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Analysis of a Lunar Base Electrostatic Radiation Shield Concept

Final Report

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INTRODUCTION

The use of passive versus active radiation shielding is a topic that will be debated more frequently as the prospect of returning to the Moon for long-duration missions becomes a reality. Based on the research to date, one would conclude that that both categories of shielding will be needed to solve the lunar radiation problem.

ACTIVE SHIELDING is based on deflecting charged particles by means of the Lorentz force:

$$\mathbf{F} = q\mathbf{E} + q\mathbf{v} \times \mathbf{B} \tag{1}$$

where q is the charge of a single radiation particle, $\mathbf{v}$ is the particle velocity, $\mathbf{E}$ is the electric field of the shield, and $\mathbf{B}$ is the magnetic field component of the shield. Whether or not the shield consists of an electric, magnetic, or both, determines the shield type:

- *Electrostatic shield* – electric field only (time-independent)
- *Magnetic shield* – magnetic field only (time-independent)
- *Plasma shield* – both electric and magnetic fields

Even though most shielding strategies using electric or magnetic fields involve time-independent fields, there is no fundamental reason that time-dependent fields could not be used. However, we have not explored that possibility during Phase I.

PASSIVE SHIELDING simply stops charged particles by multiple collisions with the shield material. The force involved is primarily the Coulomb force, the first term on the right-hand side of Equation (1), on an atomic spatial scale. Multiple collisions generate radiation by-products in the form of additional charged particles, each with less energy than the previous collision, until all kinetic energy is dissipated.

The magnitude of biological damage is proportional to the kinetic energy of the particle, as well as the cross-section. Even though biological damage will increase with increase in kinetic energy, as well as cross-sectional area, some researchers assert that at some point of increasing kinetic energy biological damage will begin to decrease because the interaction time of the particle with the biological media will decrease, resulting in fewer collision by-products. This effect needs to be better understood in the general context of shielding strategies.

CHARGED PARTICLES can be classified into two categories: *solar particle events* (SPEs); and *galactic cosmic radiation* (GCR):

- SPE particles originate from the Sun and are coincident with solar activity, such as solar flares. Most SPE radiation is approximately isotropic at a given point in space because of the influence of the solar system magnetic field lines on the charged particle trajectories. The composition of SPE radiation tends toward the low-atomic-mass ions, such as ionized hydrogen and helium, as well as free electrons. The SPE energy spectra typically cut off at around 100 MeV, even though particle energies up to 300 MeV are not uncommon. The radiation *fluence* (flux integrated over time of the event) will normally be quite low, posing little hazard to astronauts. However, during a solar storm, the radiation intensity will increase dramatically to levels that, under extreme conditions, may be lethal to unprotected astronauts.
- GCR particles originate from distant parts of the galaxy, primarily from exploding stars. GCR is also isotropic since the particle origins are distributed approximately uniformly over space. The composition tends toward higher-atomic-mass ions, maxing out at fully ionized iron. The GCR spectrum begins an energy cutoff at approximately 1,000 MeV, where lower-intensity-particle energies up to 10,000 MeV are observed. The overall radiation fluence will also normally be quite low, posing no immediate hazard to astronauts. However, accumulated GCR dosage will significantly increase the probability of cancer at some time in the unprotected astronaut's lifetime.

BREHMSSTRAHLUNG X RAYS: Charged particles with extreme energy, especially relativistic electrons, can inadvertently generate another type of harmful radiation because of the electrodynamics of charged-particle motion. High-energy X rays are generated by an abrupt change in velocity, such as that associated with high-energy electrons colliding with a metal conductor or passive radiation shield. This *brehmsstrahlung* radiation can potentially generate a lethal dose of X rays, leading to more biological damage than the original charged-particle radiation.

PREVIOUS PHASE I REPORTS can be accessed at the University-Affiliated Spaceport Technology Development Contract (USTDC) Web site: http://ustdc.com/niac_cp_04_01.cfm.

RADIATION SHIELD DESIGN CONSTRAINTS

There are numerous constraints that are fundamental to the design, construction, and operation of a practical lunar radiation shield. Some of these constraints are briefly summarized as follows:

ELECTRICAL constraints include the following:

- Electrical Breakdown of Materials: The electric field strength must remain below a value that avoids electrical breakdown of the materials. This is both a materials problem and geometry problem.
- High-Voltage Power Supply Limitations: Power supplies on Earth have not been built to generate voltages higher than about 20 MV. This value will need to be increased by at least a factor of 5 (for SPE particles) and by a factor of 50 or more (for GCR particles) to begin to yield useful performance.
- Power Consumption: Collision of charged particles with electrodes leads to a current, which must be minimized in order to constrain power requirements.

