

FABRICATION AND TESTING OF HABITAT COMPONENTS USING IN-SITU MATERIALS FOR MARTIAN EXPLORATION

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ABSTRACT

The development of Mars for human activity will require the utilization of Martian materials in building habitats and working structures. One approach is to use polymer binders with regolith to form structural elements. Not only can useful composite materials be produced in this way but the radiation protection properties are also increased. This is important since only modest protection from space radiation is provided by the Martian atmosphere. We have studied composites fabricated using Martian regolith simulant and polymers which can be synthesized from local Martian materials for their potential use as radiation shields for manned Mars missions. To validate shielding effectiveness, composites are irradiated with a 55 MeV proton beam and neutron beams up to 800 MeV. Shielding effects on microelectronic devices are measured by placing them behind samples of the composites during irradiation. To measure structural properties of the composites, preliminary characterization and mechanical testing are made for the composites.

KEY WORDS: Human exploration, Mars, Martian, Radiation, Polyimides, Regolith, Applications-Space

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1. Introduction

The Mars environment is potentially life threatening during manned Mars surface exploration missions, because Mars' thin CO₂ atmosphere cannot provide adequate protection. A surface habitat is critical for providing a safe haven for human explorers of Mars from galactic cosmic rays (GCR), solar particle events (SPE), and global dust storms (1). In order to maximize the safety of the explorers and minimize the payload weight from Earth to Mars, the use of Martian surface materials has been studied for the issues associated with the protection against hazards from exposure to ionizing space radiation (2). From the radiation attenuation characteristics of GCR assessed theoretically by using HZETRN (3), one approach of the utilization of Martian regolith is to use polymer binders to form structural elements (2, 4). Hydrogen-containing materials, such as polymers, are considerably more effective for radiation protection, but polymers or their precursors are not available on the Martian surface. One conceptual idea was proposed to synthesize polyimides from Martian atmosphere (2, 4). Efficient and effective schemes need to be developed to process them from Martian atmosphere on the Martian surface in the future. Transporting polymer binders to the Martian surface would increase the utilization of one of in-situ materials, Martian regolith, since it is not an ideal structural and shielding material.

Model structural shielding composites of Martian regolith with a polyimide, which has hydrogen atoms, are fabricated on Earth for processing development and laboratory testing. In this paper, the attenuation characteristics of laboratory beams behind fabricated targets are studied theoretically and experimentally with a 55 MeV proton beam and neutron beams up to 800 MeV. Radiation protection efficiencies of microelectronics, preliminary characterization of the composites, and their mechanical testing for the measurement of structural properties are also discussed.

The objectives of this work are to predict and measure shielding properties of the Martian regolith composites for their shielding effectiveness, and to measure structural properties of the composites. The actual processing details will be explored in greater depth and optimized for space applications in order to develop the most cost-effective and technologically feasible means of reducing the level of exposure, which is a key element of NASA's strategic plan for the human exploration.

2. Fabrication of Targets and Various Testing

2.1 Processing of Microcomposite Samples Two composite targets with randomly dispersed simulated regolith in a polyimide, LaRC Soluble Imide (LaRC-SI, Imitec, Inc.), are fabricated by compression molding as described in a previous paper (4) for beam exposures to compare the shielding effectiveness and for various laboratory testing to measure structural properties. According to the curing procedure of miniature blocks (2), they are fabricated at 320°C and 2.66 MPa for the targets of 15 cm × 15 cm cross section with 1.89 g/cm² thick (specimen 101) and 2.01 g/cm² thick (specimen 102). In this short

and easy hot pressing microcomposite processing, the pressure is a variable for producing different properties of the cured composites with different thickness. Specimen 101 (1.89 g/cm² thick) is a composite of regolith with 40 wt% LaRC-SI. For specimen 102 (2.01 g/cm² thick), the amount of LaRC-SI is decreased to 20 wt% though the final composite specimen is still well-consolidated with no voids. These targets are irradiated with nearly monoenergetic 55 MeV proton beams produced at the Texas A&M University Cyclotron facility and neutron beams up to 800 MeV produced at LANSCE (Los Alamos Neutron Science Center) to test the shielding property.

