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A One-Piece Lunar Regolith-Bag Garage Prototype

GWENETH A. SMITHERS, MARY K. NEHLS, MARY A. HOVATER,
AND STEVEN W. EVANS
NASA/MARSHALL SPACE FLIGHT CENTER, HUNTSVILLE,
ALABAMA

J. SCOTT MILLER
QUALIS CORPORATION/MARSHALL SPACE FLIGHT CENTER,
HUNTSVILLE, ALABAMA

ROY M. BROUGHTON, JR., DAVID BEALE, AND FATMA
KILLINC-BALCI AUBURN UNIVERSITY, AUBURN, ALABAMA

Shelter structures on the moon, even in early phases of exploration, should incorporate lunar materials as much as possible. We designed and constructed a prototype for a one-piece regolith-bag unpressurized garage concept, and, in parallel, we conducted a materials testing program to investigate six candidate fabrics to learn how they might perform in the lunar environment. In our concept, a lightweight fabric form is launched from Earth to be landed on the lunar surface and robotically filled with raw lunar regolith.

In the materials testing program, regolith-bag fabric candidates included: Vectran™, Nextel™, Gore PTFE Fabric™, Zylon™, Twaron™, and Nomex™. Tensile (including post radiation exposure), fold, abrasion, and hypervelocity impact testing were performed under ambient conditions, and, within our current means, we also performed these tests under cold and elevated temperatures. In some cases, lunar simulant (JSC-1) was used in conjunction with testing. Our ambition is to continuously refine our testing to reach lunar environmental conditions to the extent possible.

A series of preliminary structures were constructed during design of the final prototype. Design is based on the principles of the classic masonry arch. The prototype was constructed of Kevlar™ and filled with vermiculite (fairly close to the weight of lunar regolith on the moon). The structure is free-standing, but has not yet been load tested. Our plan for the future would be to construct higher fidelity mockups with each iteration, and to conduct appropriate tests of the structure.



MSFC-248



A One-Piece Lunar Regolith-Bag Garage Prototype

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Rutgers University
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Gweneth A. Smithers, Mary K. Nehls, Mary A. Hovater, Steven W. Evans
NASA/Marshall Space Flight Center, Huntsville, Alabama

J. Scott Miller
Qualis Corporation/Marshall Space Flight Center, Huntsville, Alabama

Roy M. Broughton, Jr., David Beale, and Fatma Kilinc-Balci
Auburn University, Auburn, Alabama



Why Regolith-Bags?

While sandbagging has been a technique on Earth for centuries, more recent years have seen some work on lunar regolith-bag concepts.

If NASA is to colonize the Moon and explore the Universe, it will certainly become necessary to use the native materials of planets of residence.

Throughout history, communities have always relied on raw materials close at hand. While recent decades (on Earth) have seen a tendency to skirt around this practice with exploitation of “free trade,” transportation realities will force us to revert to historical practice when we colonize other planets.

Regolith, properly utilized, can provide thermal insulation and radiation shielding – as well as chemicals necessary for life.



L1





Goals



- To learn, through materials testing, which materials are suitable for use in construction of a one-piece regolith-bag form to be launched from Earth, landed on the Moon, filled with raw lunar regolith, and used as a functional structure (materials - chosen from a previous literature review - to be tested in conjunction with official lunar regolith simulant).
- To successfully design, develop and construct a large one-piece regolith-bag form and fill it with a low-fidelity simulant, producing the Lunar Garage Prototype.



Candidate Fabric Materials

- 1. Vectran TM - polyester liquid crystal polymer, (LCP)
- 2. Nextel TM - aluminoborosilicate (ceramic)
- 3. Gore PTFE TM - expanded polytetrafluoroethylene (PTFE)
- 4. Nomex TM - meta-aramid fiber
- 5. Twaron TM - para-aramid fiber (used instead of KevlarTM - has similar chemistry);
- 6. Zylon TM - a rigid-rod polymer - poly (P-phenylene-2,6-benzobisoxazole), PBO.



Fabric Strength Testing, Ambient ASTM D-5035 strip test



Fabric	kN/in		MPa	
	W	F	W	F
Nextel	0.804	0.745	679	673
Nomex	0.462	0.425	522	505
Gore PTFE	1.34	1.37	736	801
Twaron	2.06	4.52	1160	2589
Vectran	2.29	4.26	1308	2535
Zylon	2.66	3.77	2509	3553



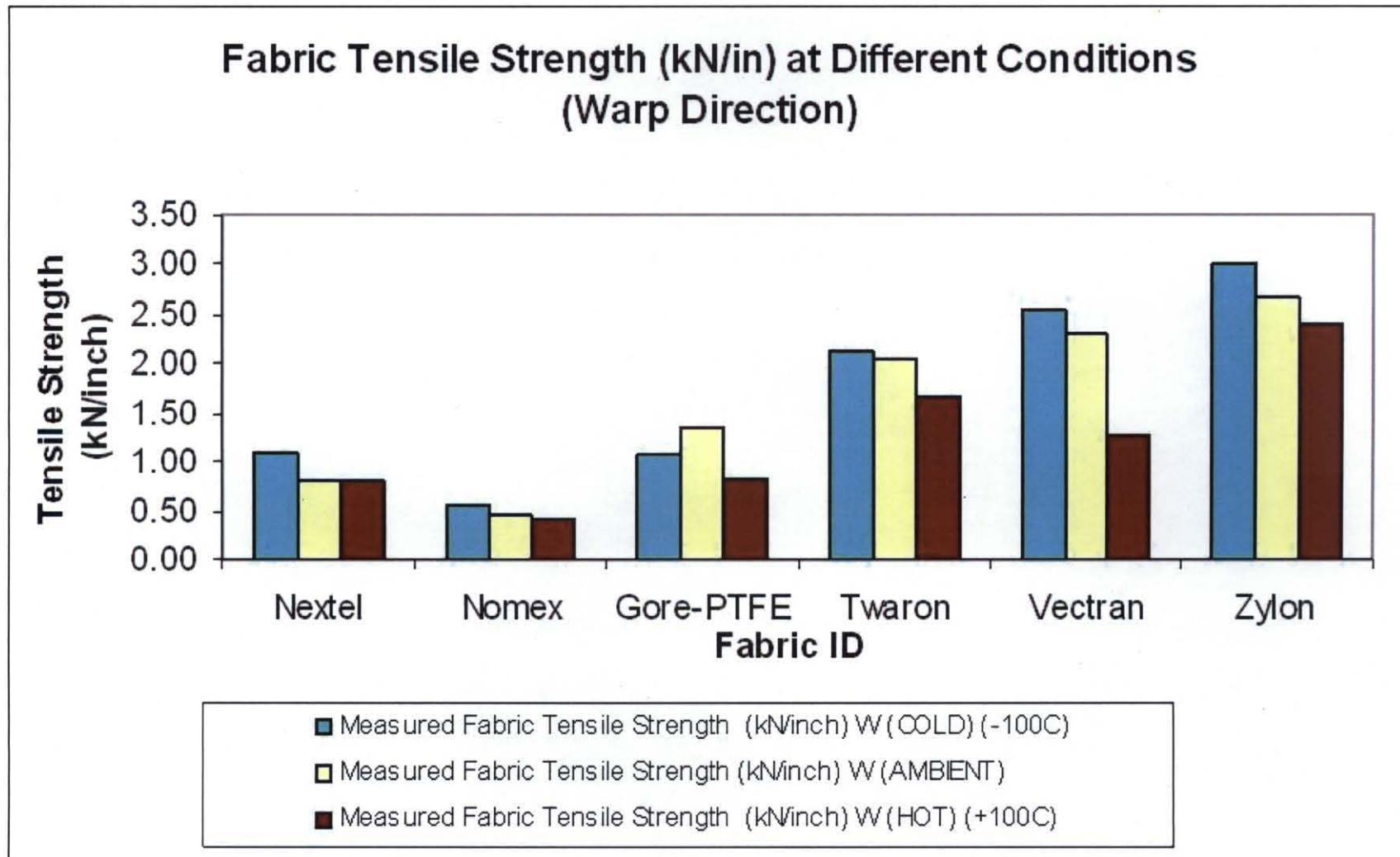
Fabric at Lunar Temperatures



- Tensile tests were performed on five samples of each fabric type according to ASTM D-5035.
- In an Instron Environmental Test Chamber model 3119 --
- Heated at 100 C (the chamber is an oven), and
- Cooled at -100 C (using the gas expelled from liquid N₂)

