

Radiation Shielding

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11.3.1 Overview

For terrestrial exposure the three pillars of radiation protection are time, distance, and shielding: limit your time of exposure to the radioactive source or environment, increase your distance from a source or environment, and add material shielding between yourself and the source or environment. For space applications, the primary defense is shielding. Time enters into the calculations in the sense that, where feasible, one may choose to minimize time in lightly shielded areas compared to time spent in more heavily shielded accessible areas. For example, in situations such as Extra Vehicular Activity (EVA) or surface excursions you may consider returning to successively more shielded regions as the radiation background gets or is reliably forecast to become more intense (from space suit to transport vehicle to habitat to storm shelter within habitat, for example).

While shielding generally refers to the matter between the environment and the endpoint that is being protected, the use of shielding is part of a radiation risk management strategy that includes:

- Approved limits based on understanding of the relative risks
- An operations concept to ensure that astronauts do not exceed these limits
- Physical shielding adequate to meet the radiation limits throughout the various phases of mission operations
 - Through the trapped radiation belts
 - In deep space
 - On the lunar or planetary surface
 - In a shielded surface module
 - In a transport vehicle
 - In a spacesuit
- Radiation environment monitoring and warning
 - Dose and dose rate monitors
 - Space environment observations
 - Space weather forecast center(s)
 - Transport codes to convert external environment to risk measures
- Communications system connecting
 - Space environment and dosimetry observations
 - Forecaster centers
 - Mission operations
 - Astronauts

Figure 1, from NRC 2006, is a cartoon representation of the elements of a radiation risk management system.

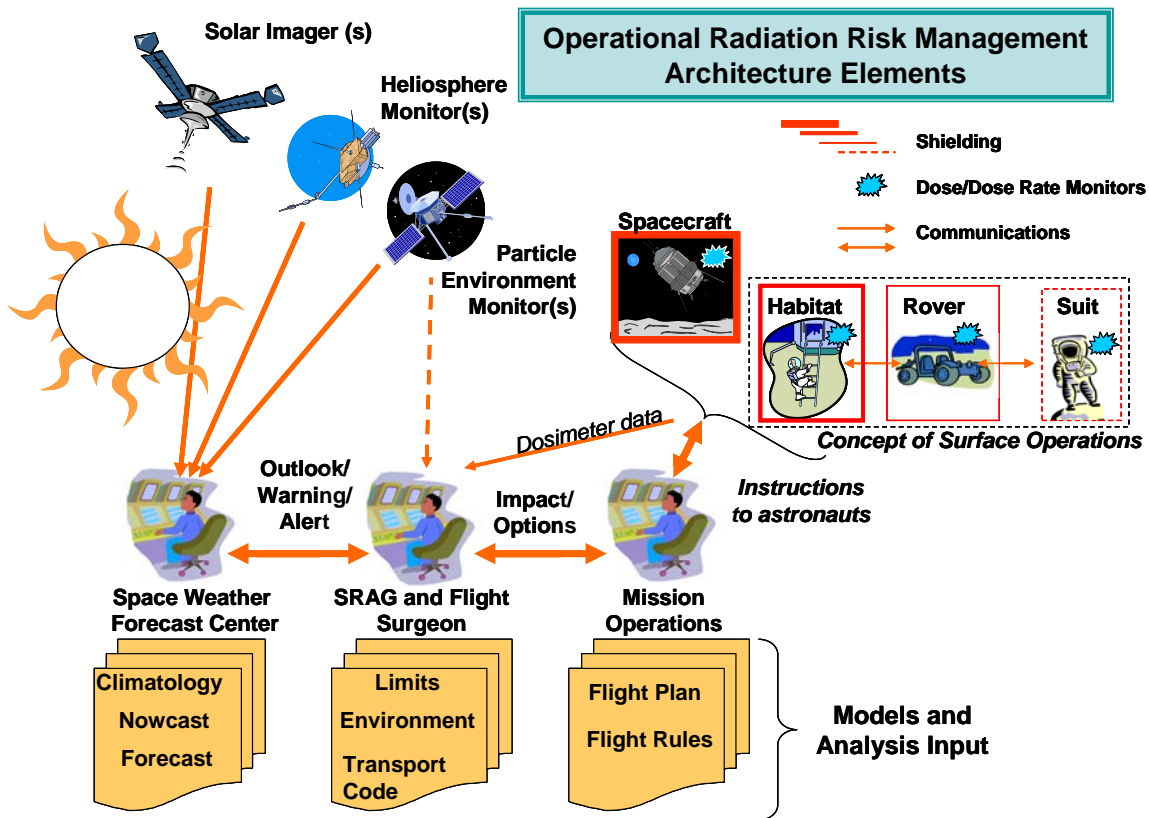


Figure 1: Elements of a Radiation Risk Management system. (from NRC 2006).

Acknowledgement

This report would be incomplete without acknowledging up front some of the pioneers who put radiation shielding strategies on a firm science-based foundation, including John W. Wilson, Larry Townsend, Walter Schimmerling, Francis Cucinotta, and Bill Atwell. This author takes the blame for leaving out others who also belong on this list, through inadvertent oversight or for not being aware of their contributions.

Background and History

To avoid duplication, the reader is referred to other sections of THREE for background information and for more depth in certain topics. Particularly useful preliminary reading includes:

2_Introduction

- 2.1_The Space Radiation Environment
- 2.2_Interactions of Radiation with Matter
- 2.3_Elementary Concepts of Shielding
- 2.4_Energy Deposition
- 2.5_Elementary Concepts of Radiobiology
- 2.6_Doses, Fluence, and Dose Rates
- 2.7_Physics Summary

And

- [4_Radiation Measurements](#)
- [4.1_Space Radiation Dosimetry](#)
- [4.2_Detectors](#)
- [4.3_Dosimeters](#)
- [4.4_Functional Dosimetry](#)

NASA has been aware of the risk of radiation exposure from its outset, based on studies leading from observations of atmospheric high-nuclear-charge (high Z) cosmic rays first reported in 1948 (Wilson et al, 1991, and references therein) and on direct measurements of the space radiation starting with Van Allen et al's Geiger counter launched into space in 1958. Risks from enhanced exposure due to periodic solar storms were also recognized early on, leading to the establishment of a solar warning network in the 1960s.