MECHANICAL constraints include the following:

- Forces Internal to the Structure: The coulomb forces between electrodes must not exceed the mechanical strength of the materials. In the case of thin-film polymers, for example, the tensile strength can not be exceeded.
- Size and Mass: Size and weight are limited by considerations related to transportation to the lunar surface and by practical assembly and construction activities.

ENVIRONMENTAL constraints include the following:

- Surface Dust and Free Electrons: The design must avoid attraction of surface dust and electrons to the high-voltage electrodes.
- Brehmsstrahlung X Rays: Solar wind electrons accelerated by high-voltage positive electrodes must not be allowed to decelerate abruptly as a result of collisions with the electrodes material.

ELECTROSTATIC SHIELD CONCEPTS

Two classes of configurations have been explored: (1) purley electrostatic, using a constant **E** field, and (2) part electrostatic **E** with a magnetostatic **B** component.

POSITIVE AND NEGATIVE SPHERES: Figure 1 is an artist's concept of an electrostatic sphere tree, consisting of negatively charged outer spheres and positively charged inner spheres. Note that the spatial scale of this drawing is probably not realistic in that distance between negative and postive spheres and the speheres and the ground screen (shown as a yellow mesh) should be large enough to limit the electric field strength to a value below a threshold value in order to prevent electrical breakdown of the shield materials.

Each sphere is a flexible "balloon" composed of a 10- to 300-nm gold layer coated onto a 1- to 2-mil-thick Kapton layer. Kapton is used for its high dielectric strength of 250 to 275 kV/mm. The balloons are inflated simply by applying voltage to the gold layer, relying on the electrostatic repulsive forces between like charges to inflate the balloon into a spherical shape.

The electric field profile along the vertical axis of symmetry is depicted in Figure 2. The important principle behind this version of the electrostatic shield is that the far-field potential remains negative. Electrons whose energies are less than the lowest negative potential magnitude, as shown in Figure 2 at roughly 75 m, will be repelled. If electron energies are larger than the outer shield maximum (magnitude of largest negative potential), then the electrons will not be stopped by the shield. It is therefore important to possess a good understanding of electron (as well as other negative-ion) energy distributions corresponding to SPE and GCR sources of radiation.

ELECTROSTATIC SHIELD WITH SPHERICAL SOLENOIDS: The coulomb repulsion of electrons and negative ions achieved by the outer set of negatively charged spheres in Figure 1 can be replaced by considering the second term on the right-hand side of Equation (1). Figure 3 shows a tree of positive-ion-repelling spheres, wrapped with current-carrying wire. A magnetic field is created by the solenoid, which then acts to deflect electrons and other low-mass negatively charged particles.

The electric field profile of the shield configuration along the vertical axis of symmetry of Figure 3 is depicted in Figure 4. The important principle behind this version of the electrostatic shield is that the far-field potential remains positive. Electrons are pulled into the potential well of the positive-ion-repelling spheres. As electrons and other negative ions accelerate inward, they encounter a transverse force proportional to the product of the particle velocity and magnetic field strength. This transverse force deflects the electron radiation, preventing it from colliding with the material of the electrostatic spheres and solenoids, thus preventing brehmsstrahlung radiation. Reducing the influence of negatively charged particles from entering the astronaut habitat area also results from this configuration. Controlling the trajectories of the electrons is not fully deterministic—more work needs to be done to develop a mathematical method to optimize an electrostatic sphere/solenoid configuration.

LOW-INCIDENT-ANGLE RADIATION: Assuming that the lunar surface under the protected habitat volume is grounded, or can be forced to be zero potential, then low-angle radiation from the horizon will not be sufficiently impeded by the shields electrostatic field. This problem is evident in Figures 2 and 4 where the positive potential barrier goes to zero near the ground screen. A passive shield wall will be needed to mitigate that low-angle radiation (see Figure 5). The passive shield wall may need to be as high as the ground screen (yellow mesh in Figures 1 and 3). Another option is to build the habitat in a small crater whose diameter is approximately that of the habitat area.

RADIATION DOSEAGE

RADIATION INTENSITY REDUCTION: The top plot of Figure 6 qualitatively depicts the relative intensity of *normal* SPE and GCR on the lunar surface. The middle plot illustrates the dramatic increase in intensity of SPE radiation during a solar storm. This intense SPE radiation can persist for an interval of hours to several days. The bottom plot shows the radiation intensity in a protected habitat volume owing to the *energy filtering* of an ideal electrostatic shield operating with a high voltage of +100 MV (where the incident angle is well above the horizontal).