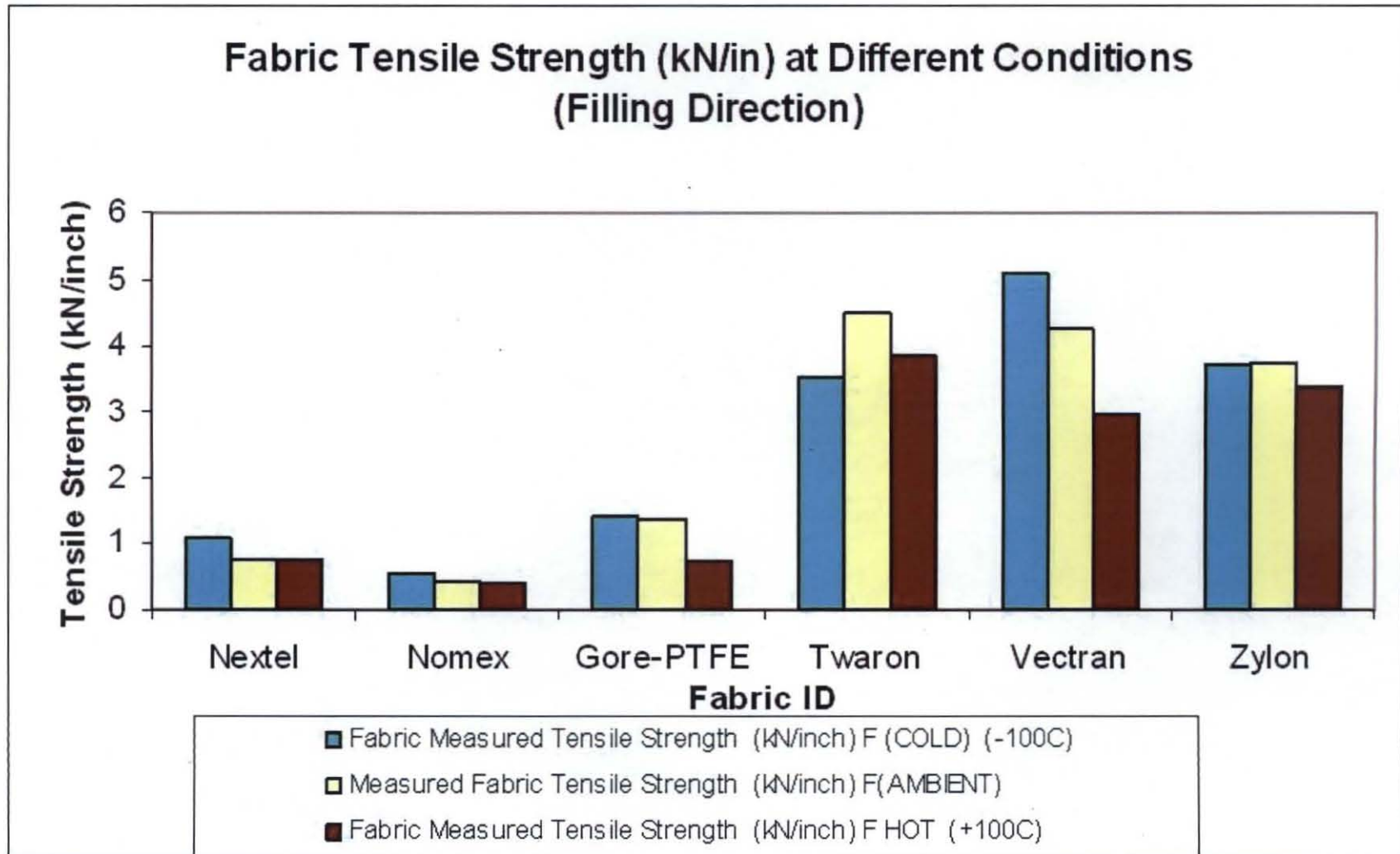


Fabric Strength at Different Temperatures





Fabric Strength at Different Temperatures





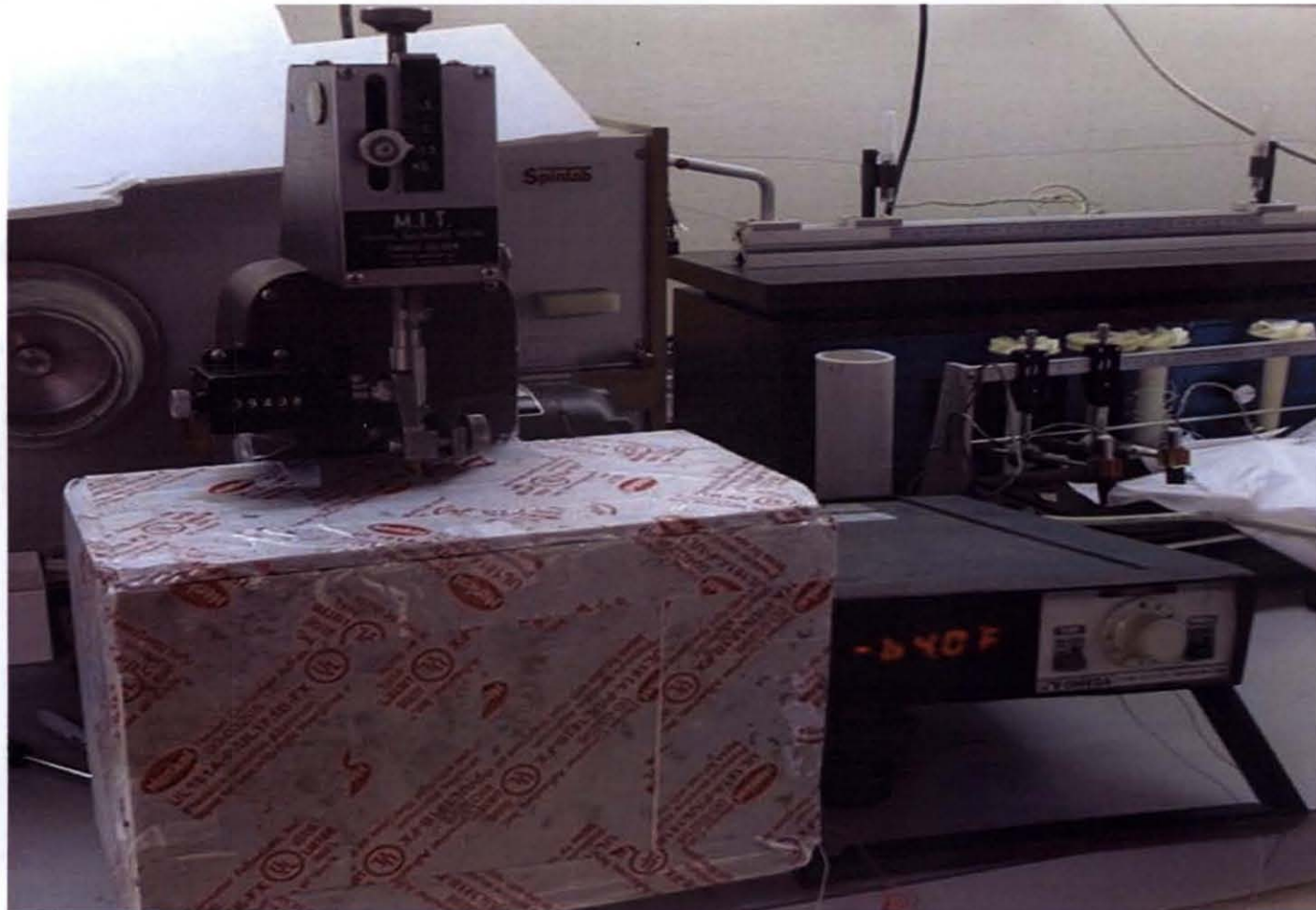
Fold Testing



- Three specimens were tested for each fabric at each temperature:
- MIT Folding Endurance Tester
- ambient lab conditions,
- - 50 C and
- - 195 C.



Folding Test Cold (-50C) with dry ice (sublimation temp: -78.5C)



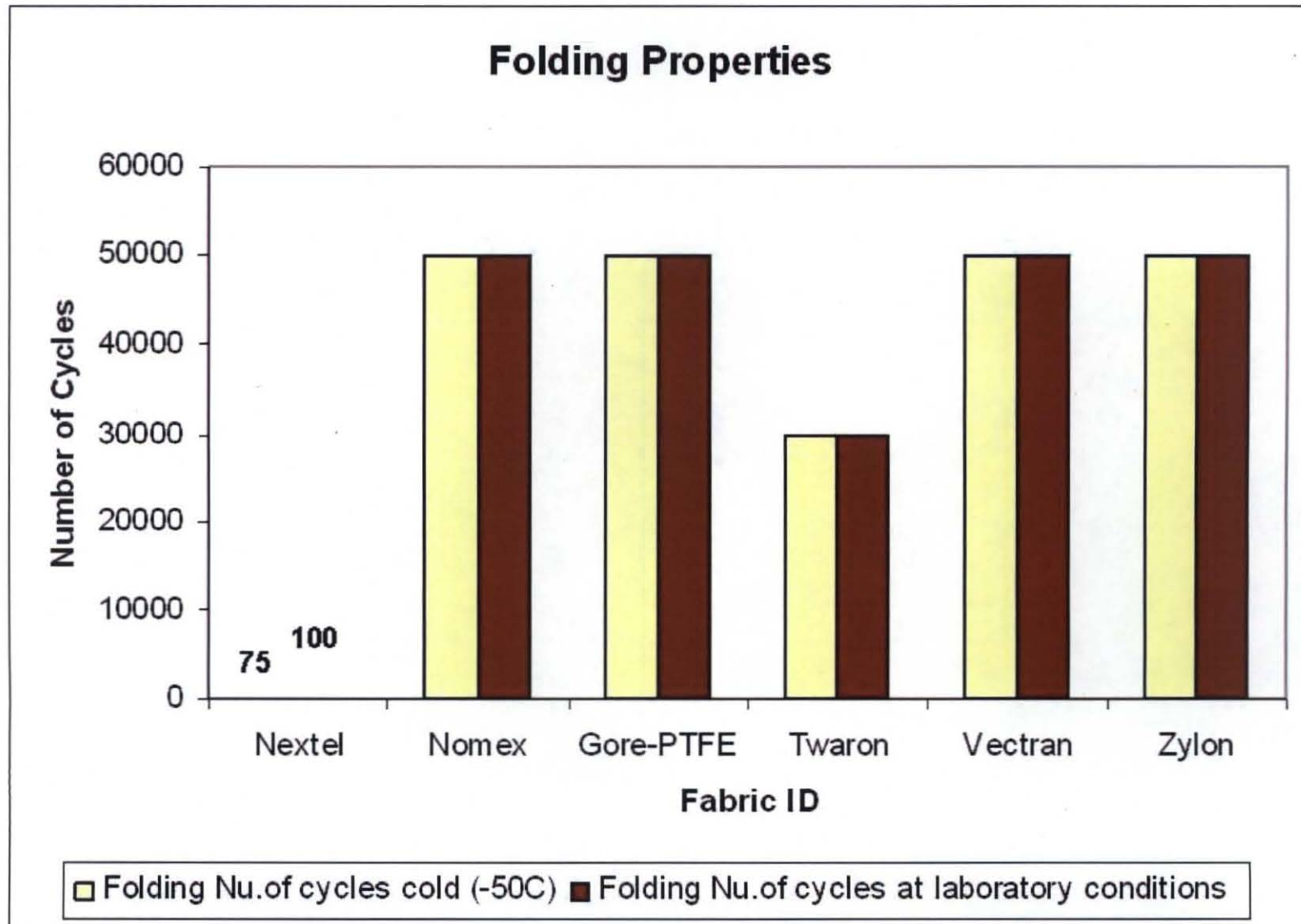


Fold Testing Results

- Nextel TM fabric samples were broken in less than a minute, after 100 cycles on average.
- Twaron TM fabrics started to show damage after 30,000 cycles and were broken at approximately 40,000 cycles.
- For Nomex TM, Gore PTFE TM, Vectran TM, and Zylon TM little damage was seen after 50,000 cycles.



