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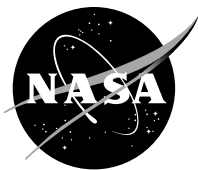
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Abstract

The preliminary design of a testbed to evaluate the effectiveness of galactic cosmic ray (GCR) shielding materials, the MISSE Radiation Shielding Testbed (MRSMAT) is presented. The intent is to mount the testbed on the Materials International Space Station Experiment-X (MISSE-X) which is to be mounted on the International Space Station (ISS) in 2016. A key feature is the ability to simultaneously test nine samples, including standards, which are 5.25 cm thick. This thickness will enable most samples to have an areal density greater than 5 g/cm^2. It features a novel and compact GCR telescope which will be able to distinguish which cosmic rays have penetrated which shielding material, and will be able to evaluate the dose transmitted through the shield. The testbed could play a pivotal role in the development and qualification of new cosmic ray shielding technologies.

Introduction

It is widely recognized that galactic cosmic rays (GCRs) pose an exposure risk to astronauts on long term missions in deep space. It has even been suggested that this may be an insurmountable hurdle to long duration human space missions (Ref. 1). This recognition is reflected in the NASA Office of the Chief Technologist (OCT) Roadmap in **TA06—Human Health, Life Support and Habitation Systems, 2.5 Radiation:** "The radiation area is focused on developing knowledge and technologies…(among other) …to minimize exposures through the use of material shielding systems." "The major technical challenge for future human exploration is determining the best way to protect humans from the high-charge and high-energy galactic cosmic radiation (GCR) permeating interplanetary space." "…shielding GCR is much more difficult than shielding terrestrial radiation…" (Ref. 2).

Developing ground tests to evaluate the effectiveness of GCR shielding materials is difficult. There are no ground-based facilities available which can subject shields to the full spectrum of GCRs. The current evaluation method is to measure the candidate shielding material response to mono-energetic ions of a single type in a facility such as the NASA Space Radiation Laboratory (NSRL) at Brookhaven National Laboratory (Ref. 3) and use that to verify a model of the shielding material. This model is used to explore the putative effectiveness of the shielding in a typical cosmic ray background. Although there have been several instruments flown on spacecraft that measure the cosmic ray flux (Refs. 4, 5, and 6) there are no in-space facilities to verify the effectiveness of cosmic ray shielding materials.

When the Materials International Space Station Experiment-X (MISSE-X) proposal was formulated, a conceptual proposal to fly a testbed to measure the effectiveness of GCR shielding materials was submitted as a core experiment to populate its initial configuration. This proposal was selected to be

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included in the MISSE-X proposal. After the MISSE-X proposal was accepted by OCT, a more detailed version was submitted to OCT for a second approval. Subsequent cost overruns in the MISSE-X program caused the MRSMAT to be dropped from the initial MISSE-X configuration. The purpose of this report is to document the progress that was made in the design of MRSMAT in the hopes that the experiment will be continued at a later date.

The MRSMAT Flight Unit had a 22 month development cycle, concurrent with the MISSE-X development cycle. The design plan presented herein is for the Engineering Model that was to test out the major systems for the Flight Unit. Since the purpose of the Engineering Model was to mimic the Flight Unit with sufficient fidelity to reduce technical risk, it was to be built with the same geometry, detector, and electronics as the Flight Unit. But the Engineering Model was to be built to operate in air, so the thermal control and the materials and connectors were not space rated. It is anticipated that the Flight Unit design will evolve as lessons are learned from the operation of the Engineering Model, but the idea is that the flight unit's salient features will be captured in the Engineering Model.

GCR Environment at ISS

GCRs emanate isotropically from space, but since ISS is in a low orbit (320 to 400 km), the Earth blocks out a nadir-facing cone with a half-angle of about 40° (Ref. 7). Shielding from the Earth's magnetic field and atmosphere also attenuates the flux. Table I compares the ion flux expected at ISS orbit with that of deep space at 1 AU as predicted by the On-Line Tool for the Assessment of Radiation in Space (OLTARIS) radiation modeling program (Ref. 8). The GCR environment at ISS is about 15 percent that of deep space, with the percentage of heavier ions somewhat higher than that of lighter. Thus, shielding materials would have to be exposed 6 to 7 times longer on the ISS to acquire GCR exposure equivalent to deep space.

