CONSIDERATIONS CONCERNING THE DEVELOPMENT AND TESTING OF IN-SITU MATERIALS FOR MARTIAN EXPLORATION

M.-H. Y. Kim,[1,2,*] L. Heilbronn,[3] S. A. Thibeault,[1] L. C. Simonsen,[1]
J. W. Wilson,[1] K. Chang,[4] R. L. Kiefer[5], and H. G. Maahs[1]
[1] NASA Langley Research Center, Hampton, VA 23681
[2] National Research Council, Washington, DC 20418
[3] Lawrence Berkeley Laboratory, Berkeley, CA 94720
[4] Christopher Newport University, Newport News, VA 23606
[5] College of William and Mary, Williamsburg, VA 23187

ABSTRACT

Natural Martian surface materials are evaluated for their potential use as radiation shields for manned Mars missions. The modified radiation fluences behind various kinds of Martian rocks and regolith are determined by solving the Boltzmann equation using NASA Langley's HZETRN code along with the 1977 Solar Minimum galactic cosmic ray environmental model. To make structural shielding composite materials from constituents of the Mars atmosphere and from Martian regolith for Martian surface habitats, schemes for synthesizing polyimide from the Mars atmosphere and for processing Martian regolith/polyimide composites are proposed. Theoretical predictions of the shielding properties of these composites are computed to assess their shielding effectiveness. Adding high-performance polymer binders to Martian regolith to enhance structural properties enhances the shielding properties of these composites because of the added hydrogenous constituents. Laboratory testing of regolith simulant/polyimide composites is planned to validate this prediction.

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

---

[*] Present address: College of William and Mary, Williamsburg, Virginia 23187

1. Introduction

The Mars environment is potentially life threatening during manned Mars exploration missions. Humans on a manned mission to Mars will require more protection from exposure to the low-intensity heavy-ion flux of the galactic cosmic rays (GCR) (1) than that which has been used heretofore on shorter missions. The primary GCR consists mostly of protons and alpha particles with a small but significant component of heavier particles. The GCR flux is modulated over the solar cycle according to changes in the interplanetary plasma, and the 1977 Solar Minimum GCR environmental model (2) represents a maximum in intensity of the GCR flux within several astronomical units (AU) of the sun. The transmitted GCR environment at the 1977 Solar Minimum behind various materials is calculated for the complex radiation environmental components as a function of shield composition and thickness.

For habitats on the Mars surface, regolith is a convenient candidate to consider for bulk shielding to avoid excessive launch weight requirements from Earth. Natural Martian surface materials, such as Martian meteorites (3) and the Martian-regolith model-composition based on Viking lander data (4), are evaluated for their potential use as radiation shields for manned Mars missions. The radiation attenuation characteristics behind each material are assessed for dose equivalent using radiation quality factors (5) and for the response of certain biological systems (6). The relative shield effectiveness of these materials is studied without including the effect of shielding due to the Mars atmosphere. Using Martian regolith has a great advantage over using Martian rock because the energy requirement for utilizing Martian rock is high compared with that for regolith (7). Therefore, the Martian habitat construction option using Martian regolith is preferred.

The second significant source of Martian in-situ material is Mars atmosphere. In this paper we are proposing to synthesize a high-performance structural polymer, polyimide, from constituents of Mars atmosphere in the presence of certain catalysts. This envisioned surface operation has promise of minimizing the amount of material transported to the Martian surface. Because hydrogenous material is known to be a good shielding material, making a structural composite of Martian regolith with polyimide, which has hydrogen atoms, is considered. To fabricate model structural shielding composite materials, we are conducting processing studies of microcomposites of regolith simulant and polyimide on Earth. These fabricated targets will be tested in ground-based facilities for the validation of theoretical predictions and for measurements of materials properties.

The objectives of this work are to predict the theoretical shielding properties of the Martian surface materials and composites for their shielding effectiveness, and to identify synthetic routes for that could possibly be employed to produce polyimides utilizing the primary constituent of the Martian atmosphere, carbon dioxide. Studies are under way to fabricate regolith simulant/polyimide targets for ground-based testing. In future studies, the actual processing details will be explored in greater depth and optimized for space applications.

2. Biological Response behind Martian Surface Materials and Composites

For the purpose of modeling the composition of Martian regolith, Martian meteorites are considered to be representative of the composition of the soil. These igneous rocks are grouped into five subgroups (Basalt, Lherzolite, Clinopyroxenite, Orthopyroxenite, and Dunite) according to their own distinct chemical signatures (3). The attenuation characteristics of biological response due to GCR exposure behind natural Martian surface materials are examined by using HZETRN (a GCR transport code, 8) with the average compositions of these subgroups and with a representative Martian regolith composition based on Viking lander data (4). The HZETRN describes the atomic and nuclear interaction of the incident GCR ions with target nuclei as they penetrate through the shield materials (8). Composition data for the Martian meteorite subgroups for up to 11 of the most prevalent elements are given in table 1. The data pertaining to the Martian-regolith model for the 5 most prevalent elements are given in table 2. For the comparison of shield effectiveness of these materials on the Martian surface, the free-space fluences are used without modification of the spectra by the Martian carbon dioxide atmosphere.

