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The Exploration Atmospheres Working Group's Report on Space Radiation Shielding Materials

A.F. Barghouty
Marshall Space Flight Center, Marshall Space Flight Center, Alabama

S.A. Thibeault
Langley Research Center, Hampton, Virginia

September 2006

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National Aeronautics and
Space Administration

Marshall Space Flight Center • MSFC, Alabama 35812

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

Al	aluminum
ALARA	As Low As Reasonably Achievable
CME	coronal mass ejection
CIR	corotating interaction region
EAWG	Exploration Atmospheres Working Group
GCR	galactic cosmic ray
ISS	International Space Station
JSC	Johnson Space Center
LEO	low Earth orbit
LET	linear energy transfer
NCRP	National Council on Radiation Protection and Measurements
PE	polyethylene (CH_2)
RBE	relative biological effectiveness
SEP	solar energetic particle
STS	space transportation system
TM	Technical Memorandum

TECHNICAL MEMORANDUM

THE EXPLORATION ATMOSPHERES WORKING GROUP'S REPORT ON SPACE RADIATION SHIELDING MATERIALS

1. INTRODUCTION

From a radiation protection perspective, extended future robotic and crewed missions to the Moon and Mars can only be described as complex and exceedingly challenging. Continuous and expansive radiation protection in such missions is needed to safeguard the health of the crew and the reliability and safety of critical systems and subsystems.

Complexity is due to the multiplicity of radiation sources (both natural and man-introduced), pervading complex geometries, and exacerbated by variability and unpredictability. Challenges are embodied in the design and operational requirements to accurately and robustly predict the radiation environment, model and simulate the myriad physical interactions of the radiation fields with matter of complex composition and geometries, and, ultimately be able to objectively evaluate and mitigate exposure risks to crew, systems, and mission.

Looking inward into the vehicle or habitat structure and performance, complexity stems from the interdependence of risk associated with, for example, effects of flammability and structural integrity due to the introduction of nonmetals for radiation shielding purposes on the overall risk and performance of the vehicle or habitat internal atmosphere. Examples of these risks include the impact of changes in the physical and chemical properties of the shielding materials due to extended exposure, in situ repair capability, and real-time monitoring of the material's health for compatibility and integration with other missions' systems and subsystems.

Looking outward from the vehicle or habitat structure and performance, further complexity is introduced in the use of nuclear systems either for electric power generation and/or propulsion. For this nuclear option to continue being attractive to mission designers, safety issues must become design drivers. In addition, and due to severe mass, volume, and power limitations the same shielding materials; e.g., lunar or Martian regolith, are likely to be used for most other shielding needs. This interdependence of crew and power systems radiation safety, for this as well as for other applications and processes; e.g., those motivated by in situ resource utilization, for example, are more likely than not to further increase and make more complex this interdependence.

This report was prepared for NASA's Exploration Atmospheres Working Group (EAWG). EAWG was created to explore options and to formulate recommendations for the design of internal atmospheres of NASA’s future exploration missions. The group chose to include space radiation shielding requirements from the early stages of developing mission design concepts and requirements in order to underscore the import and impact of exposure to space radiation in these future missions. To this end, this Technical Memorandum (TM) served as the white paper contribution of the EAWG report to NASA Headquarters (submitted in early 2006) concentrating on shielding requirements. As such, this TM was written ‘looking inward’ towards the radiation safety and protection requirements of the vehicle and/or habitat; i.e., not addressing any other shielding requirements associated with nuclear power generation, in-situ resources, etc. for the time being. The inclusion of these external factors would comprise the logical follow-on report to this TM.

2. EXPOSURE RISKS AND THE DEEP-SPACE RADIATION ENVIRONMENT

A significant technical challenge in long-duration (>6 months) deep-space (outside the protective region of the Earth's magnetosphere) missions is that of protecting the crew from harmful and potentially lethal exposure to ionizing radiation. Energetic, high-charge galactic cosmic-ray (GCR) ions and solar energetic particles (SEPs) constitute the main source of this intense radiation environment. The energy range of these particles spans more than 8 orders of magnitude (keV-TeV) while their atomic numbers populate the entire stable nuclides of the periodic table.

Charges of 1 (hydrogen) though 26 (iron), however, are considered most important for health and shielding related issues. By number, hydrogen constitutes ≈90 percent; helium, 7 percent; and all others, 3 percent of the GCR ions. The flux (number of particles at a given energy per unit time per unit area) of the GCR component is modulated by a factor of ≈4 by the heliosphere over the 11-yr solar cycle (fig. 1). The mostly hydrogen SEP component is more frequent during heightened solar activities and is typically associated with coronal mass ejections (CMEs) (fig. 2).

