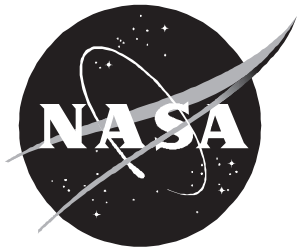


NASA Technical Paper 3668

Exposures to Solar Particle Events in Deep Space Missions

John W. Wilson, Judy L. Shinn, Lisa C. Simonsen, and Francis A. Cucinotta
Langley Research Center • Hampton, Virginia

R. R. Dubey and W. R. Jordan
Old Dominion University • Norfolk, Virginia

T. D. Jones
Oak Ridge National Laboratory • Oak Ridge, Tennessee

C. K. Chang
Christopher Newport University • Newport News, Virginia

M. Y. Kim
Langley Research Center • Hampton, Virginia

National Aeronautics and Space Administration
Langley Research Center • Hampton, Virginia 23681-2199

October 1997

Available electronically at the following URL address: http://techreports.larc.nasa.gov/ltrs/ltrs.html

Printed copies available from the following:

NASA Center for AeroSpace Information
800 Elkridge Landing Road
Linthicum Heights, MD 21090-2934
(301) 621-0390

National Technical Information Service (NTIS)
5285 Port Royal Road
Springfield, VA 22161-2171
(703) 487-4650

Abstract

The physical composition and intensities of exposures to solar particle events of sensitive astronaut tissues are examined under conditions approximating an astronaut in space. Response functions for conversion of particle fluence into dose and dose equivalent are used to establish significant fluence levels and the expected dose and dose rates of the most important events from past observations. The BRYNTRN transport code is used to evaluate the local environment experienced by sensitive tissues and is used to evaluate bioresponse models developed for use in tactical nuclear warfare. The present results will help to clarify the biophysical aspects of such exposure in the assessment of relative biological effectiveness (RBE) and dose rate effects and their impact on the design of protection systems for the astronauts. The use of polymers as shielding material in place of an equal mass of aluminum would provide a large safety factor without increasing the vehicle mass. This safety factor is sufficient to provide adequate protection if an event a factor of 2 larger than has ever been observed occurs during the mission.

Introduction

Solar cosmic radiation has long been recognized as a serious potential hazard in space operations (ref. 1). Also the provision of sufficient shielding to keep exposures at low levels was recognized to increase the complexity of spacecraft with associated increased risks of mechanical failure; trade-off of radiation health risks with the other mission risks became the rule in the early space activity. As a result of the national importance of the Apollo Project (Apollo missions) to land men on the Moon, rather high levels of exposure were allowed in the design process because other risks within those missions were also high, and a balance of radiation risks and the other mission risks were assumed (ref. 2). The exposure limits allowed in the design for the Apollo mission are given in table 1. With the development of Skylab, Space Shuttle, and now International Space Station Alpha (ISSA), the routine nature of space operations has lead to a more conservative view of risk acceptability in space exposures (ref. 3). Indeed, the National Council on Radiation Protection and Measurements (NCRP) has recommended the use of low Earth orbit (LEO) exposure limits for Space Shuttle and ISSA operations (table 2) as a guideline for shield design in deep space exploration (ref. 4).

An earlier study of the exposures received in deep space operations (the term “deep space” is used to refer to operations outside the protective magnetic field of the Earth) revealed that the solar event of August 4, 1972, was the most important observed event and could deliver a potentially lethal dose within several hours (ref. 5). This revelation was a sudden departure from earlier observed solar events that presented serious exposures but viewed early lethality as only a remote possibility. More recent studies using the August 1972 database on exposure estimates evaluated dose rate effects as being an important sparing factor (as a result of cellular repair and repopulation) in survivability (ref. 6). In the study of reference 6, a conservative approach was taken in that dose equivalent rates were used and assumed equivalent to exposures of 250 kVp X rays (ref. 7).

Many issues concerning the uncertainty in the associated health risks in space exposures remain to be resolved before one can confidently commit to new missions in deep space, and a clearer understanding of the nature of the expected exposures is a prerequisite in future radiobiological studies. In the present paper, a relatively complete picture is given of the exposures which would have been received by an astronaut in deep space for the solar particle event of August 4, 1972, and some of the protection-related issues are discussed.

Solar Particle Event Protection

Particles arriving at some remote location from the Sun diffuse through the interplanetary media and show some anisotropy in that the backscattered particles are absent on the leading edge of the expanding radiation field. Following the first 20 to 30 min after initial particle arrival, isotropy is usually achieved. The radiation fields that are incident on the spacecraft are assumed to be isotropic. The exposure of the blood forming organ (BFO) of the astronaut represented as five BFO compartments (skull, arms, legs, lower torso, and upper torso) due to a monoenergetic source of isotropic protons is shown in figure 1 as a function of proton energy for three typical shield representations assumed to be aluminum structures (space suit of 0.4 g/cm^2, pressure vessel of 1 g/cm^2, and equipment room of 5 g/cm^2). First note that the effect of shielding is to move the shape of the response curves to greater energies with little change in shape or magnitude. The shape of the response curves does depend on the BFO compartment as determined by the mass distribution of the rest of the astronaut’s body about

each compartment. In the present calculation, the computerized anatomical model (CAM) that is described in reference 8 is used. From figure 1, we surmise that the distribution of exposure within the BFO is nonuniform, which may be an important factor in evaluation of astronaut exposure risks (ref. 9).

The average BFO response is shown in figure 2 with the response for other identified critical organs (ocular lens and skin) for which exposure limits (table 2) are given (ref. 4). A critical fluence level is defined as one in which the exposure is approximately the exposure limit which is on the order of 5×10^8 protons/cm^2 for the BFO and 2×10^8 protons/cm^2 for the skin and ocular lens. A potentially debilitating event would be about 1 order of magnitude larger than these critical fluence levels because early radiation syndrome occurs at dose levels on an order of magnitude larger than the values in table 2. The energies at which the significant fluence is evaluated depends on the organ and shielding as shown in table 3. Clearly any solar particle event whose fluence exceeds these levels for the specific shielding of the astronaut requires careful consideration. The limiting biological factor depends on the spectral content in the specific event which differs from event to event as seen.

A recent evaluation of the historic events for the years 1955 to 1986 was given by Shea and Smart (ref. 10). Since 1986, data are available from the episodes of 1989 during the maximum phase of solar cycle 22 given by Sauer, Zwickl, and Ness (ref. 11) from the GOES-7 satellite. These events are summarized in table 4. The estimates of Foelsche et al. (ref. 12) based on nuclear emulsion measurements in sounding rockets for the November 12–13, 1960, event were used. The interplanetary monitoring platform (IMP) satellite data were used for the August 1972 event. From table 4, several events are shown to have the potential to exceed the skin and lens limits (that is, fluence levels above 20 MeV on the order of 2×10^9) but only a few events are likely to cause significant BFO responses (that is, fluence levels above 70 MeV on the order of 5×10^9). The clearest examples are the August 1972 and the October 1989 events. More careful analyses with computational models show the August 1972 event as the defining event for radiation protection practice (refs. 5 and 13). Only the August 1972 event has the ability to cause a potential lethal exposure (refs. 5 and 13). Clearly the August 1972 event dominates in the range of 70 to 100 MeV as seen in figure 3 which is most important to the BFO. In addition to the importance of the spectral content of the August 1972 event, the dominant portion of the exposure occurred over several hours compared with 3 days of the October 1989 event for which repair and repopulation will play vastly different roles.

Aside from the total fluence, the dose rate is an extremely important parameter. Some somatic threshold doses are observed to double with the reduction of dose rate by a factor of 10 (ref. 14). The large events in table 4 lasted for several hours to several days, and factors dependent on dose rate are expected to be important. The particle intensities of the August 1972 event are shown in figure 4. The temporal behavior is seen to be highly structured and reflects the complicated nature of the sources of these events and the associated interplanetary media. Current theory would associate this event with coronal mass ejections which occur within the disturbed region on the Sun. The particle flux is generated in the shock boundary of these ejected masses and the relatively undisturbed interplanetary medium. Superimposed on the general structure of particles arriving at 1 au are short-term increases as the shock boundaries pass the observation point. These local shock events are often limited to acceleration of only low-energy protons as seen in the first shock event for the >10 MeV flux early in the event and affect only the skin dose within a space suit. The shock on the trailing edge of the main event accelerated the flux at all three energies affecting not only the skin dose but substantial contributions to the BFO exposure. Clearly the dose rates for specific organs can be quite different and depend on the energies to which the organs are most sensitive and the spectral content of the event.

Dosimetric and Shielding Evaluation

An exponential rigidity spectrum was used to interpolate with continuity at the 30 MeV data and extrapolation above 60 MeV according to an exponential energy spectrum with a characteristic energy of 26.5 MeV for a decrease of 1/*e*. The resultant data are used to evaluate the particle spectra at specific tissue sites by using the BRYNTRN code (ref. 15). The protons are transported through the shield and the astronaut's body to the tissue point with the atomic and nuclear processes represented. The tissue environments integrated over the event are shown in figures 5, 6, and 7 for the three shield configurations. The local tissue environment is complex as a result of the nuclear reactions in the shield and the astronaut's surrounding body tissues. Although most protons present at the tissue sites shown in the figures are those incident on the outer shield surface and transported into the body interior, significant numbers of protons appear as secondaries. The neutrons are largely the product of nuclear reactions in the aluminum shield as can be seen by comparing the three shield configurations. Although the neutrons themselves contribute negligibly to the dose or dose equivalent, they have their effects on the remaining components shown. The local dose and dose equivalent are made up of the energy transfer processes

of the atomic collisions of these components plus an added contribution of the multiple charged components of atomic number greater than 2. The neutrons then play the role of transporting energy deeper into body tissues and impact the biology mainly through the production of secondary charged particle components through collisions with tissue nuclei which subsequently interact with local tissues through atomic processes.

In the current version of the BRYNTRN code, the cross sections for neutron and proton production are taken from the Bertini database (ref. 16) associated with the HETC (ref. 17) or the LAHET Monte Carlo codes (ref. 18). These cross sections are not able to describe the light ion production in collisions with the shield material as found in experimental studies aboard the Space Shuttle (ref. 19). The current light ion database is derived from cluster knockout models for not only the proton and neutron but also light ion-induced reactions; this results in very energetic light ion production and light ion breakup calculations (ref. 20) as required to match Space Shuttle experiments.

The average linear energy transfer (LET) distribution within the BFO is shown in figure 8 for the three shield configurations. About a factor of 4 decline is noted in total charged particle fluence within the BFO in increasing the shielding from 0.4 to 5 g/cm^2. The fluence near and above 100 keV/μm is less affected by the shielding due to the compensation of loss in penetrating protons in atomic and nuclear collisions by secondary neutron production mainly in the shield and transport to the BFO region. The distribution of LET components as contributions to dose equivalent is shown in figure 9. Slightly less than half the dose equivalent is from high LET components (LET > 10 keV/μm). This fact is most important in that the high LET radiations are less affected by dose rate effects compared with the low LET components. This independence of dose rate effects is interpreted as evidence that irreparable damage results from high LET exposures (ref. 7). Tissue recovery from high LET exposure components occur mainly through repopulation.

The dose and dose equivalent rates in the three critical organs are shown in figures 10, 11, and 12. The radiation quality at the skin and lens is variable throughout the event in the space suit and pressure vessel. The radiation quality in the equipment room is nearly time independent. The radiation quality within the BFO depends less on both shielding and time. The dose equivalent rates for the skin and lens can be very high (1 to 10 Sv/hr in a space suit and 1 to 3 Sv/hr even in a pressure vessel). The BFO exposures are about a factor of 10 or more smaller (10 to 20 cSv/hr in a space suit or a pressure vessel and 5 to 7 cSv/hr in the equipment room). The total dose and dose equivalent are given for the three critical tissues in table 5. The provision of a shelter with 10 g/cm^2 of aluminum will provide sufficient shielding to meet the 30-day limits in table 2. The exposure levels in the equipment room or shelter in table 5 can be reduced by large factors by replacing much of the aluminum structure with polyethylene of the same total mass as seen in comparing with table 6. Exposures on the lunar surface would be as low as half the values in the tables because the lunar mass provides a shadow shield over half the solid angle.