The level of biological injury from the transmitted GCR environment behind a shield material is assessed in terms of two biological models: a conventional dosimetry model (5) and a track structure repair kinetic model (6). The conventional approach of extrapolating the human radiation risk database to high linear energy transfer (LET) exposures is introduced by the dose equivalent using the LET-dependent quality factors defined by ICRP (5) to represent trends of measured relative biological effectiveness (RBE) in cell culture, plant, and animal experiments. The second model is a track structure repair kinetic model (6) for several biological systems for which there is a large body of experimental data with various ions and in which repair kinetic studies were made.

As can be seen in table 3, the attenuation characteristics of dose equivalent among Martian rock groups and Martian regolith vary by no more than 1% for each thickness. Therefore, Martian regolith is considered to be a reasonably accurate representation of typical Martian surface materials. As previously stated, there may be a clear advantage in the use of unconsolidated Martian regolith for construction compared with the use of rocks. For manufacturing structural blocks, the distribution of fragment size affects the production of a well-consolidated void-free composite. Rocks need to be processed first into fragments, while Martian regolith is merely gathered. The different rock fragmentation methods require different amounts of energy, referred to as the specific energy, to fragment a unit volume of rock. To make smaller fragment sizes to minimize voids requires higher specific energy (7). Using hard rocks requires higher energy and provides no advantage in shielding effectiveness. Therefore, Martian regolith is chosen as the in-situ construction material for further analysis.

Using the track structure model (6), the biological responses of the several biological systems including cell death and neoplastic transformation in C3H10T1/2 mouse cells, and Harderian gland tumor induction in mice have been calculated and are shown in table 4 for the Martian regolith and aluminum, the performance of which materials is virtually the same. Modest reduction in cell death rate is found behind both Martian regolith and aluminum at a thickness of 10 g/cm^2 or more, while transformation rate and tumor prevalence are noticeably increased relative to free space as thickness is increased. The reason for this is because each particle type transmitted through the shield and the increased number of particles due to fragmentations result in more biological injury according to its specific biological effect. Because Martian regolith is the material on Mars surface, and its shielding properties are equivalent to those of aluminum, no advantage would be gained by transporting aluminum from Earth. Although the absolute human risk is not known, the results shown in tables 3 and 4 do provide some indication of the response of living tissue behind Martian regolith.

But, the effectiveness of regolith can be enhanced by employing a polymeric binder. The effects of adding a hydrogen-containing poymer (polyimide) to the regolith are examined by varying its weight fractions from 0%, 10%, 20%, 30%, to 40%. Polyimide was selected for this investigation because of its high hydrogen content as well as its structural properties. The results are shown in figure 1 for two different biological models for thicknesses up to 50 g/cm^2. Adding polyimide to Martian regolith to bind it into a composite enhances its shielding properties for GCR; the thicker the shield, the better its shielding characteristics. Figure 1 illustrates that increasing the concentration of lighter atoms is effective for developing shield materials against GCR. A material with high hydrogen density, here a composite of Martian regolith with 40%-polyimide by weight, provides the most effective shielding at all thicknesses because of its greater efficiency in attenuating the heavier GCR ions and fragments that are most destructive to living tissue (9). In these figures, the responses behind aluminum and pure polyimide are shown for comparison.

In addition to the increased radiation shielding capability, incorporating the polyimide into unconsolidated Martian regolith for manufacturing structural blocks affords other advantages as well. Composites provide more durable structures with significantly less material and more versatility in design and utility of structures than Martian regolith. The benefits of a regolith/polyimide composite must be folded into the context of a complete design reference mission scenario which takes into account total mass of shielding, additives, processing equipment, EVA (Extra Vehicular Activity) time, etc., relative to crew exposure risks (10).

3. Schemes for Synthesizing Polyimide from Mars Atmosphere

When hydrogen, a likely fuel for space vehicles, reacts with the Mars atmosphere, which is 95% carbon dioxide (CO_2) by volume, methane (CH_4) and water are produced at elevated temperatures (11). Astronauts can collect the water for human use and the methane for use in synthesizing polyimides. On the other hand, methane, itself, is a possible space vehicle fuel, in which case this methane could be used directly. The rigid, high melting, thermally stable polyimides can be synthesized from dianhydride and diamine monomers; possible schemes for producing these monomers starting from CH_4 are shown in figures 2-4.

Benzene can be synthesized from one of the following paths. Methane can be converted to acetylene and hydrogen, and acetylene is cyclized to benzene as shown in equation [1]. Methane can also be halogenated via photochemical reactions. The number of carbon atoms can be increased further by employing many known chemical reactions including the Grignard reaction to synthesize *n*-propyl chloride and propyl magnesium chloride, the starting reagents in equation [2]. Such photochemical reactions are appealing because they offer the potential to minimize energy consumption; but, on the other hand, methods to recover the halogens in useful form would be needed in order to minimize the consumption of important chemical reactants. Considerations such as these apply not only here, but also for all the other reaction schemes discussed in this paper, and these factors need thorough consideration.