TABLE I.—COMPARISON OF FLUX OF GCR PARTICLES IN DEEP SPACE AT 1 AU AND AT ISS

Ion Flux, ion/cm^2-s	H	He	Li - Ne	Na – Fe
Deep space	3.72	0.50	0.026	0.0056
ISS 2010	0.53	0.10	0.0058	0.0013

The bulk of GCRs have energies ranging from 100 to 1000 MeV/nucleon. Although most GCRs are protons and alpha particles, the high energy heavy nuclei do so much biological damage per particle that they are of as much concern. These heavy ions are in fact more troublesome because they more efficiently transfer their energy to cellular material, and can cause cascades of ionizing secondary particles (Ref. 9).

General Parameters of MRSMAT

Since GCRs are so penetrating, any shielding will have to be relatively thick to stop an appreciable fraction of them. A requirement of the experiment is that it be able to discriminate between GCR shield effectiveness of 1 mGr/day. This will require samples with a thickness of about to 5 g/cm^2 to distinguish among shielding candidates. Practical considerations have led to the sample size of a 5.25 cm cube. Table II lists the areal density for 5.25 cm of some candidate materials. The greater thickness also enables the testing of more complex GCR shielding structures, including laminar composites.

TABLE II.—AREAL DENSITY OF 5.25 cm OF CANDIDATE MRSMAT MATERIALS

Material	Aluminum	Polyethylene	Composite	Br-Composite
Areal density, g/cm^2	14.2	4.8	8.9	9.0

Side-by-side testing of candidate materials is considered important for this to be a fair comparison among materials. A 3×3 matrix of samples sharing a common detector is proposed. The middle sample of the array would be 6061 Al as a reference and one of the samples will be polyethylene, widely considered to

be the leading radiation shielding material. The remaining samples will be selected from candidates solicited from numerous sources. Since this experiment was proposed to the OCT program, novel materials and architectures would receive priority. In order to avoid environmental degradation of the shielding materials, the sample array would not be exposed directly to the atomic oxygen and ultraviolet of the low Earth orbit (LEO) environment, but would be covered by a 0.32 cm layer of 6061 Al. This is also consistent with the environments that radiation shields would probably be exposed to on application.

As GCRs impinge on the detector from all directions, it is important to be able to determine which particles came through which sample, and avoid counting those particles that passed through a more complex shielding environment, such as multiple samples or part of the ISS. This would be accomplished by utilizing two sets of scintillator arrays, one above the other. The incidence angle of the particles can be determined from the x-y coordinates of the two detectors, and only those particles penetrating a particular sample would be counted.

The scintillator arrays would be made up of 15.75 cm long fibers of polystyrene of 3.5 mm square cross section. Each of the two arrays would have a set of fibers oriented in the x direction directly above a set oriented in the y direction. If the particle events are rare (as they will be for GCRs) there would be only one event within the coincident time window, so the x, y position can be determined without ambiguity. Thus, only 4n scintillators and photon detection units are required rather than the $2n^2$ if an array with a separate scintillator at each x, y position were used. Between these arrays, a thick Tl-doped CsI crystal scintillator (CsI(Tl)) will be used to estimate the linear energy transfer of an incoming particle and distinguish whether the incoming particle was a proton, alpha particle, or heavier ion using pulse shape discrimination similar to the method described by Guinet (Ref. 10).

A ray-tracing analysis has been done to optimize the number and size of the pixel elements (= fiber cross-section), and the spacing of the two detectors. This analysis was constrained by the maximum total thickness of a MISSE-X experiment, and the desire to have the scintillator crystals large enough to capture a countable fraction of the GCR particles that penetrate the shielding samples. Additionally, the scintillating fibers must be thick enough to produce a measureable light pulse when a minimally ionizing particle passes through the detector. Figure 1 shows part of the analysis that lead to the selection of 15 square pixels, 3.5 mm wide, with a detector thickness of 3.1 cm and a total sample/detector thickness of 8.35 cm.
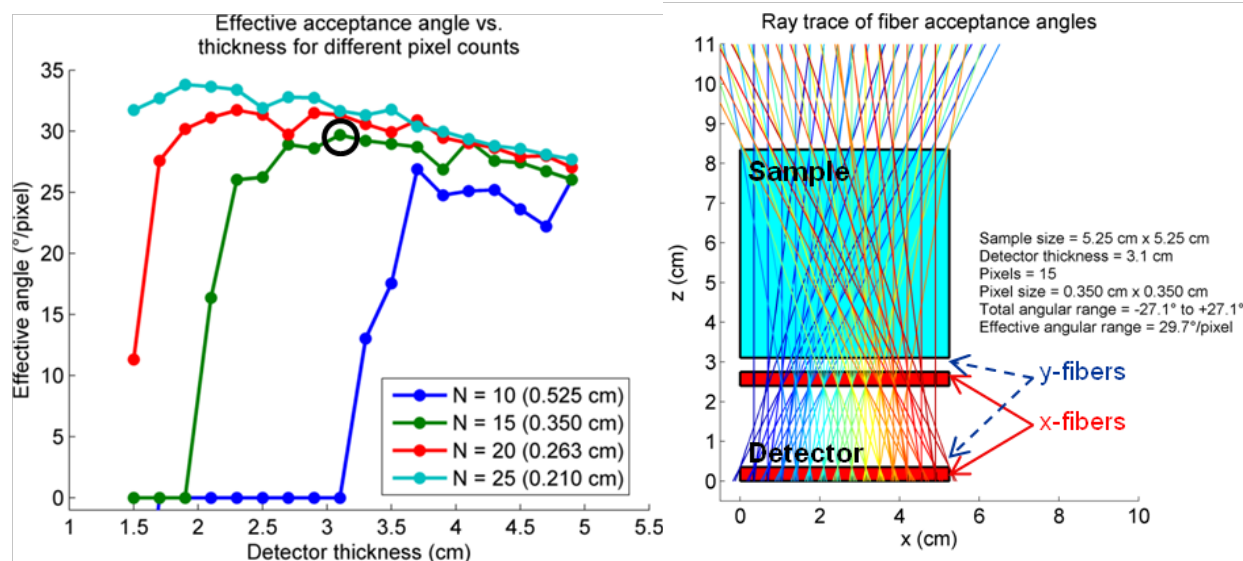