SHIELD EFFICIENCY AND TOTAL RADIATION DOSAGE REDUCTION: For the purposes of radiation shield analysis, it is useful to construct a model quantifying the dosage rate of harmful radiation received by an unprotected astronaut on the lunar surface (or in deep space). This can be empirically modeled as:

$$D_0(t) \equiv \int_0^{\infty} F(E,t)\, R(E)\, dE \tag{2}$$

where $F(E,t)$ is the flux of charged particles that intersect a critical surface, or *protected region* (see top plot of Figure 7). This critical surface could correspond to the entire surface of an astronaut's body or some other arbitrary surface surrounding the astronaut's habitat. The double integral of $F(E,t)$ over all energies *E* and time *t* gives the total number of particles n_0, a dimensionless quantity, intersecting the critical surface.

To estimate the biological damage from a particle of energy *E*, a damage coefficient $R(E)$ can be used to approximate this effect. The many simplifying assumptions called upon here include ignoring the particle angle of incidence, atomic mass of the particle and composition, charge of the particle, and specific region of the body impacted by the radiation. The only parameter used in this simplified model is the particle kinetic energy, *E*. $R(E)$ is the relative amount of biological radiation damage as a function of energy. $R(E)$ may be expressed as a polynomial series, a power-law, or some other approximation function.

A shielding efficiency $\xi(E)$ can be defined so that the total dosage rate of harmful radiation is reduced as described by the following integral:

$$D(t) \equiv \int_0^{\infty} [1-\xi(E)]\, F(E,t)\, R(E)\, dE \tag{3}$$

(see bottom plot of Figure 7). For a shield of perfect efficiency (i.e., $\xi(E)=1$) for all *E*, $D(t)=0$, according to Equation (3). Realistically, the fraction of accumulated harmful radiation dosage can be expressed as the ratio of the time integrals of Equations (2) and (3):

$$f_D \equiv \frac{\int D(t)dt}{\int D_0(t)dt} \qquad\qquad \xi_D \equiv 1 - f_D \tag{4}$$

where we define ξ_D as the *dosage attenuation efficiency*. In the case of a specific flux of radiation intersecting a critical surface, the *specific efficiency* ξ_S can be defined by calculating the total number of intersecting particles with (n_S) and without (n_0) the shield:

$$\xi_S \equiv 1 - \frac{\iint [1-\xi(E)]F(E,t)dE\,dt}{\iint F(E,t)dE\,dt}$$

$$= 1 - \frac{n_S}{n_0} \qquad (5)$$

CONCLUSIONS

The primary hurdle in implementing a practical electrostatic radiation shield is proving out the voltage generation system and preventing voltage breakdown of the system components. In addition, if the spheres are fabricated from thin polymer materials with high dielectric and high tensile strengths, can brehmsstrahlung radiation be eliminated or sufficiently reduced? Will the power consumed by the shield be small enough to be practical? In other words, what is the leakage current caused by the capture of charged particles?

The combined electrostatic and magnetostatic shield system represented by Figure 3 will probably not be practical approach since including a magnetic component brings in most of the problems associated with a magnetic-only shield systems, such as weight and power. However, it may be interesting to continue simulations of the electromagnetostatic configuration.

The next logical step is to carefully investigate material properties of conductive coated polymers for the spherical balloons. Simulations and experiments need to be performed to determine the feasibility of creating an ultrahigh voltage system on the lunar surface. Phase II would be approximately half material and high voltage experiments. Continued simulations of optimized shield geometry would be performed in parallel.

