47th International Conference on Environmental Systems
16-20 July 2017, Charleston, South Carolina

ICES-2017-258

Planetary Glove Advancements and Testing

Keith Splawn[1] David Graziosi[2] and Greg Muller, P.E.[3]
ILC Dover LP, Houston, Texas, 77058

One of the most important aspects of manned space flight are space suits, and the key functional aspect of a space suit is the ability to have dexterity in the hands while at pressure. ILC Dover has developed numerous glove designs over many years to meet the requirements and goals of NASA programs and missions. In many cases the performance and structure of the previous generation of gloves has been the building block of the future gloves. NASA's latest glove program the High Performance EVA Glove (HPEG) is no exception. Building on the current standard of ILC's EMU's Phase VI glove, The HPEG uses an infusion of emergent technologies in key areas to push the envelope in advanced glove design. Improvements in sizing, mass, materials, and dust resistance, to name a few are all part of the HPEG glove. The Phase VI glove was originally developed in the late 1990s for the mission of building the International Space Station through the use of the Space Shuttle. The HPEG design looks beyond LEO to planetary mission adaptations and enhancements. In this paper ILC will provide and overview of the HPEG design and discuss some of the testing done, and performance measures of the HPEG.

Nomenclature

ASTM = *American Society for Testing and Materials*
CAD = *Computer Aided Design*
CMC = *Carpal Metacarpal*
EPG = *Environment Protection Garment*
HPEG = *High Performance EVA Glove*
HPGD = *High Performance Glove Disconnect*
EMU = *Extravehicular Mobility Unit*
EVA = *Extravehicular Activity*
FOS = *Factor of Safety*
ISS = *International Space Station*
JSC = *Johnson Space Center*
LBS = *Pounds*
MCP = *Metacarpophalangeal*
MMOD = *Micrometeoroid Orbital Debris*
MVC = *Maximum Voluntary Contraction*
NASA = *National Aeronautics and Space Administration*
PSID = *Pounds per Square Inch Differential*
PVU = *Pattern Verification Unit*
ROM = *Range Of Motion*
RTV = *Room Temperature Vulcanizing*
TMG = *Thermal Micrometeoroid Garment*
TRL = *Technology Readiness Level*
S/AD = *Specifications and Drawings*

---

[1] Houston Engineering Manager, ILC Dover Houston, 2200 Space Park Drive, Suite 110 Houston TX USA 77058
[2] Houston Chief Engineer, ILC Dover Houston, 2200 Space Park Drive, Suite 110 Houston TX USA 77058
[3] Design Engineer, ILC Dover Houston, 2200 Space Park Drive, Suite 110 Houston TX USA 77058

I. Introduction

THE High Performance EVA Glove (HPEG) has its roots in the Phase VI glove that was originally developed in the late 1990s. The Phase VI has had many enhancements throughout its operational life. In some ways the HPEG could be considered another enhancement for the Phase VI. The HPEG also includes design enhancements developed for the ILC prototype Phase VII glove[1] as well as infusion of emergent technologies from program subcontractors NanoSonic, nGimat, and Aspen Aerogels.

Key features of the HPEG restraint include improved patterning to improve cycle life, Titanium wrist hardware fabricated using additive manufacturing and incorporating high cycle life bushings first utilized on the Z-2 EVA prototype spacesuit. Two new sizes of upper wrist gimbal ring were developed to improve sizing. A new dual gimbal ring thumb MCP joint was developed as an evolution of the joint developed for the Phase VII glove. An improved palm bar sizing mechanism was developed incorporating the lessons learned from the several previous generations ILC Dover developed for NASA.

The HPEG bladder is the same as the Phase VI design with the exception of added mobility features for the new thumb carpometacarpal (CMC) joint.

The HPEG Evironment Protection Garment (EPG) incorporates all of the emergent technologies developed on this program. These include a dust resistant coating from nGimat, cut sensor system and Hybrid Shield insulation produced by NanoSonic and two new versions of Aspen Aerogels insulation technology.