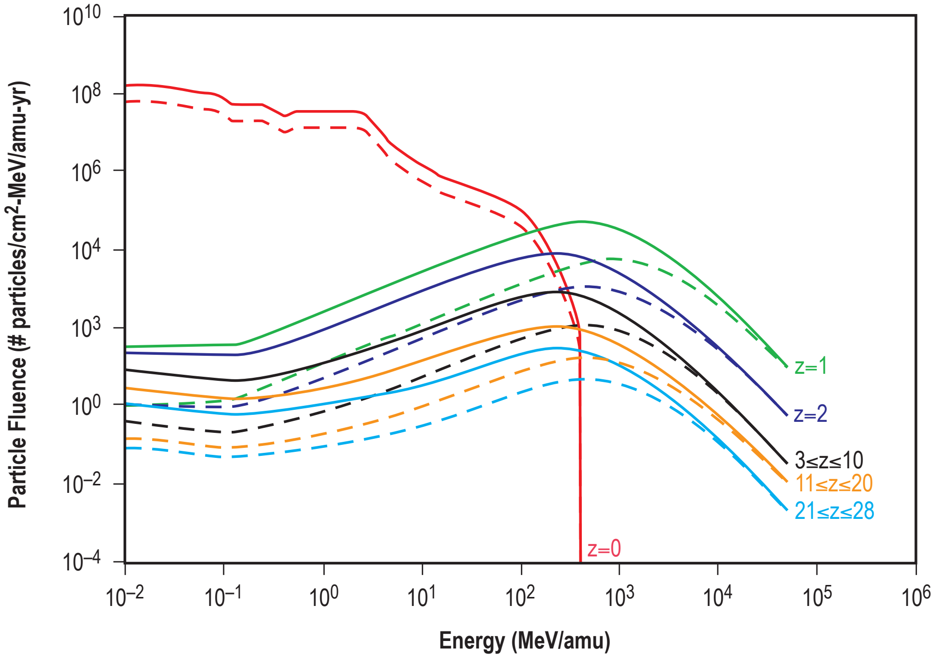

Figure 1. Typical GCR spectra (for energies above 100–200 MeV/amu) for charges 1–28 at the lunar surface (solid curves depict 1997 solar-minimum conditions and dashed ones 1977 solar-maximum conditions) in addition to the neutron component (a secondary component that results from the interaction of SEP and GCR ions with lunar regolith materials). Lower energy curves (<10 MeV/amu) are of solar, solar-wind and/or corotating interaction regions (CIRs) origin rather than GCR origin, and are much easier to shield against than GCR ions. (Figure is from ref. 1; caption by authors.)

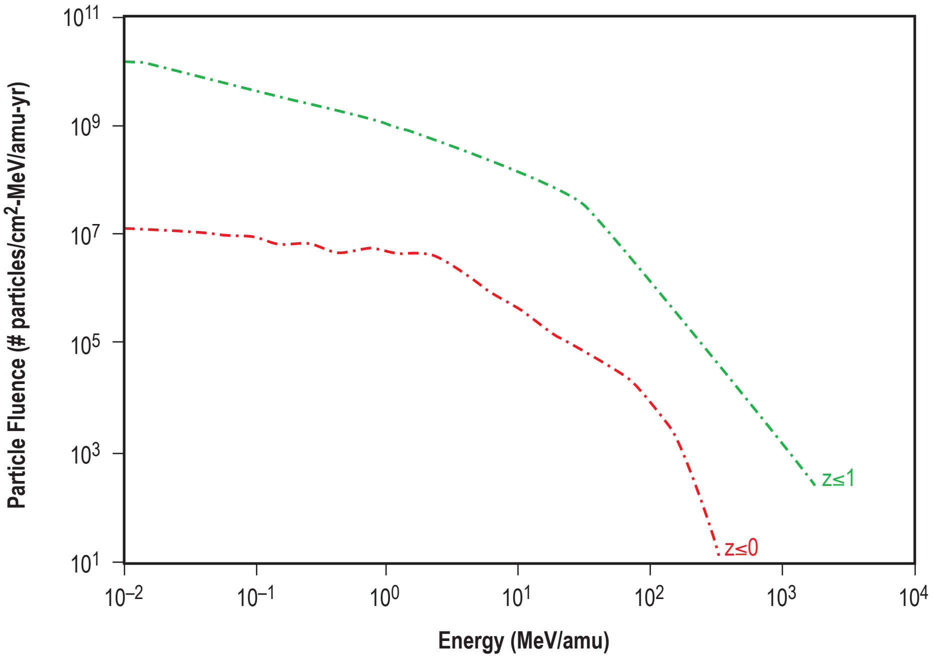

Figure 2. Proton and neutron spectra at the lunar surface during the September 1989 solar particle event. (See note about the neutron component in caption of fig. 1.) (From ref. 1.)

When these particles traverse media, they undergo both atomic and nuclear collisions with the medium's nuclei, atoms, and molecules. These collisions produce secondary components, such as neutrons, in addition to leading to the fragmentation of both GCR and target nuclei. It is these collisions, their nuclear and atomic nature, their frequency, their tracks in the medium, and their energy deposition characteristics that make the GCR and SEP components the health hazards they are.[2] For example, it is estimated that in a 2-yr Mars excursion as many as half of all the cells of an astronaut's body will be traversed by GCR ions.

Biological effects of the passage of GCR ions through cells and tissues are poorly known and difficult to study. This is due in large part to limited in situ and ground-based exposure data. In addition, the radiochemistry and radiobiology of the effects of high linear energy-transfer (LET) radiation like GCR and SEP fields are rudimentary unlike what is known about low-LET radiation; e.g., x rays and gamma rays. Exposure effects are separated into acute and chronic. Acute exposures can lead to early effects that include radiation sickness and erthyma. Chronic (and acute) exposures can lead to late effects including cataracts and cancer. Currently no astronaut dose limits, standards, or recommendations exist for GCR exposure. Standards designed and applied for LEO (low Earth orbit) missions, for example, for the International Space Station (ISS), are not expected to be directly applicable to long-duration deep-space missions.