2.2 Range and Energy Straggling Before the fabrication of the targets for beam tests, the theoretical study has been used to select the appropriate target thickness at which the transmitted radiation can be compared. The range-energy relations have been used to determine the thickness required for absorption of 55 MeV primary proton beams for regolith/LaRC-SI composites. The mean ranges in targets for the ions are given by the integration of energy-loss per unit path (stopping power), $S(E)$,

$$R(E) = \int_0^E \frac{dE'}{S(E')} \quad (1)$$

The mean ranges of monoenergetic 55 MeV proton beams, R_0 , are 3.099 g/cm² and 3.197 g/cm² for specimen 101 and 102, respectively. This shows that the composite with more LaRC-SI, which is composed of lighter elements, requires a shorter distance to stop energetic primary proton particles in the material.

The target thickness of 2 g/cm², which is a distance before the end of the particle trajectory in the target, is selected to see the basic energy loss mechanism of nearly monoenergetic 55 MeV proton beams. The fabricated thicknesses of 1.89 g/cm² and 2.01 g/cm², which are nearly 2 g/cm², are 61 percent and 63 percent of their ranges for specimen 101 and 102, respectively. Unlike the space radiation transport problem, the role of energy straggling is required in the laboratory testing of potential shielding targets with nearly monoenergetic ion beams (5) and it is considered in the present study. The average energy after penetration of each thickness of monoenergetic 55 MeV proton beam and its standard deviation are calculated as $\langle E \rangle = 32.53305 \text{ MeV} \pm 0.52396 \text{ MeV}$ for specimen 101 and $\langle E \rangle = 31.60932 \text{ MeV} \pm 0.546536 \text{ MeV}$ for specimen 102. The corresponding slowing down energy spectrum of a 55 MeV proton beam is taken as (5)

$$\phi(z, E) = \frac{\exp\left\{-\frac{[E - \langle E(z) \rangle]^2}{2s(z)^2}\right\}}{\sqrt{2\pi} s(z)} \quad (2)$$

where z is the penetration distance in a target and $s(z)$ is the standard deviation after passing through a target. These spectra are shown in [figure 1](#). This figure shows that the energy loss spectrum by specimen 101 is less than that by specimen 102, because the thickness of specimen 101 is less than that of specimen 102. This information would be essential to understand the detector response. Because specimens are not exactly the same thickness, direct comparison of the transmitted spectra is not meaningful but the relative shielding effects for transmitted primary beam can be easily shown by comparing the transmitted spectra at the same thickness, for example 2.01 g/cm², for both composites as

shown in [figure 2](#), which shows more energy loss is achieved by specimen 101 than by specimen 102.

2.3 Proton Beam Testing To acquire data that will be used for the validation of their predicted radiation transport properties, regolith simulant/LaRC-SI composites are exposed to proton beams with 1×10^6 protons/cm² from a 2.54 cm \times 2.54 cm beam. Nearly monoenergetic 55 MeV proton beams produced at the Texas A&M University Cyclotron facility are being used to measure the transmitted fluences and the number of errors on a Motorola 4MB MCM6246-5V SRAM (Static Random Access Memory) behind the target materials.

In the experimental setup, a silicon detector excludes particles with energy less than 12 MeV during the counting of the protons which pass through the shield. The primary beams are nearly monoenergetic beams of a mixture of molecular hydrogen ions and protons with a standard deviation. More protons are transmitted through specimen 101 than through specimen 102, because less energy is lost for the thinner shield target of specimen 101 as shown in [figure 1](#). Here, shield effectiveness cannot be measured by comparing the transmitted fluences but rather can be measured by comparing the single event upsets which depend on the mechanism of transmitted particle type with sensitive devices.

The single event upsets in a 4 MB MCM6246-5V SRAM are studied for the two specimens with 55MeV proton beams at several fluence levels between 1×10^7 protons/cm² to 4×10^9 protons/cm² as shown in [figure 3](#). As the fluences are increased to 5×10^7 protons/cm², measurable errors are observed. The results show clearly that specimen 101 with more LaRC-SI is much better than specimen 102 for shielding as the fluence of the beam reaches 4×10^9 protons/cm². It is reasoned that each linear energy transfer (LET) component of a given particle behind specimen 101, which represents radiation quality, is attenuated faster than that behind specimen 102. Therefore, specimen 101 more effectively shields the SRAM from 55 MeV protons. At the same thickness, less transmitted proton fluence is expected for specimen 101 than for specimen 102, because more energy loss is predicted as shown in [figure 2](#). The thick composites with 40 wt% LaRC-SI are also expected to be more effective than those with 20 wt% LaRC-SI to shield other heavier particles due to the efficient attenuation of the mixture of particle types. This will be investigated further in heavy ion beam experiments.