Diamine and dianhydride monomers can be derived from benzene as shown in figure 3. Diamine monomer is derived from benzene through the steps shown in equation [3] and dianhydride monomer can be derived from benzene as illustrated in equation [4]. The overall reaction sequence of durene synthesis is shown in equation [5] in figure 4. Mesitylene, pseudocumene and durene are obtained by trans-alkylation of toluene, xylene and trimethyl benzenes. Methylating agents include formaldehyde, methanol, and methylchloride in the presence of a catalyst of the aluminum chloride type. The process of methylation is carried out under rather severe conditions (350-400°C, 10-20 atm) and requires an increased hydrogen consumption. By using a stable catalyst obtained from zeolite, a waste-, sewage-free process has also been proposed recently by others. Durene is used for obtaining pyromellitic dianhydride (PMDA) monomer in equation [4] for heat-resistant polymers. A series of polyimides can be synthesized by condensation reactions of dianhydride monomers with diamine monomers. Various polyimides can be synthesized from modifications of the polymer backbone through monomer selection to increase some of the criteria required for high performance materials. Such polymers have distinct processing advantages and mechanical and physical properties (12-17).

4. Planning for Fabrication of Targets and Laboratory Testing

4.1 Matrix Resin and Filler for Microcomposites LaRC™ Soluble Imide (LaRC™-SI), which is the reaction product of 3,4′-oxydianiline (ODA) with biphenyltetracarboxylic dianhydride (BPDA) and oxydiphthalic anhydride (OPDA) terminated with phthalic anhydride (PA), is considered as a possible binder for the Martian regolith because of its excellent adhesive property and melt processing capability for advanced composites (12-15). Its atomic hydrogen content is rather high per unit mass (~30% in atomic number density) making it a potentially good shield material (9). Low molecular weight LaRC™-SI (MW ~9,000 g/mol, 5 mol % offset) can be purchased from Imitec, Inc., the manufacturer of LaRC™-SI, as a matrix of microcomposites. Its glass transition temperature is about 250°C.

Simulated regolith, which resembles surface materials from the Apollo 11 site on the Moon and is comparable with the Martian regolith in terms of shielding properties, is made by crushing, grinding, and sieving 1.1 billion-year old basaltic rock from Minnesota. This simulant is purchased from the Department of Geology and Geophysics, University of Minnesota, Minneapolis, Minnesota, as a filler of microcomposites.

4.2 Microcomposites Processing To make various targets of 6″×6″ cross section with 5g/cm^2 thick for radiation and other testing, predetermined quantities of the dry-uncured LaRC™-SI powder and regolith simulant powder are combined and thoroughly mixed by hand at room temperature. The varying weight fractions of LaRC™-SI powder are 0%, 10%, 20%, 30%, and 40%. Then, the mixture at a temperature of 71-77°C is deaerated under vacuum. The mixture is then carefully transferred to a tooled mold pretreated with Frekote™ release agent and cured according to the following cure profile. It is heated at the rate of 1-3°C/min to 250°C, which is the softening point (T_g) of LaRC™-SI, and held for 1 hour which is necessary to remove most of the volatile material. Then, it is heated at the same rate to 330°C under a pressure of 1.38 MPa (200 psi) to obtain the maximum benefit of the melt fluidity. Finally, it is held at 330°C for 1 hour under the same pressure based upon the crystallization behavior of LaRC™-SI, whose melting endotherm, T_m, is 310-330°C (16), to ensure the complete melting of crystalline regions of LaRC™-SI and the compaction of the mixture. The ingot is ejected from the mold when the temperature has decreased to 150°C to avoid cracks due to the different expansion coefficients of the mold and the composites. The final composite ingot is well-consolidated with no voids since LaRC™-SI possesses with adequate fluidity for relatively low molecular weight (9,000 g/mol). The cured LaRC™-SI becomes insoluble in a typical solvent (*N*-methylpyrrolidinon), yet retains its melt processing capability above T_g (17). In this short and easy hot pressing microcomposite processing, the pressure will be a variable for producing different properties of the cured composites. The minimum required pressure without major property degradation would be also examined. The calculated bulk densities of the regolith/polyimide casts are 1.400, 1.398, 1.396, 1.394, and 1.392 g/cm^3, for the 0, 10, 20, 30, and 40% polyimide concentrations, respectively.

4.3 Ground-based Testing The radiation-transport properties of the materials described above will be measured in ground-based, heavy-ion accelerators that provide GCR-like beams. In an ongoing NASA space radiation research program, in collaboration with the Brookhaven National Laboratory (BNL), 1.05 A GeV and 580 A MeV ^{56}Fe beams produced at BNL's Alternating Gradient Synchrotron (AGS) facility are being used to measure the properties of the secondary radiation field behind various materials. The beam energies of 1.05 A GeV and 580 A MeV are near the peak of the solar-modulated GCR ^{56}Fe energy spectrum, and as such, are a reasonable choice for the simulation of HZE GCR. Regolith simulant/LaRC™-SI composites will be exposed to ^{56}Fe beams at BNL in order to acquire data that will be used for the validation of their predicted radiation transport properties. These targets will be also tested for other mechanical and thermal properties and neutron absorbing abilities at the NASA Langley Research Center.