Figure 1.—Acceptance angle as a function of detector thickness for different numbers of fibers/pixels (left), and the dimensions of the optimum design corresponding to the circled point on left (right).
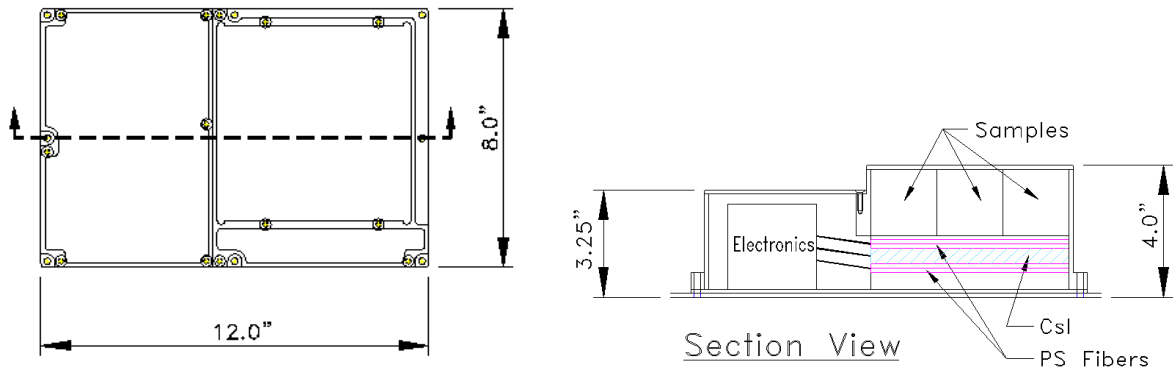
Figure 2.—Preliminary design of the MRSMAT Flight Unit.

The geometry of the samples, the constraints of the Modular Experiment Container (MEC) of MISSE-X, and the detector and electronic requirements feed into the preliminary design of the MRSMAT Flight Unit (Figure 2). Details of the mechanical coupling with the MEC, the electrical interface with the Data Acquisition Unit (DAU), and the thermal control structures are unknown at this time, and so not included in Figure 2.

The detector recovery time required to ensure a low probability (P) of multiple events being counted as a single event can be calculated using Poisson statistics (Eq. (1)).

$$P_r = \frac{\mu^r e^{-\mu}}{r!} \tag{1}$$

where r is the number of events, and μ is the product of the probability density over time and the time. Such an analysis for a 15.75 cm square plate, with the probability density defined using the values in Table I, yields that with a recovery time of 100 µs only 1 in 9300 measurements will have the results of two particles in it, and one in 1.9 million will have the results of three particles in it. Thus, if there are multiple signals in a measurement, 99.3 percent of the time it will be due to a cascade of secondary particles from a single incident particle. So if the recovery time is 100 µs or shorter, cascades of secondary particles will be distinguishable from multiple particles. Because of other considerations detailed below, our sampling times would actually be on the order of 10^{-2} µs.