2.4 Neutron Beam Testing After proton beam testing, the specimens for the neutron testing are prepared from the 15 cm \times 15 cm original targets by cutting to a size of 0.635 cm \times 1.27 cm \times 2.54 cm that is determined by ASTM Standard D695 (6). This is done to prevent damage to the specimens if they are cut for compression testing after exposure to the high-energy neutrons. Five small specimens cut from an original portion of not exposed to proton beams, are put together to construct the neutron-testing specimen of 2.54 cm \times 3.18 cm cross section with 1.89 g/cm² (specimen 101) and 2.01 g/cm² (specimen 102). They are irradiated with neutrons at the Los Alamos Nuclear Science Center

(LANSCE) neutron facility produced by an 800 MeV proton beam striking a tungsten target with the primary and secondary charged particles being separated with bending magnets. The numbers of errors are measured while neutron beams with 5×10^9 neutrons/cm² that propagate from a 15-cm diameter circular beam are focused on different sets of chips on a circuit board as shown in [table 1](#). Because our specimens are fabricated specifically for a 55 MeV proton beam test, these targets with thickness of ~ 2 g/cm² are not sufficient at all to shield neutron beams especially at a high energy like 800 MeV. Moreover, the regolith specimen cannot cover the entire neutron beam in the present setup of target geometry. At high energies, neutrons would behave rather similarly with protons in which a small increase in shielding thickness of ~ 2 g/cm² increases the fluence, dose, and dose equivalent that is a well-known build-up phenomenon (7). In [table 1](#), the error measurements are within the statistical uncertainties. Even though we cannot conclude any qualitative result for shielding effectiveness between the two composite targets, it is clearly shown that placing thin shield targets increases the numbers of errors due to the build-up phenomenon.

The modification of the LANSCE neutron energy spectrum by the introduction of thin regolith/LaRC-SI composites and polyethylene targets in the beam path is shown in [figure 4](#). The regolith targets cannot be directly compared to the polyethylene target because of the different geometries: the polyethylene target of 15 cm \times 15 cm cross section covers the entire primary neutron beam and has a thickness of 4.95 g/cm². However, some explanation of the data can be shown by a comparison. The first item to notice in [figure 4](#) is that the regolith targets do not modify the primary beam and create a moderate level of secondary neutrons and protons (not shown). Therefore, the regolith targets should create more errors in the SRAM chips than without a shield and actually do as shown in [table 1](#). The original beam intensity behind polyethylene is decreased at its lower energies: however, because of the large amounts of hydrogen, large numbers of secondary particles (both neutrons and protons) are created that can generate more errors in the SRAM chips than without a shield. This is shown in [table 1](#) for the second set of chips but not for the first. The chips response function, unknown at this time, will determine the energies of importance for error generation. If the regolith targets covered the entire beam and were 4.95 g/cm² thick, then it can be assumed that more secondaries would be created and the primary beam would be reduced at the low energy end. Whether this would reduce the number of chip errors is unknown until more experimental data is generated to determine the detector response function.

2.5 Characterization of Regolith/LaRC-SI Microcomposites For the characterization of regolith composites, thermomechanical analysis (TMA) and thermogravimetric analysis (TGA) have been used to measure the glass transition temperature (T_g) and mass loss, respectively. The glass transition temperatures measured by TMA are shown in [figure 5](#) and they indicate that these composites should contain good mechanical properties up to at least 223 °C. The temperatures at 5% mass loss and 10% mass loss measured by TGA in this figure show that mass loss temperatures are increased as the amount of LaRC-SI

decreases due to the smaller erosion rate of the polymer in the composites. These data indicate that the composites are reasonably stable at high temperature.

2.6 Compression Testing For compression testing, the baseline specimens have been prepared after proton beam testing from the portion of the original targets that is not exposed to the proton beam, because the proton beam area of $2.54\text{ cm} \times 2.54\text{ cm}$ is smaller than the target area of $15\text{ cm} \times 15\text{ cm}$. The targets are cut into specimens according to ASTM Standard D695 (6). Compression tests using an Instron Model 8500 Testing System are performed at room temperature with a crosshead speed of 0.127 cm/min . A 4.54 kg pre-load is applied to each specimen. Structural properties of maximum load, Young's modulus, and stress at maximum load are measured and shown in [figure 6](#) for regolith 101 specimens on the left-hand side and for regolith 102 specimens on the right-hand side. From the Young's modulus in [figure 6\(b\)](#), some degradation is noticed in the neutron-exposed specimens. The Young's modulus of neutron-exposed specimens for both regolith 101 and 102 are decreased by 10% from the baseline and those for regolith 102 are distributed wider than those for regolith 101 due to the non-uniformity of each specimen. By contrast, the proton-exposed specimens for both regolith 101 and 102 composites experience even an increase in the Young's modulus possibly due to the crosslinking between polymer molecules. These composites have reasonable range of structural properties in addition to the increased radiation protection property from a 55 MeV proton beam.