Estimating the health risks associated with deep-space radiation exposure is hampered mostly by uncertainties in the biological response to GCR; e.g., reference 3, in addition to others associated with the radiation environment itself, its physical interactions, as well as dose-related volatility, as depicted by figure 3(a). Figure 3(b) compares the projected radiation exposure risk (defined as excess in the likelihood over the general population to develop cancer) for a nominal Mars mission to those for ISS and STS missions. For a Mars mission the risk is mostly due to GCR and SEP ions plus their secondaries; i.e., their nuclear interactions products, whereas for ISS and STS missions the risk is due mostly to trapped protons as well as secondaries.

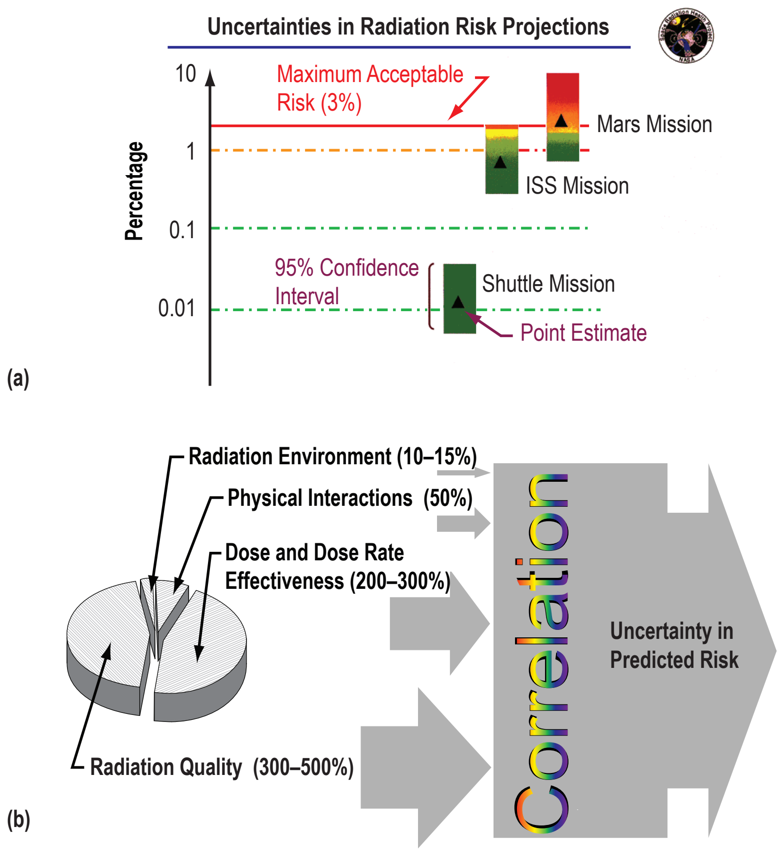

Figure 3. (a) Inherent uncertainties and (b) risks associated with exposure to space radiation ((a) is taken from the Space Radiation Health Project at JSC and (b) from the National Academy of Sciences 1996). (http://hacd.JSC.nasa.gov)

3. SHIELDING EFFECTIVENESS OF POLYMERIC MATERIALS VERSUS ALUMINUM

Materials* rich in hydrogen and carbon are known to be effective shielding materials against GCR.[4] This is because of their ability to fragment (via nuclear spallation and fragmentation reactions) the incoming GCR ions into smaller fragments—thus reducing the ionization damage, which is proportional to the charge squared—with minimal secondary particles production such as neutrons and other short-lived particles. Aluminum (Al), while also able to fragment the GCR ions produces enough secondary radiation to make the transmitted component (and thus the dose behind the shield) almost independent of material thickness. This property makes the radiation transport characteristics of light, hydrogen-rich materials; e.g., polymers, superior to aluminum and metals in general.

Table 1 compares the hydrogen content of select materials. On the basis of its hydrogen content alone, but of no practical consequence from a structural perspective, the 'best' shielding material is liquid hydrogen (LH_2); LH_2 propellant tanks have been considered as part of a spacecraft shielding design.[6] Water, known to be an effective shielding material, has also been considered as a part of a spacecraft system for radiation shielding purposes.[6]

Table 1. Hydrogen content of select materials.

Material	No. Hydrogen Atoms Per cm^3 ($\times 10^{22}$)	No. Hydrogen Atoms Per g ($\times 10^{22}$)
Hydrogen (solid; liquid)	5.7; 4.5	59.7; 59.7
Water	6.7	6.7
Lithium hydride	5.9	7.6
Pure polyethylene (PE)	8.9	8.6
5% borated PE	6.6	8.2

Since different radiations are known to produce different biological effects for the same delivered dose (dose is energy per unit mass expressed in units of Gray where 1 Gray (Gy) = 1 J/kg = 100 rad), a quantity that is more relevant for comparing the shielding effectiveness of various materials for health purposes is the dose-equivalent. Dose-equivalent is calculated from the dose corrected by a dimensionless quality factor, Q. For example, GCR ions can have a quality factor of 3.5 while x rays have a quality factor of 1. This implies that a GCR ion can be 3.5 times as effective in delivering energy (dose) to the cell or tissue as an x-ray beam with the same incoming energy. Dose-equivalent is expressed in units of Sievert (Sv) where 1 Sv = 100 rem. The National Council on Radiation Protection and Measurements (NCRP) has recently recommended the use of Gray-equivalent to express received dose, a unit that incorporates the relative biological effectiveness (RBE) of radiation instead of its quality factor, Q.[7] The new unit emphasizes the deterministic effects of radiation as opposed to its late effects that include cancer.