Fold Endurance -- Cold



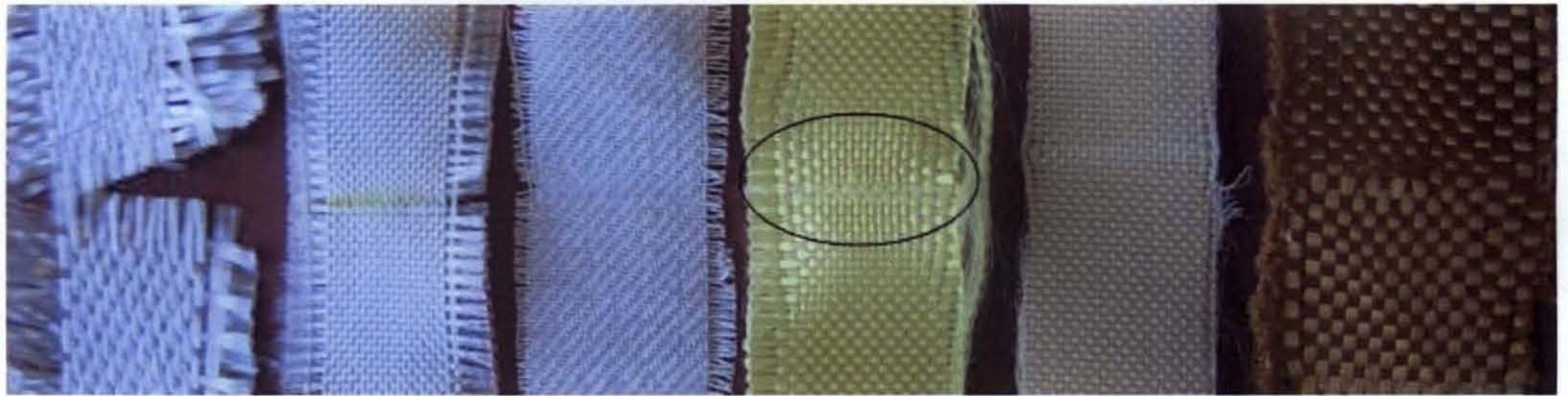


Cryogenic Fold Testing

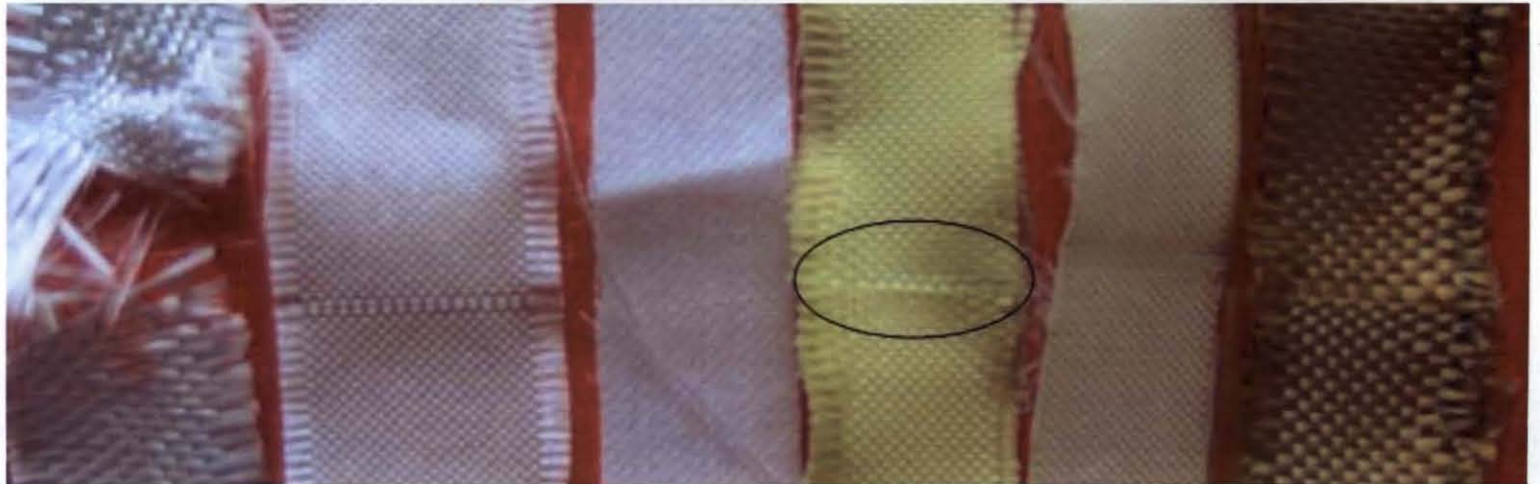


- The Styrofoam box was used around the fabric folding area.
- Liquid nitrogen was poured over the fabric and the folding mechanism while concurrently running the machine – precise temperature not measured but should approach -195 C .
- The time for testing was restricted to ~one minute - about 100 cycles.
- Fabrics were examined under the microscope. Fold area of all samples and are shown in Figure 2.27.
- Nextel TM fabrics still failed completely after ~ 250 cycles.
- No other fabric showed signs of filament breakage after 100 cycles of folding at cryogenic temperatures.

**(a) Ambient
Conditions**



**(b) Cold
Temperature**



**(c) Cryogenic
Conditions**





- Folding endurance is unlikely to be a problem for any fabric tested, except Nextel.
- Twaron ranked somewhat poorer in fold resistance than the other organic fibers.



Abrasion Testing

- The resistance of fabrics was determined on a CSI-Stoll Quartermaster Universal Wear Tester (Custom Scientific Instruments Inc.) by a modification of ASTM D-3885 (flexing and abrasion method).
- The resistance to abrasion is affected by many factors: the inherent mechanical properties of the fibers, the dimensions of the fibers, the structure of the yarns, the construction of fabrics and finish type. The resistance of fabrics to abrasion as measured by this method is generally only one of the several factors contributing to durability.



- In this test, 3 fabric samples, cut 3 x 8 inches in both warp and filling direction, are subjected to unidirectional reciprocal rubbing over a sandpaper surface, under 5 pounds weight. The sample is placed between the pressure (upper) plate and reciprocating (lower) plate. The lower plate was covered by sand paper (220 Grit).
- A 2.5mm thick, soft fabric padding was placed under the sample to provide conformability. The number of cycles is recorded upon failure of the fabric or after 1000 cycles.