3. Discussion and Concluding Remarks

For manned exploration to Mars, the initial studies for utilization of Martian materials have been conducted in ground-based facilities. Regolith simulant/polyimide composite targets are fabricated based on the theoretical calculation of target thickness and are tested using proton and neutron beams in order to validate the shielding effectiveness. From a 55 MeV proton beam test with sensitive devices, regolith specimen 101 with 40 wt% LaRC-SI is a more effective shield material than regolith 102 with 20 wt% LaRC-SI. The thick composites with 40 wt% LaRC-SI are also expected to be more effective to shield other heavier particles which are components of space radiation, such as GCR. From a neutron beam test, any qualitative result for the shielding effectiveness cannot be made at this time because the error measurements in the SRAM chips are within the statistical uncertainties due to the small size of cross section and small thickness of the targets. The attenuation of the mixture of heavy particle types through thick composites needs to be investigated further in heavy ion and neutron beam experiments. By this approach, it will be possible to verify the transport codes used to predict the transport of space radiations through these materials in order to protect humans.

In addition to measuring the transport properties of the composite materials, their physical and mechanical properties are also characterized; this is important information because it is desirable to utilize these materials not only for radiation shielding but also as structural components. The preliminary characterization shows that the composites are reasonably

stable at reasonable temperature. These composites hold reasonable range of structural properties in addition to the increased radiation protection property from a 55 MeV proton beam. Since properties of transmitted radiation and structural quantities of specimens are also variation in selected target area, uniform distribution of fillers in thick composites must be considered for the processing. The actual processing details to make thick composites with various energy sources will be explored in greater depth for producing different properties of the cured composites, and they will be optimized for space applications which will be employed by astronauts on Martian surface when the necessary processing equipment and adequate source power are available from propellant manufacture.

4. References

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5. Biographies

Myung-Hee Y. Kim received B.S. degrees in Chemical Engineering and in Computer Science, a M.S. in Applied Mathematics. She received a Ph.D. in Applied Science from the College of William and Mary. She was a NRC post-doctoral fellow at NASA Langley Research Center. Presently, she is a Research Scientist at the College of William and Mary and conducts the research in the shield analysis for future spacecraft, aircraft, and space construction designs against space radiations.

Sheila Ann Thibeault received a B.S. degree in Physics from the College of William and Mary and M.S. and Ph.D. degrees in Physics from North Carolina State University. She is a Senior Materials Research Engineer in the Structures and Materials Competency at the NASA Langley Research Center. At NASA she has received 13 Outstanding Performance/Superior Accomplishment/Special Achievement Awards. Her research expertise includes the development of environmentally-durable materials and the development of radiation shielding materials. She is the author or coauthor of over 115 formal publications/referenceable presentations.

Richard L. Kiefer is Professor and Chair of the Chemistry Department at the College of William and Mary. His original training was in Nuclear Chemistry but for the past 15 years, he has been interested in radiation interactions with polymers. Currently, he is developing and testing materials for radiation shielding and materials resistant to atomic oxygen.

John W. Wilson received his Ph.D. in HZE reaction theory from the College of William and Mary in 1975. He is a Senior Research Scientist at NASA Langley. He has served as science advisor to the Long Duration Exposure Facility (LDEF) and the Space Environmental Laboratory (SEL). He is a member of the Radiation Discipline Working Group, an advisory committee to the NASA Radiation Health Program. He was a faculty member of the NATO Advanced Study Institute on Biological Effects and Physics of Solar and Galactic Cosmic Radiation in 1991. He has received 13 Outstanding Scientific Achievement/Exceptional Scientific Achievement/Distinguished Service Awards. His research interests include radiation physics, radiation health, and radiation effects on electronic devices. He has published over 300 refereed reports and articles with numerous other papers and presentations.

Robert C. Singleterry Jr. received his Ph.D. in particle transport mathematics from the Nuclear Engineering Department at the University of Arizona in 1993. He is a Research Scientist at the NASA Langley Research Center and is working on space based, ionizing radiation interactions with materials. His current research interests are in fully 3-D transport methods utilizing unstructured mesh for charged and neutral particles, the connection of these methods to CAD drawings of aerospace vehicles, and the various input/output interfaces to connect the CAD drawings to the radiation environment.