The challenge to NASA has been, and to some degree continues to be, quantifying the risk and establishing a system-wide risk mitigation strategy. Earlier sections discuss the radiation risk to astronauts and the development of permissible exposure limits. This section focuses on the physical elements of a radiation risk management strategy, which are built around material shielding, monitoring the environment, and forecasting and responding to changes to the radiation environment.

For general shielding concepts and some early history on radiation shielding:

- IAEA. Engineering Compendium on Radiation Shielding, Vol. I Shielding Fundamentals and Methods (R.G. Jaeger, Editor-in-Chief; E.P. Blizard, A.B.Chilton, M. Grotenhuis, A. Höning, and Th. A. Jaeger, Editors; and H.H. Eisenlohr, Coordinating Editor). Springer Verlag, New York, 1968.

For the “bible” of space radiation transport calculations, including history:

- John W. Wilson, Lawrence W. Townsend, Walter Schimmerling, Govind S. Khandelwal, Ferdous Khan, John E. Nealy, Francis A. Cucinotta, Lisa C. Simonsen, Judy L. Shinn, and John W. Norbury. Transport Methods and Interactions for Space Radiations, NASA Reference Publication 1257, National Aeronautics and Space Administration, Washington, D.C., December 1991, 616 p.

For particular strategies and aspects of space radiation shielding:

- Shielding Strategies for Human Space Exploration (J.W. Wilson, J. Miller, A. Konradi, and F.A. Cucinotta, Editors). NASA Conference Publication 3360, December 1997.

For more recent reviews of shielding strategies the interested reader should see two National Research Council reports.

The first examines NASA's shielding strategy for exploration missions:

- [Managing Space Radiation Risk in the New Era of Space Exploration](#), National Academy Press, March 2008.

The second has more of an emphasis on the state of understanding the physics behind the radiation environment:

- [Space Radiation Hazards and the Vision for Space Exploration](#), National Academy Press, 2006.

Physical Shielding Concepts

For space missions, shielding is the first line of defense against the radiation environment. The purpose of shielding is to reduce exposure so that the cumulative total is below permissible limits, ideally substantially below the limits in accordance with the philosophy “as low as reasonably achievable.” As an incident particle interacts with material shielding it loses energy until ultimately it transits the shielding at lower energy or comes to a halt. Along the way, the energy it gives up is absorbed by the shielding

material or is transferred to secondary energetic particles which, in turn, continue losing energy as they transit through the shielding.

For particles with energies less than a few GeV/nucleon) the rate of energy loss increases as the particles slow down, but less ionizing secondary particles are also generated. Thus, the dose and effective dose may slightly increase relative to no shielding, particularly if the shielding material is high z (metals, for example), before shielding becomes effective in reducing them, as may be seen in Figure 2, adapted from Wilson *et al* (1997).

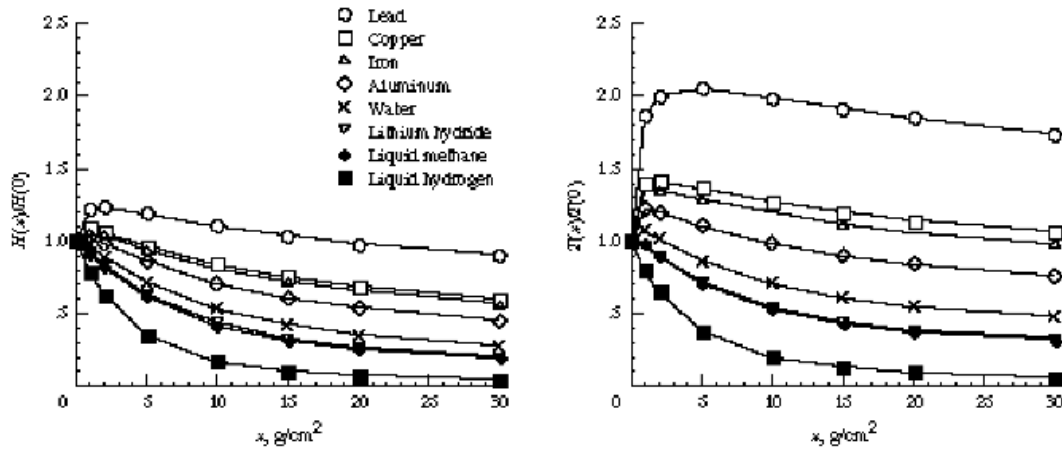


Fig. 2. Attenuation of dose equivalent and cell transformation in one year exposure behind several shield materials (Wilson *et al.*, 1997).

In Fig. 2a, the authors plot the ratio of dose-equivalent due to one year's exposure to GCR at a given depth to the dose equivalent from the same exposure, at the entrance to a slab of the material listed. In Fig. 2b, the authors plot the similar ratio of cell transformation using a model for neoplastic transformation of C3H10T1/2 mouse cells for illustration. The differences illustrate that the usual dose equivalent approach to radiation protection does not necessarily reflect detailed biological consequences of GCR radiation exposure. It also illustrates the advantage of using low- Z materials (e.g., hydrogen) relative to high- Z materials like lead. This advantage is due to the complex interaction of changes in LET and in particle fluence as a function of depth, discussed elsewhere in THREE. The ideal shielding material would be pure hydrogen. Since that is not realistic, in practice low Z material with appropriate structural strength can be employed where practical. Water and polyethylene are good examples of effective shielding material. Low Z composites, approved for spacecraft applications, can be used as substitutes for interior structural elements.

Eventually, however, the dose and effective dose decreases with increasing shielding, as can be seen in Fig. 2, and also in Fig. 3 below. Space suits are generally considered to have thicknesses of a fraction to a few g/cm^2 . Thin spacecraft, such as the Apollo lunar lander, had average thickness on the order of a few g/cm^2 . The Apollo command module had a nominal thickness on the order of ten g/cm^2 . The space shuttle and ISS nominal thickness is on the order of tens of g/cm^2 .