GCRs are not the only high energy particles that would impinge on the MRSMAT surface. The solar wind particles have a flux that is 10^{12} times as high as the GCR flux, but the particle energies are 10^{-5} to 10^{-6} that of GCRs. It is important that the solar wind particles be blocked so they do not saturate the detector. The Bragg curve indicates that ionizing particles lose their energy and stop within a well-defined length of matter (Figure 3(a)). Figure 3(b) shows that range as a function of energy for H, He, C, O, and Fe ions in Al and polystyrene. Note that the 0.32 cm cap of aluminum over the samples will stop H^+ with energies up to about 10 MeV. This is well above the energy of solar wind protons. This is not to say there are no secondary particles generated, but no significant number of primary solar wind protons would make it even to the upper surface of the candidate shielding materials. The difference in the projected range between 0.32 cm of Al and 5.25 cm of Al is the amount of radiation predicted to be stopped by the Al shield sample.

The GCRs which make it through the shielding sample must interact with the scintillator material to generate the light to be detected. Discussions with the scintillator manufacturer Saint-Gobain revealed that, in doped polystyrene fibers, about 7 percent of the light generated in a 3.5 mm diameter scintillator would reach a detector that fully covers one end of the scintillator. As is illustrated in Figure 4, the minimum ionizing particle is a H^+ with a kinetic energy of about 2 GeV which will produce around 300 detectable photons. All other particles at all energies produce more photons. A 1.2 cm thick CsI(Tl)
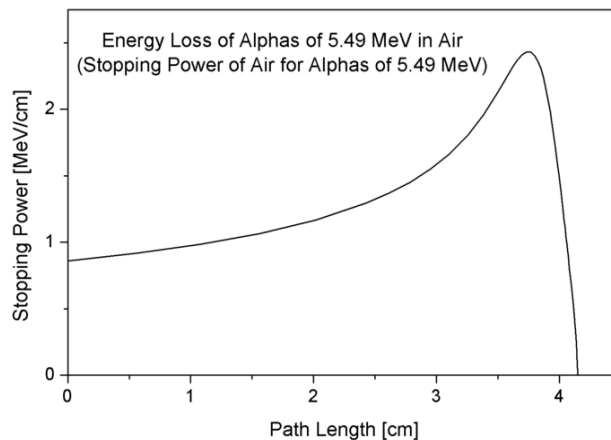
(a)
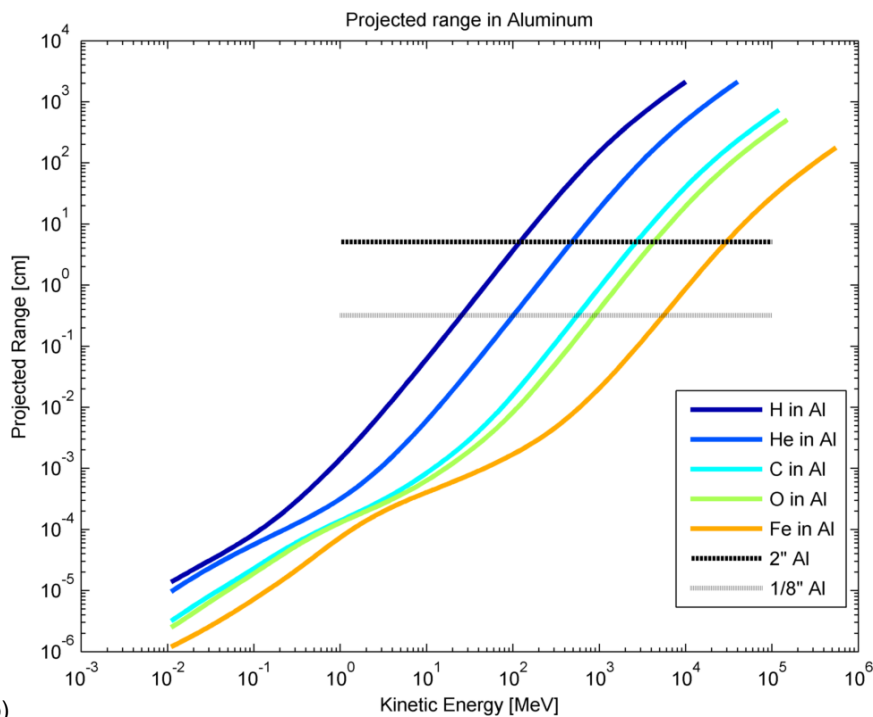
(b)