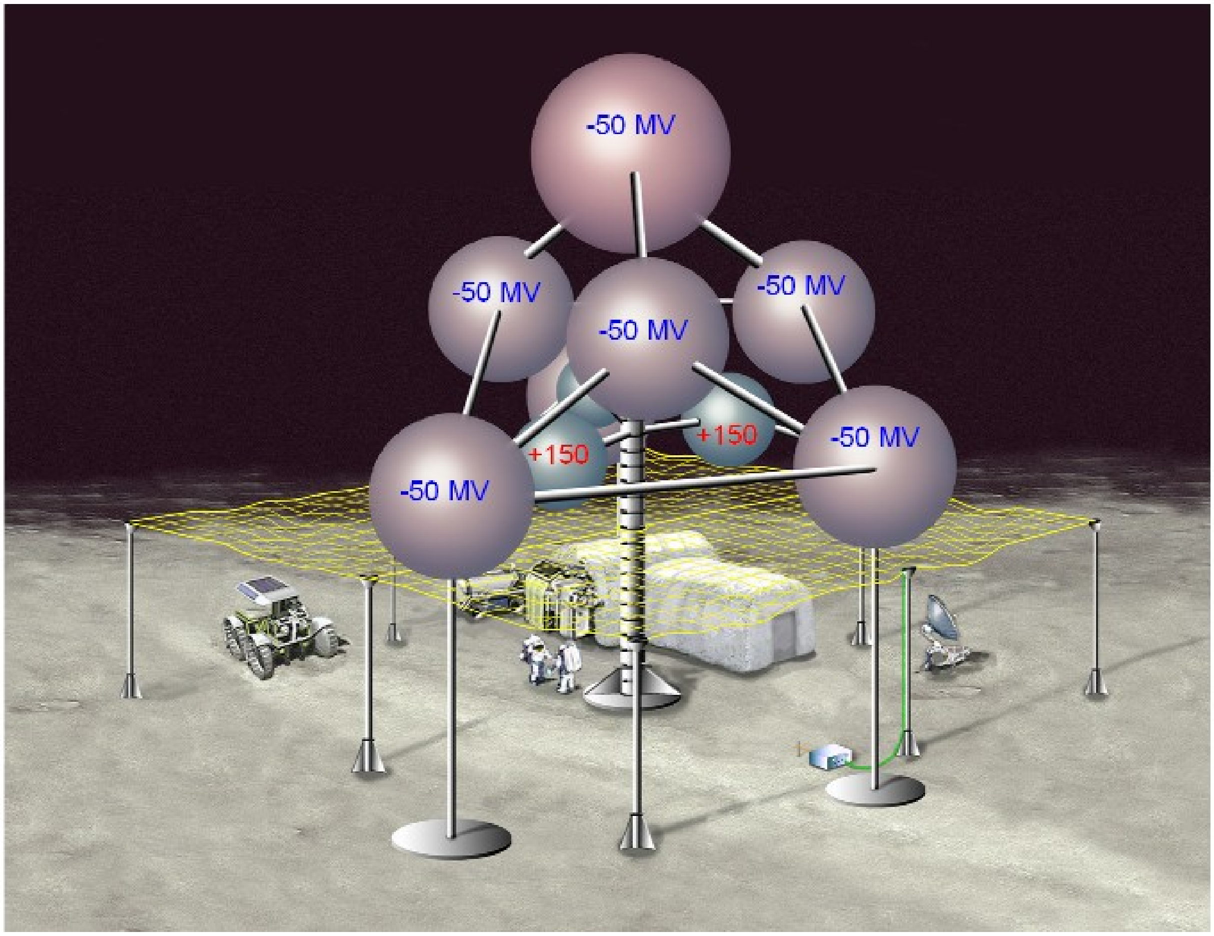

Figure 1. Artist's concept of a sphere tree, consisting of positively charged inner spheres and negatively charged outer spheres. The screen net is connected to ground potential (at infinity).

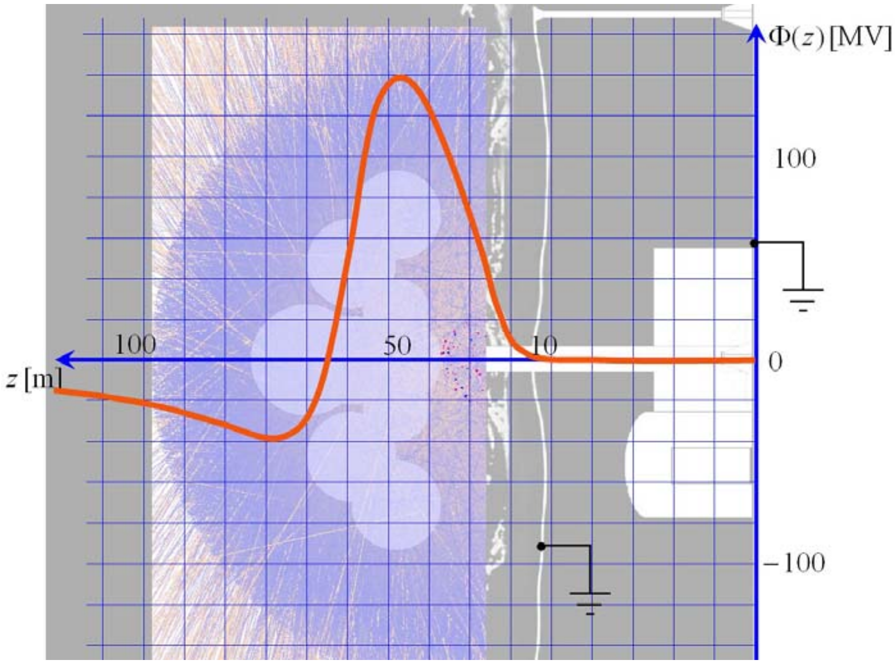

Figure 2. Electric field potential profile along the vertical axis of symmetry (z-axis) for the sphere configuration shown in Figure 1.