5. Discussion and Concluding Remarks

The preceding sections have discussed, in a conceptual manner, selected key issues relating to the protection of humans from the hazards of ionizing radiation while on the Martian surface. Numerous issues remain to resolved. Key among these are how the several existing biological response models relate to human tissue damage and cancer induction. Without such fundamental information, it is not possible to design, with any degree of confidence, radiation shields that provide adequate protection to humans, and at the same time are not over-designed and excessively heavy so that launch weight is large and the mission is unnecessarily penalized in terms of launch vehicle size and fuel requirements. A clear illustration of the existing biological uncertainty is seen in figure 1: If a shield were designed on the basis of dose equivalent, one would conclude that significant reduction in biological damage can be obtained by increasing the thicknesses of aluminum, regolith, or polyimide−with the polyimide clearly providing the greatest protection. On the other hand, if a shield were designed on the basis of excess Harderian Gland tumor prevalence, one would have to conclude that any thickness of these same materials (out to at least 50 g/cm^2) would not only be ineffective, but their use would actually *enhance* tumor prevalence. Hence, it is imperative that studies be conducted to resolve these biological uncertainties and that data be developed that are relevant to the particular biological system that is to be protected (namely, humans), and for the proper radiation environment (namely, GCR).

From the preceding sections, it is also clear that Martian regolith, although abundantly available on the Martian surface, is not an ideal shielding material. Namely, it does not pack well and its shielding effectiveness is virtually equivalent to that of aluminum−not a particularly good shield material. It is clear that hydrogen-containing materials, such as organic polymers are considerably more effective. But, polymers or their precursors are not available on the Martian surface, and efficient and effective schemes need to be developed to transport them (or their precursors) to Mars and process them on the surface. Several conceptual reaction schemes have been proposed. Certainly, there may be others. All these schemes must be considered in detail regarding individual benefits and drawbacks. Specifically, various reagents and catalysts will have to be transported to the surface, and these consume spacecraft volume and add to the weight to the launch. Furthermore, processing on the Martian surface poses special problems concerning equipment and power needs. The necessary processing equipment must also be transported to the surface, and an adequate source of power must be available to achieve the temperatures and pressures associated with the various reaction schemes. These must be examined in depth on a case-by-case basis, and there is no simple answer. For example, one reaction scheme may require the transporting the smallest amount of reagents and catalysts to the surface, but it could, on the other hand, require the heaviest and most complex equipment and the greatest power consumption. Toxicity, hazard, and containment issues are also problems, since these materials will have to be processed by astronauts in an extremely hostile environment. Finally, much of what can be accomplished, and what will eventually be practical depends on specific mission parameters: namely, mission objectives on the surface, surface mobility requirements, mission duration, and other factors. Hence, these trades are not simple and considerable work remains to be done to sort out all the factors that will impact reaching the final optimum solution.

In spite of the foregoing considerable uncertainties, however, to get a start on the problem initial studies are being planned to be conducted in ground-based facilities. Regolith simulant/polyimide composite targets will be fabricated and tested in order to validate the shielding predictions in this paper. By this approach, it will be possible to verify the transport codes used to predict the transport of radiations through these materials even though the particular biological implications still remain unknown. But, by closely cooperating with biologists in their quest to develop adequate biological response and risk models appropriate to humans, it is hoped that this very complex problem can be solved in a timely manner to enable a human expedition to Mars in the early 21st century. In addition to measuring the transport properties of the composite materials, their physical and mechanical properties will also be characterized; this is important information because it is desirable to utilize these materials not only for radiation shielding but also as structural components.

Acknowledgment — This work was performed while the first author held a National Research Council-NASA LaRC Research Associateship. We would like to acknowledge Dr. Gary Hammer at Christopher Newport University for providing the synthetic steps of monomers.

6. References

1. Guidance on Radiation Received in Space Activities, NCRP Rep. No. 98, National Council on Radiation Protection and Measurements, 1989.
2. G. D. Badhwar, et al., Radiat. Res., 134, 9 (1993).
3. C. Meyer, compiler, Mars Meteorite Compendium-1996, NASA JSC # 27672, 1996
4. R. E. Smith and G. S. West, compilers, Space and Planetary Environment Criteria Guidelines for Use in Space Vehicle Development, 1982 Revision (Volume 1), NASA TM-82478, 1983.
5. 1990 Recommendations of the International Commission on Radiobiological Protection, ICRP Publ. 60, 1991, Pergamon Press Inc.
6. J. W. Wilson, et al., Biological Effects and Physics of Solar and Galactic Cosmic Radiation, Part B, C. E. Swenberg, G. Horneck, and E. G. Stassinopoulos, eds., Plenum Press, 1993, pp. 295-338.