The HPEG wrist bearing/disconnect is an evolution of the high performance glove disconnect (HPGD) previously developed for NASA by Air Lock Inc. The new design is lighter weight and more dust resistant while still being compact and low torque.

Since its delivery, the HPEG has been used for laboratory testing at the NASA-Johnson Space Center.

Figure 1. ILC HPEG with EPG installed.

II. Summary of the HPEG Design

A. Restraint

The restraint (Figure 2) is primarily made up of the proven Phase VI design that was used to build the International Space Station and is now used to maintain it. This consists of a complex set of patterns for the hand and wrist. The wrist is comprised of a dual gimbal ring toroidal convolute design that places the flex/ex joint above the ad/ab joint closer to the actual center of rotation of the wrist since this motion is used more and requires greater range of motion (ROM).

For HPEG, the base wrist softgoods were not altered. An examination of Phase VI fit issues with smaller crewmembers revealed that most with smaller hands have a rubber pad sewn into the back of their comfort gloves to make up excess space in the glove. This is due to the fact that Phase VI was designed with one wrist size that has to fit the 95 percentile male hand size. Through a series of manned glove box tests, it was determined that two new sizes of upper wrist gimbal rings could be developed for HPEG without changing the base wrist softgoods. The wrist axial restraints were also changed from stainless steel swivel hardware with sewn webbings to all Titanium hard links to improve strength. In order to improve cycle life and reduce cost, the gimbal rings were fabricated via Direct Metal Laser Sintering and the existing Phase VI synergistic pivot surface coating was replaced with high performance

Figure 2. ILC HPEG Restraint

plastic bushings. This bushing design was implemented on the Z-2 rolling convolute shoulder joint with much success.

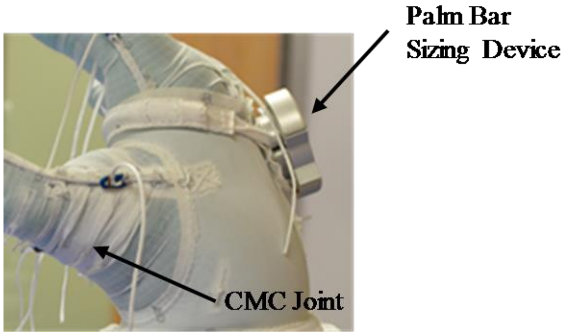

Figure 3. ILC HPEG CMC Joint

The hand portion of the HPEG restraint has three important improvements over the existing Phase VI design. The Phase VI restraint is currently limited in cycle life due to damage to the index finger base seam experienced during certification testing. For HPEG, the patterning was revised to remove this seam. The HPEG incorporates the latest evolution of the palm bar sizing device first developed for NASA in 2010. This design is more robust by utilizing the existing palm bar webbing instead of needing to transition to small diameter textile cord in the previous versions. The device also has an improved locking mechanism. The most significant improvement to the restraint on the HPEG is the dual gimbal ring rolling convolute thumb carpometacarpal (CMC) joint (Figure 3). This joint is an evolution of the single gimbal ring design incorporated into the Phase VII EVA glove prototype in 2012. The CMC joint gimbal rings are attached to the inside of the restraint and linked to the thumb sides seams with axial restraint webbings. This approach was taken to better control the CMC joint softgoods and reduce torque.

B. Bladder

The HPEG bladder is fabricated from the same urethane polymer utilized on the Phase VI flight gloves. This design is a one-piece pressure retaining layer dipped on tooling fabricated using stereolithography additive manufacturing. The bladder features are unchanged except for the CMC joint which has extra convolutes added for the dual ring rolling convolute joint. The flange of the bladder is reinforced with a layer urethane coated nylon fabric primarily to mitigate material damage from inserting and removing glove attachment screws.