- Stoll Flex-Abrasion Tester

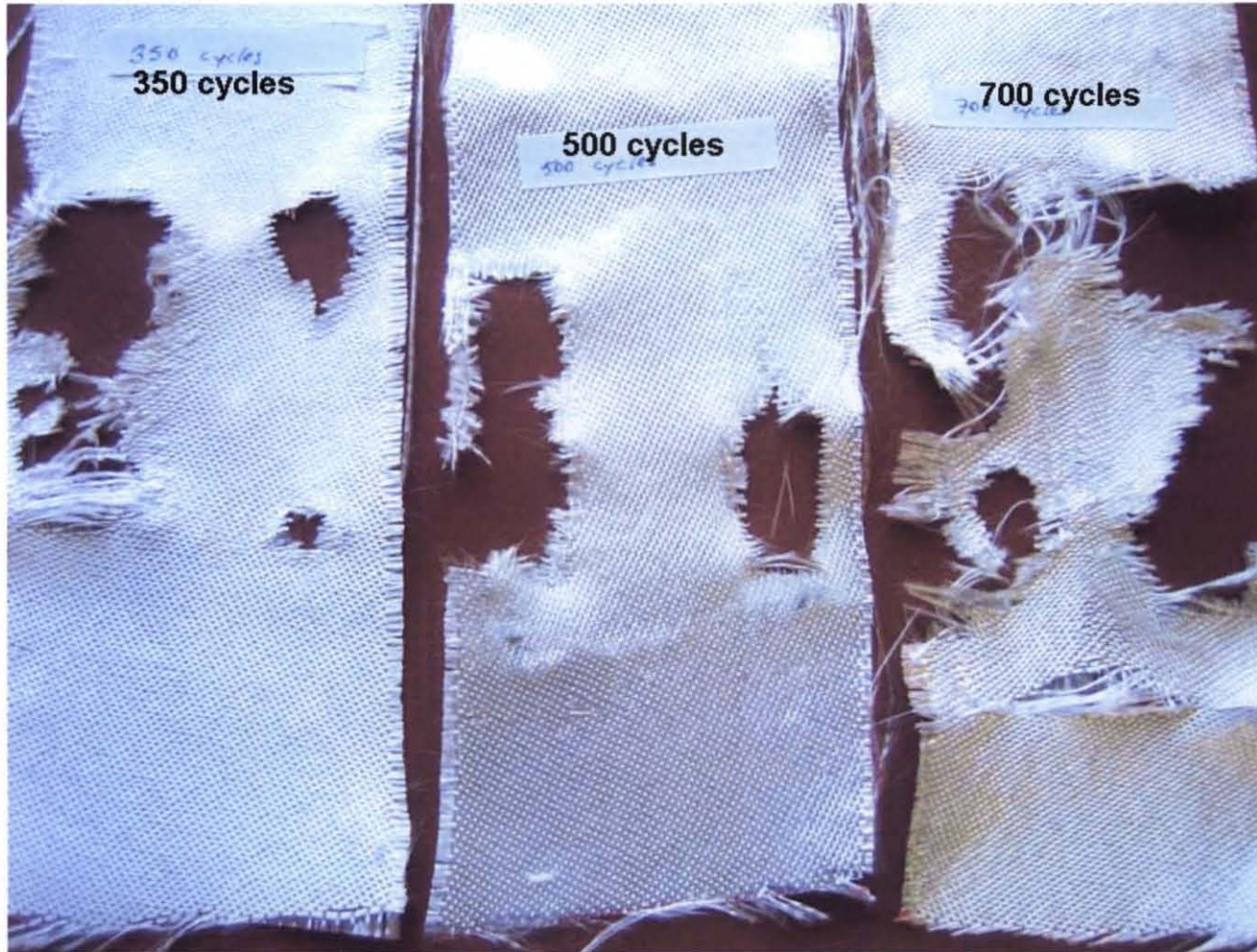




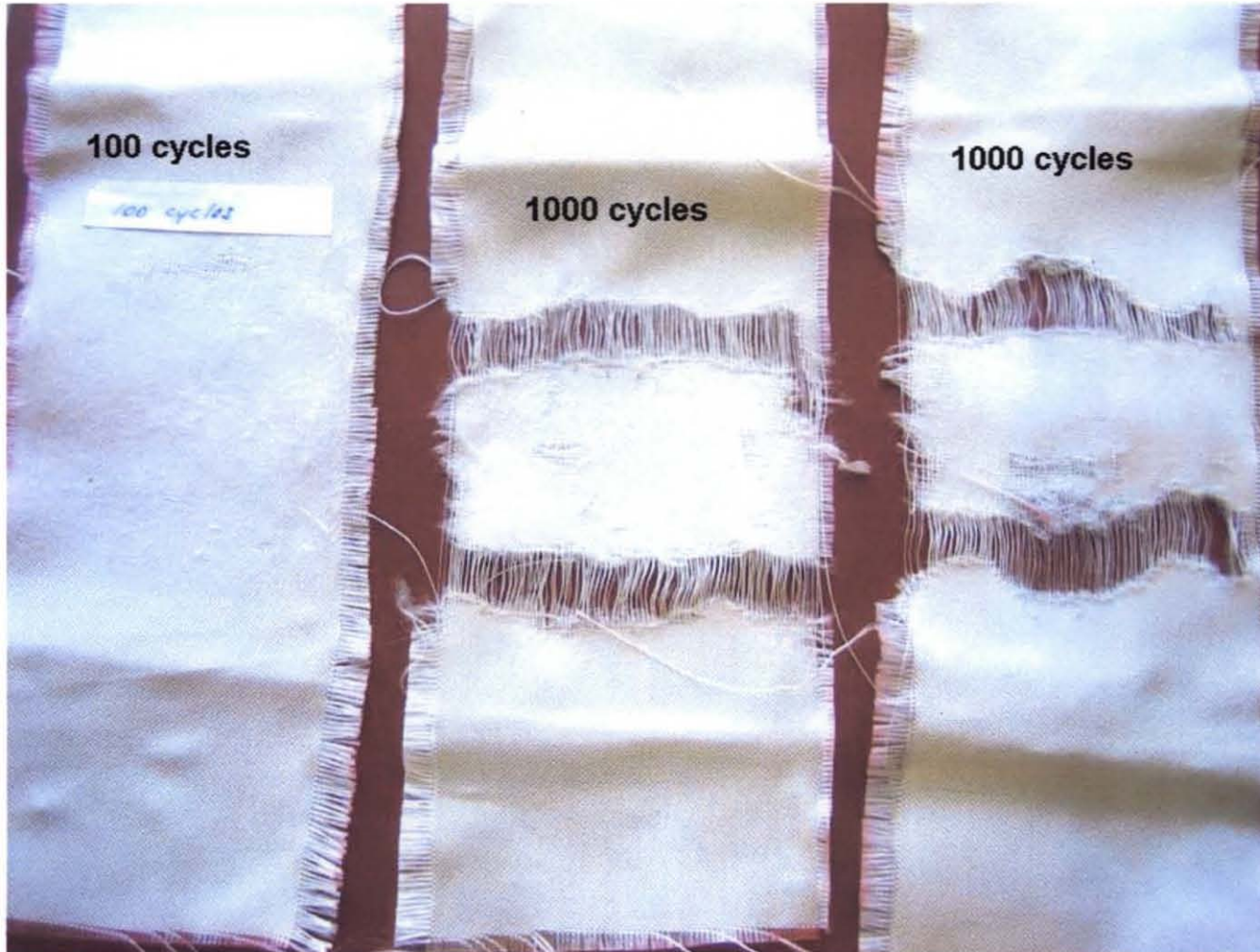
Abrasion Results



- Gore PTFE TM left some little particles on the sand paper surface but the fabric damage was not excessive.
- Vectran TM and Twaron TM were in very good condition even after 1000 cycles
- Although the failure criteria are somewhat subjective: Nextel TM samples had failed after 350 cycles, and
- Nomex TM and Zylon TM fabrics had failed after 500 cycles



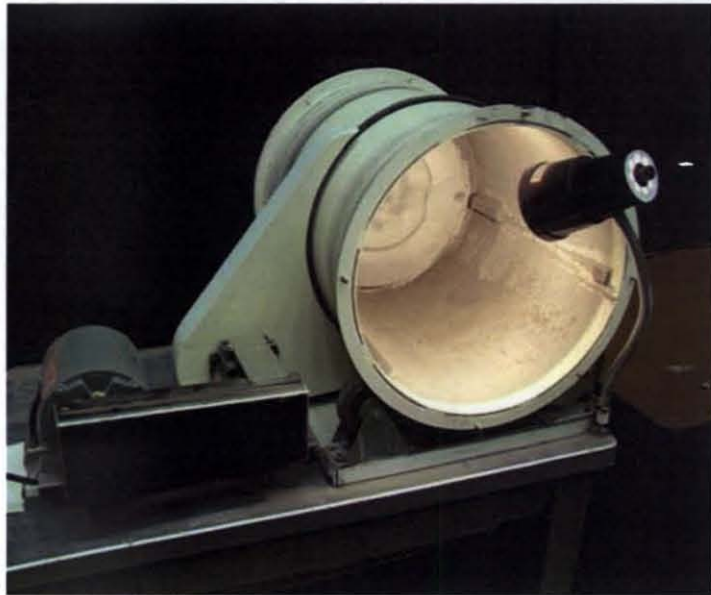
NEXTEL



NOMEX



Zylon



A



B



C



D



JSFC Abrasion Test



- One bag of each fabric loosely filled bag (of regolith simulant) was placed in the tumbling drum along with regolith simulant on the outside of the bags,
- The drum was rotated at 13rpm for 1 hour.
- Subsequently, the remaining bags were placed in the drum and were tumbled for 1 hour.



JSFC Abrasion Results



- Nextel and Gore PTFE showed some damage, but mainly at the seams.
- The other fabrics were essentially undamaged.



Radiation Resistance



- Vacuum Ultra Violet - VUV
- Particle radiation
- Gamma radiation
- Compare strength before and after radiation.



The Lunar Radiation Environment



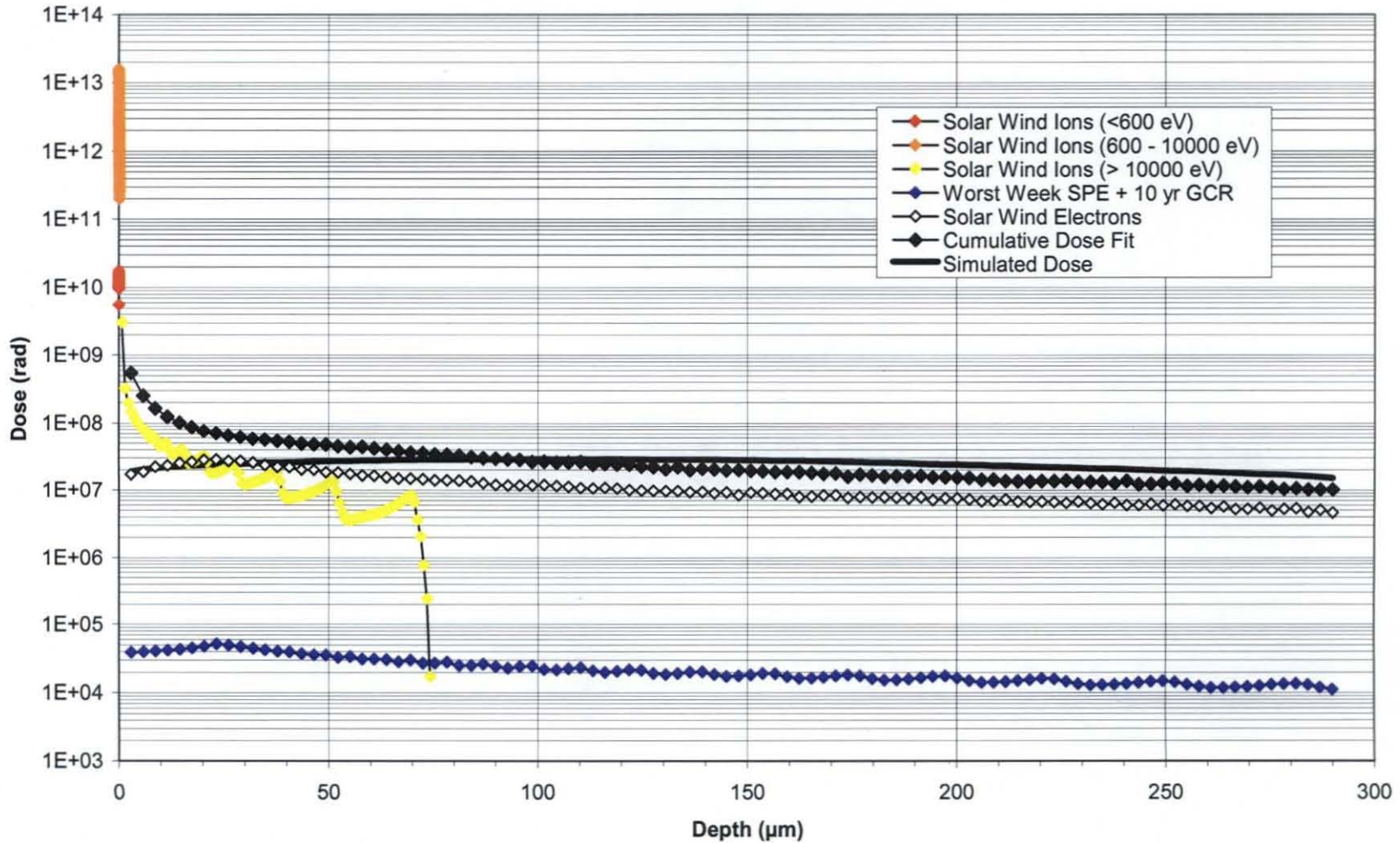
- Referenced recent natural environment study performed by MSFC EV13
- Lunar surface environment is predominantly
 - Solar wind (mostly low to mid energy e- and H⁺)
 - Cosmic ray environment (Solar Particle Events and Galactic Cosmic Rays)
 - Impact (although this is not radiation)
- Analysis indicates that the dose driver for the bulk material is from solar wind