The problem of shield design for protection from such events is complicated by the statistical nature of solar particle event occurrence. The confidence level is about 97 percent of not exceeding the fluence level above 30 MeV from the August 1972 event on a 1-year mission near the next solar maximum (ref. 21). (Note that high annual fluence levels are usually dominated by the largest event within the year.) To achieve 99.5 percent confidence level above 30 MeV, one must assume a fluence level about 4 times the August 1972 event or approximately 10 times the fluence of the October 1989 events. To make an exact assignment of ratios is difficult because the spectral contents of the events are markedly different. We also note that 4 times the August 1972 event is not equivalent to 10 times the October 1989 event even if the fluence levels and spectral content were the same because the time structure of the events is radically different. We suggest that four times the August 1972 event be taken as an approximation to the 99.5 percentile annual fluence with the time structure that most particles arrive in several hours. A rationale for shield design may be to design for the largest event observed but recognize that it may be exceeded with 3 percent confidence. An event of four times the August 1972 event would appear as an accidental exposure not considered during the design process; one would design medical procedures to cover the possibility of accidental exposure. One can contemplate that the health of the astronaut can be severely impacted in the unlikely occurrence of a 99.5 percentile event as seen in table 7. Again the added safety provided by using an equal mass of polymer as opposed to aluminum shielding can be important as seen in table 8. Although the design limits in table 2 would be exceeded within the shelter made of polyethylene, early radiation hematopoietic syndrome is unlikely as seen from table 9; again the potential importance of organic materials for radiation shielding to add a safety margin without adding to mission launch costs is emphasized.

Accidental Exposure

The design process would be aimed at keeping exposures within acceptable limits as given in table 2 under normal operating conditions. Even so the nature of space

operations requires that work or exploration activity be extended into relatively unprotected regions (e.g., space suit or poorly shielded rover) or in living quarters, which tend to be an enclosed compartment surrounded by little more than a pressure vessel wall. The exposures can be kept at relatively safe levels by a warning to the astronaut to seek shelter in a protected region during a solar event. Even so, the occasion may arise that the shelter may not be acquired as planned and the exposures to the astronaut can be very high especially in a space suit and unsafe even in a pressure vessel as seen in table 5. Alternatively, the design may be to provide adequate protection only against the August 1972 event. Any improbable more intense event occurrence that leads to higher than anticipated exposures would be considered an accident. Exposures (given promptly) at which significant health effects occur have been summarized from various sources by the National Academy of Sciences (ref. 14) and NCRP (ref. 4) and are shown in table 9. The dose associated with 50 percent mortality (LD_{50} value) is affected by the degree of medical support; intensive medical care can greatly increase the chances of survival (ref. 4). Clearly a significant probability of early radiation hematopoietic syndrome would result unless dose rate effects are sufficiently important to reduce the risks due to cellular repair and repopulation.

The thresholds for early skin response is about 6 Sv for prompt exposures (approximately 30 min). The effects of protraction of the exposure to several hours increases the effective threshold as $T^{0.29}$ where T is the exposure time for an overall correction factor of 2.15 for the August 1972 event (raising the erythema threshold from 6 Sv to 12.9 Sv). Even then the exposures in table 5 are likely to cause early adverse skin responses even in a pressure vessel. Aside from this crude analysis, no detailed models for many tissues exist as the one for the BFO response developed by the military for field assessment in tactical nuclear warfare (refs. 7 and 22). Probably enough data exist for dose and dose rate effects on skin and crypt cells of the gut to develop a model similar to that available for the BFO.

Recent practical experience was gained as a result of the Chernobyl accident where most exposures were characterized as a relatively uniform whole-body exposure due to gamma rays and surface exposure an order of magnitude larger from beta emitters (ref. 23). This combination of exposure is somewhat similar to space exposure distributions (ref. 5) as shown in tables 5 to 8. No deaths occurred among those whose whole-body exposure at Chernobyl was less than 2 Gy. All 84 patients having exposures from doses greater than 2 Gy to the bone marrow system were given supportive care including isolation, antibiotics, and in extreme cases transfusions and transplants (ref. 23). Radiation-induced skin reaction was a complicating factor in overall treatment of the Chernobyl victims (ref. 23). Only one death occurred among the 43 exposed between 2 to 4 Gy under conditions of intense supportive care.

The diagnostics of the Chernobyl accident relied on biological and physical dosimetry. The blood elements within exposed individuals were monitored within 12 hr of the accident and used as a biological dosimeter to indicate the level of exposure. To understand this methodology, the kinetics of the marrow system are shown in figure 13. The stromal cells reside on the bone surface and consist of those populations associated with the yellow marrow in distinction to the hematopoietic red marrow. The stem cells attach to the stroma, and cytokines are transferred through cell-to-cell gap junction channels during hematopoiesis; however, stem cells are highly mobile inside the body and circulate in the blood to other, perhaps depleted, sites of the marrow, and thus, repopulation and survival are aided. The stromal cells provide growth factors which are responsible for the rate of cell propagation among the lineage-committed stem populations. The long-term repopulating stem cells differentiate into lymphoid and myeloid stem populations which further propagate into specific blood elements. Humoral factors added by the stromal cells control the rate of progression of these differentiated stem populations. All other blood elements are produced by further differentiation among these two stem populations. Radiation injury to these stem and stromal populations will have its ultimate consequences in the peripheral blood. The time variation of these peripheral blood elements (specifically the lymphocytes, neutrophils, and platelets) were used to estimate the level of exposure (ref. 23) by using the nadir of the peripheral blood response curves. Kinetic models of the stem and stromal populations based on animal studies are used in the present report to develop a better understanding of the anticipated response of the astronaut to solar particle event exposure. This discussion has been greatly simplified. Actually, cytokines are produced by several lineages including the stroma, macrophages, T lymphocytes, and B lymphocytes. Also, cells respond autogenously to cytokines or by humoral diffusion in addition to the dominant pathway involving gap junctions and cell to cell contact.

The human LD_{50} (lethal dose for 50 percent mortality) to bone marrow seems to be about 3 Gy for the atomic bomb survivors (ref. 24). But the LD_{50} for man can be increased with antibiotics, blood transfusions, and cytokine therapy to about 6 Gy of low LET radiation delivered at a high dose rate. Supportive medical care including bone marrow or blood stem cell transplant could increase survivability to high levels as shown in table 9 but such medical procedures themselves carry additional attendant risks (ref. 23) that may be

modified by preconditioning to the space environments. Conversely Morris and Jones (refs. 25 to 27) have modeled 13 species of test animals and predicted the LD_{50} for man to be only about 1.8 Gy if confined in a cage under nonsterile conditions similar to that used for test animals. Such shifts may in fact be typical for space exposure and would be an important determinant of astronaut health. The genetic selection of astronauts and their conditioning may increase their radioresistance, but space environmental factors, stress of close confinement, biological stress from microgravity, anxiety regarding high radiation fields, cabin atmosphere, and other factors may decrease their radioresistance.

The model for early lethality as adapted by Jones et al. (refs. 22 and 7) is used to examine the repair/recovery effects in humans due to rather large exposures. Fig- ure 14 shows the mortality for a 2-Gy dose to the bone marrow by 250 kVp X rays delivered as multiple equal fractions 1 hr apart. Each fraction was given in a 15-min exposure. Mortality can be quite large when received in a single high dose rate exposure. (Note that Jones estimates that the bone marrow LD_{50} of 250 kVp X rays is 2.15 Gy whereas that of ^{60}Co gamma rays is 2.95 Gy.) Supportive medical treatment is expected to allow survival as shown in figure 14. As the number of fractions is increased, the mortality drops dramatically to less than 10 percent (even without medical treatment) beyond 15 fractions (or equivalently 15 hr). The stem and stromal cell survival at the end of each fractionated exposure is shown in figure 15. Stem cell survival for the single 2-Gy bone marrow dose is very low (much less than 10 percent). As the number of fractions is increased, the stem cell survival shows a dramatic increase approaching 40 percent. Likewise, similar but less dramatic changes in the stromal cell population and repopulation reduces the probability of death for the 20 fractions at 2 Gy to 10 percent. Clearly, cellular repair and repopulation are effective in reducing the risk when the exposure is highly fractionated with adequate time between fractions for repair. (Little repopulation takes place between the hourly fractions.) The stem and stromal cell populations during and after exposure to a 2-Gy bone marrow dose given as 20 fractions are shown in figure 16. The recovery period in this case is about 2 to 4 weeks.

In a more recent study by Jones et al. (ref. 28), the fission neutron RBE for repopulation was found to be from 2 to 7 relative to ^{60}Co gamma rays, which is somewhat smaller (by a factor of 3 to 5) than the quality factor used for carcinogenesis. Because over half the dose equivalent is due to low LET radiations (fig. 9), the use of dose equivalent would be a somewhat conservative approximation to the RBE. The average BFO dose equivalent rates in figure 12 are used in conjunction with the bioresponse model of Jones et al. to estimate the corresponding health risks.

Space suit life support systems are limited to 8 hr of continuous use; therefore, the effects of the worst 8-hr exposure on the biological response is studied. The estimated cell populations shielded by a space suit and pressure vessel are shown in figure 17 for the August 1972 event. The stem cell population drops to about 58 percent in the space suit and 66 percent in the pressure vessel. Under these conditions, little risk of death exists. Of course, responsible protection practice would still require the astronaut to seek shelter to reduce exposures to the levels in table 2. For an event with a flux factor of 2 higher (approximately a 99 percentile annual fluence level), the worst 8-hr exposures are higher with large changes in cell populations as shown in figure 18. The corresponding risk of death without treatment is 12 and 5 percent, and medical treatment is likely required. In each case, the effects on the cell populations are slight although the accumulated dose equivalent is large. Note that the higher event flux (2 times that of August 1972) is near the LD_{50}, but mortality (adequate medical treatment assumed) is negligible as a result of dose rate effects and the sparing factor is about 4.

The August 1972 episode was a sequence of three distinct events over 8 days (fig. 4). The effect of spending the first 50 hr of the event in a pressure vessel or equipment room is shown in figure 19. The surviving fraction of stem and stromal cells exhibit repopulation after the passing of the peak of the event so that the latter portion of the event has little effect on mortality. Indeed, the mortality estimate for the first 50 hr is within 10 percent of the mortality of the worst 8 hr. Death is not expected for the August 1972 event. If an event twice as large as the August 1972 event occurs (fig. 20), then the risk of death (12 percent) without medical treatment is small. Taking the 99.5 percent annual fluence as four times the August 1972 event leads to the estimates in figure 21. Depopulation of both stem and stroma cells is severe in the pressure vessel and significant even in an equipment room. The risk of death in the pressure vessel is about 88 percent unless supportive medical care is given; then the risk is reduced to 9 percent. These results are summarized in table 10. Again, the use of polymer structures would provide an important safety margin and greatly reduce the risks with minimal impact on mission cost. These events are extremely improbable, but if one occurs it is apt to have dire consequences in exposure accidents unless adequate planning is made to provide necessary medical support. In the equipment room, the radiations are greatly reduced and risk of death is small (3 percent) even without medical treatment. Use of polymer materials instead of aluminum would provide an

added safety factor to assure survivability for exposures within the equipment room.

In the estimates of mortality, no increase in radiosensitivity due to space stress factors or the possible complications arising from injury to other organs, especially the skin, has been included. Even so, astronaut survivability will occur with some medical planning for an accidental exposure except in the improbable case of an event four times larger than that observed on August 4, 1972, occurring and the exposures are protracted only for several hours.

Discussion

The August 1972 solar particle event is the single most important observed event in relation to the protection of astronauts in deep space in nearly 50 years of observations. Although a potentially lethal dose would have been received by an astronaut in a space suit or even in a typical pressure vessel, the modest shielding provided by an equipment area within spacecraft structures (approximately 5 g/cm^2 of aluminum) would have been sufficient to assure survival and a shelter of 10 g/cm^2 would have maintained exposures within the prescribed 30-day limits. Even greater protection is provided if large quantities of the aluminum structure is replaced by an equal mass of polymer materials. In any event, the mission could proceed by providing adequate warning to the astronauts to seek a protected region within the spacecraft.