C. EPG

Similar to the other HPEG subassemblies, the EPG is an evolution of the existing Phase VI EVA Glove TMG. The EPG is incorporates all of the five emergent technologies developed for the HPEG. The EPG also incorporates a prototype wrist cuff to minimize potential dust migration throught the end of the EPG gauntlet. The hand back of the EPG also incorporates a palm bar sizing device cover retained by velcro aiding EPG indexing to the restraint while also providing access for turning the sizing device rotary knob. The EPG also retains the finger tip indexing certified for flight on Phase VI glove.

Two new technologies are multi-environment insulation and flexible rubber Aerogels from Aspen Aerogel. Two different materials were developed under the HPEG project. In order to provide enhanced insulation but also retain flexibility, a flexible rubber based Aerogel was loaded into the existing Dacron non-woven material used as a spacer between the existing aluminized Mylar layers. The goal is to maintain the current multi-layer insulation performance needed for vacuum environments while providing added insulation for cold micro-pressure environments like Mars. The limited mobility areas of the handback and gauntlet utilize a thicker insulation. Commercially available Thinsulate insulation was loaded with flexible rubber Aerogel. This new insulation is utilized as a spacer between non-reinforced aluminized Mylar layers.

The third emergent technology is a passive dust management coating. A Superhydrophobic Coating was incorporated by nGimat onto the outer shell material of the HPEG EPG. Three existing base fabrics were evaluated during the program including Teflon, Gortex and Ortho fabric. The Superhydrophobic coating was applied to all three fabric materials and self-cleaning behavior was demonstrated using lunar dust simulant and water droplets. Dust removal methods of shaking and blowing off were also examined. A new method of dust removal using a hydrophilic cleaning pad to hold water and absorb dust was developed and demonstrated. It was decided after initial dust testing to not pursue the Gortex fabric due to its more open weave. Cycle testing and dynamic pressure testing was performed on coated fabric samples utilizing both lunar and Mars dust simulant to characterize the behavior of the coating. Each of the four deliverable EPG were coated with nGimat's Superhydrophobic coating once the EPG was completely manufactured.

The fourth emergent technology is an in-glove sensor system for cut detection. NanoSonic Inc. developed a flexible film cut sensor system based on their metal rubber technology. A Metal Rubber (MR™) Fabric was developed for the HPEG project. The MR™ Fabric is thinner and lighter weight that standard Metal Rubber and exhibits the same electrical resistance. The cut sensors were made up of three layers providing cut sensing as small as 1/4” in any orientation. The sensors are patterned for the palm side of the index finger, thumb, metacarpal joint, and carpo-metacarpal joint. The system includes a small electronics box with power switch and red and green LED lights to indicated if a glove was cut. The green LED stays on as long as no cuts are experienced. Once the glove is cut, the green LED turns off and the red LED turns on. The cut system was delivered separate from the HPEG gloves.

The fifth emergent technology is a reduction in material bulk. This was accomplished in several ways. The EPG hand patterning was modified from the existing Phase VI to reduce material bulk in the side seams. This approach was first demonstrated on a Phase VI TMG enhancements project in the mid-2000s but never incorporated into the flight program. Improvements to how the RTV palm pads are molded and applied was also incorporated into HPEG for reduction in bulk. The Nomex felt insulation utilized on the palm of the glove was replaced with NanoSonic’s Hybridshield™ insulation. The Hybridshield™ insulation is similar to one produced by ILC Dover for previous enhanced Phase VI TMG prototypes as well as the Phase VII TMG.

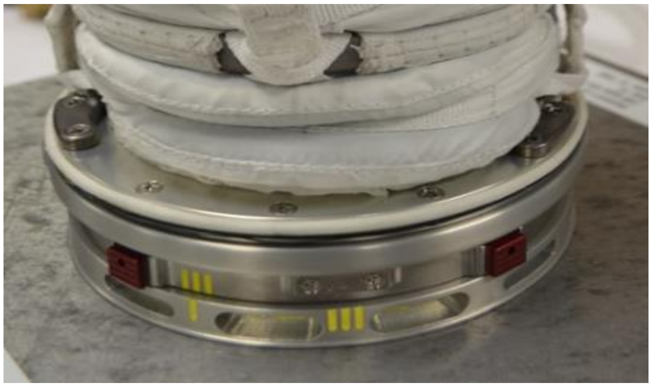

Figure 4. HPEG Wrist Bearing/Disconnect.