Figure 3.—The Bragg curve (a) shows that essentially all of a particle's kinetic energy is given up within a well defined range as it travels through a material. The Bragg range for several ions through 0.32 cm (~1/8 in.) and 5.25 cm (~2 in.) of Al (b).
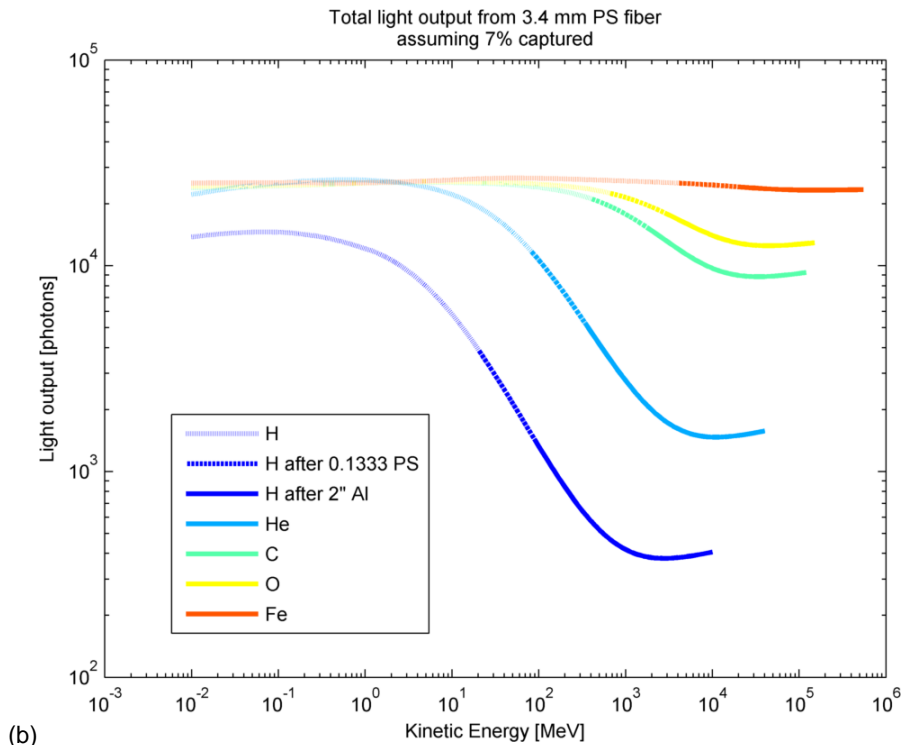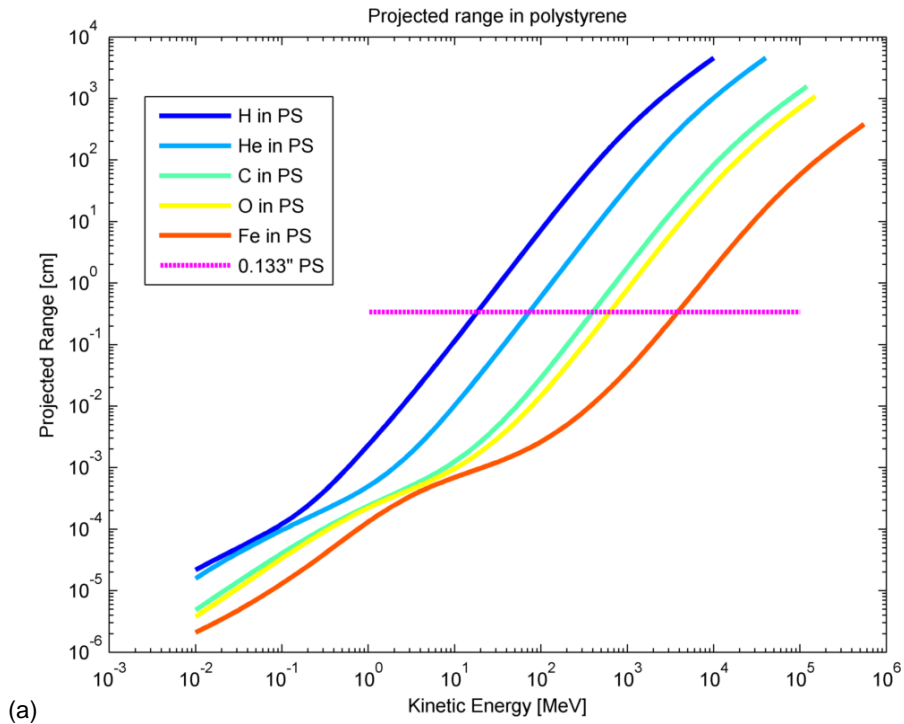
Figure 4.—The Bragg range for several ions passing through a 3.5 mm (~0.133 in.) polystyrene (PS) scintillator (a) and a 1.2 cm CsI crystal (c). Light output in PS for several ions as a function of energy assuming that 7 percent of the photons generated are captured by the detector (b) and the total light output for several ions in a CsI(Tl) crystal of 1.2 cm thickness (d).