Adequate protection (table 2) from the hazard of observed solar events of the past can be provided to the astronaut in deep space by adding a shelter of approximately 10 g/cm^2 of aluminum. A safety factor of 2 can be added if the shelter is constructed of an equal mass of polyethylene (or, alternatively, water, food stuffs). Protection from the 99.5 percentile annual fluence (which is usually dominated by a single solar event and was assumed in the study discussed herein) will not be provided unless additional massive shielding is added. However, the risk of death is small within a shelter of 10 g/cm^2 of aluminum, and little risk of death occurs if the aluminum of the shelter is replaced by an equal mass of polyethylene. Furthermore, the use of an equal mass of polyethylene for the shelter will reduce astronaut exposures to within a factor of 2 of the protection standards in table 2. From a practical point of view, one may wish to design for the largest observed event and view the less probable and higher intensity events as potential accidental exposures on the basis that no such events have ever been observed in nearly 50 years of observations. With this philosophy, the improbable high fluence events indicate in application of the bioresponse model that a high degree of medical preparedness is required.

A warning system needs to provide information for (1) warning the astronaut to seek shelter, (2) an assessment of the astronaut health status in the event adequate shelter is not acquired during the event (accidental exposure), and (3) interdiction therapies if the shelter is inadequate because a much larger event may occur than accounted for in the design. The spectral qualities of the radiation needs to be measured as well as the intensities during the event. The most important spectral information is in the range of 20 to 110 MeV with critical fluence levels of 2×10^8 protons/cm^2 for skin and ocular lens and 5×10^8 protons/cm^2 for the BFO. The spectral intensities would be used with required mission software to estimate the dose and dose equivalent rates to specific tissues. Bioresponse models would be required to determine prognosis and proper medical treatment. In this respect, the hematopoietic response is strongly dependent on radiation quality, dose rate, and uniformity to the marrow; useful extensions to the current calculations should include direct considerations of these factors instead of adding modifying factors to idealized assumptions as was done in the present report. Such calculations, plus medial triage based on initial changes in blood counts (e.g., lymphocytes) could contributess significantly to postexposure therapeutic planning for interdictive measures such as antibiotics, infusion of irradiated blood elements, barrier conditions, granulocyte-monocyte colony stimulating factor (specific cytokine therapy) marrow transplantation. On the basis of the present study, it appears safe to say that mortality is not expected to be an issue if adequate medical provision is made to treat adverse effects of the exposure unless there is an unlikely occurrence of an event on the order of four times the size of the August 1972 event. The design of medical treatment facilities is an issue beyond the scope of the present report. Even in a simple pressure vessel, a significant risk of death exists even with good medical practice. Again one needs to emphasize that these events are very unlikely.

Concluding Remarks

Adequate protection from the largest solar event ever observed from an astronaut protection point of view (August 4, 1972) is provided by a shelter made of 10 g/cm^2 of aluminum. Although the exposure levels are potentially lethal, the dose rate effects reduce the risk by a sparing factor of 4 to a small mortality even if adequate shelter is not acquired in a timely fashion from the less protected regions of the spacecraft or a space suit and if the complications of injury to other organs such as the skin are not severe. Although exposure limits are exceeded within the more protected regions of the spacecraft outside the shelter (an equipment room), the astronaut should suffer minimal early illness. The scale of the

August 4, 1972, event is on the order of the 97 percentile annual fluence.

If the mission shielding was designed on the basis of the largest event observed, there is a small probability (3 percent) that an even larger event may happen during the mission. An event two times larger than the August 1972 event would pose a greater hazard if shelter is not acquired; health risks would demand that medical procedures be part of mission planning to ensure survival. Although the 30-day exposure limits would be exceeded in a shelter of 10 g/cm^2 of aluminum, the use of an equal mass of polyethylene is sufficient to keep the exposure within acceptable limits with minimal impact on mission cost. There is an unlikely chance (1 percent) of an even larger event such as four times the August 1972 event occurring. For such an event, dire consequences could occur if shelter is not acquired. Even in the shelter of 10 g/cm^2 of aluminum, exposures are well above the accepted limits although no early radiation illness is expected. The use of an equal mass of polyethylene reduces the exposures within the shelter to within a factor of 2 of accepted exposure limits.

Outstanding questions resulting from the present study concern added factors which may alter the biological response as represented in the present model, such as stress of confinement, microgravity, the complications arising from related tissue injury. These concerns need to be addressed by radiation experiments in space and laboratory studies.

NASA Langley Research Center
Hampton, VA 23681-2199
June 23, 1997

References

1. Schaefer, Hermann J.: Cosmic Ray Dosage During the Giant Solar Flare of February 26, 1956. *J. Aviation Med.*, vol. 28, no. 4, Aug. 1957, pp. 387–396.

2. Billingham, John; Robbins, Donald E.; Modisette, Jerry L.; and Higgins, Peter W.: Status Report on the Space Radiation Effects on the Apollo Mission. *Second Symposium on Protection Against Radiations in Space*, Arthur Reetz, Jr., ed., NASA SP-71, 1965, pp. 139–156.

3. Radiobiological Advisory Panel, Committee on Space Medicine: *Radiation Protection Guides and Constraints for Space-Mission and Vehicle-Design Studies Involving Nuclear Systems*. National Academy of Sciences, 1970.

4. National Council on Radiation Protection and Measurements: *Guidance on Radiation Received in Space Activities.* NCRP Rep. No. 98, July 1989.

5. Wilson, J. W.; and Denn, F. M.: *Preliminary Analysis of the Implications of Natural Radiations on Geostationary Operations*. NASA TN D-8290, 1976.

6. Wilson, John W.; Cucinotta, Francis A.; Jones, T. D.; and Chang, C. K.: *Astronaut Protection From Solar Event of August 4, 1972*. NASA TP-3643, 1997.

7. Young, Robert W.; Jones, Troyce D.; and Morris, Max D.: Dose-Rate RBE Factors for Photons: Hematopoietic Syndrome in Humans vs. Stromal Cell Cytopenia. *Health Phys.*, vol. 67, no. 5, Nov. 1994, pp. 495–508.

8. Billings, M. P.; and Yucker, W. R.: *The Computerized Anatomical Man (CAM) Model*. NASA CR-134043, 1973.

9. Wilson, J. W.: Distribution Effectiveness for Space Radiation Dosimetry. *Health Phys.*, vol. 28, June 1975, pp. 812–813.

10. Shea, M. A.; and Smart, D. F.: A Summary of Major Solar Proton Events. *Solar Phys.*, vol. 127, June 1990, pp. 297–320.

11. Sauer, Herbert H.; Zwickl, Ronald D.; and Ness, Martha J.: *Summary Data for the Solar Energetic Particle Events of August Through December 1989*. Space Environment Lab., National Oceanic and Atmospheric Adm., 1990.

12. Foelsche, T.; Mendell, R. B.; Wilson, J. W.; and Adams, R. R.: *Measured and Calculated Neutron Spectra and Dose Equivalent Rates at High Altitudes; Relevance to SST Operations and Space Research*. NASA TN D-7715, 1974.

13. Simonsen, Lisa C.; Atwell, William; Nealy, John E.; and Cucinotta, Francis A.: *Radiation Dose to Critical Body Organs for October 1989 Proton Event.* NASA TP-3237, 1992.

14. Langham, Wright H., ed.: *Radiobiological Factors in Manned Space Flight*. Publ. 1487, National Academy of Sciences, 1967.

15. Wilson, John W.; Townsend, Lawrence W.; Nealy, John E.; Chun, Sang Y.; Hong, B. S.; Buck, Warren W.; Lamkin, S. L.; Ganapol, Barry D.; Khan, Ferdous; and Cucinotta, Francis A.: *BRYNTRN: A Baryon Transport Model*. NASA TP-2887, 1989.

16. Bertini, Hugo W.; Guthrie, Miriam P.; and Culkowski, Arline H.: *Nonelastic Interactions on Nucleons and π -Mesons With Complex Nuclei at Energies Below 3* GeV. ORNL-TM-3148, U.S. Atomic Energy Commission, 1972.

17. Alsmiller, R. G.: High-Energy Nucleon Transport and Space Vehicle Shielding. *Nucl. Sci. & Eng.*, vol. 27, no. 2, 1967, pp. 158–189.

18. Prael, Richard E.; and Lichtenstein, Henry: *User Guide to LCS: The LAHET Code System*. LA-UR-89-3014, Los Alamos Nat. Lab., Sept. 1989.

19. Badhwar, Gautam D.; Patel, Jagdish U.; Cucinotta, Francis A.; and Wilson, John W.: Measurements of the Secondary Particle Energy Spectra in the Space Shuttle. *Radiat. Meas.*, vol. 24, no. 2, 1995, pp. 129–138.

20. Cucinotta, F. A.; Townsend, L. W.; Wilson, J. W.; Shinn, J. L.; Badhwar, G. D.; and Dubey, R. R.: Light Ion Components of the Galactic Cosmic Rays: Nuclear Interactions and Transport Theory. *Adv. Space Res.*, vol. 17, no. 2, 1996, pp. (2)77–(2)86.

21. Feynman, Joan; Armstrong, T. P.; Dao-Gibner, L.; and Silverman, S.: New Interplanetary Proton Fluence Model. *J. Spacecr.*, vol. 27, no. 4, July–Aug. 1990, pp. 403–410.

22. Jones, T. D.: Hematologic Syndrome in Man Modeled From Mammalian Lethality. *Health Phys.*, vol. 41, July 1981, pp. 83–103.

23. United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR): *Sources, Effects and Risks of Ionizing Radiation*. United Nations, 1988.

24. Levin, S. G.; Young, R. W.; and Stohler, R. L.: Estimation of Median Human Lethal Radiation-Dose Computed From Data on Occupants of Reinforced-Concrete Structures in Nagasaki, Japan. *Health Phys.*, vol. 63, no. 5, 1992, pp. 522–531.

25. Morris, M. D.; and Jones, T. D.: Hematopoietic Death of Unprotected Man From Photon Irradiations—Statistical Modeling From Animal-Experiments. *Int. J. Radiat. Biol.*, vol. 55, no. 3, 1989, pp. 445–461.

26. Morris, Max D.; Jones, Troyce D.; and Young, Robert W.: A Cell Kinetics Model of Radiation-Induced Myelopoiesis—Rate Coefficient Estimates for Mouse, Rat, Sheep, Swine, Dog and Burro Irradiated by Photons. *Radiat. Res.*, vol. 135, no. 3, Sept. 1, 1993, pp. 320–331.

27. Morris, M. D.; and Jones, T. D.: A Comparison of Dose-Response Models for Death From Hematological Depression in Different Species. *Int. J. Radiat. Biol.*, vol. 53, no. 3, 1988, pp. 439–456.

28. Jones, Troyce D.; Morris, Max D.; Young, Robert W.; and Kehlet, Robert A.: Neutron RBEs for Cytopenia and Repopulation of Stroma and Hematopoietic Stem Cells: Mathematical Models of Marrow Cell Kinetics. *Health Phys.*, vol. 72, no. 4, 1997, pp. 530–543.

Table 1. Exposure Limitations for Apollo Missions

[Missions were approximately 2 weeks]

Organ	Exposure limitations, cSv or rem
BFO	200
Skin	700
Lens	200
Hands and feet	980

Table 2. Recommended Organ Dose Equivalent Limits

[From NCRP 98 (ref. 4)]

Exposure interval	Dose equivalent, Sv, for—		
	Blood forming organ	Skin	Ocular lens
Career	[a]1–4	6	4
Annual	0.5	3	2
30 Days	0.25	1.5	1

[a]Varies with age and gender at initial exposure.

Table 3. Critical Fluence Levels in Astronaut Exposures

Organ	Fluence, protons/cm^2	Critical energy, MeV, in—		
		Space suit	Pressure vessel	Equipment room
BFO	5×10^8	≈70	≈80	≈110
Skin and lens	2×10^8	≈20	≈30	≈75

Table 4. Fluence Levels of Solar Events of Cycle 19–22 Likely to Exceed Exposure Limits

Date			Fluence, protons/cm^2, for energy of—	
Month	Day	Year	>10 MeV	>30 MeV
February	23	1956	2×10^9	1×10^9
July	10–11	1959	5×10^9	1×10^9
July	14–15	1959	8×10^9	1×10^9
July	16–17	1959	3×10^9	9×10^8
[a]November	12–13	1960	8×10^9	2×10^9
November	15	1960	3×10^9	7×10^8
July	18	1961	1×10^9	3×10^8
November	18	1968	1×10^9	2×10^8
April	11–13	1969	2×10^9	2×10^8
January	24–25	1971	2×10^9	4×10^8
[b]August	4–9	1972	2×10^{10}	8×10^9
February	13–14	1978	2×10^9	1×10^8
April	30	1978	2×10^9	3×10^8
September	23–24	1978	3×10^9	4×10^8
May	16	1981	1×10^9	1×10^8
October	9–12	1981	2×10^9	4×10^8
February	1–2	1982	1×10^9	2×10^8
April	25–26	1984	1×10^9	4×10^8
August	12–…	1989	8×10^9	2×10^8
September	29–…	1989	4×10^9	1×10^9
October	19–…	1989	2×10^{10}	4×10^9
November	26–…	1989	2×10^9	1×10^8

[a]Foelsche et al. (ref. 12).
[b]Wilson and Denn (ref. 5).