D. Wrist Bearing/Disconnect

The wrist bearing/disconnect design (Figure 4) is an evolution of the High Performance Glove Disconnect (HPGD) developed for NASA previously. The primary focus was on weight reduction and improved dust protection. The HPEG design was optimized to reduce weight through reduced cross-sections and scallop cuts throughout the hardware. A pair of HPEG wrist bearing/disconnects are lighter than the HPGD and ISS EMU designs by .44 lbs. and 1.16 lbs. respectively.

The HPEG wrist bearing/disconnect has four dust protection improvements. The Nomex braided rope external dust seal was reduced in cross-section. A molded internal wiper seal was added to prevent dust that gets past the main seal from reaching the bearing races. A third seal was added at the bottom face of the bearing that seals against the disconnect to prevent dust from reaching the static pressure seal. The sliding lock button shape and style was redesigned to minimize dust entrapment.

III. Verification[2]

A. Summary

The verification plan was completed verifying 12 manned requirements and 34 unmanned requirements[3]. A total of 7 requirements were either not met with all test subjects or dertermined to be not applicable or unattainable. Of the 12 manned requirements, 2 were determined to be a fail at the completion of glove box testing. Of the 34 unmanned requirements 1 failed (Wrist Flex/Ex) during requirements verification testing. The 4 remaining requirements not met were agreed to by NASA as N/A or unattainable.

The following 4 requirements originally levied on the HPEG design were later found to be difficult or not able to achieve. Relief for these requirements were requested and granted by NASA at the Pre-Test Review. The requirements that were removed are as follows:

- Dusty Bearing Leakage - Each HPEG Bearing/Disconnect shall not leak more than 7 sccm air when operated at 4.3 psid above ambient in a dusty environment.

- Insulation - Each unique material layer stack of the HPEG system shall have a K value equal to or less than the applicable location K values listed in Table 2 3 (Table 2.3 is part of a NASA requirements document not shown)

- Dusty Bearing Torque - The HPEG bearing shall not exceed 5.0 in-lb running torque at 80º/sec, when used at 4.3 psid in a dust environment for 16 hrs [TBR].

- Sharp Edges - The edges of all HPEG system hardgoods shall have a minimum of 0.10 inch (0.25 cm) radius.

Leading up to the Pre-Test Review it was determined that ILC didn't have the same equipment as NASA did to perform/verify 3 of the requirements listed above so NASA relieved ILC of these requirements. With respect to the sharp edge requirement, most hardware on the gloves is smaller than .1 inches thick so meeting this requirment cannot be completely achieved. Keyhole brackets and other smaller hardware on HPEG are present of the Phase VI glove as well. This hardware has never caused injury to personnel handling it or damaged other suit components. This hardware is always covered by the EMG during operation.

The following two requirements were failed during requirements verification testing. During glove box testing is was noted that not every test subject was able to accomplish the following tasks.

- Thumb Mobility - The HPEG system shall allow the user to touch their thumb to their little finger when at 4.3psid.

- Peg Board Task - The HPEG system shall allow the user to complete the peg board task within 25 seconds, when used at 4.3psid.

The standard Phase VI glove of these same sizes cannot meet the complete requirement for thumb mobility. Design enhancements were made to improve the mobility of the thumb but being that these glove sizes are small and the thumb is a bidirectional joint, not designed to point towards the little finger, it was unable to achieve touching each point by every subject. It was discovered during glove box testing that Peg Board requirement was based on suited testing. The glove box inhibits mobility and makes achieving this timed requirement near impossible. A couple of subjects were able to complete it within the time but the glovebox was the problem not the mobility of the gloves.