Projected range in CsI

(c)

Approximate total light output from 1.2 cm CsI(Tl)
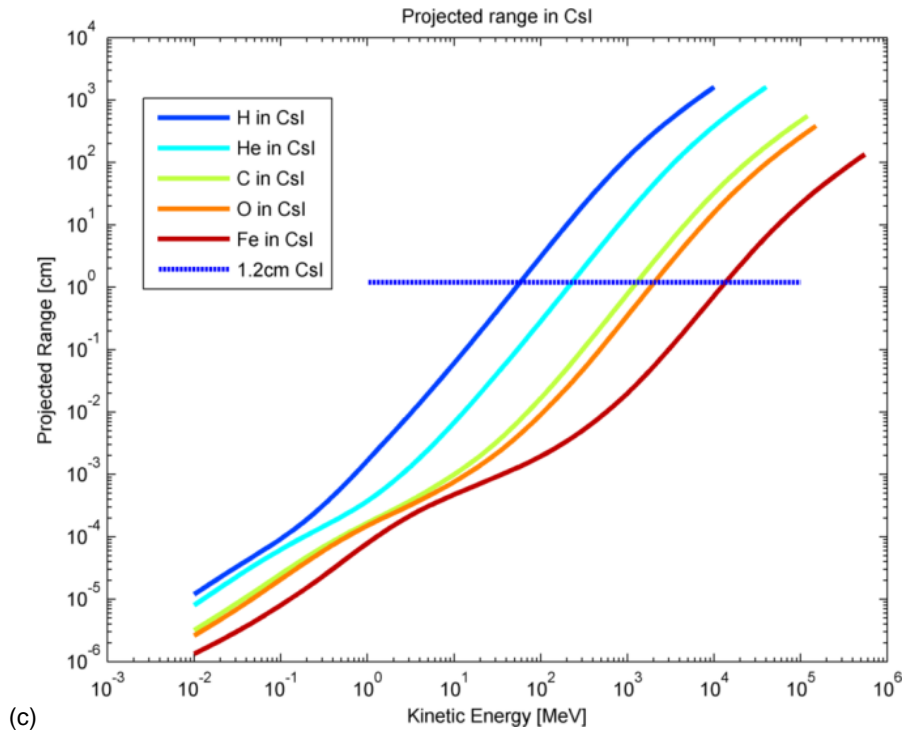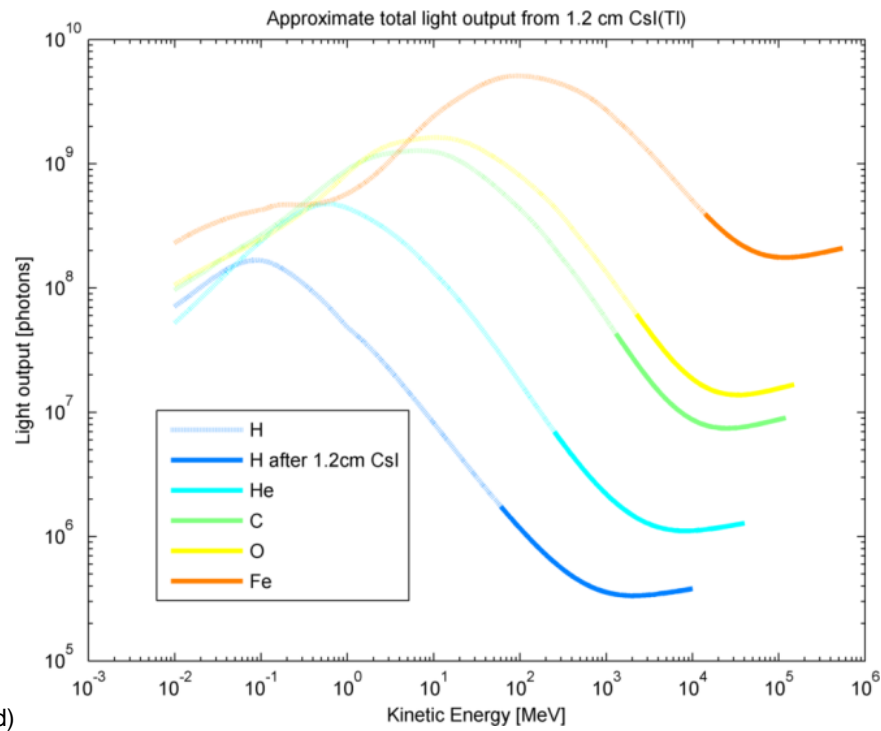
(d)

Figure 4.—Concluded.

crystal produces a much greater number of photons than the polystyrene fibers. The number of photons produced in polystyrene and CsI(Tl) is drawn in solid lines for those ions which have a range greater than the thickness of the scintillator. Lower energy ions would not be counted, as they would not penetrate all levels of the detector. The detector should be sensitive to H^+ with energies higher than 65 MeV, and Fe^{n+} with energies higher than 16 GeV (280 MeV/nucleon).