Figure 3 illustrates that shielding thickness against GCR has diminishing return but high system mass penalty (cost). As the aluminum equivalent of shielding increases from 0 to 50 g/cm^2 , the dose equivalent in the blood forming organs (represented in the figure as the dose equivalent in tissue beneath an additional 10 g/cm^2 water) decreases from just over 70 cSv/yr to just under 50 cSv/year.

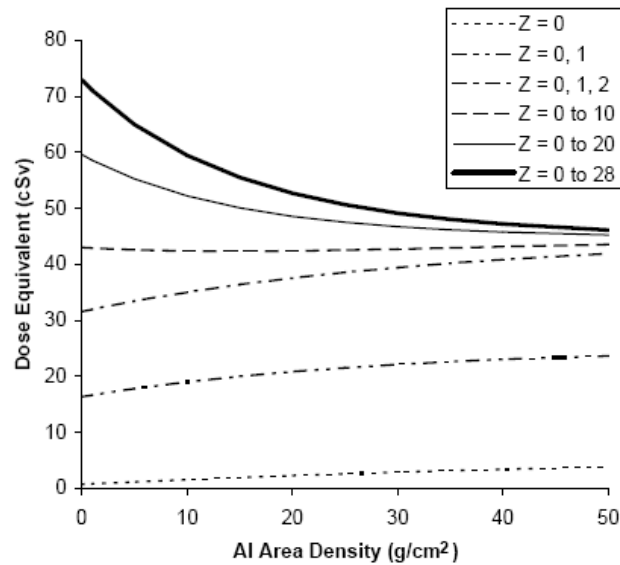


Figure 3: NRC 2008. Annual dose equivalent in cSv for the 1977 GCR solar minimum spectrum of Badhwar and O’Neill as a function of aluminum shielding area density plus 10 cm of water (to approximate body self-shielding for bone marrow).

To see the magnitude of the mass penalty for a modest percent reduction, assume the first 10 g/cm² is provided by a roughly cylindrical shell with dimensions of the ISS Destiny Module:

- Length: 8.53 m (28 ft)
- Radius: 2.13 m (7 ft)
- Surface Area ($2\pi r (r + L)$): 1.4×10^6 cm²
- Mass: 14,520 kg (32,000 lb)

At this point, the annual BFO dose equivalent is approximately 60 cSv. The next 10 g/cm² to cover the 1.4×10^6 cm² surface area would be another 14×10^6 g, doubling the mass of the module. But this additional 10 g/cm² only reduces the BFO dose equivalent by about fourteen percent, to 52 cSv. To get a twenty-five percent reduction would require three more layers, each 10 g/cm² thick, increasing the total mass of the module by more than a factor of five over the base mass (each successive layer is added to a larger cylinder with larger surface area to cover.)

In contrast to the highly penetrating GCR, radiation from SPEs can be effectively reduced with reasonable shielding coupled with a “storm shelter” for the largest events (See Figure 4). Note, however, this approach assumes adequate warning is available to enable the astronauts to move to these heavily shielded areas, since prolonged exposure to a large event under thin shielding (less than a few g/cm²) will lead to increased cancer risk and can lead to acute effects such as nausea or skin damage (Figure 5).

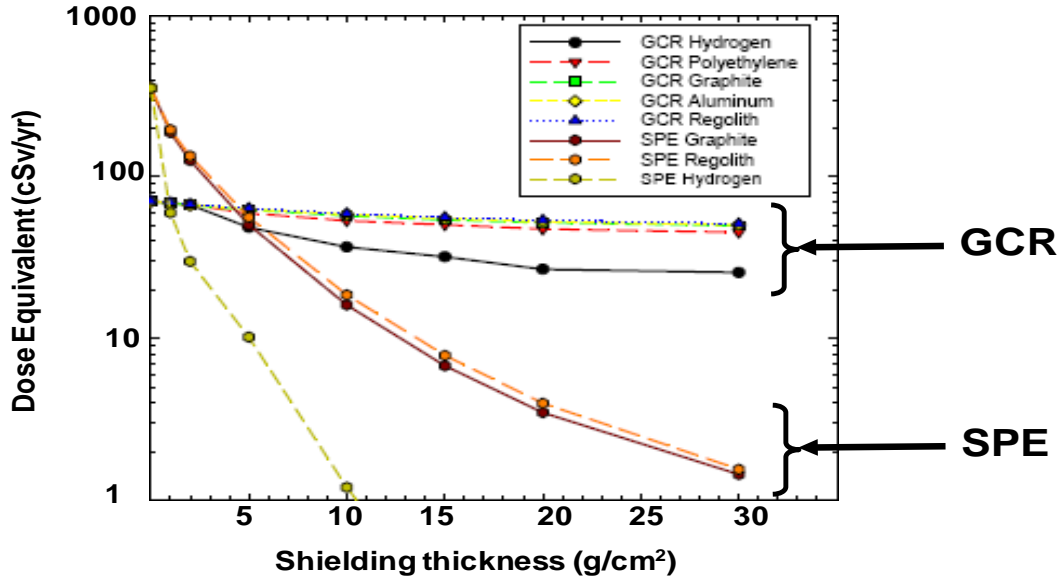


Figure 4: Dose equivalent under increasing shielding depth for both solar minimum GCR and August 1972 SPE for a variety of shielding materials. Source: Radiation Risk Assessments for Lunar Missions-Shielding Evaluation Criteria, Francis A. Cucinotta, presented to the NAS Lunar Shielding Study Panel December 12, 2006