Representative 10 Year Lunar Radiation Environment Simulation



Vectran Radiation Dose Calculations

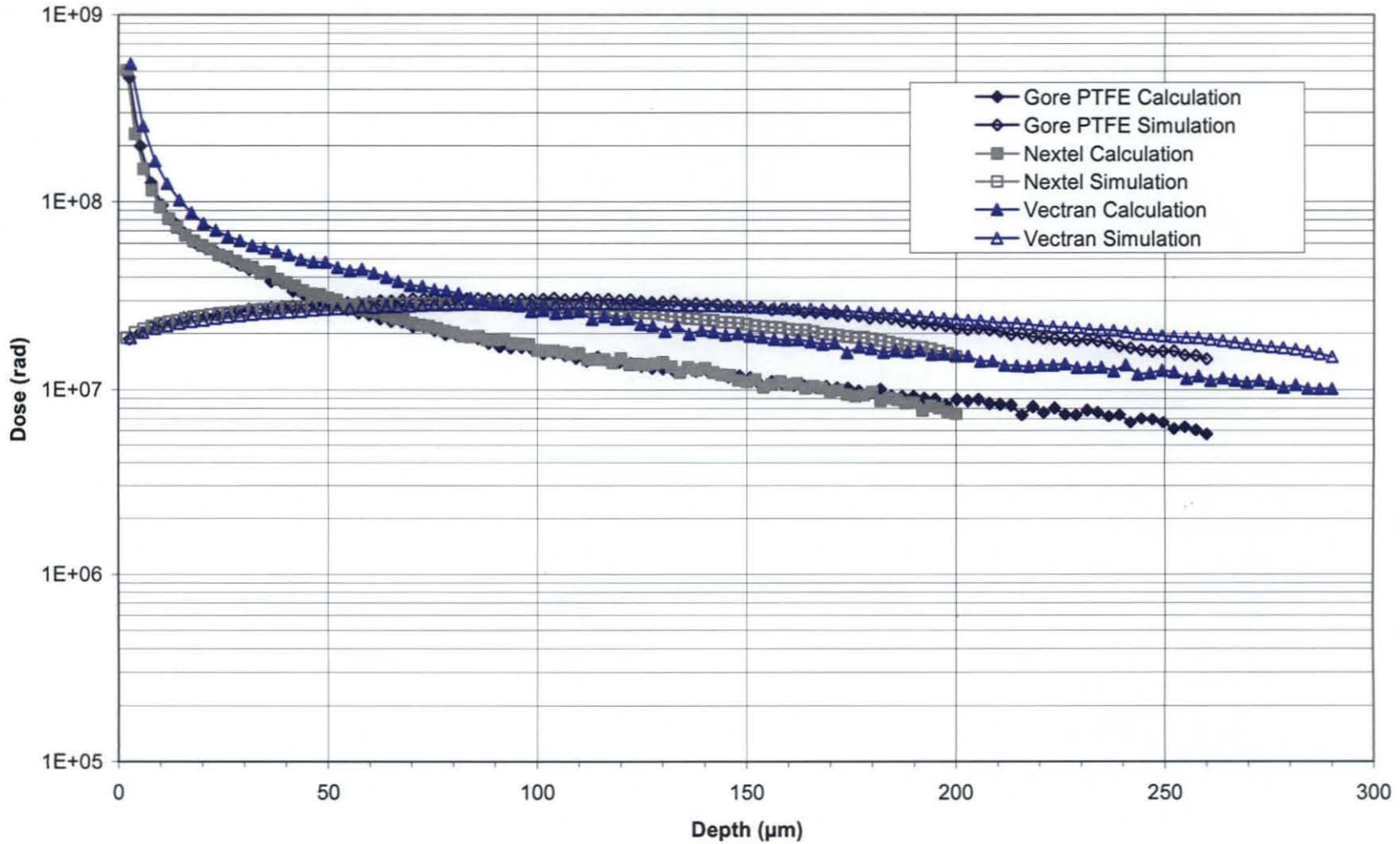




Dose Profile Matching



Radiation Dose Calculations vs. Simulations





MSFC Combined Environmental Effects Facility





Charged Particle Radiation Exposure



- Three replicate tensile samples
 - Gore PTFE
 - Nextel
 - Vectran
 - *Samples were exposed on a 1" (fill) x 4" (warp) area*
 - *Samples were sent to Auburn post-irradiation for mechanical (tensile) testing*
- One bag specimen constructed of Vectran
 - *Sample was sent to the MSFC Impact Test Facility post-irradiation for impact testing*



Charged Particle Exposures



Representative samples for total ionizing dose testing



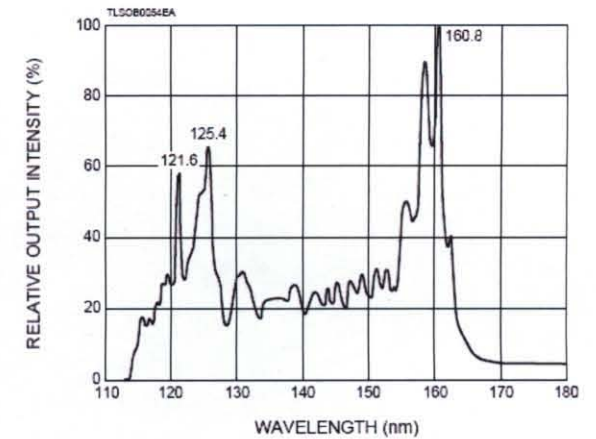
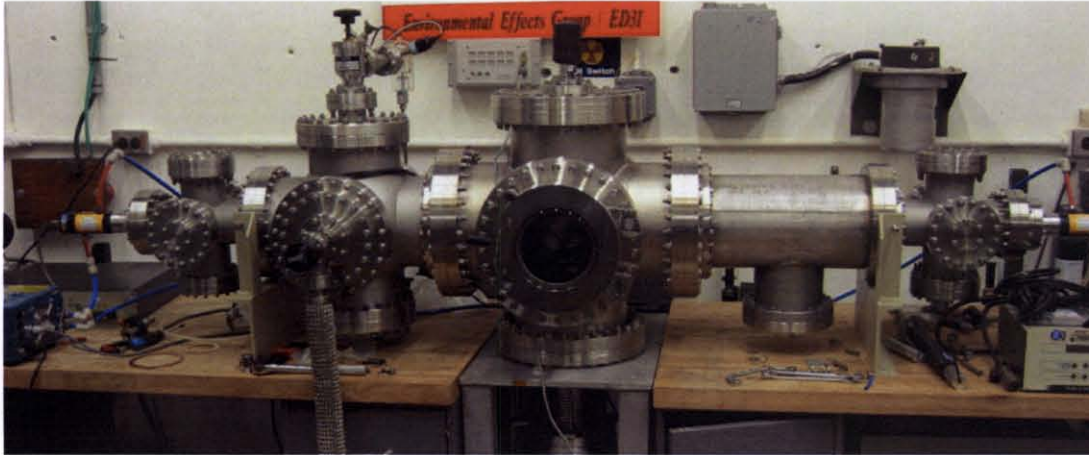
Vacuum Ultraviolet Radiation Exposure



- Three replicate tensile samples of
 - Gore PTFE
 - Nextel
 - Vectran
 - Twaron
- Two replicate tensile samples of
 - Nomex
 - Zylon
- *Each sample was exposed on a 1" (fill) x 2" (warp) area*
- *All samples were sent to Auburn post-irradiation for mechanical (tensile) testing*



VUV Exposures





Radiation Exposure Summary

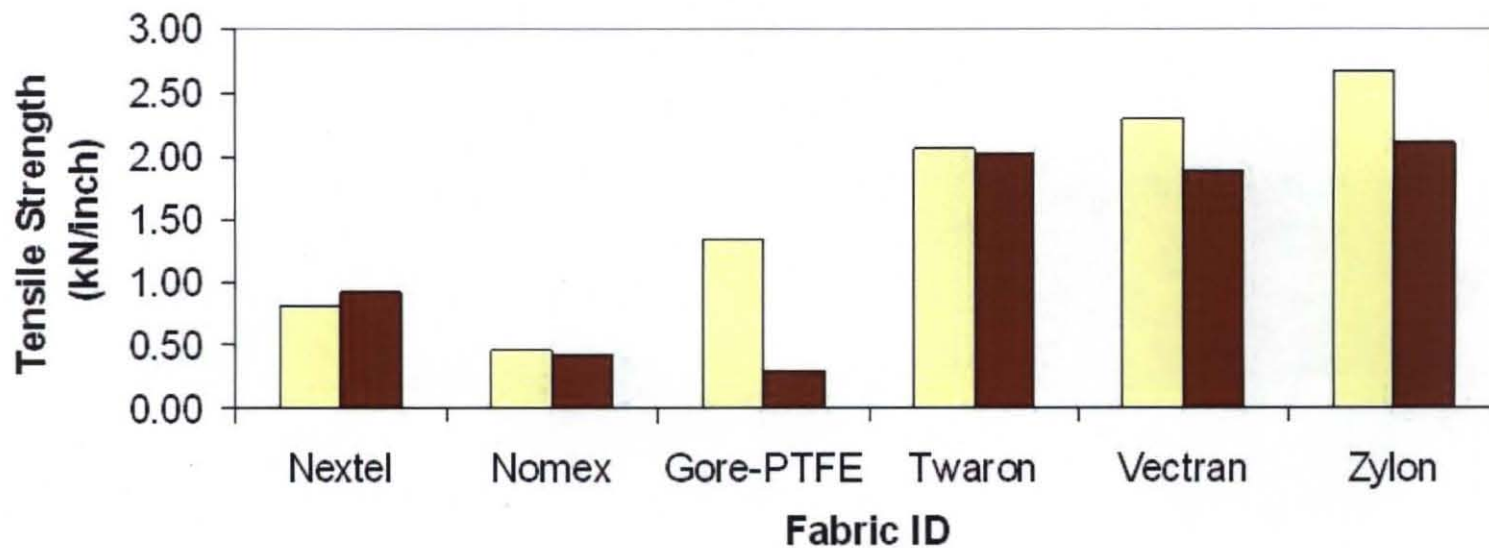


- We determined through radiation transport calculations an appropriate Lunar radiation simulation approach for a **10 year total charged particle ionizing dose** in three materials
- Using the MSFC Combined Environmental Effects Facility we irradiated a total of *10 material samples* to an expected 10-year lunar charged particle radiation dose and delivered these samples for tensile or impact testing
- We irradiated a total of *16 samples* with vacuum ultraviolet radiation to *at least 3115* equivalent hours of solar VUV exposure and delivered these samples for tensile testing