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*Nonmaterial or active shielding solutions using strong magnetic fields or magnetized plasmas, while scientifically feasible, remain technologically and operationally distant.[5]

NCRP publishes and regularly updates recommended limits appropriate for LEO missions. Table 2 lists the 1999 recommendations for dose limits for organs for all ages for 30-day, annual, and career exposures. Table 3 lists NCRP–recommended career dose limits by age and gender. To put these limits in perspective, on the ISS for the period 2001–2003 (during solar maximum), the average effective dose was about 6.1 cSv and the measured effective dose-rate was about 0.037 cSv per day.[8] On the ISS, in addition to protective geomagnetic effects, which are not present outside the magnetosphere, shielding equivalent to about 5–10 cm of aluminum is provided by the ISS structure and systems materials.[9]

Table 2. 1999 NCRP-recommended dose limits by organ and exposure time.

Limit (Sv)	Bone Marrow	Eye	Skin
30-day Exposure	0.25	1	1.5
Annual	0.5	2	3
Career	(0.5–3.0); Table 3	4	6

Table 3. 1999 NCRP-recommended career dose limits (based on 3 percent lifetime risk of induced cancer) by age and gender.

Age at Exposure (yr)	Female Limit (Sv)	Male Limit (Sv)
25	0.5	0.8
35	0.9	1.4
45	1.3	2
55	1.7	3

Figure 4 compares calculated dose-equivalent as a function of depth behind a number of shielding materials. The main conclusion to be drawn from figure 4 is that polymeric materials are superior to aluminum in their ability to degrade the ionization damage of GCR and SEP particles. In this regard polymeric materials behave as a group; i.e., compared to aluminum differences among them in terms of shielding are known (cf. fig. 7, sec. 6) to be small. In addition, polymeric materials being of low mass density can offer this protection at a much lower cost in weight but not in volume.

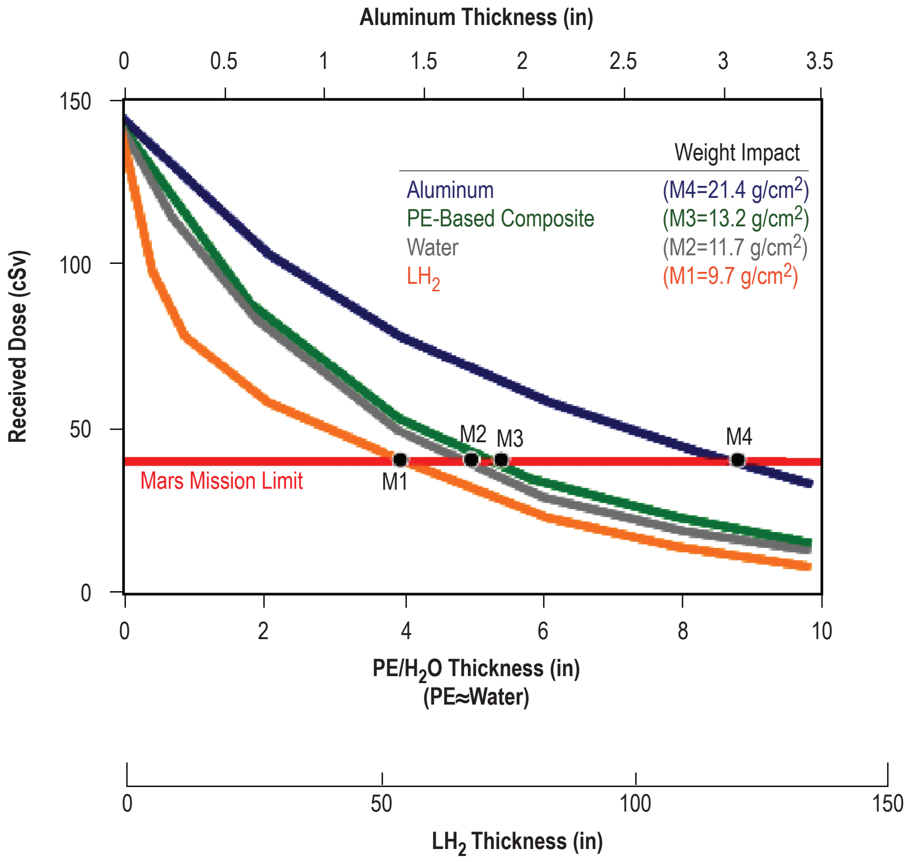

Figure 4. Calculated dose-equivalent as a function of depth in various materials. The ‘Mars Mission Limit’ is a reference point chosen for comparison purposes only and is not a true or standard limit since no such limits have been adopted as of yet. This hypothetical limit is extrapolated from and made more stringent than LEO limits. The assumed radiation environment is a hypothetical worst case scenario that superimposes the solar-minimum GCR field (fig. 1) on top of the September 1989 solar particle event (fig. 2). This superposition is an overestimation of the radiation environment level for the sake of comparison. Points M1–M4 give the corresponding depth that intersects this hypothetical reference limit for each material in units of its areal density (depth=areal density/mass density). (Figure from ref. 10; caption by authors.)