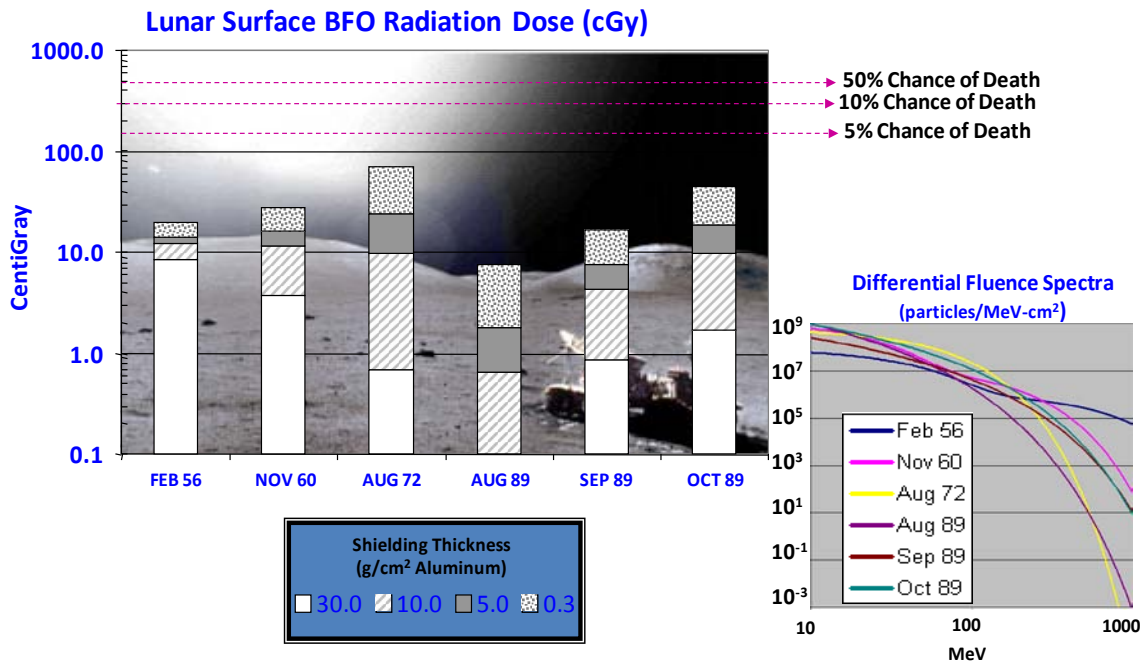


Figure 5: Absorbed dose for select historically large solar particle events under a range of shielding thicknesses.

Use of in situ resources

It is occasionally proposed that future lunar bases take advantage of natural caves known to exist (lava tubes) to provide ready-made radiation shelter (and thermal stability). In the near term, it is possible to rely on layers of lunar regolith as shielding material. A trade-off ensues between the cost to bring

shielding from Earth, and the cost of first bringing associated regolith-moving equipment (digging, transporting, and placing the regolith) added to the cost to operate the equipment (both in terms of the power and the astronaut time). A recent NRC study (NRC 2008) looked at the feasibility of lunar regolith for shielding, and concluded:

“For sortie missions, it is likely that regolith shielding will not be practical. However, as missions lengthen the utility of the shielding increases. Furthermore, constructing an outpost means that the cost of shielding construction is amortized over the duration of the program. This will be true of either sculpted regolith or of shielding that has been brought from Earth but left behind when the Lunar Lander departs.”

Active Shielding

The possibility of generating an electromagnetic field around a spacecraft to deflect the high energy particles, similar to the way that the Earth’s magnetic field operates, has been proposed numerous times and has been studied extensively and in great detail. Careful analysis of such concepts shows that all proposed methods to generate such fields are either in violation of physical principles or thoroughly impractical. The most significant issue is the field strength required to deflect, high energy particles, especially high Z nuclei found in the GCR. The most popular schemes are systems that employ superconducting magnets. Such systems have a high mass penalty, a mass that provides no more attenuation than the same mass of passive shielding. In addition, there is the system safety issue associated with the very high energy stored in the fields, equivalent to the energy of a nuclear explosive. Magnet quenching, resulting from minute frictional heating inside the superconducting wires, could lead to a catastrophic loss of mission. Even if the fields are turned off safely, for example, to enable astronauts to exit for an EVA, a similar amount of energy is needed to re-establish the fields and would have to be generated in space.

Transport Codes

In the previous section references were made to nominal thickness of “typical” space suits and spacecraft. In practice, any point in a vehicle is surrounded by a complex distribution of thickness and material composition, which varies with the location within the vehicle. It is impacted by windows, structure, wiring, plumbing, water and fuel tanks, waste storage, electronic modules, etc, and exterior elements such as solar panels, antenna, and instrument booms. When calculating the human exposure, even the self shielding of the body must be taken into account to get an accurate estimate of the variation of dose between the skin and various internal organs. On the surface of the Moon or Mars, the effective shielding will depend on the topography of the local terrain (are you on a mountaintop, next to a cliff, or in a crater or valley?) On Mars there will be natural shielding from the atmosphere which will vary significantly with height above the mean surface, or the Martian analogue of Earth’s “sea level”.

NASA uses state-of-the-art radiation transport codes and CAD-based models to reflect increasingly more sophisticated representations of the actual spacecraft shielding distribution, composition, and surroundings (see Figure 6 and Table 1). These modeled results are validated through comparison to measurements taken on board the shuttle and ISS.