VUV Radiation Results

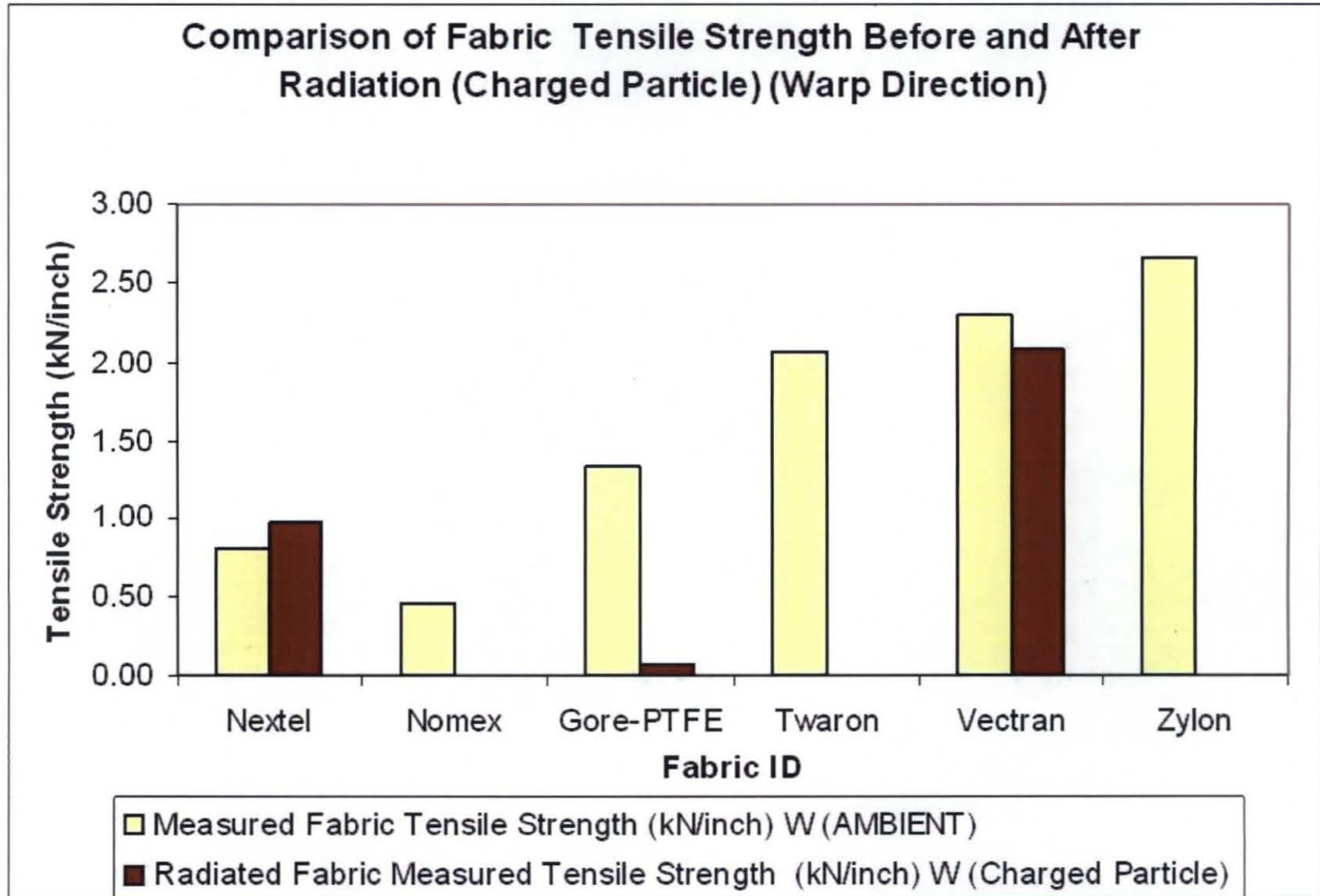
Comparison of Fabric Tensile Strength (kN/in) Before and After Radiation (Vacuum UV) (Warp Direction)



Legend:
■ Measured Fabric Tensile Strength (kN/inch) W (AMBIENT)
■ Radiated Fabric Measured Tensile Strength (kN/inch) W (Vacuum UV)



Particle Radiation Results

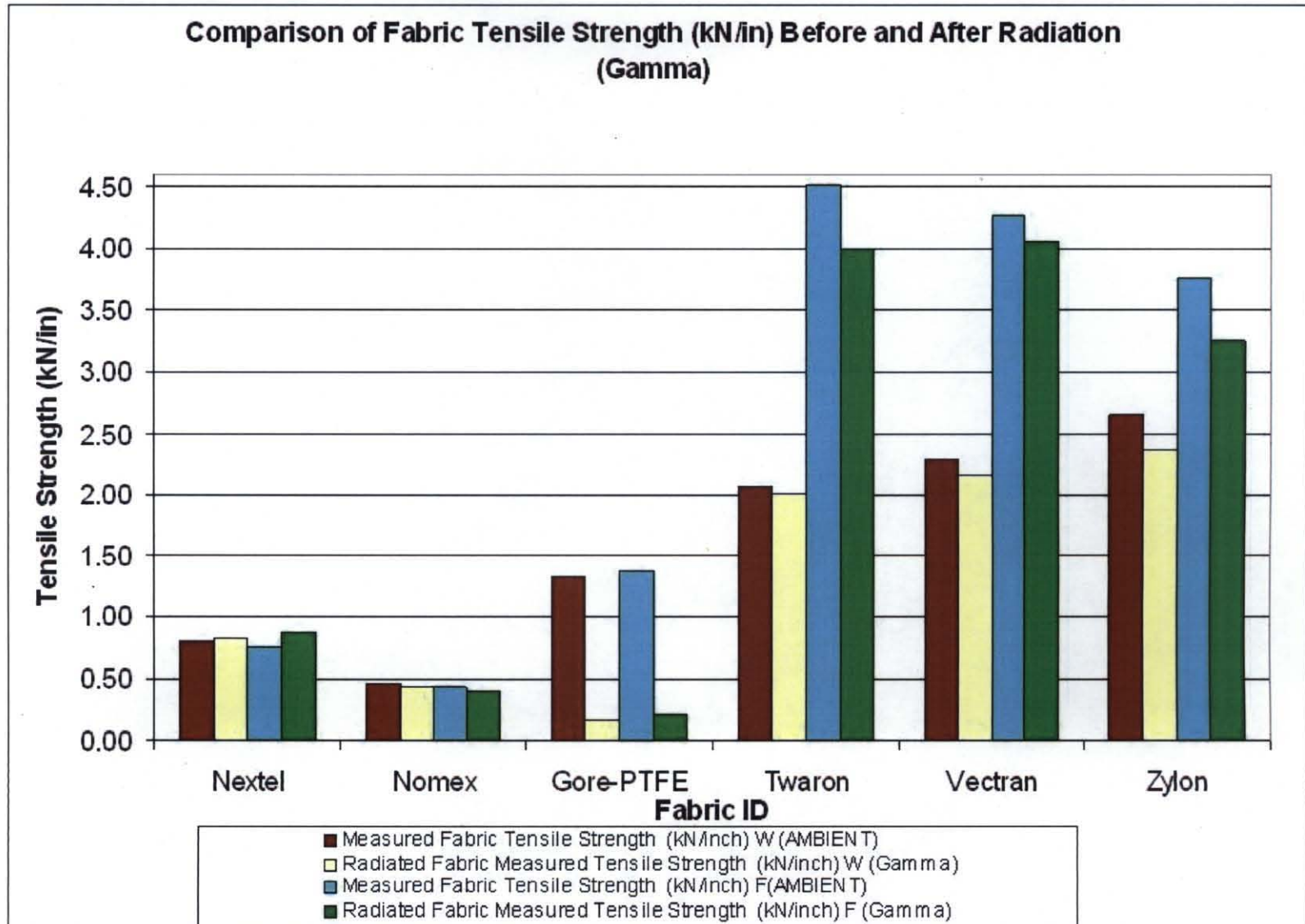




Gamma Radiation Results



Exposure to 10 megarads over one day. Co⁶⁰ radiation source

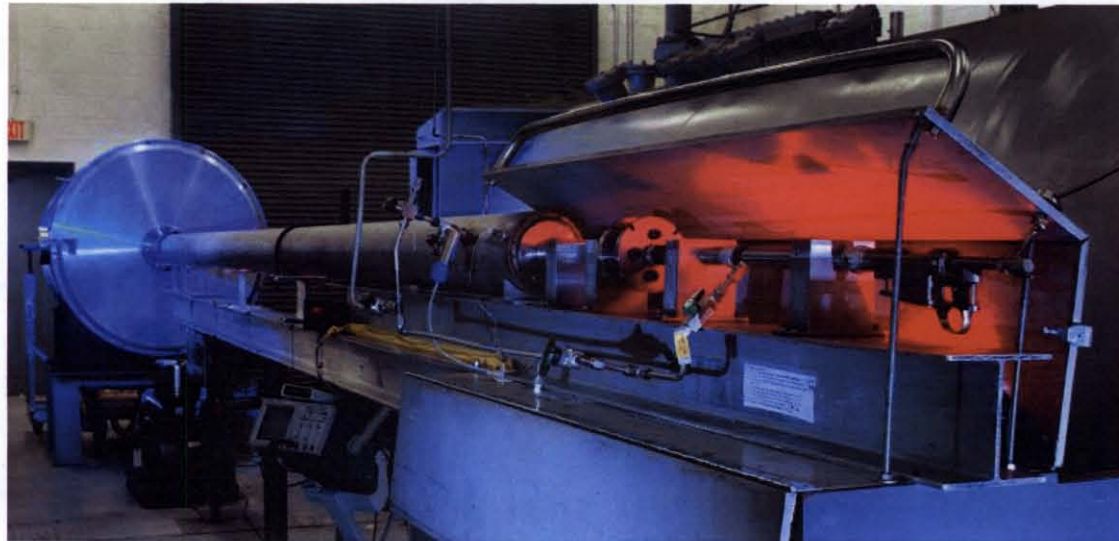




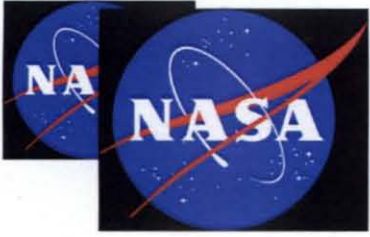
Hypervelocity Impact Testing of Proposed Regolith Bag Materials