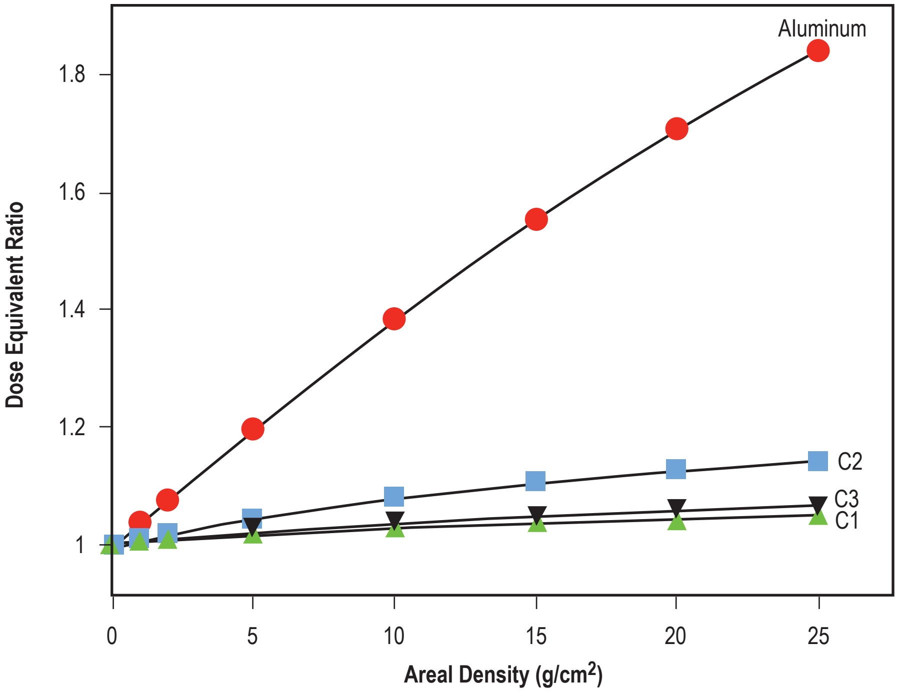

Figure 5. Calculated dose-equivalent (normalized to pure PE) as function of depth in the material for aluminum and three similar PE-based composites developed at Marshall Space Flight Center. The figure showsthe effect of the relative weight of the epoxy resin to PE on the shielding performance of PE-based composites. Composite C1 is 30 percent epoxy while C3 is 20 percent epoxy. (Note that C2 is 30 percent epoxy but only 40 percent PE, whereas both C1 and C3 are 70 percent PE). The difference in the shielding performance between C1 and C3 relative to Al is seen to be quite small (<2–3 percent). (Figure is from ref. 11; caption by authors.)

This small difference in the radiation shielding effectiveness among polymer-based composites suggests that research and development emphases should be on methodologies and processes to optimize the nonradiation characteristics of these composites; e.g., their structural and environmental properties, as opposed to efforts to further improve their radiation transmission properties per se.

4. STRUCTURAL PROPERTIES OF POLYMER-BASED COMPOSITES VERSUS ALUMINUM

Advanced fiber-reinforced composite materials enjoy significant property advantages that make them excellent candidates for use in aircraft and spacecraft structural applications. Properties such as specific tensile strength, specific tensile modulus, fatigue resistance, damage tolerance, and design flexibility all make these materials very attractive for aerospace applications. Additionally, a wide range of fiber reinforcement types and matrix resin systems are available to the engineer and designer for application specific use.

With the use of a variety of fiber-matrix combinations, composites serve a more general function for a host of applications, including structure. Use of composite structures for aerospace applications is steadily increasing; 50 percent of the structural weight of the new Boeing 787, including its fuselage, is in carbon-based and similar composites.

Figure 6 shows a comparison of the specific tensile strength and specific tensile modulus of several common reinforcing fibers. Note that both polyethylene (PE) and graphite are high-strength and high-modulus fibers. Note also that the polyethylene fibers have the highest specific tensile strength, or strength per unit weight, of any reinforcing fiber and a specific modulus that is approximately equivalent to graphite and boron fibers. Polyethylene fibers have the additional advantage in their ability to shield against GCR and SEP particles as illustrated in sec. 3. Another added benefit in using PE fibers for radiation shielding is that hydrogen also acts to slow, or thermalize, fast neutrons due to their large collision cross section. Such neutrons are produced in GCR/SEP ion collisions with the shielding material, just as they are also copiously produced in fission-based nuclear power systems. Thus, added radiation protection can be realized when using PE as a matrix with PE fibers (note that the hydrogen content of PE fiber is the same as that of pure PE, table 1). Boron may be added to the matrix resin to further improve the shielding effectiveness of these materials since boron attenuates the thermal neutrons that have been slowed down by hydrogen.

Figure 7 compares the specific strength and modulus for a polyethylene-based composite to standard Al alloys that are used as structural elements. Figure 5 demonstrates that fiber-reinforced polyethylene composites can be made to combine superior structural properties with their known superior shielding properties.