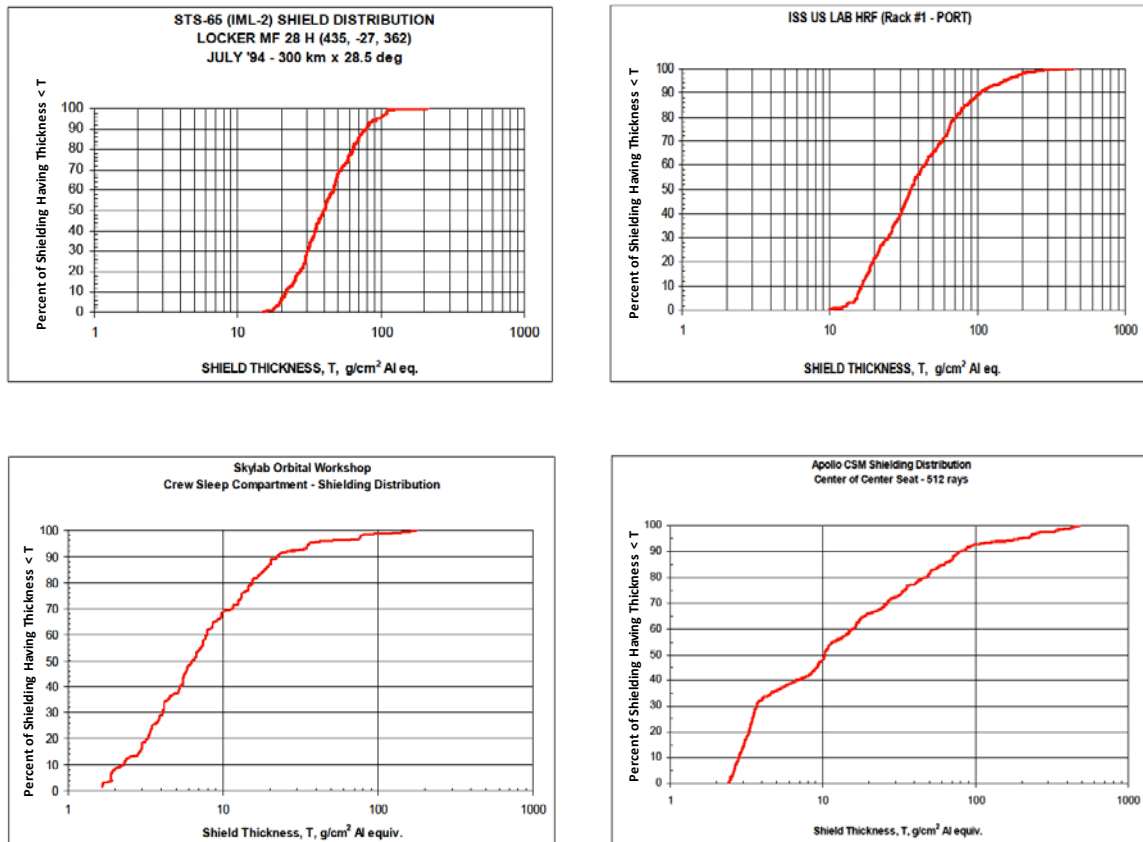


Figure 6: Representations of the aluminum-equivalent shielding distribution at specific locations within four vehicles: Apollo Command module, Skylab, Space Shuttle, and ISS (lab module). Figure courtesy Bill Atwell, Fellow, Boeing Corporation.

Table 1: Representation of the complexity involved in realistic calculations of transport through shielding: the Shuttle Space Suit Assembly, from Wilson, et al, NASA Conference Publication 3360, 1997

A: Material layups (from exterior to interior) for the helmet of the Shuttle spacesuit

Layer	Material	Areal Density g/cm ²
Outer layer	Orthofabric Cover- Teflon/Nomex/Kevlar	0.049
Insulation	Reinforced aluminized Mylar - 5 plies	0.004
Spacer	Non-woven Dacron -5 plies	0.011
Inner liner	Teflon	0.028
EVVA shell	Polycarbonate	0.381
Sun visor	Polysulfone	0.19
Eye shades	Polysulfone	0.19
Protective visor	Polycarbonate	0.182
Helmet bubble	Polycarbonate	0.182
Total		1.217

B. Material layups (from exterior to interior) of hard upper torso of the Shuttle suit

Layer	Material	Areal Density g/cm ²
Outer layer	Orthofabric Cover- Teflon/Nomex/Kevlar	0.049
Insulation	Reinforced aluminized Mylar - 5 plies	0.014
Inner liner	Neoprene coated nylon ripstop	0.028
Hard shell	Fiberglas	0.354
LCVG	Spandex/water/Ethyvinylacetate	0.154
Total		0.599

C. Material layups (from exterior to interior) for the lower torso (arms and legs) of the Shuttle suit

Layer	Material	Areal Density g/cm ²
Outer layer	Orthofabric Cover- Teflon/Nomex/Kevlar	0.049
Insulation	Reinforced aluminized Mylar - 5 plies	0.014
Inner liner	Neoprene coated nylon ripstop	0.028
Pressure restraint	Dacron	0.021
Pressure bladder	Urethane coated nylon ripstop	0.014
LCVG	Spandex/water/Ethyvinylacetate	0.154
Total		0.28

Dosimetry

Dosimetry is an essential component of any shielding strategy. Passive dosimeters measure the cumulative dose through the mission, while active dosimeters provide near real time dose rate information. Dosimetry measures the effectiveness of the shielding and temporal fluctuations in the radiation environment during its use. Thus, it provides essential cues for operational measures involving crew actions to seek refuge (e.g., move to a “storm shelter” during an SPE, limiting EVA exposure, or a planetary surface sortie). Maintaining active dosimeters with the astronauts through all phases of the mission ensures against over-reliance on forecasts or on instruments at different locations.

On the space shuttle, NASA provides an operational dosimetry system to monitor individual astronaut exposures, and to monitor the radiation environment. A Crew Passive Dosimeter (CPD) is provided to each astronaut, who is required to wear it through all phases of the mission, including EVAs. Six Passive Radiation Dosimeters (PRDs) are provided for each flight at various locations inside the crew compartment. An Area Passive Dosimeter (APD) and pocket ion chambers are stored in a middeck locker with the Shuttle medical kits. A Tissue Equivalent Proportional Counter (TEPC) is hard-mounted in the middeck for high-altitude (greater than or equal to 205 nautical miles) and/or high-inclination flights (greater than or equal to 50 degrees).

On the ISS, each astronaut wears a Personal Radiation Dosimeter throughout the mission. In addition, there are passive and active radiation monitors throughout the ISS. The active monitors include:

- Intra Vehicle Charged Particle Directional Spectrometer (IVCPDS)
- Extra Vehicle Charged Particle Directional Spectrometer (EVCPS)
- Tissue Equivalent Proportional Counter (TEPC)

For more about operational dosimetry, go to <http://srag.jsc.nasa.gov/>

Solar Storm Alerts and Warnings

The third component in a comprehensive shielding strategy provides alerts and warnings for pending solar storms. This section describes the various components of a system, or architecture, that may be employed to produce the space weather data needed for SPE and SPE-precursor observations, ultimately to reduce the risk these events pose.

