD protection for the spacesuit

LDEF – Long Duration Exposure Facility, a NASA satellite deployed and retrieved years later by the Shuttle with the express mission of evaluating materials durability in a space environment

LEO – Low Earth Orbit

LSS – Life Support System of the EMU, the backpack (hardgoods)

MEM – Micrometeoroid Environments Model, next generation NASA model for micrometeoroids

MOD – Mission Operations Directorate, the NASA group with the primary responsibility to train astronauts

MLI – Multi-Layer Insulation, a stack-up of aluminized Mylar and non-woven scrim; very effective in space

MMOD – Micrometeoroids and Orbital Debris

MWS - EMU Mini-Work Station (a tool caddy for astronauts)

NASA – The National Aeronautics and Space Administration

NBL – Neutral Buoyancy Laboratory, in Houston, TX, an underwater spacewalk simulation lab

NCN – Neoprene Coated Nylon, the absorber layer in the EMU's protective garment

OCF - Open Cell Foam

ORDEM xxxx - Orbital Debris Environments Model, a NASA MMOD environments model of a given vintage (xxxx), this model is an input to BUMPER

PNP - Probability of No Penetration (of the EMU, 1 = 100% safety from MMOD)

Softgoods – Soft , fabric based elements of the EMU, includes the TMG, these locations are most vulnerable to MMOD strikes

SSA – Space Suit Assembly, the non-life support system elements of the EMU (primarily softgoods)

SSN – Space Surveillance Network, a network of radar resources used to track and catalog space debris

STS-xxx – Space Transportation System (the Shuttle) and flight number (xxx), for example, STS-116

+XVV – Positive X axis of the ISS flown in the direction of travel (Velocity Vector)

-XVV – Negative X axis of the ISS flown in the direction of travel (Velocity Vector)