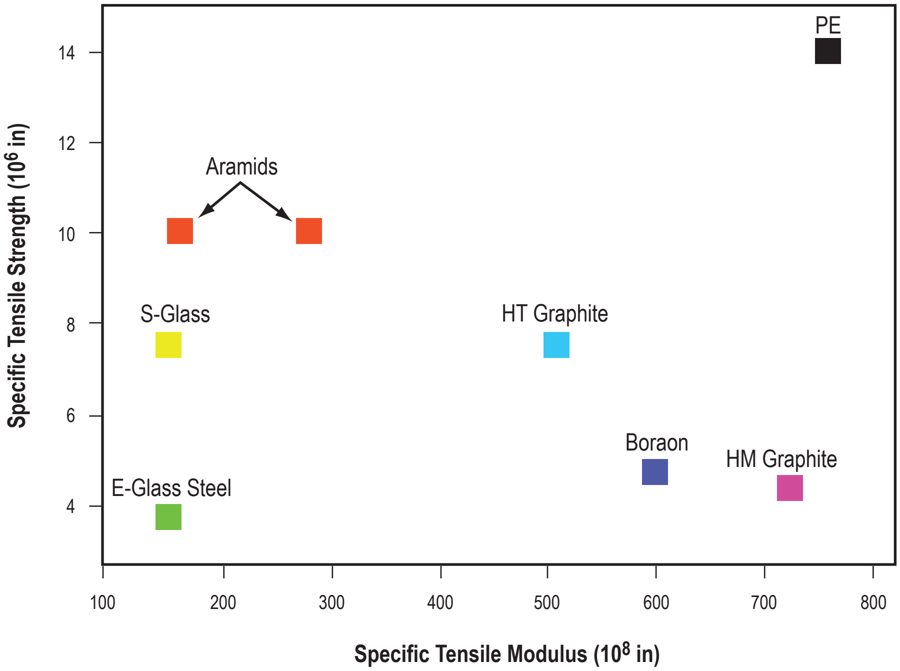

Figure 6. Specific tensile strengths of select reinforcing fibers. Note the high values of PE fibers for both modulus and tensile strengths. (From ref. 11.)

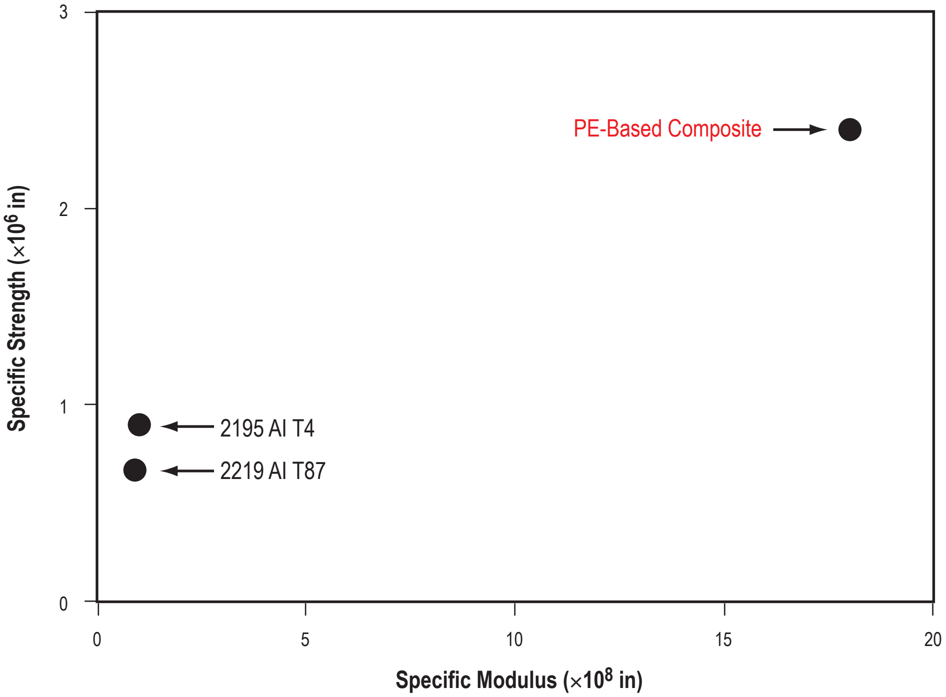

Figure 7. Specific tensile strengths and modulus of a PE-based composite developed at Marshall Space Flight Center along with two standard Al alloys that are used as structural elements. This PE-based composite, known as RXF1, combines superior radiation shielding properties with superior mechanical properties. (Data from ref. 11.)

5. TOWARDS POLYMER-BASED COMPOSITES AS MULTIFUNCTIONAL MATERIALS

Ever since the beginning of the composites era, towards the end of World War II, it was known that fibers immersed in the matrix of a lightweight, lower strength material results in a stronger material as the fibers absorb and scatter cracks. A polymer lacking the required strength or stiffness could be reinforced with fibers to produce a stronger, lighter, and more versatile material. The mutual interfacial bonds between polymer and fibers create an interdependence or synergy between the two: The polymer matrix provides a medium in which the fibers reside and are protected, and the reinforcement supplied by the fibers supplies the strength to the polymer material by supporting much of the stress load that was transferred from the polymer to the fiber through the bonds.

Superior mechanical and other properties are achievable thanks principally to this interdependence between the reinforcing fiber and the matrix, spawning possibilities and innovations. Fiber-reinforced polymer composites are currently in use and being further developed in various industrial areas such as automotive, marine, transportation, civil, military, and aerospace applications.