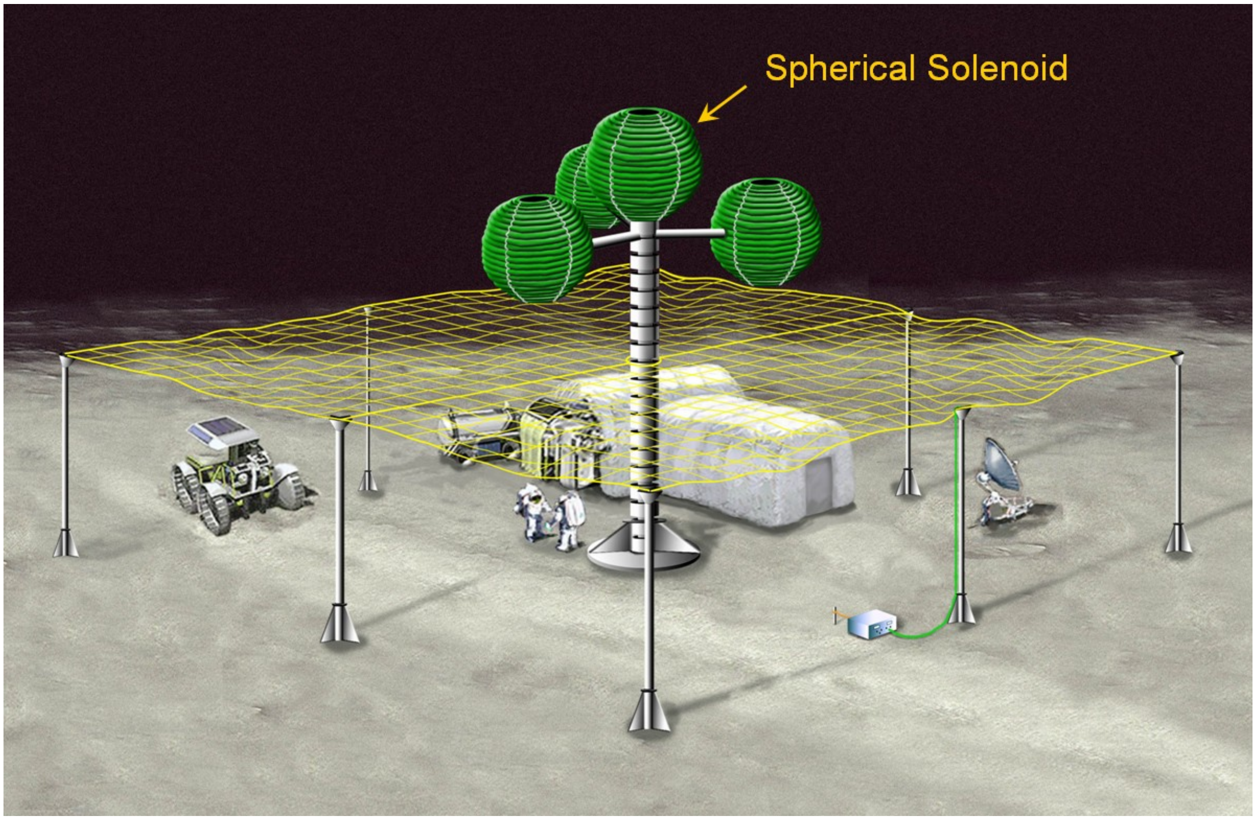

Figure 3. Electrostatic shield concept using only positively charged spheres, wrapped with a current-carrying wire. Electrons are repelled by the magnetic field generated in the spherical wire loops.