Table 5. Dose Equivalent and Dose in Critical Body Organs in Aluminum Structure During August 1972 Solar Event

Organ	Space suit		Pressure vessel		Equipment room		Shelter	
	Dose equivalent, cSv	Dose, cGy	Dose equivalent, cSv	Dose, cGy	Dose equivalent, cSv	Dose, cGy	Dose equivalent, cSv	Dose, cGy
Skin	9350	4830	3560	2120	427	294	110	76
Lens	3830	2400	2140	1420	367	263	101	71
BFO	217	157	180	130	65	47	24	17

Table 6. Dose Equivalent and Dose in Critical Body Organs in Polyethylene Structure During August 1972 Solar Event

Organ	Space suit		Pressure vessel		Equipment room		Shelter	
	Dose equivalent, cSv	Dose, cGy	Dose equivalent, cSv	Dose, cGy	Dose equivalent, cSv	Dose, cGy	Dose equivalent, cSv	Dose, cGy
Skin	6770	3620	2510	1540	267	184	58	40
Lens	3530	2080	1810	1150	251	171	57	38
BFO	212	151	174	120	50	34	16	10

Table 7. Dose Equivalent and Dose in Critical Body Organs in Aluminum Structure for Event Four Times That of August 1972

Organ	Space suit		Pressure vessel		Equipment room		Shelter	
	Dose equivalent, Sv	Dose, Gy	Dose equivalent, Sv	Dose, Gy	Dose equivalent, Sv	Dose, Gy	Dose equivalent, Sv	Dose, Gy
Skin	374	193	142	85	17	12	4.4	3.0
Lens	153	96	86	57	15	11	4.0	2.8
BFO	8.7	6.3	7.2	5.2	2.6	1.8	1.0	0.7

Table 8. Dose Equivalent and Dose in Critical Body Organs in Polyethylene Structure for Event Four Times That of August 1972

Organ	Space suit		Pressure vessel		Equipment room		Shelter	
	Dose equivalent, Sv	Dose, Gy	Dose equivalent, Sv	Dose, Gy	Dose equivalent, Sv	Dose, Gy	Dose equivalent, Sv	Dose, Gy
Skin	271	145	100	62	10.7	7.4	2.3	1.6
Lens	141	83	72	46	10	6.8	2.3	1.5
BFO	8.5	6.0	7.0	4.8	2.0	1.4	0.6	0.4

Table 9. Exposure Levels for Single, High-Dose Rate Exposure at Which Health Effects Appear in Healthy Adults

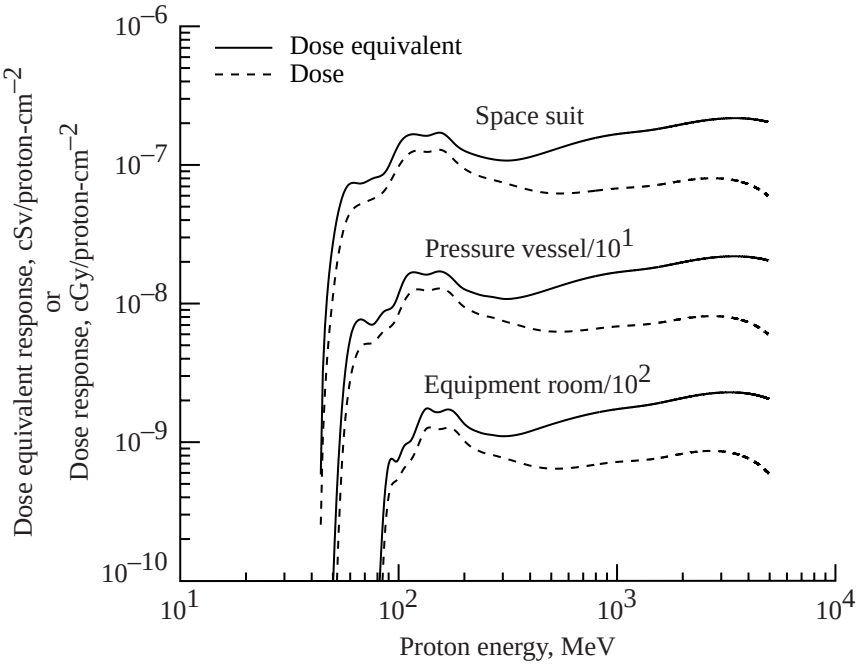
[From refs. 4 and 14]

Health effect	Dose, X or gamma radiation, Gy
Blood count changes in a population	0.15–0.25
Blood count changes in individuals	0.5
Vomiting effective threshold	1.0
Mortality effective threshold	1.5
LD_{50} with minimal supportive care	3.2–3.6
LD_{50} with supportive medical treatment	4.8–5.4
Erythema threshold	6.0
Moist desquamation	30.0

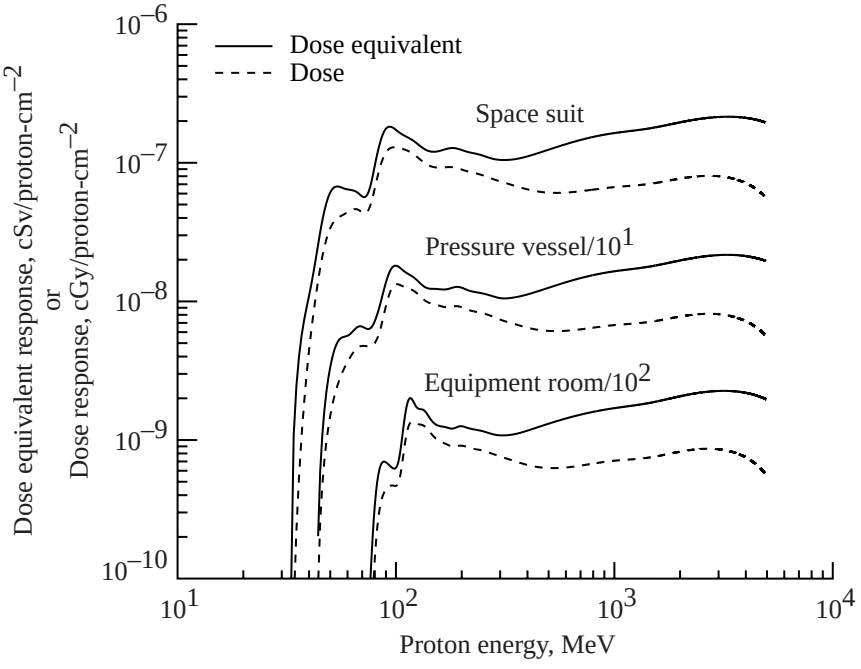
Table 10. Expected Mortality Without Adequate Medical Treatment for Various Aluminum Shield Configurations

Event	Expected mortality, percent, in—			
	Space suit	Pressure vessel	Equipment room	Shelter
August 1972	[a]1	1	0	0
2 × Aug. 1972	[a]12	12	0	0
4 × Aug. 1972	[a]87	88	3	0

[a]Worst 8 hr.

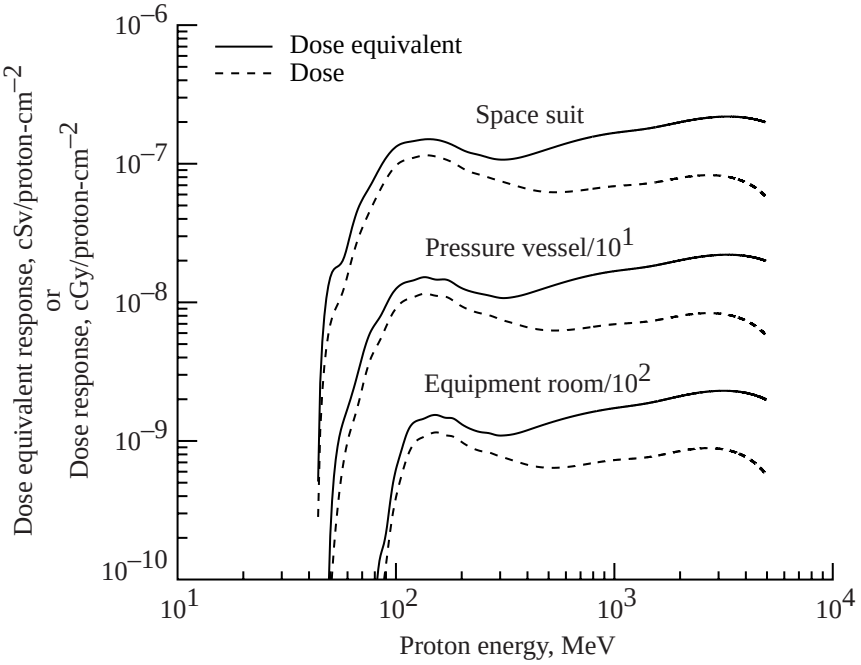


(a) BFO of skull.

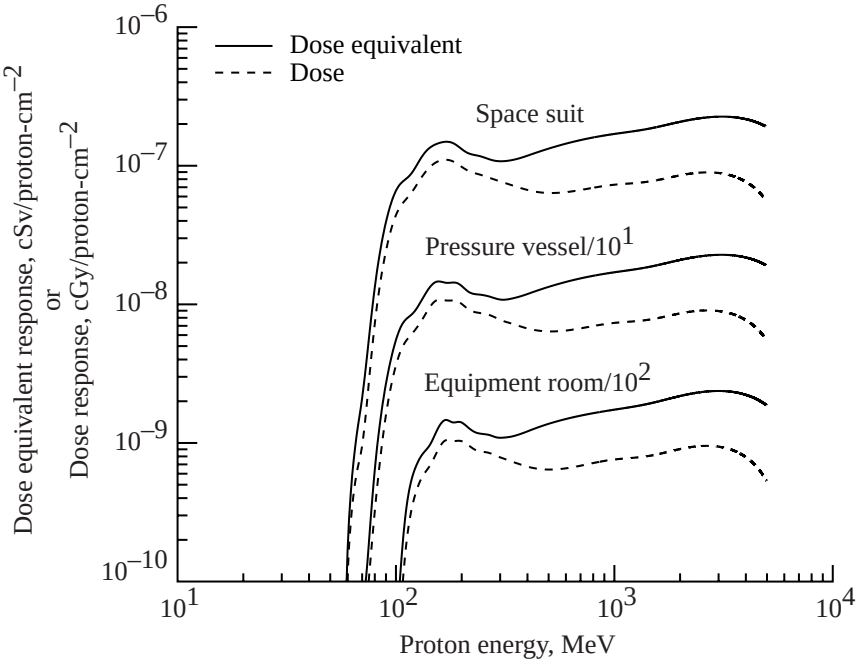


(b) BFO of arms.

Figure 1. Dose and dose equivalent response functions in various blood forming organ (BFO) compartments in various shield configurations (space suit, pressure vessel, and equipment room).

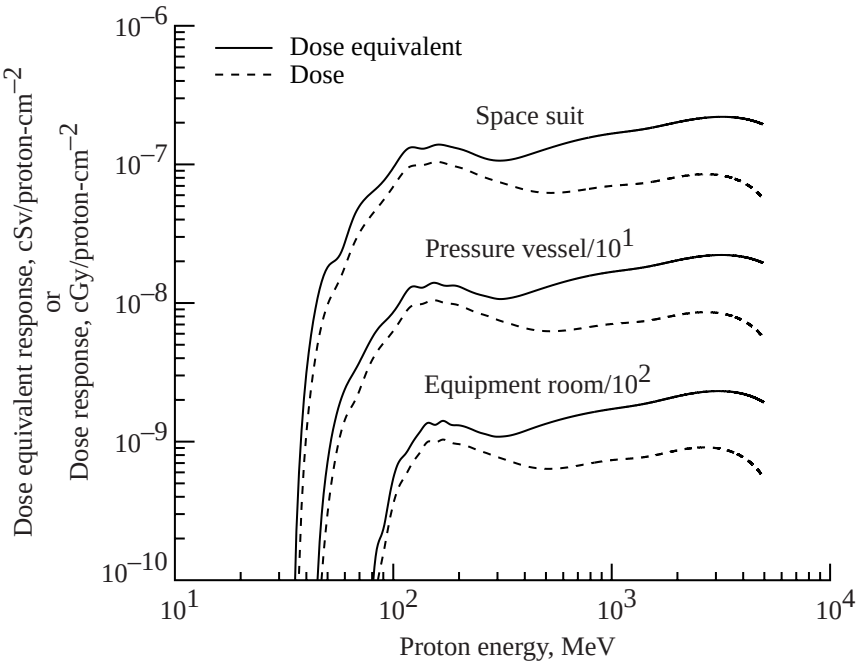


(c) BFO of legs.