Table 1. SEU Measurement behind Regolith Composites Irradiated with Neutron Beams

Shield Material	Beam focused On Chips 1, 2, 4	Beam focused On Chips 20, 40, 80
No Shield	474	401
Specimen 101	580	483
Specimen 102	633	428
Polyethylene	454	446

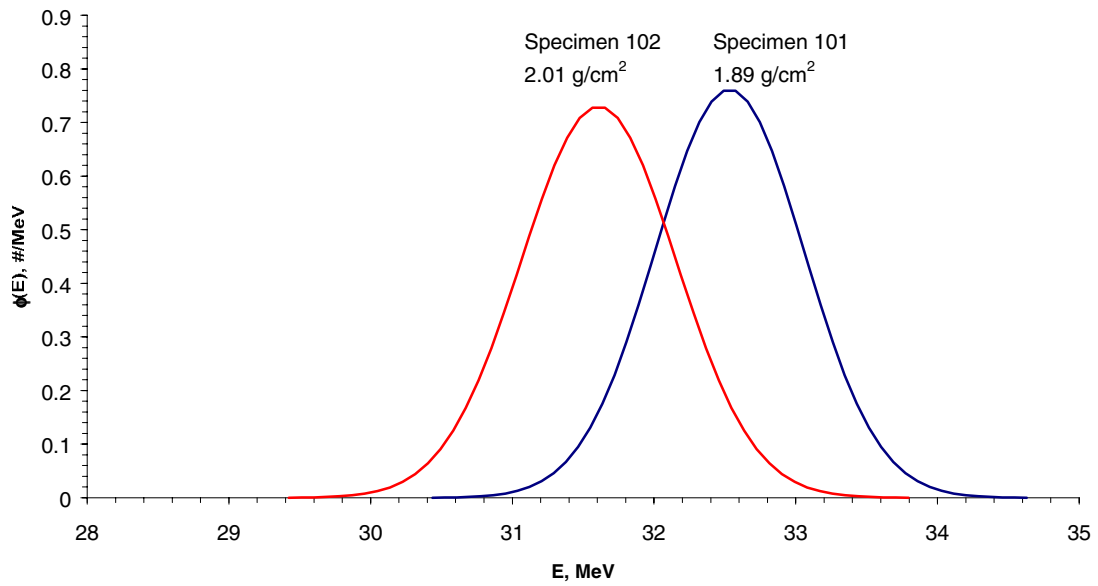


Figure 1. Transmitted differential proton energy spectrum of a 55 MeV proton beam by regolith/LaRC-SI microcomposite specimens.