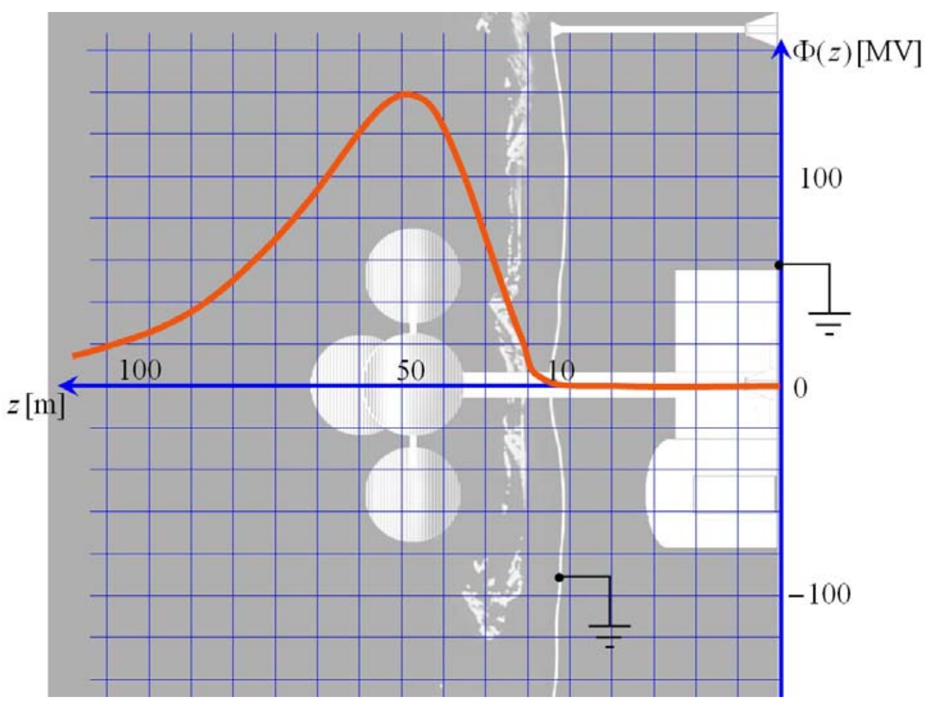

Figure 4. Electric field potential profile along the vertical axis of symmetry (z-axis) for the sphere configuration shown in Figure 3.