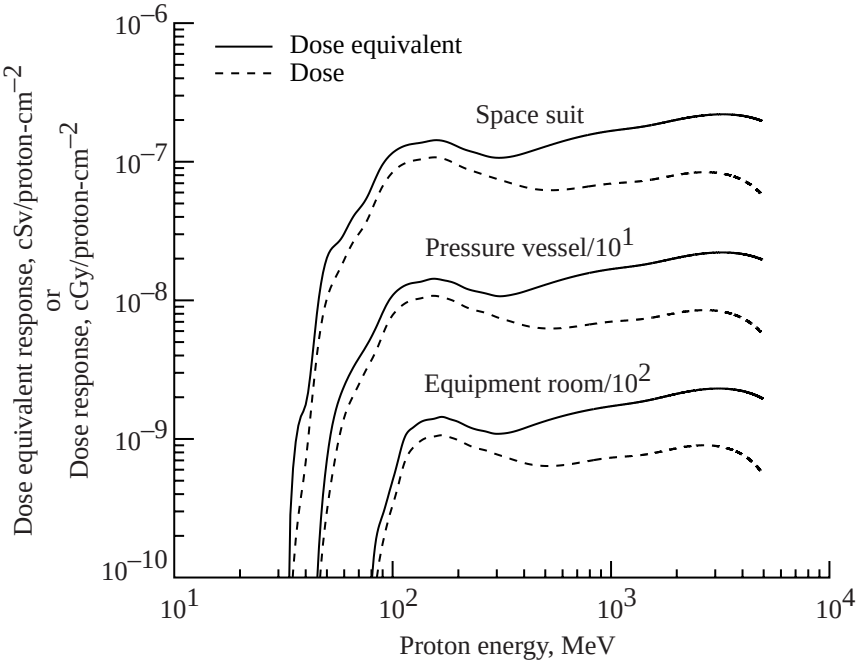
(d) BFO of lower torso.

Figure 1. Continued.

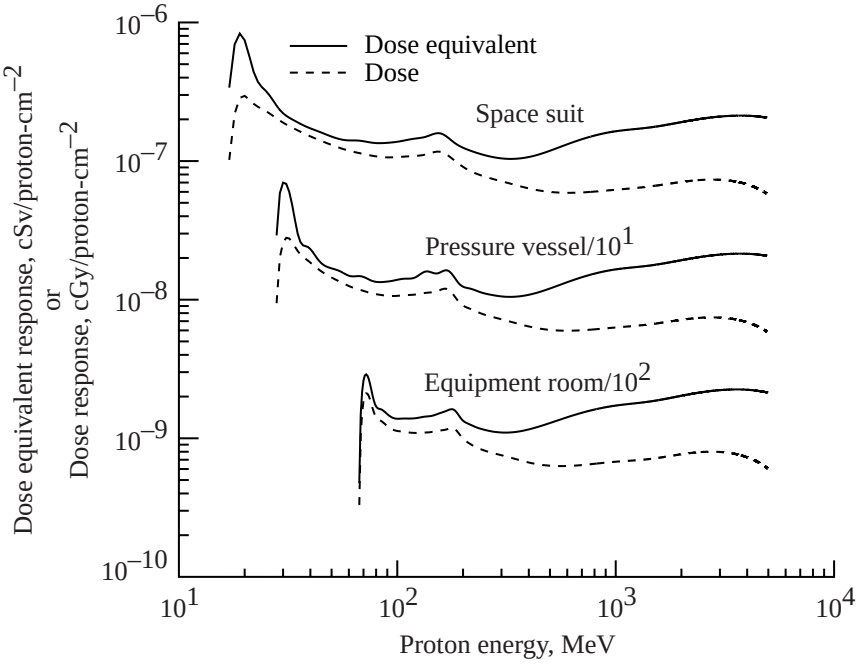


(e) BFO of upper torso.

Figure 1. Concluded.

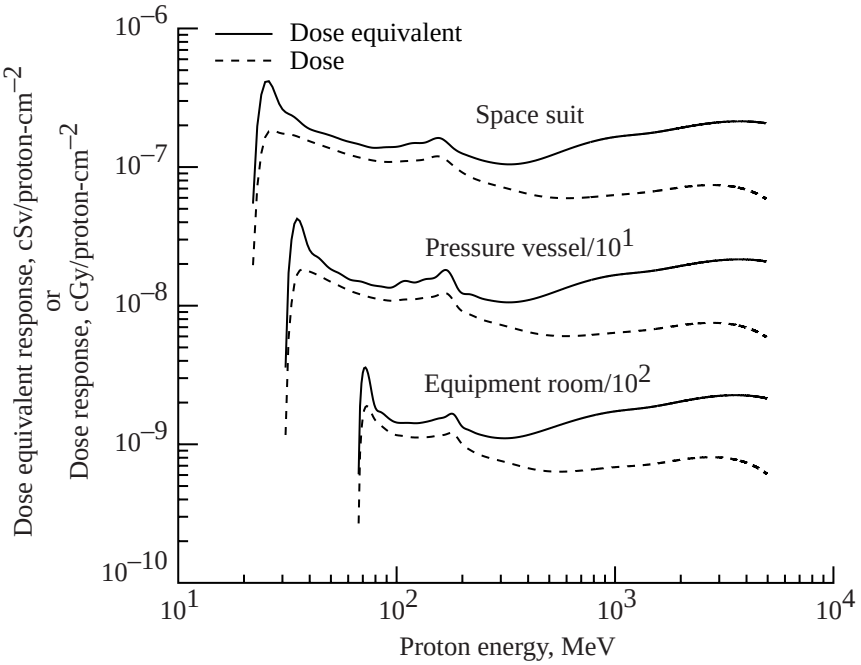


(a) BFO average.



(b) Skin.

Figure 2. Dose and dose equivalent response functions in three critical body tissues in various shield configurations.



(c) Ocular lens.

Figure 2. Concluded.

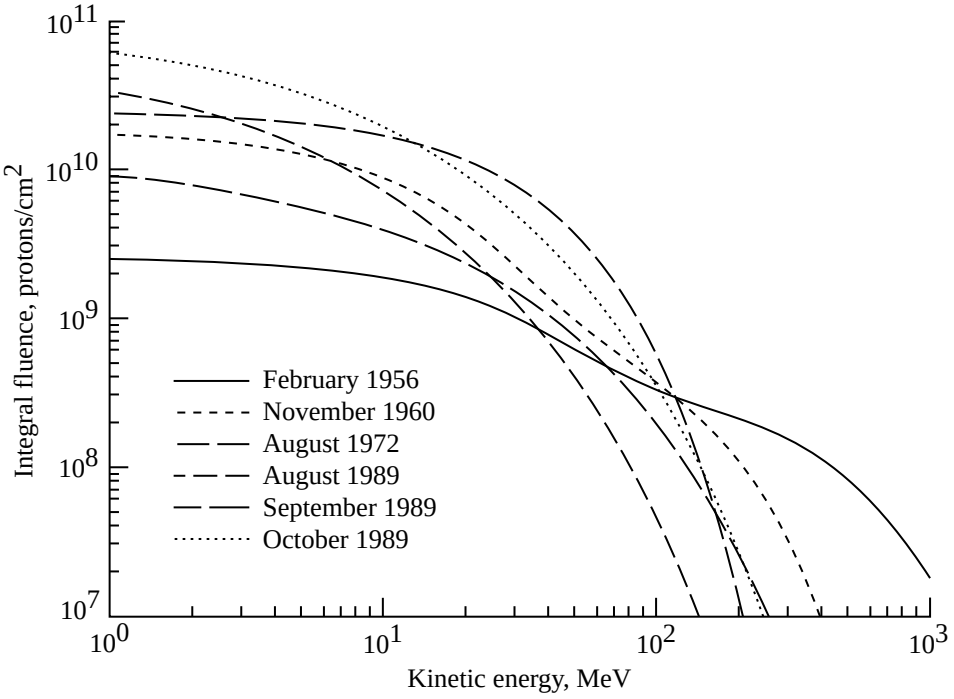


Figure 3. Large solar proton event integral fluence spectra at 1 au.

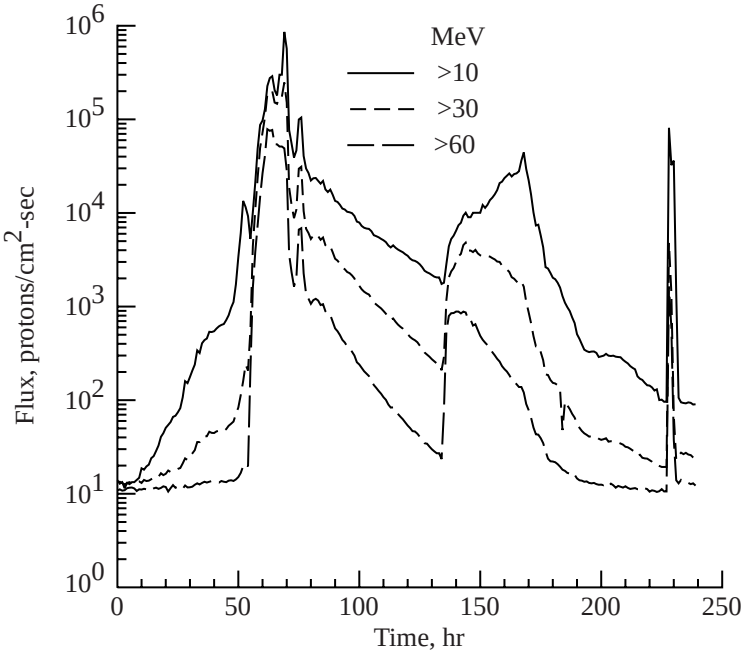
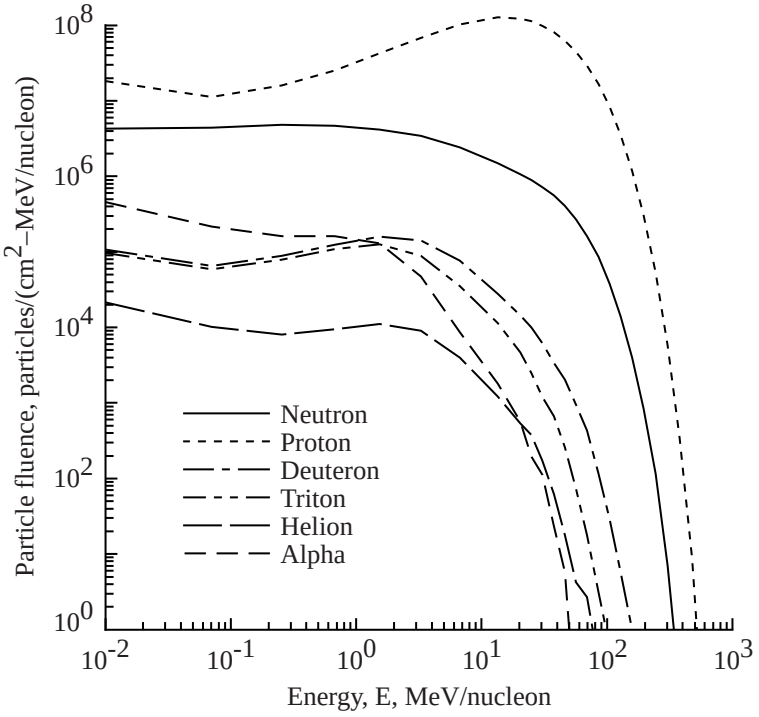
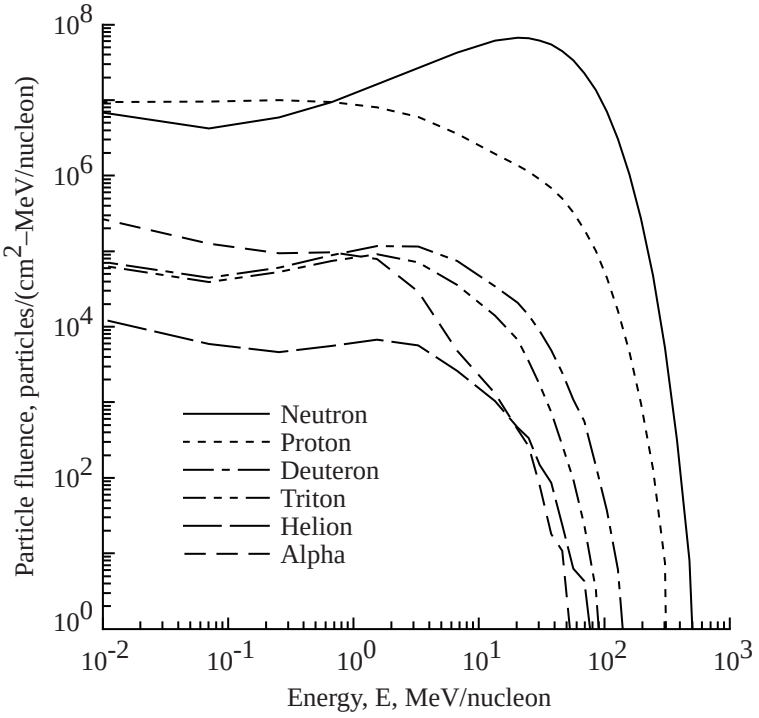


Figure 4. Measured intensities at 1 au of solar event of August 2–11, 1972.