Materials scientists focus on the relationship between structure and properties while designers are, naturally, more concerned with the symbiosis between functions and properties. Historically for general terrestrial applications, the predominance of function over structure inspired and drove composites research and development, and use. For exploration missions, structure and safety; e.g., radiation protection, and stringent utility requirements; e.g., mass and power, are both the driving and constraining factors. In designing these pathfinding missions an integrated systems approach is required, where structure and design engineers, materials scientists and engineers, chemists and physicists, and computational scientists and mathematicians together would make this approach work in a mutually adaptive, synergetic framework serving structure, properties, processes, and mission.

As an example of this adaptive framework applied to composites design and properties, on the one hand, and structural requirements, on the other, Morozov presents recent developments in the modeling and characterization of reinforced composites.[12] In particular, Morozov considers an application of spatial reinforcement to the design and manufacture of composite thin-walled structures. Stress analyses of thin-walled structures composed from spatially oriented composites demonstrate the basic weight and strength advantages that can be provided with the use of these composites. In addition, analysis of the three-dimensional stress state of composite material at the level of elementary layers is able to demonstrate its structural integrity. Morozov's analysis suggests and draws a theoretical framework that is consistent with a systems approach for a design process in which the microscopic structure of the composite is driven by the requirements of the composites-based overall structure; i.e., a bottom-up design process.

Cohen, in his study on the use of carbon and nonmetallic composites in the construction of a Lunar habitat, argues that these composites can be employed as structural elements; e.g., for pressure vessel and thermal insulation, in addition to their radiation shielding functions.[13] Carbon-reinforced carbon composites can, according to Cohen, be used for pressure vessel and external applications because these composites can tolerate extreme variations in temperature.[13] Polyethylene and polyethylene-based composites, on the other hand, are not as resilient to thermal fluctuations without significant modification to their chemical structure. As a result, polyethylene-based composites without thermal shields will have to support the structure (in addition to providing radiation shielding) from within the interior of the pressure vessel or, as has recently been proposed, from within a cavity between two metallic and/or carbon-based composite walls.[10]

Because of their shielding as well as their mechanical properties, polymer-based composites are expected to make up a good part of the internal structure of the future space vehicle designed for extended deep-space missions. This assertion is based on savings in mass, power, and better handling and processing of consumables and expendables.[14] However, in an oxygen-rich spacecraft atmosphere (oxygen concentration levels >21 percent, Earth-normal—as some of the design parameters require) issues related to the flammability of polymeric materials in general must be adequately addressed before this assertion is made credible.

6. FLAMMABILITY AND TOXICITY OF POLYMER-BASED COMPOSITES

High-density polyethylene has been evaluated and actually used as “parasitic”; i.e., nonstructural, shielding materials on the ISS, and its flammability characteristics have been measured in microgravity conditions.[15] Flammability experiments on the Mir station have demonstrated that combustion of nonmetallic materials in microgravity conditions is characterized by the existence of both minimum and maximum flow velocities that can sustain combustion.[16]

In microgravity, as for thermally thin materials, the lower flow velocity arises from the relative increase in radiative heat losses from the material, which tends to suppress combustion and reduce the spread of flame. However, at elevated oxygen levels (≈30 percent) combustion is possible without the existence of flow to provide for oxygen intake.

For nonmetallic materials, and at lower levels of oxygen, nonzero limiting flow velocities for combustion have been measured in space and on the ground. For example, for a glass-epoxy composite, a limiting flow velocity of less than 0.5 cm/s was measured at an oxygen concentration of 15.5 percent. When the oxygen concentration was increased to 19 percent, the flow velocity increased to 15 cm/s.[16] For high-density polyethylene, Ivanov et al. report a limiting flow velocity of 0.3-0.5 cm/s at an oxygen concentration of 25.4 percent.[16] The study also finds that the spread rate of the flame decreases with decreasing flow velocity. The study underscores the fact that either as parasitic materials for radiation protection purposes, or as structural elements, polyethylene-based composites must first be made flame retardant. Flame retardants; e.g., metallic lining, can be added to the polymer matrix, or, for more significant results as have been reported, for example, for nanoparticle polymers incorporated in the chemical structure of the polymer’s matrix or resin.[17]

A recent experimental study has found that the introduction of about only 1.5 percent by weight of phosphorous to epoxy structural resins significantly improves their flame retardation.[18] Phosphorous was incorporated in the chemical structure (polymeric chain) of epoxy resin as opposed to simply being added to it. Phosphorous, when incorporated in polymers, is known to impart fire resistance through the formation of a char layer on the surface, which prevents oxygen from reaching the combustible material. Unlike the simple addition of fire-retardant materials into the resin, phosphorous retards the spread of fire as well and, hence, can minimize the release of toxic gases.[19] The Hergenrother et al. study applies to polymer-based composites since they can contain up to 20–30 percent by weight epoxy resins without significantly affecting their shielding characteristics, as figure 7 demonstrates.[18] Hence, polymer-based composites upon the incorporation of a fire retardant; e.g., phosphorous, in the polymeric chain of their epoxy resins, can be made much less flammable and toxic.