The pulse intensity in the scintillating materials due to a penetrating particle is dependent on the stopping power within the material, modified by quenching effects. The quenching effects increase with greater energy transfer, but they are generally well known and can be described by modeling. In the CsI(Tl) crystal, the quenching effects are much less than the polystyrene fibers. The CsI(Tl) crystal also has the advantage that the decay of the pulse is a function of the stopping power, so that particles of different mass (and different stopping power) can be distinguished. By determining the particle type and stopping power of that particle, the linear energy transfer can be estimated for each event.

The photons produced by the scintillators would be collected using silicon photomultipliers (SiPMs), which are compact arrays of miniature avalanche photodiodes operated in Geiger mode. They are compact, are insensitive to magnetic fields, require less than 70 V to operate and are available with 3×3 mm square active areas (among other sizes). Models are available with quantum efficiencies of 20 to 60 percent within the emission wavelength range of the scintillating materials and gains of around 10^5. They can operate between 0 and 40 °C but are sensitive to temperature changes. The temperature must be monitored so that the bias voltage can be adjusted to maintain constant gain (~50 mV/°C).

The electronics to read the SiPMs are summarized in the schematic shown in Figure 5. They are grouped into three types of modules: 1) four fiber scintillator detection modules, 2) one CsI(Tl) scintillator detection module, and 3) one mainboard. The function of each is described below.

One SiPM would be attached to each of the 45 scintillating fibers in each of the four fiber scintillation detector modules, two in the x direction and two in the y, for a total of 180 fibers. When a SiPMs detects a scintillation event, it outputs a current pulse which is converted to an analog voltage pulse. When a pulse exceeds a threshold value (to minimize noise) a digital signal is sent from a discriminator to the FPGA. The temperature of the SiPMs is monitored so that the gain on the bias voltage can be controlled, as described above.
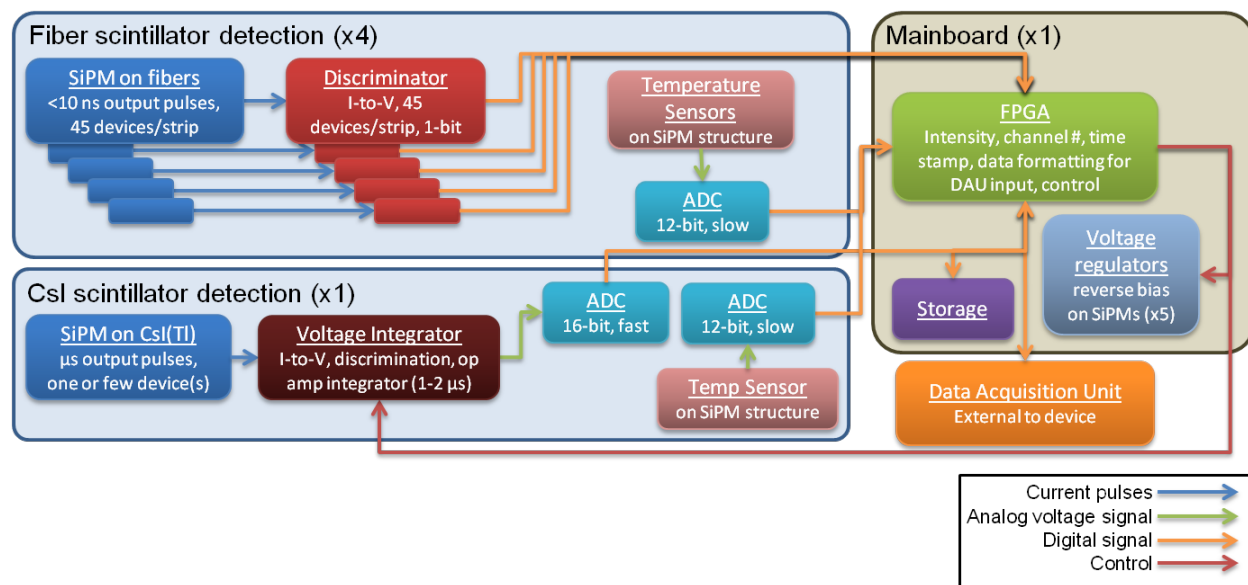

Figure 5.—Schematic of electronics system for scintillation light detection and signal processing.