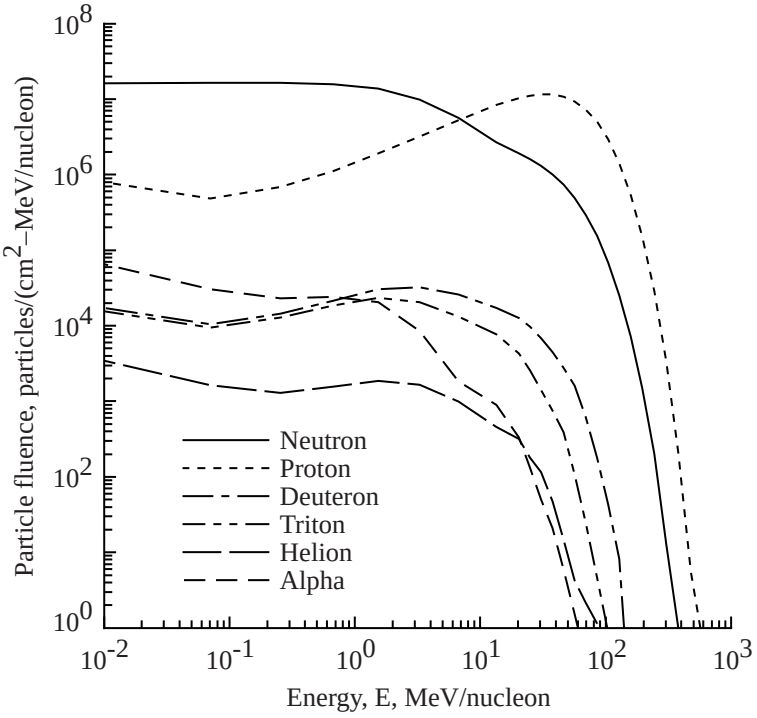


(a) Space suit.



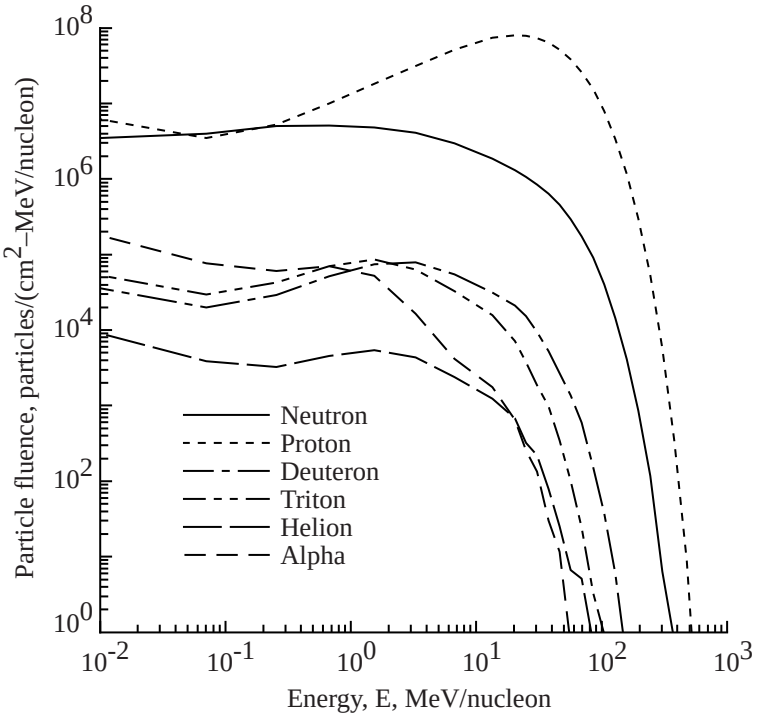
(b) Pressure vessel.

Figure 5. Calculated local skin tissue environment in various shield configurations.

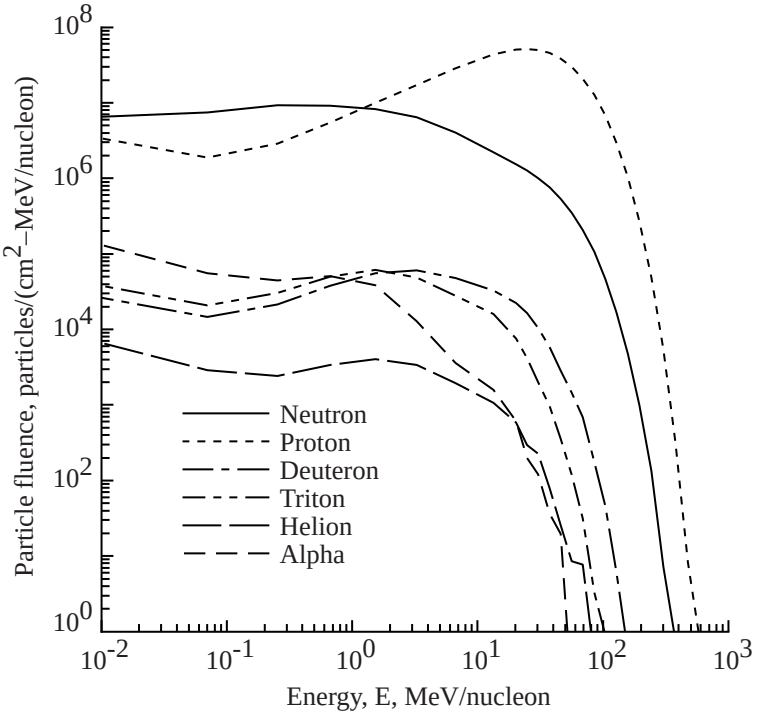


(c) Equipment room.

Figure 5. Concluded.

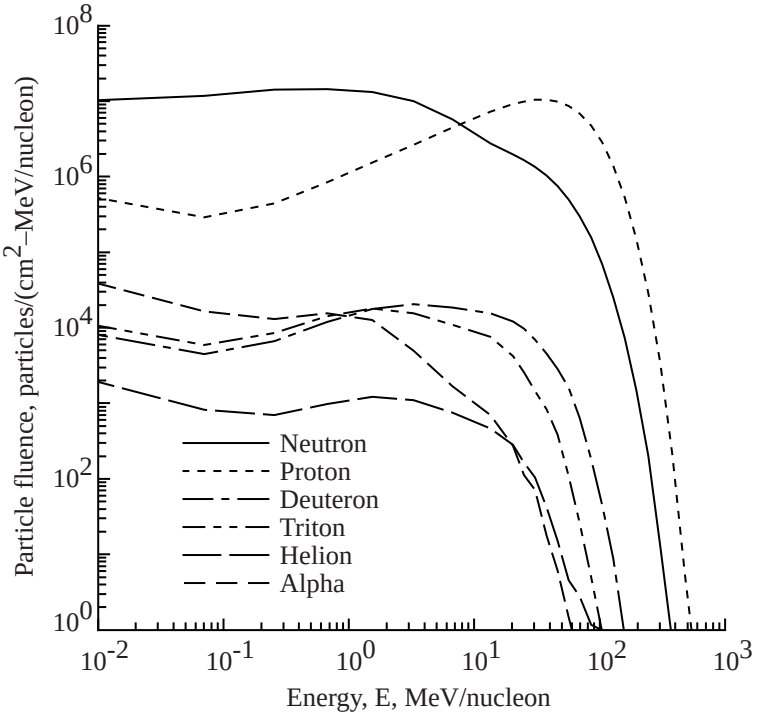


(a) Space suit.



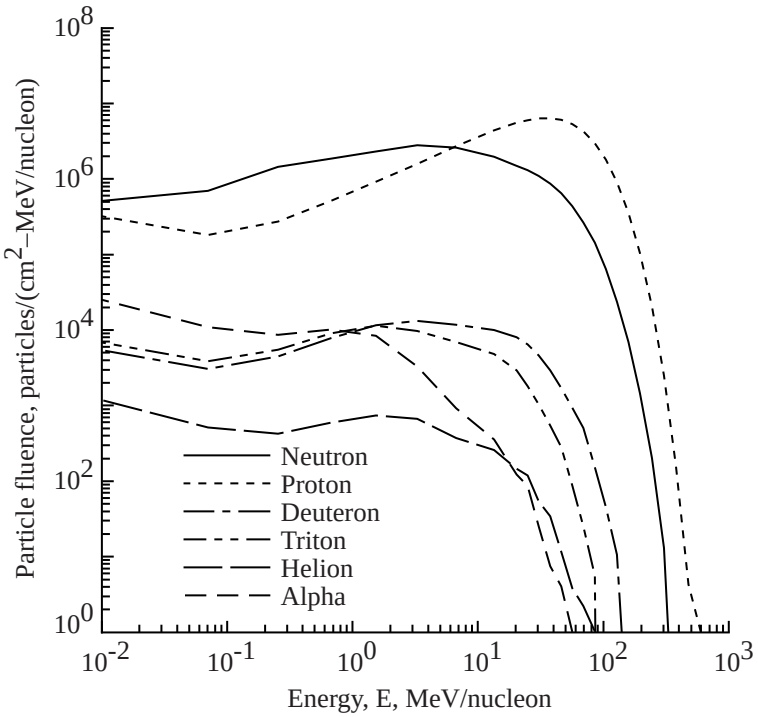
(b) Pressure vessel.

Figure 6. Calculated local ocular lens tissue environment in various shield configurations.

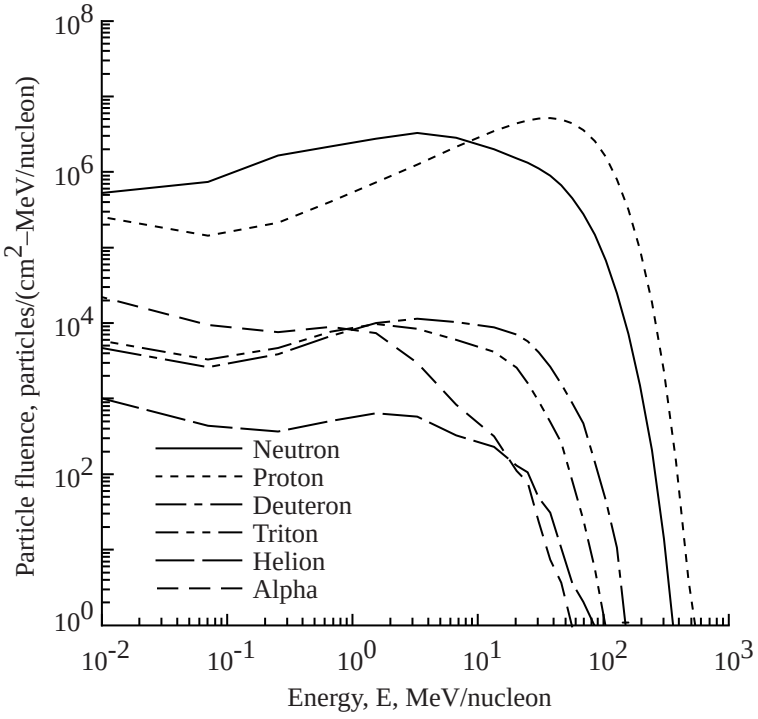


(c) Equipment room.