A comprehensive architecture would monitor the Sun, the heliosphere, the near-spacecraft energetic particle environment, the trapped radiation environment (for Earth-orbiting operations) and would have a communications infrastructure complete and robust enough to get the right information to the right users. This approach is summarized in Figure 7.

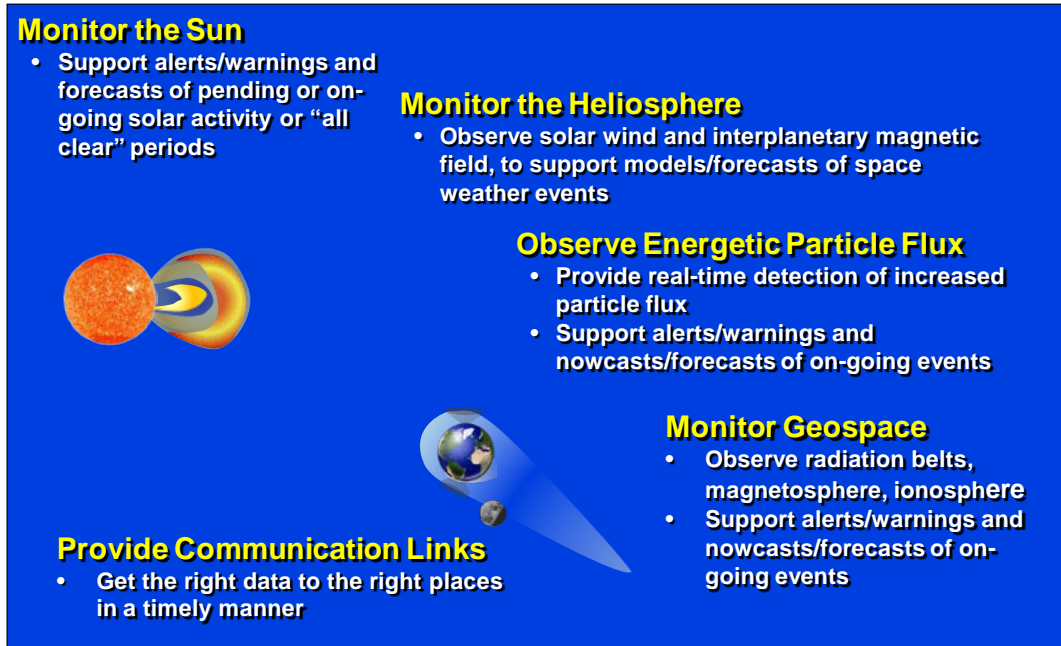


Figure 7: Space Weather Observations that contribute to solar warning forecasts.

Solar monitoring is required to place the forecasts and observations of SPEs into a context of ongoing and potential solar activity. Near-real time observations of solar active regions and emerging Coronal Mass Ejections (CMEs) may provide data useful to predict the occurrence and project the progress of an SPE over a period of hours to days. Additional progress in understanding the physics of CMEs is required to get to a multiday forecast of the probability of a CME eruption and its potential for producing an associated SPE. Equally useful, and more readily attainable in the near term, would be a reliable forecast that there would not be a significant CME/SPE over the next few days (an “All Clear Forecast”).

A variety of solar monitoring instruments are needed to support SPE forecasts, from solar surface imagers (observing the Sun in visible, ultraviolet, X-ray, and radio wavelengths) to solar coronagraphs observing the near-Sun heliosphere from a few to a few tens of solar radii. There is an extensive suite of research spacecraft and ground-based facilities providing experience and proof of concept from which we will be able to select the appropriate operational instruments for an SPE risk mitigation architecture. NASA’s SOHO, STEREO, and the soon-to-be-launched SDO, are significant examples.

The sun rotates with a period of about 27 days (the rotation rate varies with solar latitude). Among other effects, this leads to a spiral form to the interplanetary magnetic field (IMF) (imagine an overhead snapshot of the water streaming from a rotating water sprinkler). Since high energy particles accelerated by solar storms follow the IMF, active regions that may spawn earth-impacting storms could be around

the leading, west limb of the sun not visible from Earth. Similarly, evolving active regions rotating toward the earth are out of view behind the trailing solar east limb. Today operational solar monitors are either in orbit around the Earth or are in the Earth-sun line at the Lagrange L1 point (about 100 Million km from earth toward the sun). Operational solar observations to date are taken from sensors near Earth. A more complete picture of the state of the sun would involve observations taken away from the Sun-Earth line. Solar activity near or over the west limb may impact the Earth. Active regions that will rotate into a position threatening Earth may be evolving out of sight of the Earth beyond the east limb. A more complete picture of solar regions that threaten or may threaten the Earth may require “off-axis” solar monitors, as shown in Figure 8. NASA’s twin STEREO spacecraft are providing proof of concept of the value of off-axis viewing of the sun, with one spacecraft leading and one trailing Earth at gradually increasing separation.