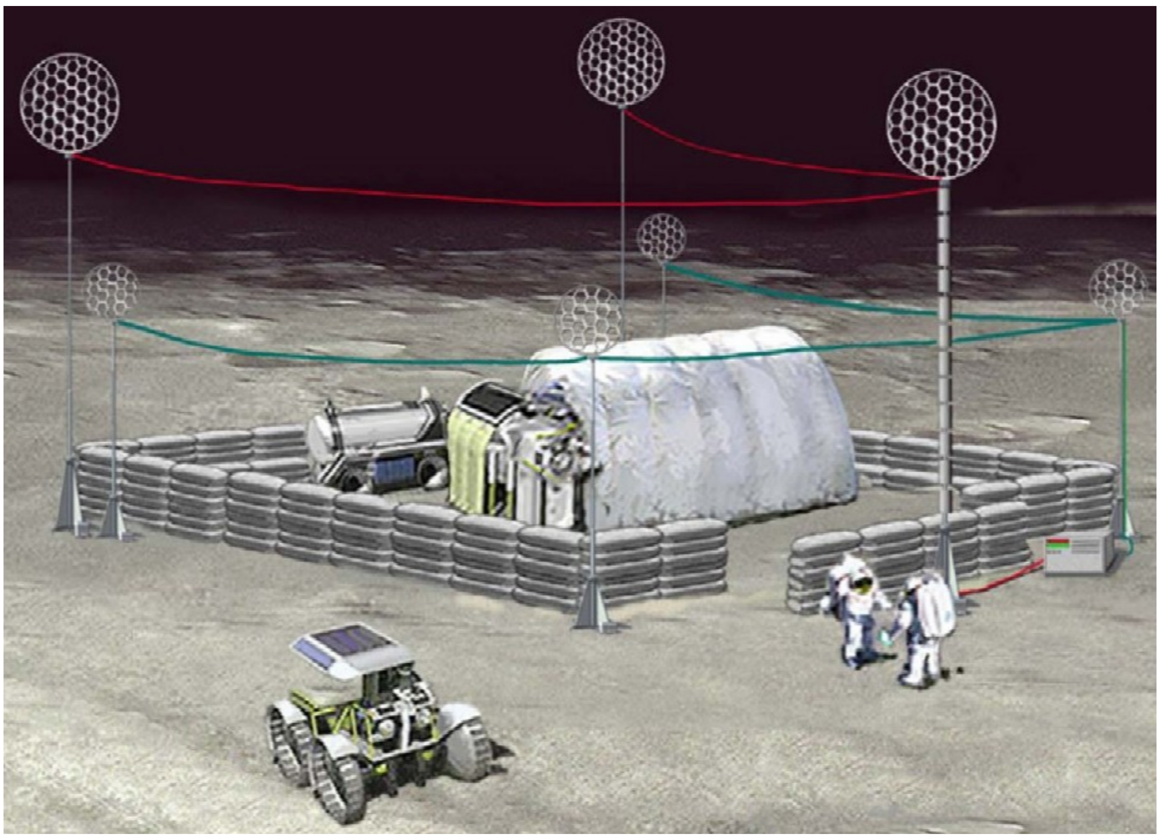

Figure 5. Assuming that the lunar surface under the protected habitat volume is grounded, then low-angle radiation from the horizon is not sufficiently impeded by the shield's electrostatic field. A passive shield wall will be needed to mitigate that low-angle radiation.

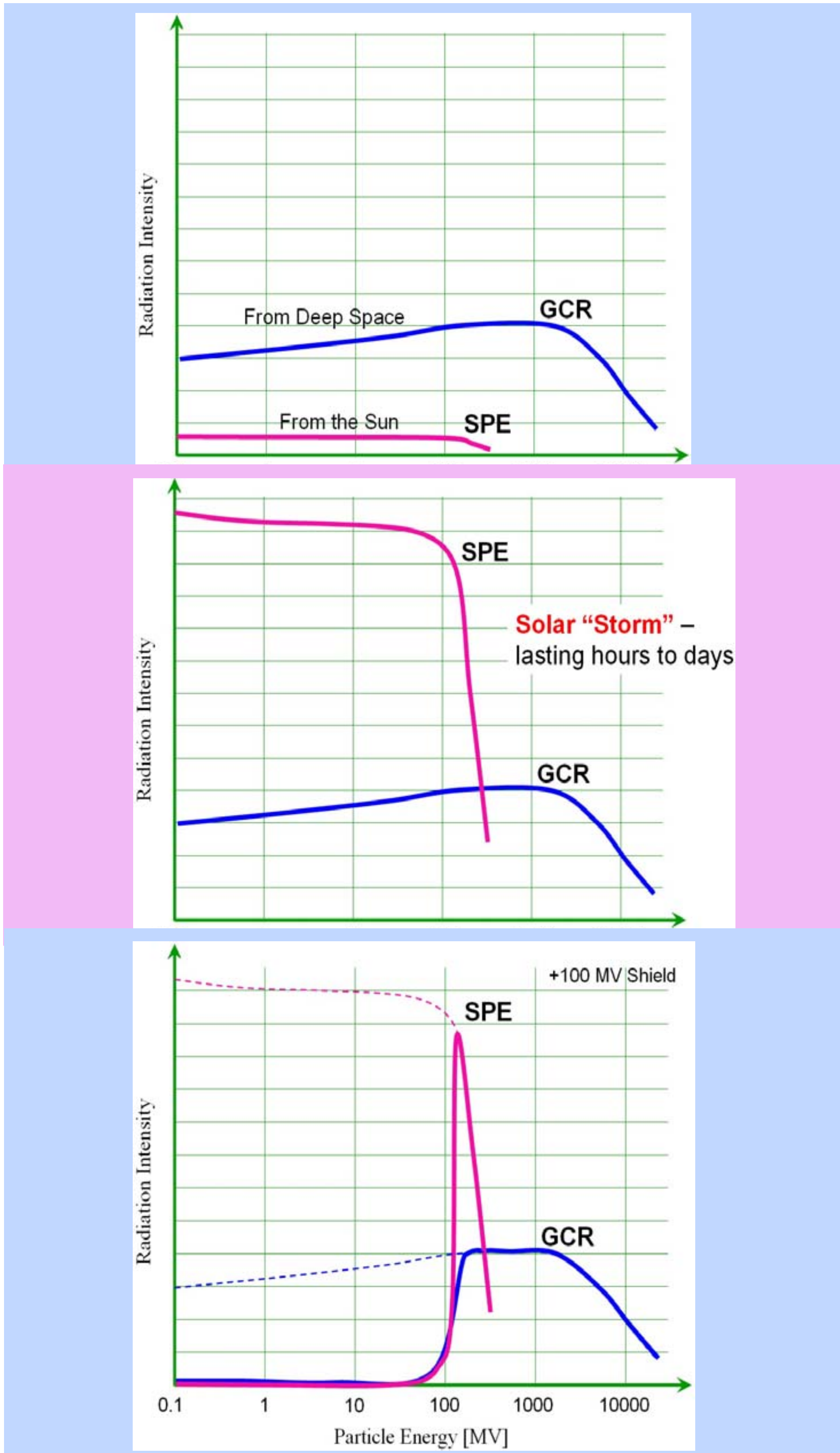

Figure 6. Considering positive ions only, Top: Unshielded radiation intensity (fluence) consisting of low-level SPE and GCR; Middle: High-level SPE radiation due to a solar storm; Bottom: Radiation intensity plot with shielding using 100-MV electrodes.