Figure 6. Concluded.

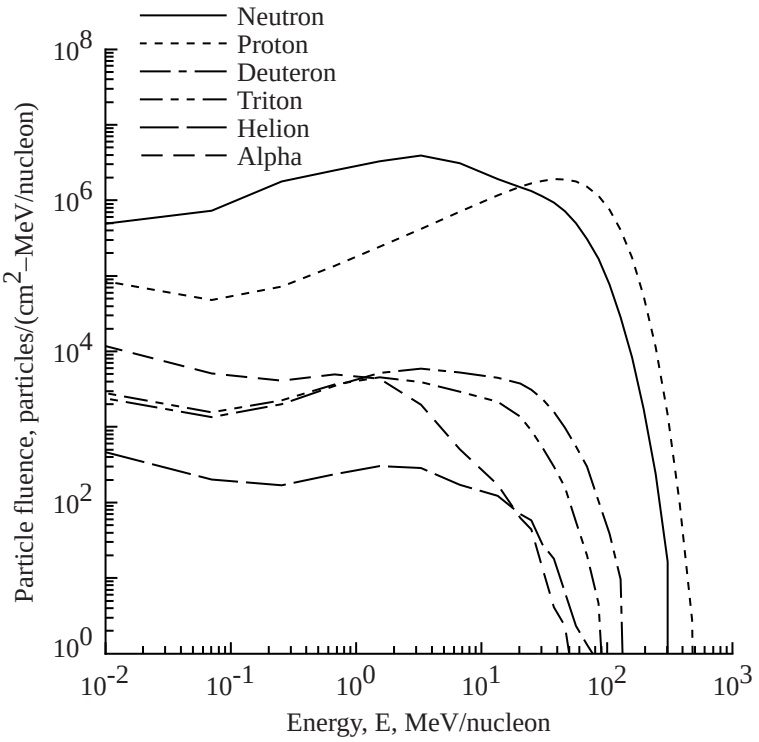


(a) Space suit.



(b) Pressure vessel.

Figure 7. Calculated local average BFO tissue environment in various shield configurations.



(c) Equipment room.

Figure 7. Concluded.

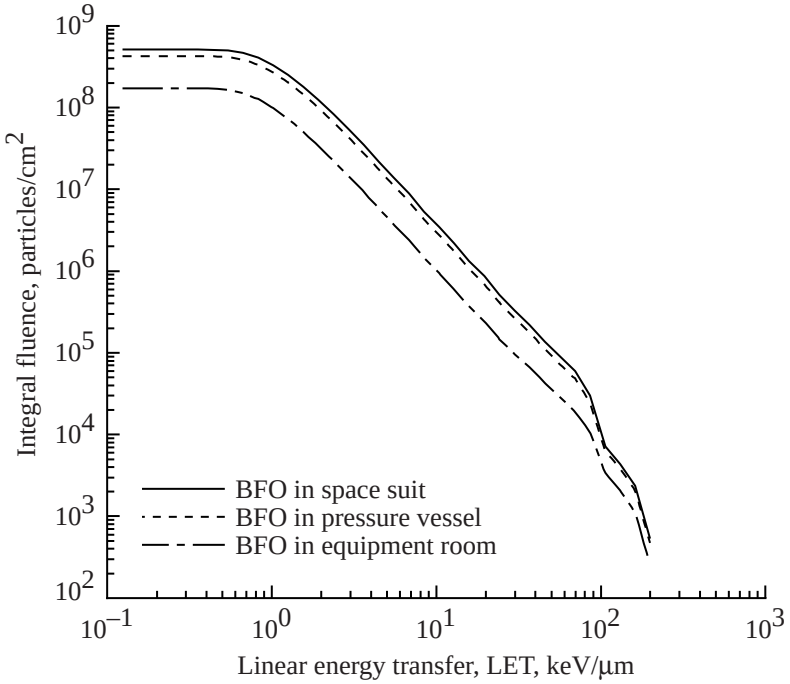


Figure 8. Average BFO tissue environment LET distribution in various shield configurations.

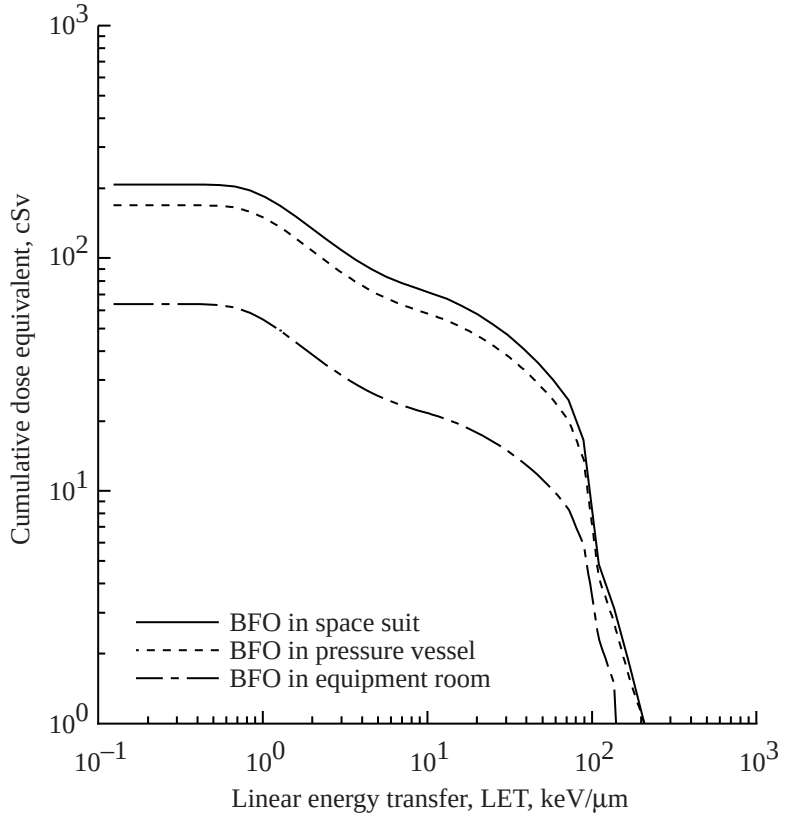
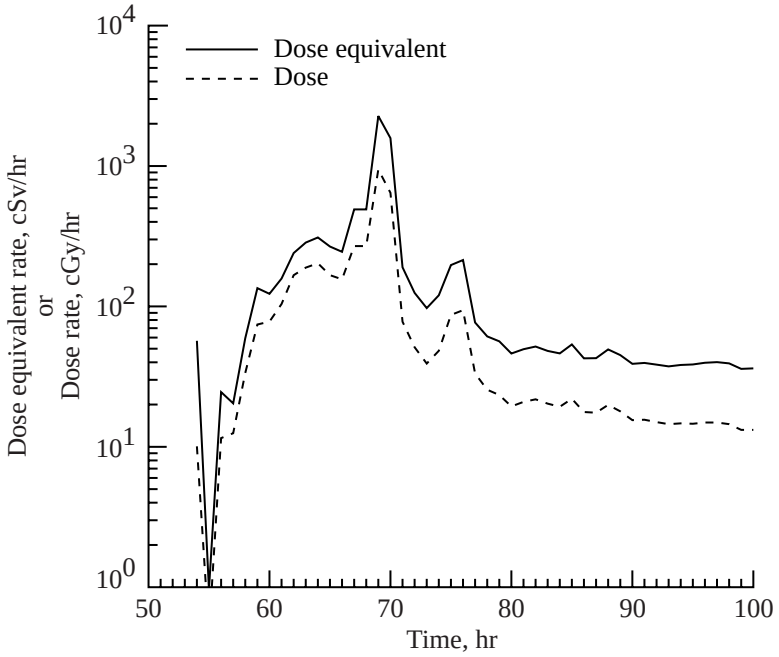
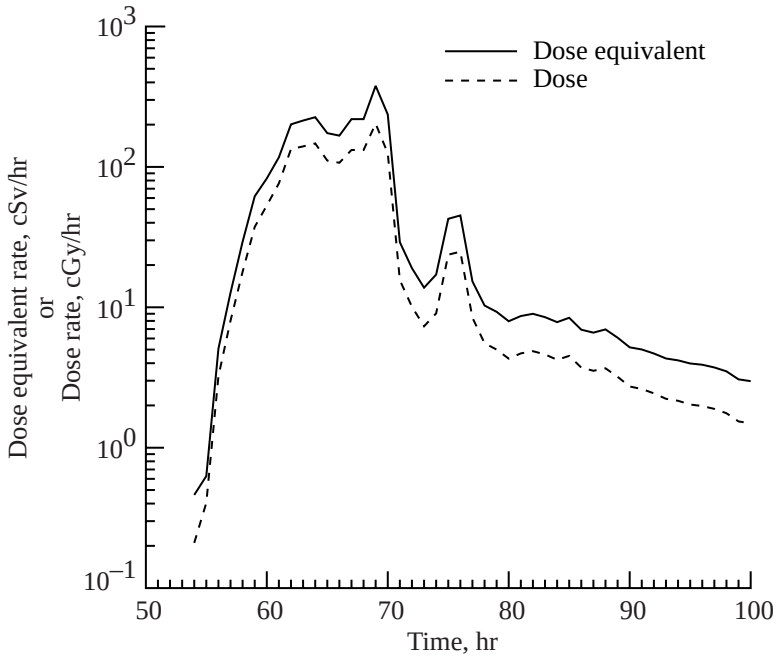


Figure 9. Average BFO dose equivalent LET distribution in various shield configurations.

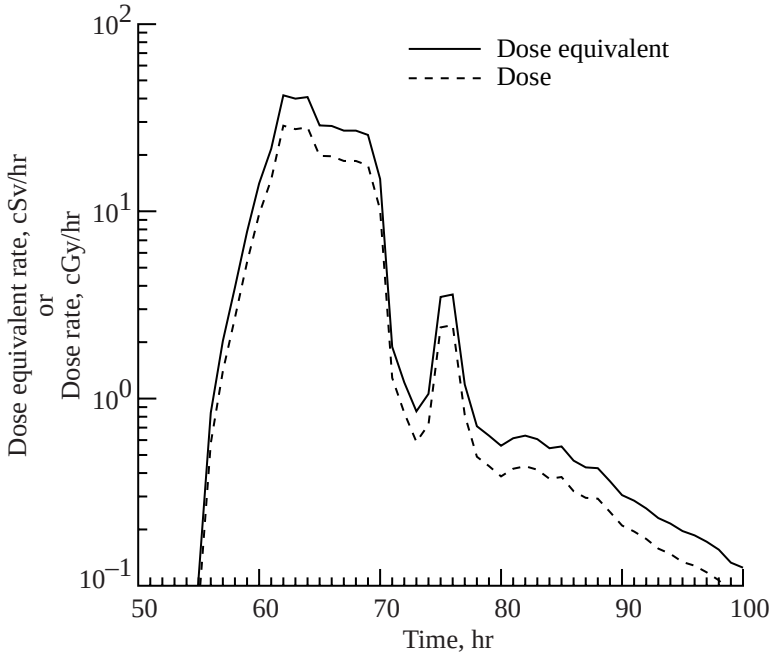


(a) Space suit.



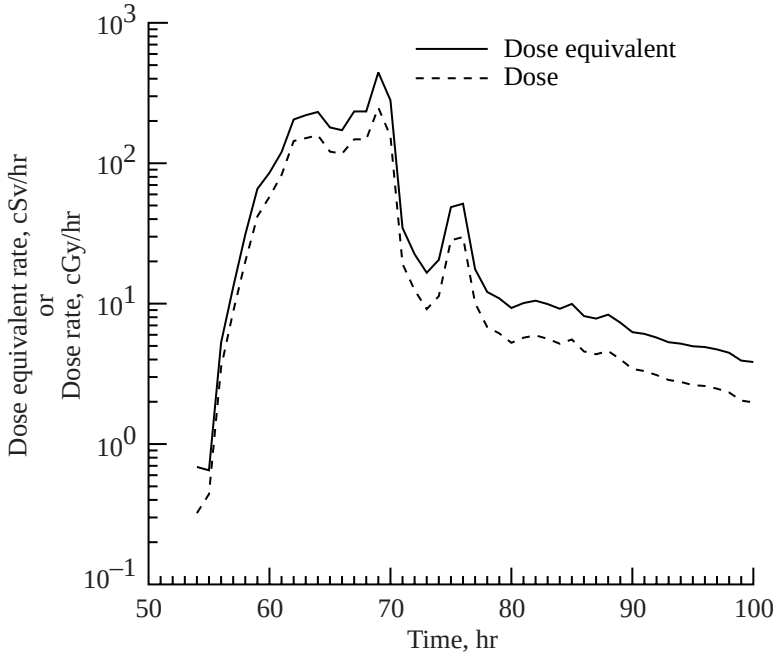
(b) Pressure vessel.