The HPEG glove also failed the unmanned requirement for wrist joint flexion/extension range requirement of 60º and 90° respectively at 4.3psid. ILC thought the requirement was the same as the Phase VI glove requirement. The requirement was initially read as being a total of 90 deg range of motion not 90 deg for just the extension direction. To meet the 90 deg extension requirement would require a completely different wrist joint from the Phase VI wrist which is the basis of HPEG. The HPEG wrist extension range of motion exceeds the Phase VI nomial range of 45 degrees by 4 degrees but does not meet the HPEG requirement.

The HPEG Compliance Matrices for Manned Requirements and Unmanned Requirements are shown in Tables 1 and 2 respectively.

TRL J.3 VERIFICATION	**PRESSURE (psid)**	**REQUIREMENT DESCRIPTION**	**VERIFICATION METHOD**
SM18	8.3 +/- 0.5	EPG Grip	Test
SM19	0 - 8.3 +/- 0.5	EPG Glove Assembly Coverage	Inspection
SM20	0	EPG Wrist Disconnect Access	Demonstration
SM22	0	Soft Dock Mechanism	Inspection/Demonstration
SFM1	8.3 +/- 0.5	Glove Size	Test
SFM2	8.3 +/- 0.5	Goal – Different Sized Pair	Test
SFM3	4.3 +/-0.5	Thumb Mobility	Test
SFM4	4.3 +/-0.5	Index Finger Mobility	Test
SFM5	4.3 +/-0.5	Peg Board Task	Test
SFM6	4.3 +/-0.5	Tactility	Test
SFM9	4.3 +/-0.5	Gloved Hand Grip Strength	Test
SFM10	0	EPG Fingertip Indexing	Inspection/Demonstration

Table 1: HPEG Manned Requirements

TRL J.3 VERIFICATION	PRESSURE (psid)	REQUIREMENT DESCRIPTION	VERIFICATION METHOD
PL1	8.3 +/-0.5	Normal Operating Pressure	Demonstration
PL2	10.6	Maximum Operating Pressure	Demonstration
PL3	13.2	Structural Test Pressure	Demonstration
PL4	17.6	Proof Pressure	Analysis/ Demonstration
PL5	21.2	Ultimate Pressure	Analysis/Test
PL6	4.3 +/-0.5	Maximum System Leak Rate: 25 sccm	Test
PL7	4.3 +/-0.5	Maximum Bearing Leak Rate: 5 sccm	Test
PL8	4.3 +/-0.5	Maximum Dusty Bearing Leak Rate: 7 sccm	**N/A**
SM1	N/A	Goal – Cycle Life	Analysis
SM2	N/A	Goal – Time between Required Maintenance	Analysis
SM3	N/A	Single Glove Max Weight: 3.5 lbs	Inspection
SM4	N/A	Wrist Length	Inspection
SM5	N/A	Isometric Man Loads	Analysis/Test
SM6	N/A	Insulation	**N/A**
SM7	N/A	Goal – Dust Migration	Inspection/Test
SM8	N/A	Removability for Inspection and Repair	Demonstration
SM9	N/A	Resize with Specialized Tools	Inspection/ Demonstration
SM10	N/A	Factor of Safety	Analysis/Test
SM11	N/A	Labeling	Inspection
SM12	N/A	Sharp Edges	Inspection
SM13	N/A	Use of NAS Fasteners	Inspection
SM14	N/A	Use of Helicoils	Inspection
SM15	N/A	EPG Tear Protection	Test
SM16	N/A	Goal – EPG Dust Abrasion Protection	Test
SM17	N/A	EPG Fabric Stretch	Inspection/ Demonstration
SM21	N/A	Bearing/Disconnect Bolt Hole Pattern	Inspection
SM23	N/A	Lock-Lock Mechanism	Inspection
SM24	N/A	Restraint Line Loading	Demonstration
SM25	N/A	Heat, RF, Laser Seal Verification	Demonstration
SFM7	4.3 +/-0.5	Wrist Flexion/Extension Mobility	Test
SFM8	4.3 +/-0.5	Wrist Adduction/Abduction Mobility	Test
SFM11	4.3 +/-0.5	Bearing Starting Torque	Test
SFM12	4.3 +/-0.5	Bearing Running Torque	Test
SFM13	4.3 +/-0.5	Dusty Bearing Running Torque	**N/A**
ET1	N/A	Incorporation of Low TRL Technologies	Inspection/ Demonstration
ET2	N/A	Nominal Current Limit	Inspection
ET3	N/A	Off-Nominal Current Limit	Inspection