7. L., Gertsch and R. Gertsch, Shielding Strategies for Human Space Exploration, J. W. Wilson, J. Miller, A. Konradi, and F. A. Cucinotta, eds., 1997, NASA-CP 3360, pp. 327-364.
8. J. W. Wilson, et al., HZETRN: Description of a Free-Space Ion and Nucleon Transport and Shielding Computer Program, 1995, NASA TP 3495.
9. W. Schimmerling, et al., Adv. Space Res. 17(2), (2)31 (1996).
10. L. C. Simonsen, W. Schimmerling, J. W. Wilson, and S. A. Thibeault, "Prefabricated Versus In-Situ Materials For Lunar Base Space Radiation Shielding," Workshop on the Moon as an International Scientific Resource, European Geophysical Society XX General Assembly, Hamburg, Germany, April 3-7, 1995.
11. T. D. Sullivan, et al., Journal of Propulsion and Power, 11(5), 1056, (1995).
12. U.S. Pat. LAR 15205-1 (1994), R. G. Bryant.
13. E. I. Soichi, et al., SAMPE International Symposium, 40(1), 11 (1995).
14. R. G. Bryant, Proceedings of the 19th Annual Meeting of the Adhesion Society, 36, 1996.
15. R. G. Bryant and A. Buchman, Proceedings of the 20th Annual "Anniversary" Meeting of the Adhesion Society, 20, 335 (1997).
16. R. G. Bryant, Polym. Prep., 35(1), 517 (1994).
17. M. M. Angelovici, et al., Materials Letters, 36, 254 (1998).

7. 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 Polymer Science from the College of William and Mary. She was a NRC post-doctoral fellow at NASA Langley. Presently, she is involved in the shield analysis for future spacecraft, aircraft, and space construction designs against space radiations.

Lawrence Heilbronn received his Ph.D. in Experimental Nuclear Physics from Michigan State University in 1991, and has been funded by NASA to conduct research in fragmentation of GCR-like beams at Lawrence Berkeley National Laboratory since then. That research includes charged-particle production studies at LBNL, the AGS facility at Brookhaven National Laboratory, and the HIMAC facility at the NIRS in Chiba, Japan. He has also conducted research in the production of neutrons from GCR-like interactions at LBNL and at the National Superconducting Cyclotron Laboratory at Michigan State University.

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 has been an aerospace technologist at the NASA Langley Research Center since 1966. Since 1981 she has been a materials research engineer in the Materials Division. 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.

Lisa C. Simonsen is an aerospace engineer in the Vehicle Analysis Branch at NASA Langley Research Center. She holds a BS and an ME in Chemical Engineering from Clarkson University (Potsdam, NY) and the University of Virginia, respectively. She received her doctoral degree from the University of Virginia in the "Radiation Protection and Health Physics Program" of the Mechanical, Aerospace, and Nuclear Engineering Department. Her most notable contributions have been in the development of algorithms for the Mars atmospheric attenuation of solar flares and galactic cosmic radiation and the calculated radiation doses based on a detailed geometric atmospheric model; and in the develpment of an integrated engineering design methodology incorporating radiation transport analyses and computer-generated vehicle/habitat models to evaluate radiation shield requirements during the conceptual design phase.

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.

Ken Chang received a Ph.D. in Chemistry from University of Notre Dame in 1969. He was a NRC-NAS postdoc at NASA Langley and a NSF postdoc at the Radiation Laboratory, University of Notre Dame. Currently, he is Professor of Chemistry at Christopher Newport University. His research areas are microwave spectroscopy, radiation chemistry, ESR spectroscopy, and space radiation effects.

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 13 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.

Howard G. Maahs is Head of the Environmental Interactions Branch, Materials Division. He holds a B.S. degree in Chemical Engineering from Stanford University and a Ph.D. degree in Chemical Engineering from the University of Washington. He has been at NASA Langley Research Center since 1964. Currently he manages programs in composite materials research for spacecraft, aircraft, and launch vehicles, as well as programs in radiation protection. His primary area of personal research is in carbon-carbon composite materials for a wide range of demanding aerospace applications.

Table 1. Atomic parameters for each group of Martian meteorites

Element	Atomic number, Z	Atomic weight, A	Atomic density, atoms/g				
			Basalt	Lherzolite	Clino-pyroxenite	Ortho-pyroxenite	Dunite
O	8	16	1.60×10^{22}	1.58×10^{22}	1.54×10^{22}	1.65×10^{22}	1.51×10^{22}
Na	11	23	2.35×10^{20}	9.15×10^{19}	1.13×10^{20}	2.66×10^{19}	2.51×10^{19}
Mg	12	24	1.61×10^{21}	4.07×10^{21}	1.79×10^{21}	3.77×10^{21}	4.81×10^{21}
Al	13	27	8.50×10^{20}	3.34×10^{20}	1.94×10^{20}	1.45×10^{20}	8.23×10^{19}
Si	14	28	5.01×10^{21}	4.50×10^{21}	4.88×10^{21}	5.38×10^{21}	3.87×10^{21}
P	15	31	5.60×10^{19}	2.00×10^{19}	3.76×10^{18}	0.00×10^{00}	6.41×10^{18}
K	19	39	1.23×10^{19}	3.31×10^{18}	2.93×10^{19}	1.95×10^{18}	5.31×10^{18}
Ca	20	40	1.06×10^{21}	4.04×10^{20}	1.56×10^{21}	1.98×10^{20}	6.52×10^{19}
Ti	22	48	8.21×10^{19}	3.28×10^{19}	2.59×10^{19}	1.53×10^{19}	7.60×10^{18}
Mn	25	55	4.42×10^{19}	3.91×10^{19}	5.69×10^{19}	4.04×10^{19}	4.51×10^{19}
Fe	26	56	1.58×10^{21}	1.67×10^{21}	1.79×10^{21}	1.46×10^{21}	2.29×10^{21}