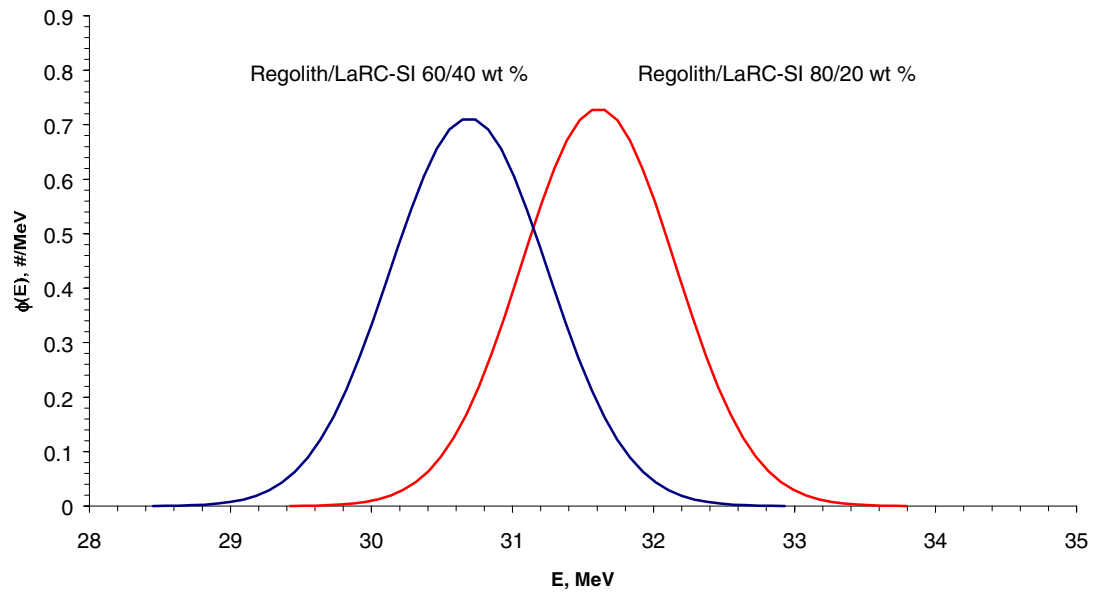


Figure 2. Transmitted differential proton energy spectrum of a 55 MeV proton beam by regolith/LaRC-SI microcomposite targets of 2.01 g/cm².

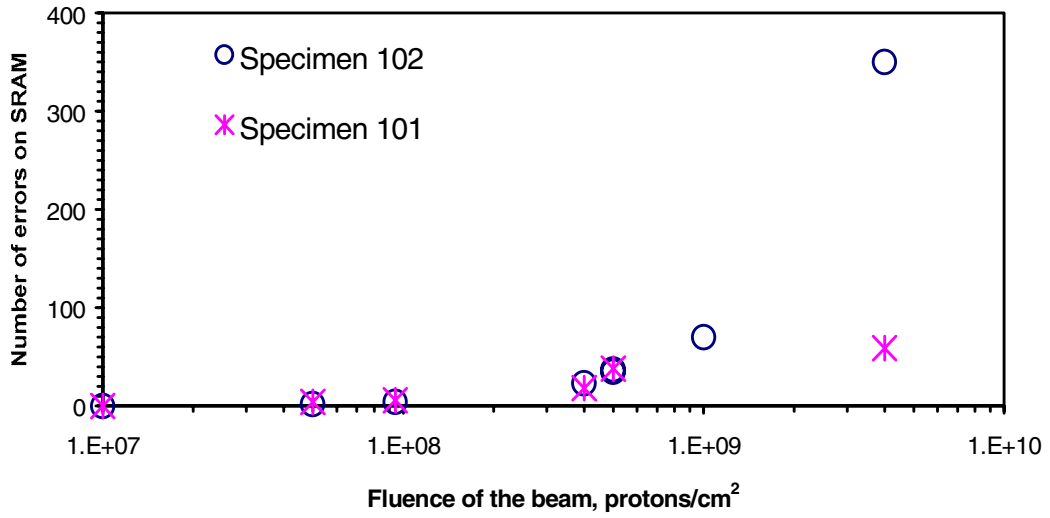


Figure 3. Single event upsets on Motorola MCM6246-5V SRAM from 55-MeV proton beams behind regolith/LaRC-SI microcomposite shields.

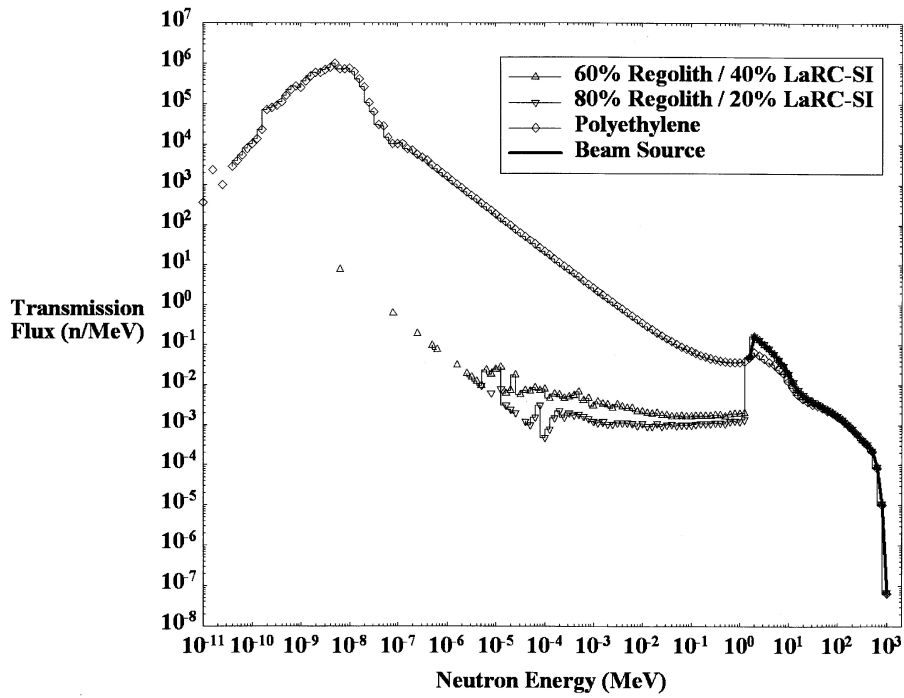


Figure 4. Transmitted differential neutron energy spectrum of LANSCE neutron beams by regolith/LaRC-SI microcomposite and polyethylene targets.