Table 2: HPEG Unmanned Requirements

B. Pressure and Leakage Test Results

Pressure and ventilation requirements include several operating and structural pressures as well as leakage with and without dust. The HPEG gloves were proof tested to 17.6 psid for 15 minutes minimum to show that the gloves meeting pressure requirements. The requirement for Ultimate pressure of 21.2 psid was certified by analysis. Maximum system leakage requirement was met by test and the highest leakage recorded post proof was < 4.0 sccm

(Req. 25 sccm max). The maximum bearing leakage requirement was tested at Air Lock Inc. and the worst leakage post ultimate pressure testing was < 1.0 sccm (Req. 5.0 sccm max). The requirement for Dusty Bearing Leakage was agreed to as N/A by NASA.

C. Structure and Mass Test Results

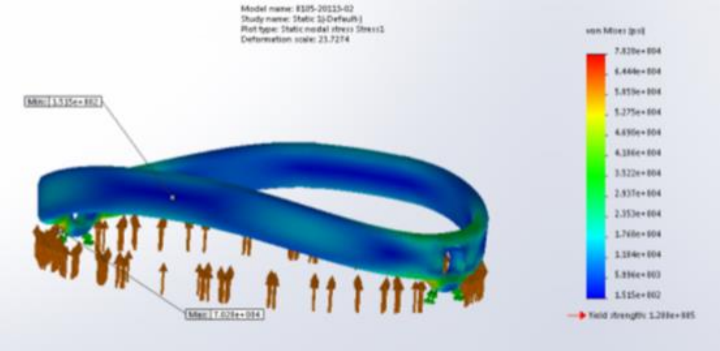

Figure 5. Lower Gimbal Ring FEA

There were a total of 14 Structure and Mass requirements. Rationale was provided to NASA for cycle life and time between maintenance. Weight and wrist length were measured and recorded. The HPEG Assembly has a 39% weight reduction over the existing Phase VI EMU Glove. Isometric manloads were verified by test using an Instron machine with no anomalies. The Dust Mitigation requirement was verified by analysis and rationale was provided to NASA. Requirements for subcomponent removabability and glove resizing without tools was verified by demonstration. The Factor of Safety (FOS) requirement of 1.5 against yield and 2.0 against ultimate was verified by test and analysis. The lowest FOS on the HPEG is the lower wrist gimbal ring (Figure 5) at 2.63 over ultimate load (2.0 Min. Req.) and 2.31 over yield (1.5 Min. Req.). Labeling and Fastener requirements were all verified by inspection. Air Lock Inc. analyzed the HPEG Bearing and the lowest factor of safety is 7.4 for the Outer Race. It should also be noted that Air Lock pressurized each Wrist Bearing/Disconnect to the ultimate pressure of 21.2 psid and performed a follow-up leakage test prior to delivery with no issues. The glove secondary webbings and all HPEG fabric seams were verified by test and analysis using a combination of new and historical data. The lowest factor of safety for the HPEG webbing secondaries is 3.0 over ultimate load. Unlike the HPEG wrist, the stress in the fabric restraint hand is driven by the ultimate pressure requirement of 21.2 psid. The lowest factor of safety determined by test and analysis is 2.8 in the hand seams.