Table 2. Atomic parameters of a representative sampling of Martian regolith

Element	Atomic number, Z	Atomic weight, A	Atomic density, atoms/g
O	8	16	1.67×10^{22}
Mg	12	24	1.62×10^{21}
Si	14	28	5.83×10^{21}
Ca	20	40	7.81×10^{20}
Fe	26	56	1.80×10^{21}

Table 3. Annual dose equivalent behind Martian-rock groups and Martian regolith, cSv/yr

Thickness, g/cm^2	**Basalt**	Lherzolite	Clino-pyroxenite	Ortho-pyroxenite	Dunite	Martian Regolith
free space	120.1	120.1	120.1	120.1	120.1	120.1
1	132.3	132.3	132.4	132.2	132.4	132.3
5	111.5	111.4	111.8	111.1	111.8	111.5
10	94.0	93.8	94.3	93.4	94.3	93.9
30	64.8	64.6	65.2	64.2	65.2	64.8
50	56.5	56.2	56.8	55.9	56.8	56.5

Table 4. The biological responses behind Martian regolith and aluminum shieldings after 1- year GCR exposure

Thickness, g/cm^2	C3H10T1/2 Cell Death Rate	C3H10T1/2 Cell Transformation Rate	Excess Harderian Gland Tumor Prevalence, %
Martian regolith			
free space	3.18×10^{-2}	1.13×10^{-5}	2.23
1	3.92×10^{-2}	1.74×10^{-5}	3.50
5	3.28×10^{-2}	1.65×10^{-5}	3.28
10	2.74×10^{-2}	1.54×10^{-5}	3.02
30	1.89×10^{-2}	1.34×10^{-5}	2.63
50	1.65×10^{-2}	1.29×10^{-5}	2.56
Aluminum			
free space	3.18×10^{-2}	1.13×10^{-5}	2.23
1	3.94×10^{-2}	1.76×10^{-5}	3.57
5	3.33×10^{-2}	1.70×10^{-5}	3.37
10	2.80×10^{-2}	1.59×10^{-5}	3.12
30	1.91×10^{-2}	1.39×10^{-5}	2.73
50	1.65×10^{-2}	1.33×10^{-5}	2.63