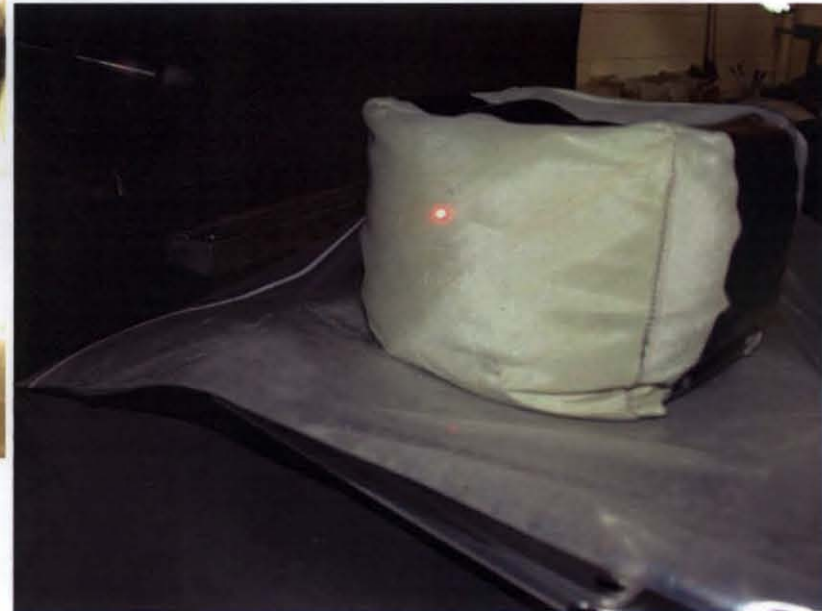
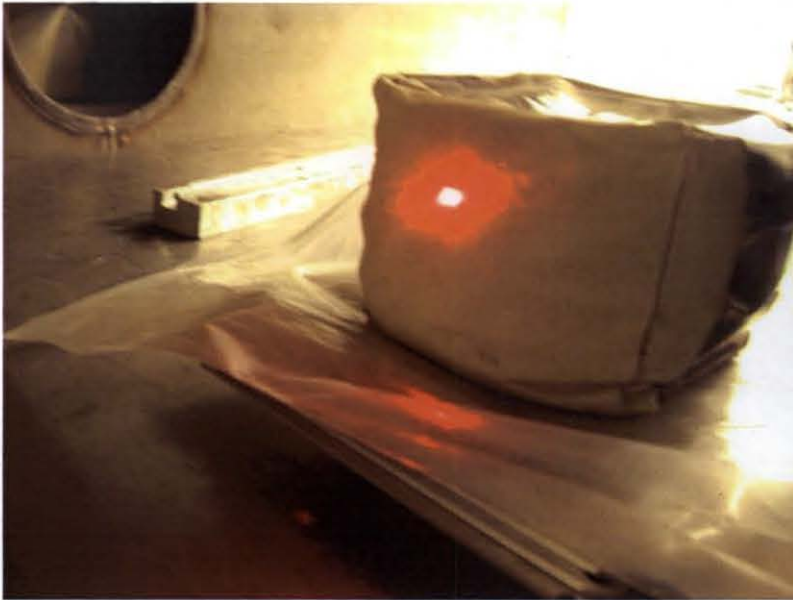
Testing Facility



Hypervelocity impact testing was completed on the proposed regolith bag materials at the MSFC EM50 Impact Testing Facility (ITF) using the Micro Light Gas Gun (MLGG). Projectiles used for this testing were 1mm aluminum spheres with average velocities of 7km/s. Each bag was placed in the chamber and aligned with a laser before each test.



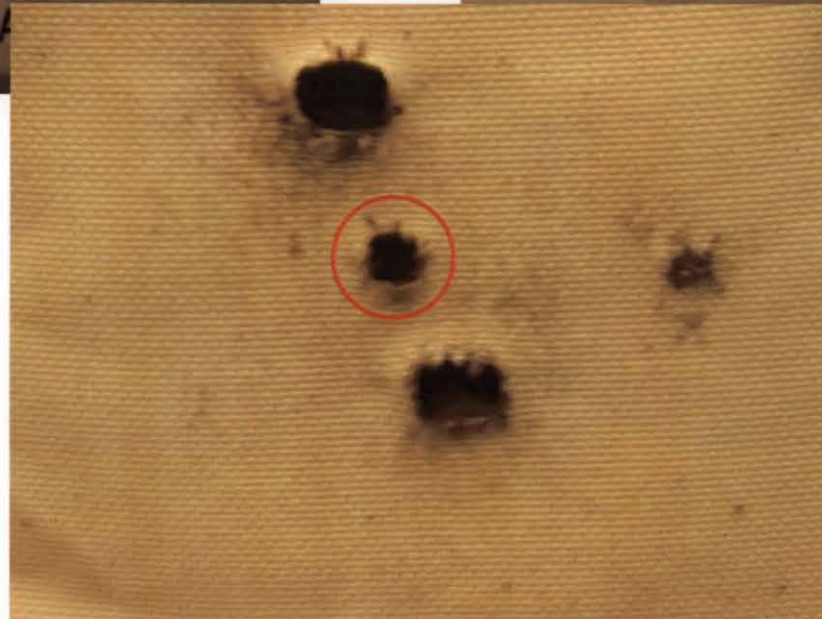
Basic bag set up in chamber and laser aligning



Each bag is approximately 6"x6"x4"
filled in bldg 4493 with Portland
cement to represent lunar regolith.
Approximate weight of bag is 6.5lbs.



Exposed Vectran (Vectran-R)
Penetration dia + damage dia = 4mm





Material	Velocity (km/s)	penetration dia+ damage dia (mm)	Notes
VECTRAN	6.1	6	slight fraying on edges of penetration
VECTRAN-R	7.16	4	almost no fraying of edge of pen...very clean
ZYLON	7.16	9	Slack in material taken up with clips before testing. Some fraying...material looks pulled and stretched post test.
TWARON	6.8	5	small penetration dia...lots of fraying right at edge of penetration
NEXTEL	6.8	8	Regolith material coming out of bag at corners...corners are pulling apart. Material appears very frayed and pulled, even torn, at pen site.
NOMEX	6.8	6	Slack in material had to be taken up with clips before testing. Material very pulled and torn at pen site.
Gore PTFE	6.8	5	regolith material everywhere even before testing...pen very clean but with a lot of dust leaking from bag

Note: Bag penetration diameters were measured using a hand held scale. No precision measurements were taken due to the filled bag shape. Precision measurements could be taken if the bags were emptied carefully as to not disturb the penetration site.



Design Specification

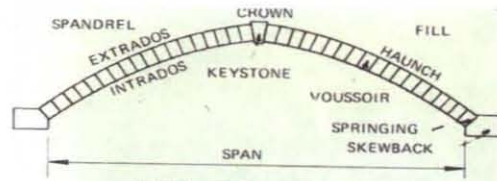


Fig. 1.2 The parts of a masonry bridge.



Fig. 1.3 Voussoirs and parapet at Pontypridd (photographed by Ted Riddock, reproduced by permission of Cambridge University Press).

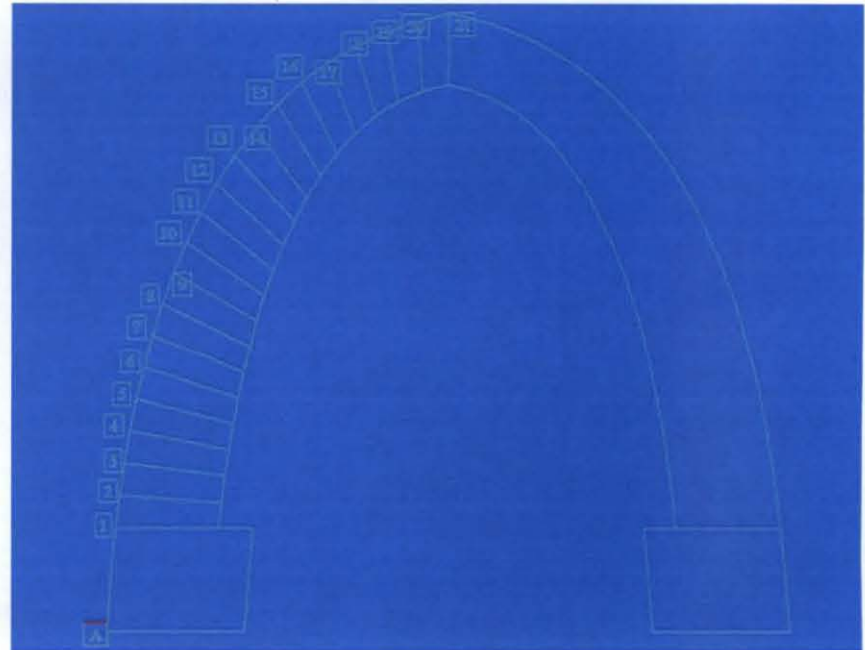


The design of this prototype was based on the principles of the classic masonry arch.



Final Design – Construction Template

- The fabric consisted of a top Kevlar layer, to which fabric “teeth” were stitched. “Top Connected Bag Configuration”
- Construction Template – x-y coordinate of numbered points
- Template based on structural analysis techniques for masonry arches (“Funicular Polygon”).
- A catenary shape
- Pipes attached to frame were used as guides at points 10, 14 and 21.





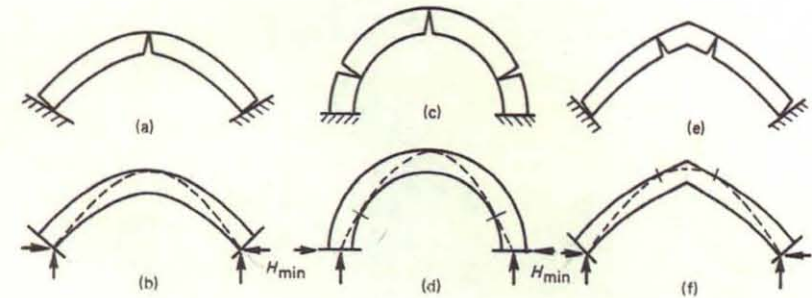
Concepts That Led to the Design



- Vermiculite was chosen to simulate regolith; Its weight on earth/unit volume (density .16-.2 g/cc) is the near that of weight of lunar regolith/unit volume (density .27 g/cc) of any bulk material.
- Strength of vermiculite-filled bags depends on vermiculite pressure. At high pressure, the grain interlock, increasing resistance to shearing failure of the vermiculite. Pressure could be generated by
 - 1) Weight and loads from the structure above. Used for bottom bags.
 - 2) Packing the bags tightly so they strain the bag, and try to round. Used for top bags.
- The “beam” (next slide) demonstrated the advantages of the “top-connected” configuration for erecting of the structure, by being able to support bending loads.
- The assumptions used to design a masonry arch were assumed valid for the design the regolith bag arch. These include: 1) No sliding between bags, 2) Only compressive forces are transmitted across brick boundaries (bricks cannot transmit tensile loads), 3) The bricks have infinite compressive strength.
- Masonry Arches fail by “hinging”. This was also observed in the regolith bag arch.
- The foundation provides the horizontal force at the base. Taller arches are more stable. Build the arch on a frame, then remove the frame.