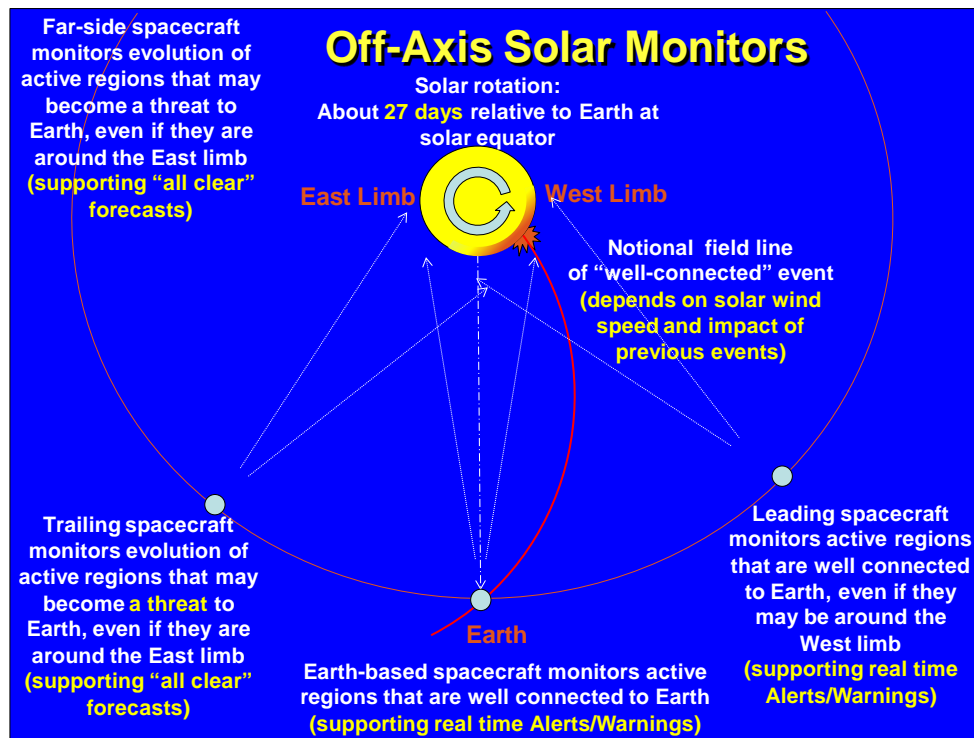


Figure 8: Operational solar observations to date are taken from sensors near Earth. A more complete picture of the state of the sun would involve observations taken away from the Sun-Earth line.

Heliospheric observations provide information necessary to model or monitor the propagation of solar energetic particles from the source to the astronauts. Density fluctuations from solar emissions and from boundaries between slow and fast solar wind streams affect the shape of the interplanetary magnetic field, along which the energetic particles move. They also affect the strength, structure, and motion of CMEs and the associated shocks that accelerate the energetic particles. The data that may be necessary for SPE propagation models include information on the general state of the solar wind plasma, the interplanetary magnetic field, and local disturbances moving through the inner heliosphere. Both in situ and remote sensing methods may contribute to the characterization of the heliosphere. The in situ instruments are typically small, low-cost sensors with long heritage. Remote sensing techniques include white light observations of interplanetary mass density fluctuations and recently implemented observations of interplanetary radio signals that may provide a measure of CME shock speed.

Direct measurements of in situ solar energetic particles will continue to provide the most important contributions to an SPE risk management strategy. Measurements at the astronauts’ location will be able to confirm that a solar particle event is underway and to provide information about the flux, rate-of-

change of flux, and total fluence of the event. In addition, instruments may be needed to measure the relative contribution to the total flux from particles with different energies, from tens of MeV through several hundred MeV. Finally, it may be necessary to identify the flux of high energy, high mass ions that make up an on-going SPE. Additional energetic particle measurements at locations significantly away from the astronauts may also contribute to forecasting the evolution of an on-going event. A variety of instruments are available to provide these measurements, including particle telescopes, solid state detectors, and proportional counters.

Space Environment Models

Near-term forecast tools are needed to provide estimates of the probability of an event within the next few hours to days and the expected peak flux, time to peak flux, total fluence, and duration of predicted events.

There is no capability to predict SPEs one to a few days in advance, because today there is no capability to predict the onset or character of CMEs. Even after an SPE has been observed to be under way, forecasts of peak flux are only good to within an order of magnitude or worse. The two operational forecast models are PROTONS, developed by the NOAA Space Weather Prediction Center (SWPC), and Proton Prediction System, PPS, developed by the Air Force. These models are inherently limited by the fact that they are fundamentally based on x-ray flare proxies to the SPE. A related major weakness of each of these models is an inability to predict shock enhancements to the proton flux — potentially the most dangerous period to a human in space.

SWPC provides a one to three day probability estimate of energetic particle activity (along with estimates of the probability of significant x-ray flares and geomagnetic activity). The particle event forecast is based on qualitative observations of on-going solar activity and solar active regions and their history. Long-lived active regions occasionally have a pattern of multiple eruptions. NOAA may upgrade the potential for a particle event when a region that produced one on a previous solar rotation (with a period of about 27 days) returns.

NOAA SWPC routinely monitors x-ray flux, solar radio bursts, and other indicators of significant solar activity. When there is evidence that an SPE may be likely, the SWPC uses a computer program, PROTONS, to estimate the likelihood and potential magnitude of the event. PROTONS is a phenomenological / empirical model of SPEs first developed in 1972 and modified incrementally as experience accrued.

The United States Air Force does not attempt one to three day proton event forecasting but operates in a “near-term mode” and generates system-specific forecasts (the times when a specific system might expect interference from solar protons) within 15 minutes after the occurrence of a significant solar flare.

Both PROTONS and PPS have orders of magnitude uncertainty in intensity forecasts, as illustrated in Figure 9 for PPS (similar charts are available for PROTONS). Significant advances in near-term forecast capability will require the development of a physics-based model that incorporates the current understanding of the relationship between CMEs and SPEs.