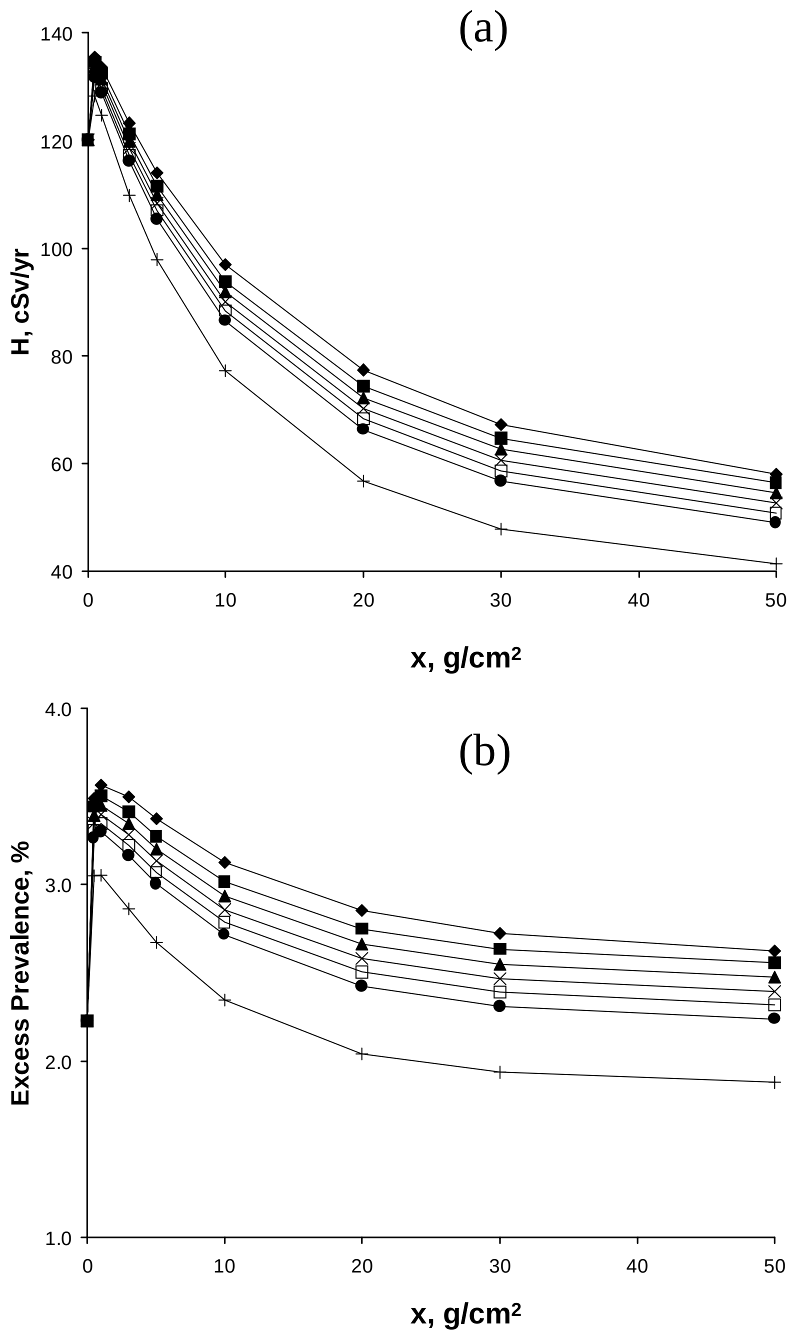
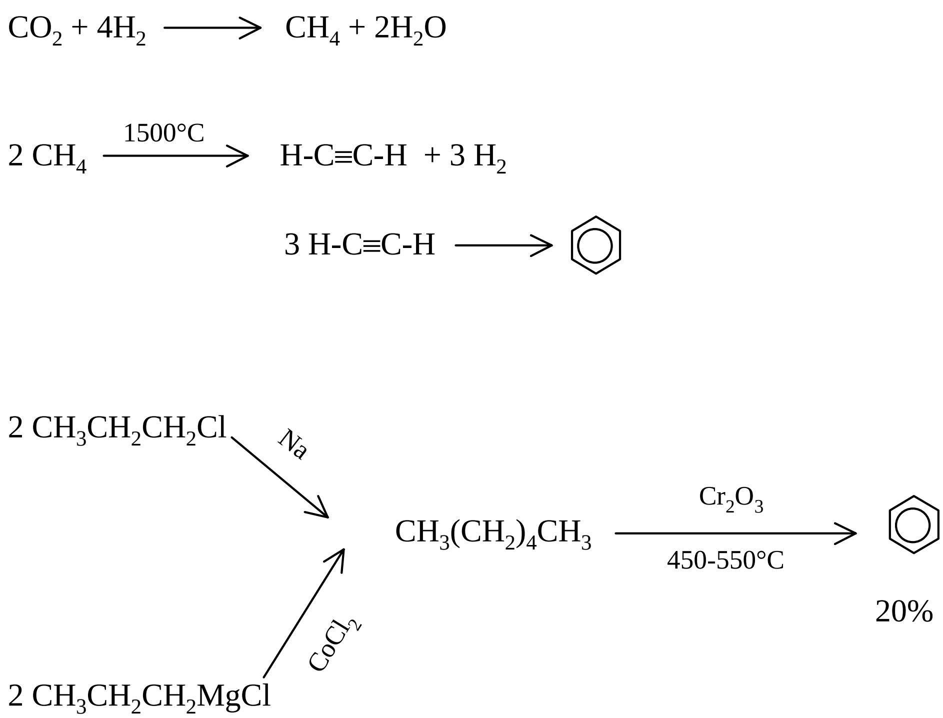


Figure 1. Biological response behind various materials after 1-year GCR exposure (a) dose equivalent and (b) excess Harderian Gland tumor prevalence.
(◆: Aluminum; ■: Martian regolith; ▲: Martian regolith/LaRC™-SI composite of 90%/10% by weight; ✕: 80%/20% composite; □: 70%/30% composite; ●: 60%/40% composite; +: LaRC™-SI)



[1]

[2]

Figure 2. Synthesis of benzene.