A few SiPMs (to ensure adequate signal strength) would be attached to the CsI(Tl) scintillator. A series of measurements by a voltage integrator will be triggered by a valid signal from the four layers of fibers. The voltage integrator would measure two or more 1 to 2 µs intervals during the scintillator pulse duration. The integrated value is read by a fast analog to digital converter (ADC).

In this design the mainboard contains a radiation-tolerant field programmable gate array (FPGA) with 270 digital I/O connections. It monitors all digital discriminators and ADC outputs listed above. It would also monitor the temperatures of the SiPMs and adjust five separate voltage regulators which adjust the SiPM reverse bias voltage on each of the four fiber scintillator strips and the CsI scintillator. Additionally the FPGA determines which events are valid, formats the data, stores the data temporarily, and communicates with the DAU.

When the x, y coordinates of excited scintillators indicate a particle has penetrated a single shielding sample, the CsI(Tl) scintillation signal is counted and processed by the FPGA. Each event contains the x, y coordinates, the pulse intensity of the CsI(Tl) scintillator as a function of time, and a timestamp. The luminescent decay of the CsI(Tl) is well below the 100 µs recovery time limit established above. Accepted events are transferred as a serial string to the DAU which formats the data such that it can be transmitted by the ISS to a ground control station daily. The MISSE-X project would provide data decoding, and would send the data to the PI on a regular basis. The PI would analyze the data and provide both raw data and the analysis to the Co-Is on a regular basis.

Once the data trends describing the relative performance of the GCR shields are clear, nominally 1 year, the MRSMAT would be discarded. Evaluation of additional samples would be carried out by subsequent MRSMATs.

MRSMAT Engineering Model Testing

The principal testing to be carried out on the Engineering Model is the operation of the detector system. In lieu of testing on GCRs, modeling and testing would be carried out at high energy particle beam facilities yet to be determined. Detector response would be determined for proton beams varying in energy from 50 to 500 MeV directed from multiple angles in a yet to be identified particle accelerator. The response to α particles and heavier ions in the 50 to 500 MeV/nucleon energy range would also be measured, perhaps at the NASA Space Radiation Laboratory (NSRL).

After beam testing, the electronics of the Engineering Model would be tested for vacuum compatibility. After vacuum testing, the Engineering Model would be vibration tested at GRC up to loads at least 50 percent higher than the greatest loads expected during launch.

Conclusions

The preliminary design of a testbed to evaluate the effectiveness of GCR shielding materials is presented. The testbed is intended to fly on the ISS as part of the MISSE-X platform. A key feature is the ability to simultaneously test nine samples, including standards, which are 5.25 cm thick, which will enable most samples to have an areal density greater than 5 g/cm^2. A novel and compact GCR telescope would be used to distinguish which cosmic rays have penetrated which shielding material sample, and would be able to evaluate the dose transmitted through the shield. The testbed could be key in the development and qualification of new cosmic ray shielding technologies.

References

1. E.N. Parker, "Shielding Space Travelers," Scientific American **294** (2006) pp. 40–47.
2. http://www.nasa.gov/pdf/500436main_TA06-ID_rev6_NRC_wTASR.pdf
3. http://www.bnl.gov/medical/nasa/nsrl_description.asp

4. M. Aguilar et al., "Cosmic-Ray Positron Fraction Measurement from 1 to 30 GeV with AMS-1," Physics Letters B, Vol. 646(4) (2007) pp. 145-154.
5. R. Bogue, "Mars Curiosity: Sensors on the Red Planet," Sensor Review Vol. 32(3) (2012) pp. 187–193.
6. E.C. Stone et al., "The Cosmic Ray Isotope Spectrometer for the Advanced Composition Explorer," Space Science Reviews Vol. 86 (1998) pp. 285-356.
7. D.F. Smart and M.A. Shea, "A Review of Geomagnetic Cutoff Rigidities for Earth-Orbiting Spacecraft," Advances in Space Research 36 (2005) pp. 2012–2020.
8. R.C. Singleterry, Jr., et al., "OLTARIS: On-Line Tool for the Assessment of Radiation in Space," NASA/TP-216722 (2010).
9. M. Durante and F.A. Cucinotta, "Physical Basis of Radiation Protection in Space Travel," Reviews of Modern Physics, Vol. 83 (2011) pp. 1245–1281.
10. D. Guinet, et al., "Using the Combination of CsI(Tl) and Photodiode for Identification and Energy Measurement of Light Particles," Nuclear Instruments and Methods in Physics A278 (1989) 614-6.