D. Environmental Protection Garment (EPG)

This section of requirements includes tear protection, abrasion protection, stretch resistant, grip and glove assembly EPG coverage. EPG Tear Protection is verified by test and shown to be as good or better than Phase VI. Material testing was performed to document the trapezoidal tear strength of Ortho fabric and Teflon fabric. Since the HPEG uses the same materials it passes by test and similarity. The requirement for EPG Dust Abrasion Protection was verified by test. The testing was performed by depositing lunar and mars simulant on fabric samples and performing folding and fabric manipulation cycles. EPG Fabric Stretch was verified by test and inspection and no issues were noted after the required 50 EPG install/remove cycles. EPG Grip was verified by test and all subjects passed the requirement by handling smooth metal and Teflon objects without slipping. Requirements for glove coverage and access were verified by inspection and demonstration.

E. Bearing/Disconnect/Manufacturing Practices

This set of requirements includes bearing bolt circles, soft dock and locking redundancy. The current Phase VI bolt circle was mandated by NASA and therefore used for the HPEG Bearing/Disconnect bolt circle. The requirements for soft dock and a redundant primary lock were verified by inspection and demonstration. To meet requirements for best manufacturing practives, all glove restraint lines were loaded to a minimum of 1.0 times the NASA defined limit load prior to incorporation into the gloves. ILC also provided NASA with heat seal startup and shutdown peel strength samples for all bladder fabrication showing the quality of the manufacturing process.

F. Size, Fit and Mobility

The requirement for two different glove sizes was considered a pass verified by testing the glove box with a total of six subjects provided by NASA. Thumb Mobility is a failed requirement due to the inability to touch the thumb to the little finger as explained in the summary above. Requirements for Index finger mobility, Peg Board and Tactility passed after verification by pressurized testing in a glove box. It was noted during testing that verifying the Peg Board Test (Figure 6) was difficult due to the limited mobility of the glove box. It would be better to perform this test fully suited. Requirements for unmanned wrist mobility were a pass except for Wrist Extension. The HPEG dual gimbal wrist did not meet this requirement and the details are explained in detail in the summary above. Glove Hand Grip Strength was verified by test and all but one subject passed the requirement so it is deemed a pass. EPG Fingertip Indexing was verified by demonstration and inspection through 25 glove don/doff cycle at the finger sizing extremes. Requirements for bearing starting and running torque were verified at Air Lock Inc. pre-delivery by test. NASA relieved the HPEG project of the Dusty Bearing Running Torque as noted in the summary above.

Figure 6. HPEG Glove Peg Board Test

G. Emergent Technologies

In order to meet the requirement for incorporation of Low TRL Technologies, the following 5 emergent technologies have been incorporated into the HPEG.

- Flexible Rubber Aerogel Insulation
- Combination of Insulation
- Passive Dust Management Coating
- In-Glove Sensor for Cut Detection (Delivered Separately)
- Reduction in Material Bulk

IV. Conclusion

The HPEG is another major step in the evolution of the ILC Phase VI EVA Glove. The latest advancements in materials and manufacturing have been incorporated into the restraint layer to provide increased strength, cycle life and mobility. Emergent Technologies such as advanced thermal insulation and coatings have been incorporated into the HPEG EPG to provide multi-environment performance. These technologies will allow the HPEG to be used for space vacuum EVA as well as EVA on a planetary surface. EVA's during project Apollo showed how severe the dust challenge is when working on a planetary body. The HPEG's fabric coating technology takes a major step in mitigating the detrimental effects of working in a dusty environment. Finally, improved patterning and manufacturing techniques reduce the torque associated with the EPG and improve its robustness.

Acknowledgments

ILC Dover would like to acknowledge our NASA Technical Monitors Sarah Walsh and Dana Valish. We would also like to acknowledge our teammates Air Lock Inc., Nanosonic, nGimat, and Aspen Aerogels.

References

1Jones, R., Linsner, A, Wyatt, S, Scheir, C, Muller, G, Sung, J, Hewes, L, Graziosi, D, "Enhancements to the ISS Phase VI Glove Design" 2014-ICES-67 ICES Conference, 2014.

[2]Graziosi, David. "HPEG Verification Test Plan."*Report deliverd to NASA,* 8105-77002, Sept. 2016. ILC Dover

[3]"HPEG Technical Requirements List." *NNJ15514032R Attachment J.3,* December 2014