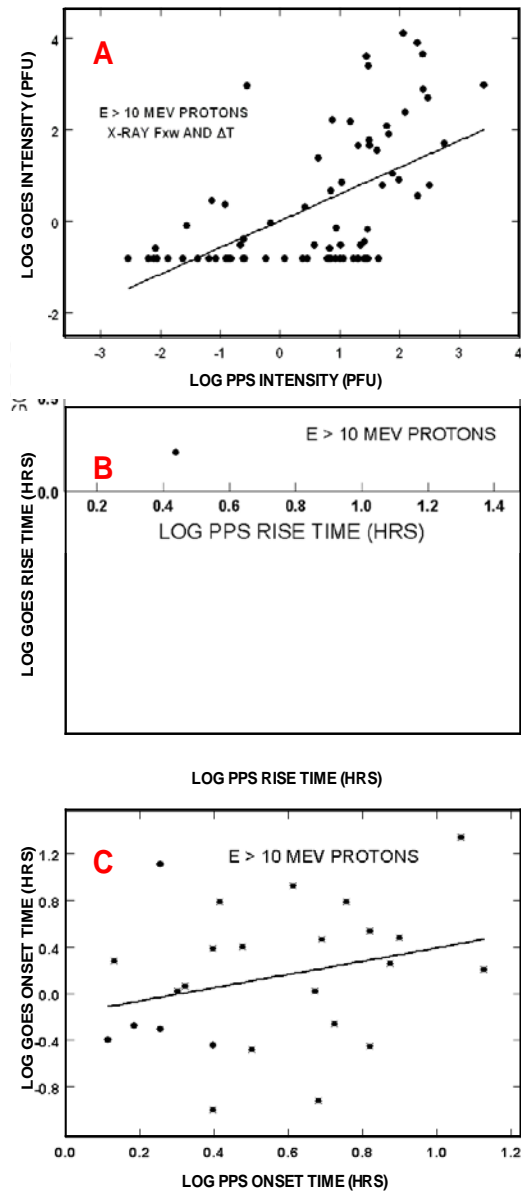


Figure 9. Comparison of PPS prediction with NOAA SPE observations for A. Peak intensity, B. SPE rise time, and C. SPE onset. [Kahler, S. W., E. W. Cliver, A. G. Ling, Validating the proton prediction system (PPS), Journal of Atmospheric and Solar-Terrestrial Physics (JASTP), 2006].

Forecast Centers

Operational space weather support is provided today through a close working relationship of:

- The NOAA Space Weather Prediction Center
- The Space Radiation Analysis Group
- The Crew Surgeon and the Radiation Health Officer

NOAA Space Weather Prediction Center (SWPC) monitors and forecasts space weather activity. The Space Radiation Analysis Group (SRAG) at the NASA Johnson Space Center is responsible for ensuring

that the radiation exposure received by astronauts remains below established safety limits. The Crew Surgeon provides the overall safety evaluation of crew radiation risks to the Flight Director. The Radiation Health Officer (RHO) is an interface between the Crew Surgeon and SRAG.



Figure 10: NOAA's Space Weather Prediction Center (www.swpc.noaa.gov)

The Space Weather Prediction Center (SWPC), located in Boulder, Colorado, is one of nine National Weather Service National Centers for Environmental Prediction. (See Figure 10). It is responsible for issuing alerts and warnings of hazardous space environment conditions that may impact US civil or commercial concerns. SWPC provides real-time monitoring and forecasting of solar and geophysical events, conducts research in solar-terrestrial physics, and develops techniques for forecasting solar and geophysical disturbances. Data sources include

- NOAA-operated operational spacecraft (GOES and POES)
- Ground-based solar optical and radio telescopes
- Ground-based magnetometers
- Ground-based neutron monitors
- Data, as available, from instruments on NASA and ESA science missions
 - ACE
 - SOHO
 - STEREO

Space environment data are posted in near-real-time on a website accessible to the public. SWPC develops and maintains operational models to forecast the space environment. It produces a variety of products for the space weather community, including daily, weekly, and monthly routine reports. Alerts and warnings are sent to a broad distribution of recipients via email, phone, or pagers at the users' request.

Communications

The communications infrastructure is an often overlooked element of a risk management infrastructure. Typically the discussion about communications focuses on the data link between a satellite and a ground antenna. However, to ensure that all elements of a risk management system work together to provide timely, accurate, accessible, and actionable information, the communications system is much more than the data link from sensors to Earth antennae.

- **Timely:** time from collection through delivery to end user is consistent with operational planning requirements
- **Accurate:** Observations and subsequent derived products are reliable, validated, and at appropriate fidelity for operational use

- Accessible: At each step in the process from collection through final action, content is provided in appropriate format for subsequent processing and the end product clearly conveys actionable options to decision makers
- Actionable: Clear and concise instructions are provided to the mission elements

Figure 11 illustrates components of an end-to-end communications infrastructure. It is important to include these components into the architecture from the outset. There may be a variety of sensors on multiple platforms that provide data to forecast models. Multiple models may be needed to create a clear picture of an evolving radiation environment. Once generated, the environment forecast must then be assessed by mission support in the context of the on-going mission, and risks associated with alternative courses of action must be compared to commensurate risks associated with aborting or delaying planned mission objectives. Mission control must then make the call on a specific course of action. This must then be relayed to and understood by the affected mission elements in time to respond.



Figure 11: Illustration of components of an end-to-end communications infrastructure, with an indication of factors that contribute to the timeliness of actionable response.

Summary

The three elements of a shielding strategy include physical shielding, employing an effective operational concept to respond to direct observations of enhanced radiation, and providing an infrastructure to provide actionable alerts and warnings of pending solar storms. Today, SPE forecasts, based by heritage on the x-ray flare paradigm, are inadequate to provide advance warning with sufficient credibility to lead operators to initiate proactive protective measures. As a result, SPE risk management is largely based on “cope” (through adequate shielding) and “avoid” (canceling activities during periods of observed elevated flux). While adequate shielding and direct monitoring of the radiation dose will continue to be the mainstay of astronaut defense against the radiation health risk, research on SPEs and CMEs suggests that the space weather community is on the verge of substantial improvements in understanding CME eruption and solar energetic particle acceleration and propagation. This improved understanding, combined with the observatories and sensors that can be available, will provide the comprehensive space weather data necessary to implement physics-based SPE risk management. In the near term that may lead to longer periods of “all-clear” forecasts, enabling scheduling of otherwise risky endeavors (extended EVAs, and longer transits from a home base in lighter, more energy-efficient transports). In the long

term, multiday forecasts of radiation flux could expand the “all-clear” and “low-risk” forecasts. This could enable shielding methodologies that may reduce the total shielding mass (for example by reconfiguring the spacecraft for “just-in-time” shelters that are more crowded but for shorter time periods), minimizing the discomfort and disruption to the crews.

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