Useful Concepts That Led to the Design





The Final Garage Structure – A Top-Connected Regolith Bag Arch



- Notice top fabric layer and bags (“teeth”).
- Fabric made from coated Kevlar
- Zippers (other side) for filling
- Wooden frame with pipe supports at locations dictated by the construction template
- Used 46 of 60 bags

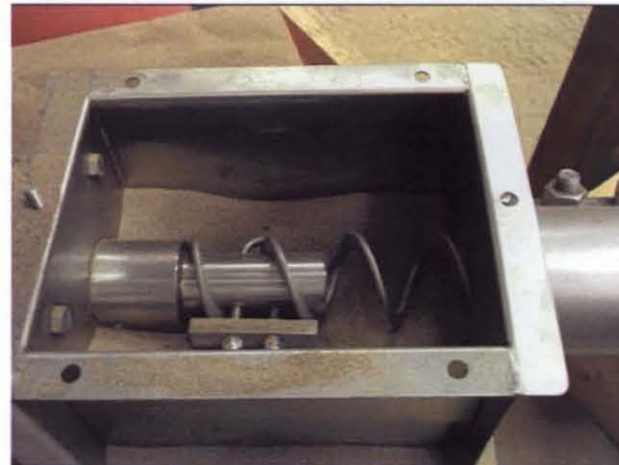




How Bags Were Filled



- Series 300 Haupman helical flexible screw conveyor system, with green hopper.
- 3" diameter, 12' helical screw inside pipe had no central shaft, making screw axially flexible, limiting the feed force. This significantly impacted the ability to fill bags with substantial pressure.
- The pipe was inserted to the end of the bag and slowly withdrawn as vermicullite filled the bag.





The Final Garage Structure



- Final Features
 - “Top-Connected” Kevlar Bags hanging from a fabric layer, filled w/vermiculite
 - 3 bag sizes, 46 bags
 - 2’/1.5’/1’x6”x8’
 - Inside: ~8’ ht x 6’ wide





Comments on Final Garage Structure



- Notice Pipe no longer supported.
- Sagging on right hand side in this view, but still a stable structure.
- Sagging here is a result of visible slipping. Bags were just not packed tight enough.





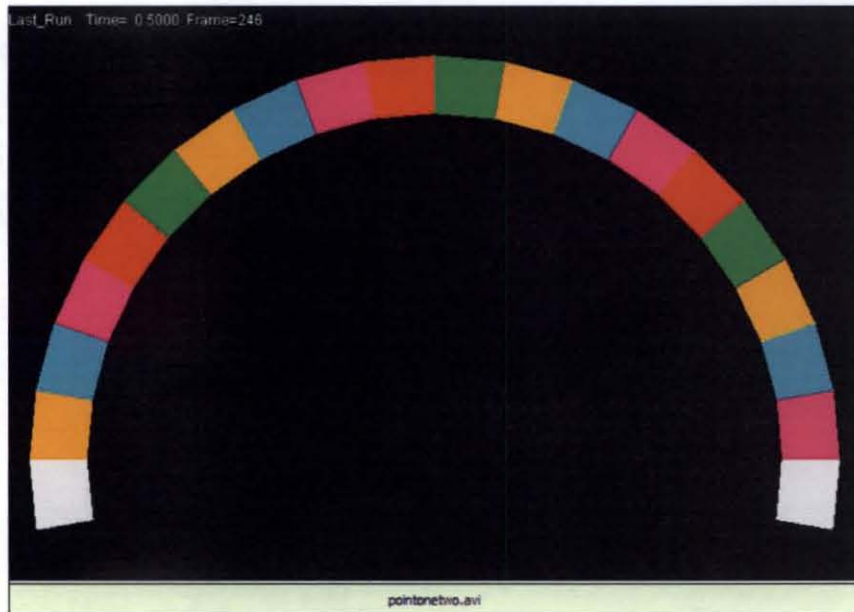
Conclusion



- The structure exhibits both good and bad packing, and the structural response of each.
- The structure stands, but is not as stable as it could have been if top 3 bags could have been filled tighter. This could have been corrected with a helical screw attached to a central shaft.
- Well packed bags are hard-to-the-touch, and can transmit compressive and shearing loads across the bag boundary and through the vermiculite.
- The top-connected bag structure was found advantageous in the erecting phase.
- Computational analysis, e.g. FEA, needs to be performed to aid the engineering of future designs.



Computer Simulation





MCP Award Winners

Environmental Design Requirements

September 9, 2005

Requirements and Assumptions



Assume the mission will be in South Pole region of the Moon:

Exterior temperature range: -60° to -220°C

Exterior atmosphere: 10-12 torr vacuum

Assume radiation: See attached paper entitled "Lunar Radiation Environments for characterization of ISFR/Habitat Structures Materials," by J. I. Minow and R.L. Altstatt for further definition of radiation environment

1. Ultraviolet
2. Ionizing radiation

Lifetime of habitat: 30 years

Lunar Meteoroid Environment:

Diameter (cm) ^{***}	Mass (g) [*]	Flux (#/m ² *hr) ^{**}	
0.01		5.24E-07	0.000150685
0.03		1.41E-05	5.70776E-06
0.05		6.55E-05	9.80251E-07
0.07		1.80E-04	2.90297E-07
0.1		5.24E-04	7.70548E-08
0.3		0.014	1.11621E-09
0.5		0.065	1.48973E-10
0.7		0.18	3.92237E-11
1		0.524	9.47831E-12
3		14.137	1.17009E-13
5		65.45	1.50799E-14
7		179.594	3.90639E-15

*Masses are computed assuming a meteoroid density of 1 g/cm³

**Average velocity = 20 km/sec

***It should also be noted that even though the fluxes of the larger particles are quite small, many of them strike the lunar surface over the course of a year. For example, there are over 1200 lunar impacts by 7 cm diameter meteoroids each year.



Conclusions and Recommendations



(1) Having completed this initial materials testing program, we recommend that Vectran™ (which tested best overall) be carried into the next stage of study. Kevlar™ or Twaron™ could also be considered for additional study, but Gore PTFE™, Zylon™, and Nomex™ should be dropped as base material candidates. If Gore PTFE™ is considered as an auxiliary material, a higher strength type of Gore PTFE™ should be tested. Nextel™ should be dropped as a candidate, with the possible exception of its consideration for limited use in any rigid area where it is sandwiched in between other materials (or, if some type of coating could be developed for Nextel™ to make it more flex and abrasion resistant and thereby exploit its radiation resistance).

(2) The simulated 10-year total ionizing dose we used for radiation exposure worked well, since it showed sensitivity differences in fabric candidates. In future radiation exposure testing, we should test Vectran™ at 30-year total ionizing dose, if possible.



Conclusions and Recommendations



(3) Vectran™ and Twaron™ tested best in the standard abrasion test. These two materials should be tested to failure in the standard abrasion test. They also tested well in the JSC regolith simulant tumble abrasion test, but the duration was not long enough to draw final conclusions, so another tumble test of longer duration is recommended. Also, there is a question about the ability of the simulant (JSC-1) to behave as harshly as the actual material.

(4) Although Zylon™ showed superior tensile strength in general, it is not recommended for further consideration due to its inferior abrasion testing performance.

(5) Vectran™ appears to have high folding endurance; however, a higher number of cycles is recommended for the cryogenic folding test.



Conclusions and Recommendations



(6) More extensive hypervelocity impact testing is recommended for Vectran™ , the highest overall performer.

(7) At this point, we have a "demonstration article," the one-piece lunar regolith-bag garage prototype, standing, on its own, in Building 4493 at MSFC. Work to date indicates that the theory that a regolith-bag arch can behave in much the same manner as the classic masonry arch is valid; however, we have taken only the first step in proving this theory, and other steps are required.



Conclusions and Recommendations



(8) Our task team should discuss what a "next phase" would look like, as there are many possible approaches, such as the choice to proceed one small increment at a time, or to look at several "angles" at once.

(9) We should consider a study (materials testing program) which looks at using multiple layers of fabric for the regolith-bag pockets. For example, we might look at a two-layered structure, using VectranTM and TwaronTM or KevlarTM. Or, we might look at a three-layered structure, using NextelTM sandwiched in between two layers of VectranTM.

(10) We should consider a materials testing program looking at VectranTM as a single layer but with various coatings.



Conclusions and Recommendations



(11) We should consider a materials testing program looking at the materials used in the sample prototype section which was produced by Techsphere, Inc. This material was Vectran™ on top of which had been laminated a thin layer of aluminum foil. This is the material we wanted to use to make the prototype; however, the cost and the lead time were prohibitive.

(12) We should consider what type of customized blended fiber could be used to make a fabric tailored for this application.

(13) We should consider the simulated lunar environment to be used for testing materials and structures - ways to improve on procedures used in this work. . We should aim for increasingly higher fidelity lunar environment simulation.



Conclusions and Recommendations



- (14) Before follow-on investigations, discuss considerations for robotic construction of a regolith-bag structure on the Moon
- (15) Additional materials testing should be performed before a larger prototype is constructed.
- (16) At some point in materials testing, we need to use either actual lunar regolith samples or a simulant which provides the harshness/abrasiveness equivalent to the actual material.
- (17) We should consider regolith-bag "blankets" which, in layers, could be used as temporary radiation shields.
- (18) We need to have a focus session on automated filling. What equipment must be carried from Earth to Moon?



Conclusions and Recommendations



(19) Future prototypes on Earth need to use a filling material that simulates both the texture and sharpness of regolith as well as its weight under lunar gravity. One suggestion would be a simulant made from something like JSC-1, plus crushed, jagged glass, plus some material to reach an overall lower weight - we need to have a big discussion just on this – and opinions may vary sharply.

(20) We should consider a concept using connected regolith-bags as a component in a radiation protection system which rises above and covers a habitat system.