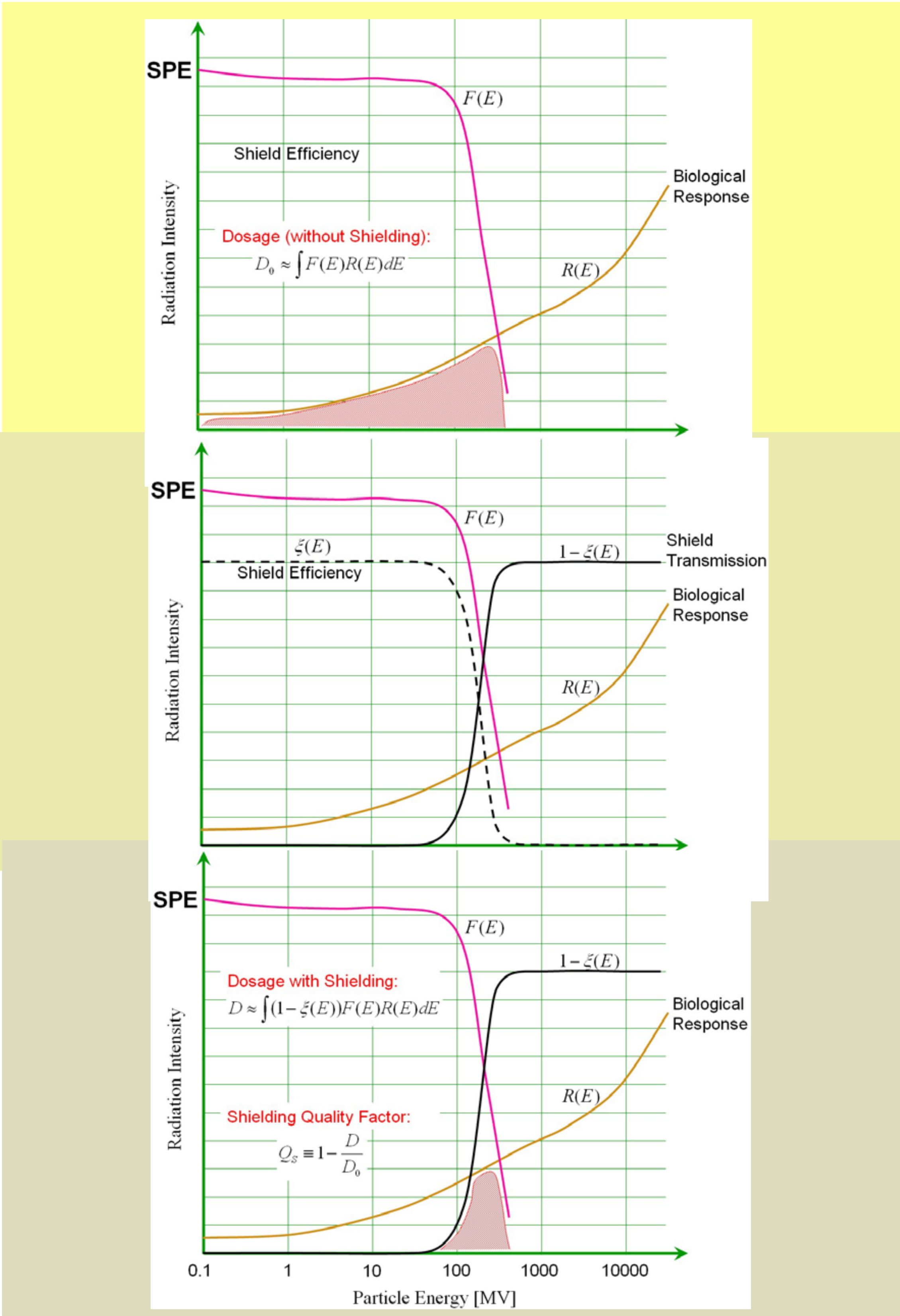

Figure 7. Qualitative dosage analysis of electrostatic shield (SPE only). Dosage is shaded area corresponding to integral over all energies. Top: Dosage without shielding; Middle: Shield efficiency; Bottom: Dosage with shielding.