Toxicity of polymer-based composites is directly related to their combustion products’ toxicity. Carbon monoxide is known to be the principal toxic agent in the pyrolysis gases from polymeric materials.[20] Carbon monoxide is released when the decomposition temperature of the material is reached. In ground testing, for high-density polyethylene, this temperature is about 500 ºC. The amount of carbon monoxide released, while a function of time, was measured to be of the order of 12,000 ppm (carbon monoxide levels of ≈4,000 ppm are fatal).

7. SUMMARY AND CONCLUSIONS

In addition to other flight risks and hazards, space flight beyond the confines and protection of the magnetosphere and for extended periods of time will have to face the challenges of radiation exposure and its risks on crew health and mission safety. The primary source of this penetrating and highly ionizing radiation are the energetic ions of GCRs and SEPs. Unlike low Earth or near-Earth flights or orbits, shielding against GCRs and SEPs will be required in extended deep-space missions. Aluminum is known to be a poor shielding material. Effective shielding against GCRs and SEPs requires the use of polymeric materials. Polymer-based composites are known to have superior shielding properties. With the addition of reinforcing fibers, polyethylene-based composites have been shown to combine superior shielding properties with superior mechanical properties.

Polymers are not as resilient to thermal fluctuations. Polymer-based composites without thermal shields will have to support the structure from within the interior of the pressure vessel. Untreated polymeric materials are flammable and toxic. Polymer-based composites can be made much less flammable and toxic through the incorporation of a fire retardant, e.g., phosphorus, in the polymeric chain of their epoxy resins.

Long-duration space missions will very likely require the use of multifunctional materials for mass savings, radiation protection, safety, and efficiency purposes. As this brief analysis has shown, nonmetallic composites; e.g. fiber-reinforced, cured, polymer-based composites, can be made to be safe and reliable multifunctional materials. In addition, due to processability, these composites in principle can be made into “smart” multifunctional materials. Smart multifunctional materials are needed for purposes of the real-time monitoring of material health and its surrounding conditions. For polymer-based composites this can be accomplished by the threading of radiation dosimeters and microsensors; e.g. optical and radiation-sensitive fibers, into the composites themselves.

Shielding against space radiation is an engineering challenge amplified mostly by biological uncertainties. These uncertainties aside, the materials aspect of the challenge reduces, for the most part, to relationships between structure and properties (see for example ref. 21). However, when safety is the prime motivator of the design decisions, as is the case with this challenge, and in the presence of uncertainties, these relationships are best expressed not only as objective probabilities for the sake of risk assessment, for example, but also as design parameters in a noisy design space. Minimization of this noise becomes the task.

When this task is accomplished the challenge is addressed with adherence to the principle of as low as reasonably achievable (ALARA), from the bottom up; i.e., the solution is engineered in a basic and fundamental way. The principle of ALARA is currently the NASA accepted guideline as well as being a part of the legal requirements with regard to ionizing radiation exposure and crew health and protection as stipulated by NCRP Report no. 98.[7] In contrast, when the solution is imposed on an already determined design (based mostly on past experience and practice) and whose performance may be known in a deterministic sense but whose value to the underlying safety (radiation protection) is uncertain, adherence to ALARA in this case (the top-down approach) serves more the design rather than the ultimate goal of meeting the space radiation challenge: The protection and the safeguarding of the crew. This top-down approach to radiation protection, on account of mass and power requirements alone, is clearly neither the most efficient nor most economical one, and does not necessarily make the mission any safer.

The main points of this analysis are:

- Extended deep-space missions require effective shielding against highly ionizing and penetrating particles of solar and galactic origins that pervade the entire heliosphere.
- Aluminum is known to be ineffective in this regard
- Polymeric materials are vastly superior to metals in their ability to degrade the ionization damage of these penetrating particles.
- Fiber-reinforced, polymer-based composites can combine superior structural properties with their known superior shielding properties.
- Polymer-based composites without thermal shields will have to support the structure from within the interior of the pressure vessel.
- Polymer-based composites can be made much less flammable and toxic through the incorporation of a fire retardant; e.g., phosphorus, in the polymeric chain of their epoxy resins
- Cured, polymer-based composites can be made into true and smart multifunctional materials through the use of embedded dosimeters and sensors for real-time monitoring of material health and its surrounding conditions.
- Smart polymer-based composites are an enabling technology for safe and reliable exploration missions; however, due to the cross-disciplinary aspect of any shielding strategy, an adaptive, synergetic systems approach is required to meet the mission's requirements from structure, properties, and processes, to crew health and protection.

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13. ABSTRACT *(Maximum 200 words)*

This part of Exploration Atmospheres Working Group analyses focuses on the potential use of nonmetallic composites as the interior walls and structural elements exposed to the atmosphere of the spacecraft or habitat. The primary drive to consider nonmetallic, polymer-based composites as an alternative to aluminum structure is due to their superior radiation shielding properties. But as is shown in this analysis, these composites can also be made to combine superior mechanical properties with superior shielding properties. In addition, these composites can be made safe; i.e., with regard to flammability and toxicity, as well as "smart"; i.e., embedded with sensors for the continuous monitoring of material health and conditions. The analysis' main conclusions are that (1) smart polymer-based composites are an enabling technology for safe and reliable exploration missions, and (2) an adaptive, synergetic systems approach is required to meet the missions requirements from structure, properties, and processes to crew health and protection for exploration missions.

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