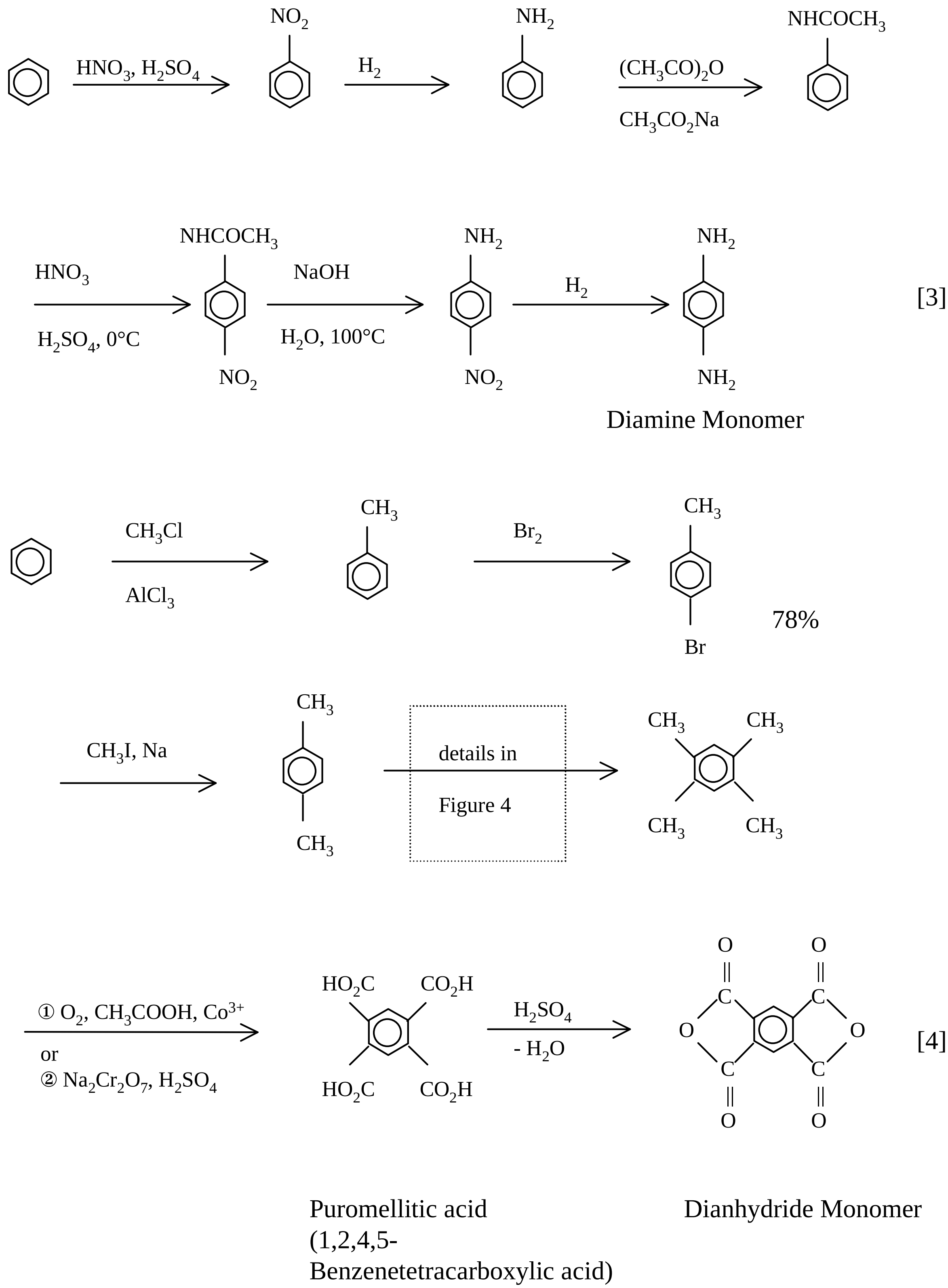
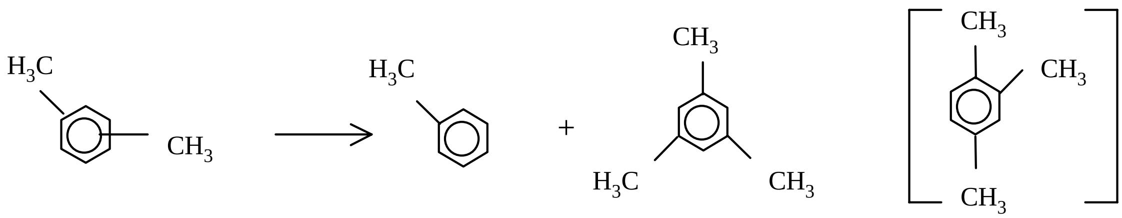
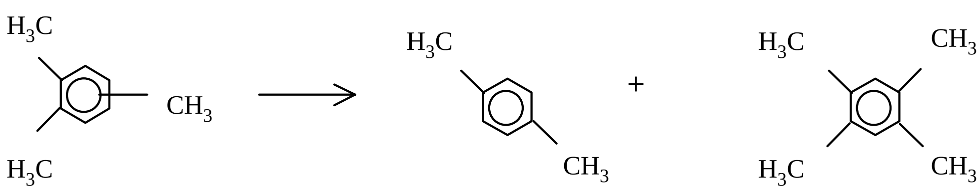


Figure 3. Synthesis of monomers.



Xylene Toluene Mesitylene (1,3,5-Trimethyl benzene) Pseudocumene (1,2,4-Trimethyl benzene)

 [5]

Trimethyl benzene Durene (1,2,4,5-Tetramethyl benzene)

350 ~ 400°C, 10 - 20 atm

Figure 4. Process of durene synthesis from mesitylene and pseudocumene produced by trans-alkylation of toluene, xylene, and trimethyl benzenes.