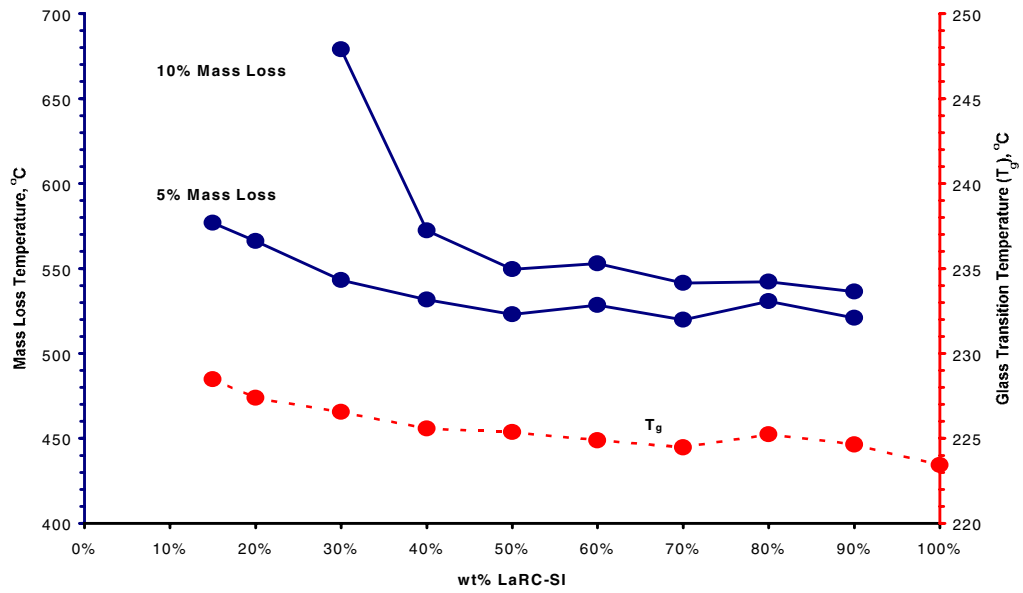


Figure 5. TGA mass loss and TMA glass transition temperature for regolith/LaRC-SI microcomposite shields.

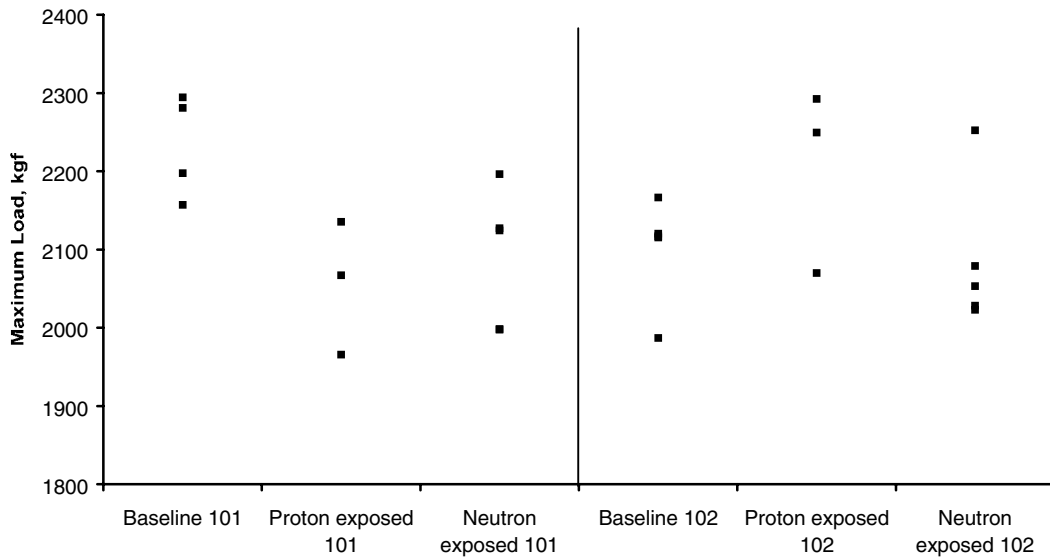


Figure 6(a). Maximum load for regolith 101 specimens on left-hand side and for regolith 102 specimens on right-hand side.

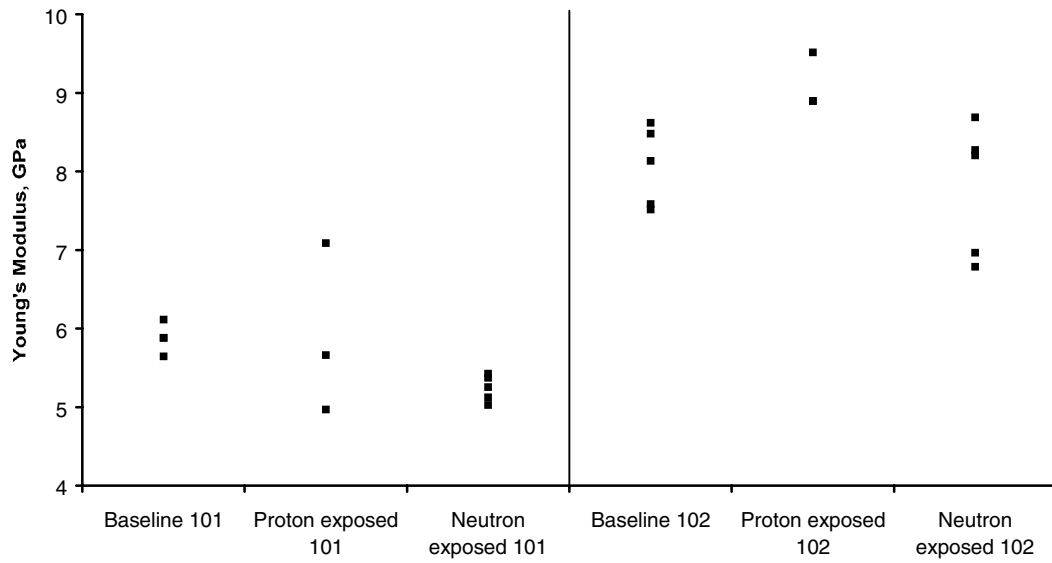


Figure 6(b). Young's modulus for regolith 101 specimens on left-hand side and for regolith 102 specimens on right-hand side.

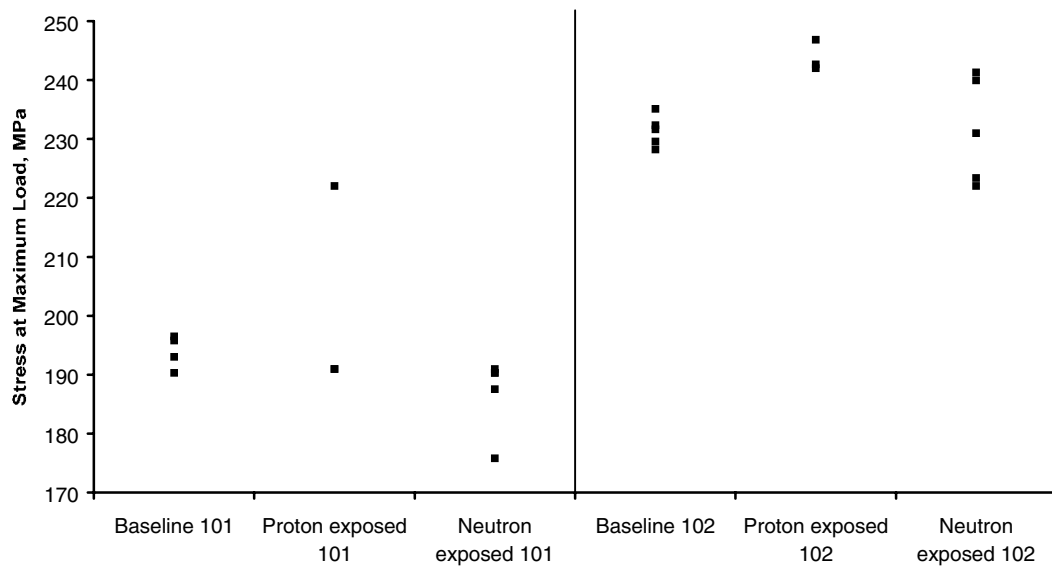


Figure 6(c). Stress at maximum load for regolith 101 specimens on left-hand side and for regolith 102 specimens on right-hand side.