Figure 10. Calculated skin dose and dose equivalent rates inferred for solar event of August 1972 in various aluminum shield configurations.

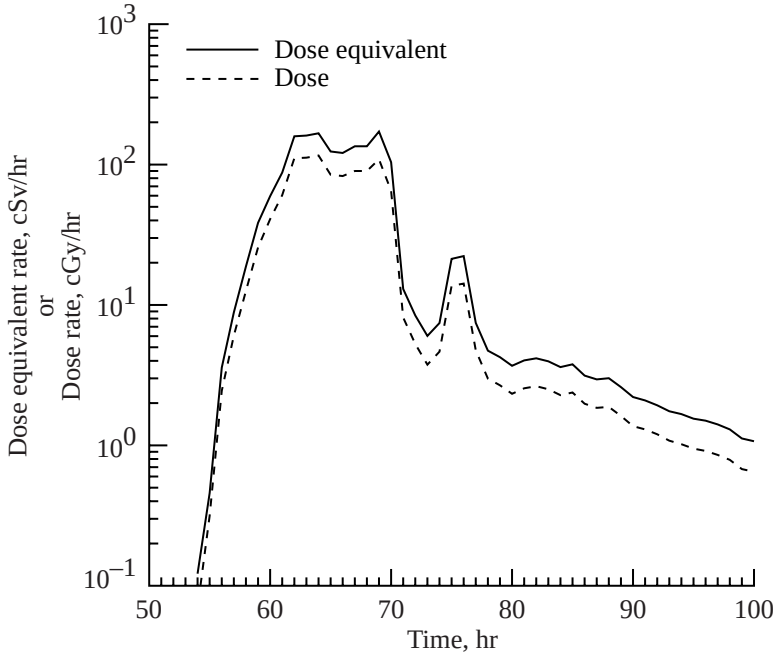


(c) Equipment room.

Figure 10. Concluded.

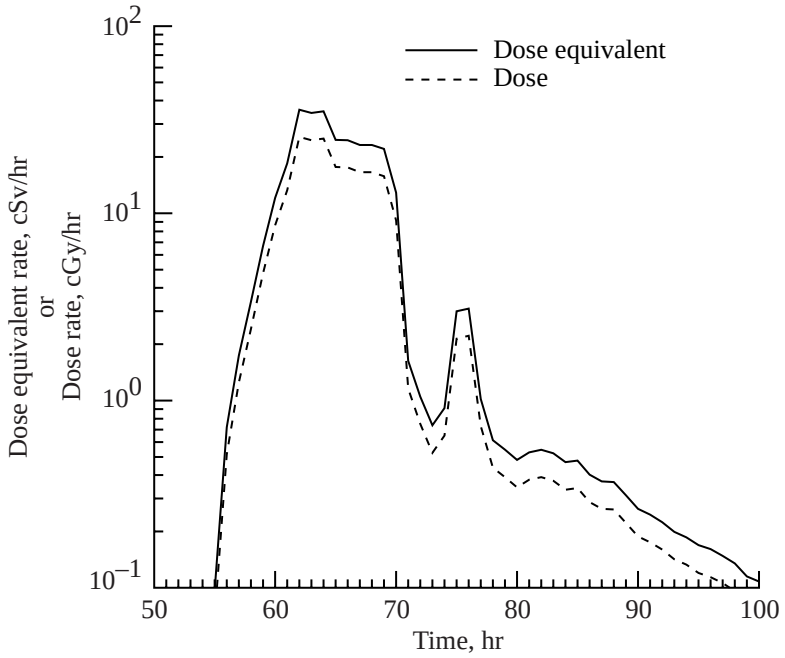


(a) Space suit.



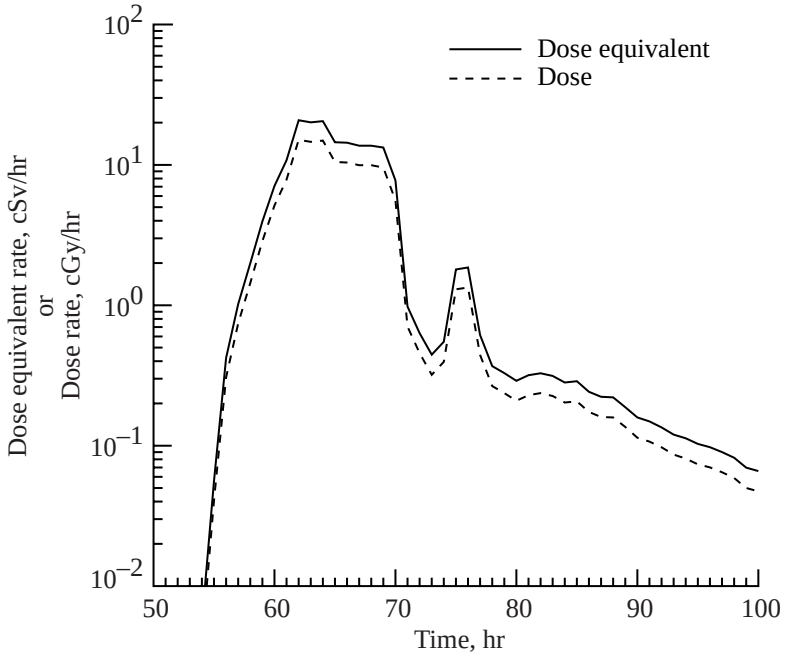
(b) Pressure vessel.

Figure 11. Calculated ocular lens dose and dose equivalent rates inferred for solar event of August 1972 in various aluminum shield configurations.

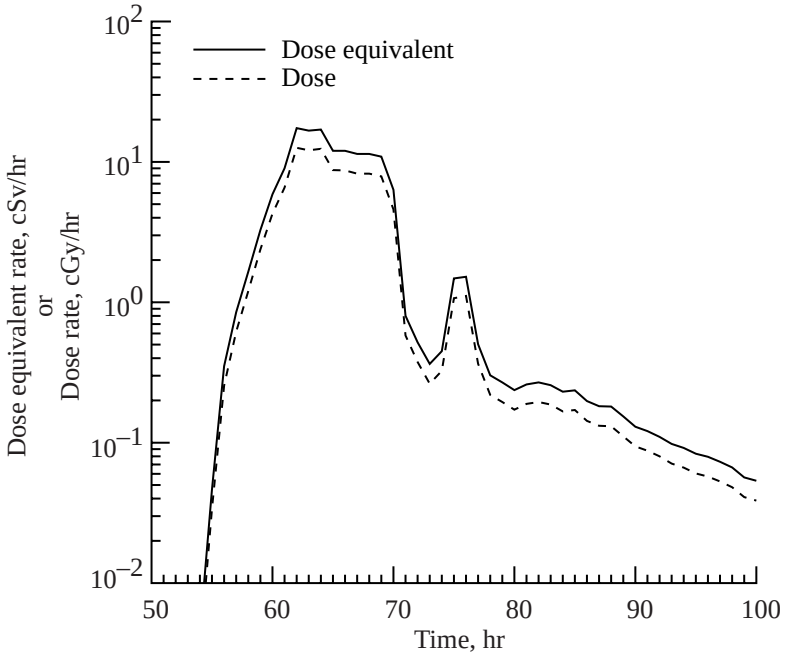


(c) Equipment room.

Figure 11. Concluded.

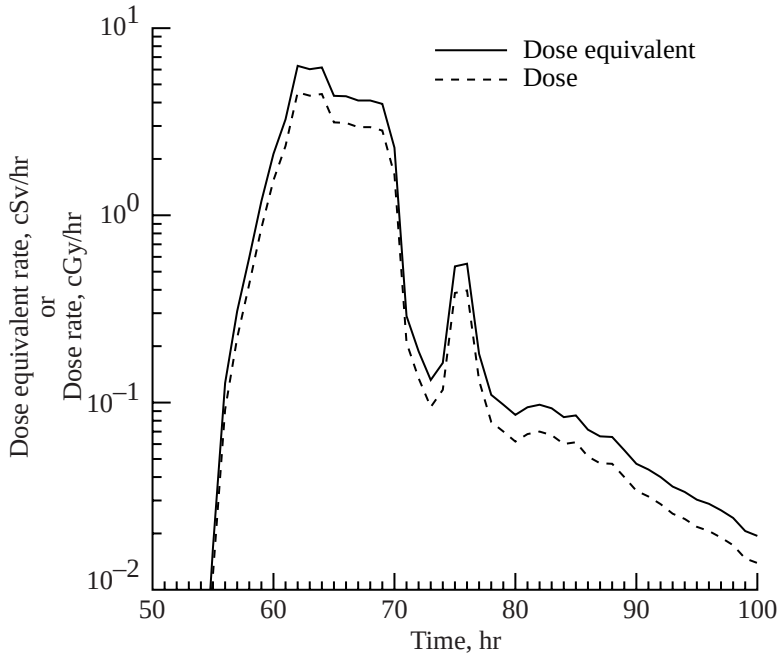


(a) Space suit.



(b) Pressure vessel.

Figure 12. Calculated average BFO dose and dose equivalent rates inferred for solar event of August 1972 in various aluminum shield configurations.



(c) Equipment room.

Figure 12. Concluded.

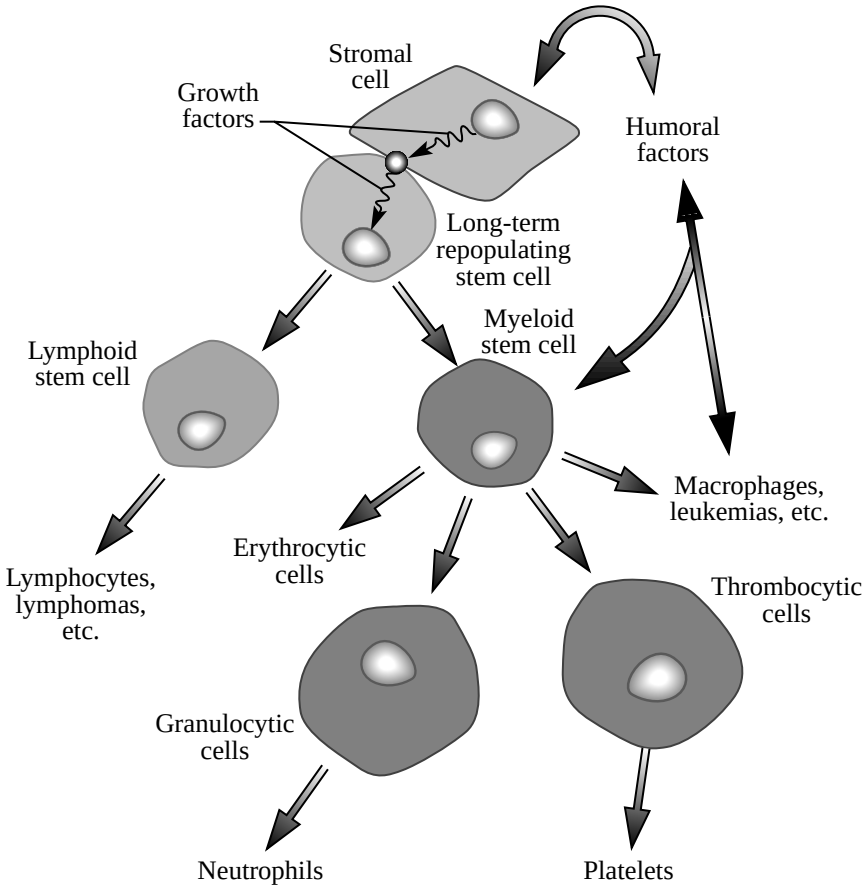


Figure 13. Cell populations and humor factors controlling peripheral blood elements.

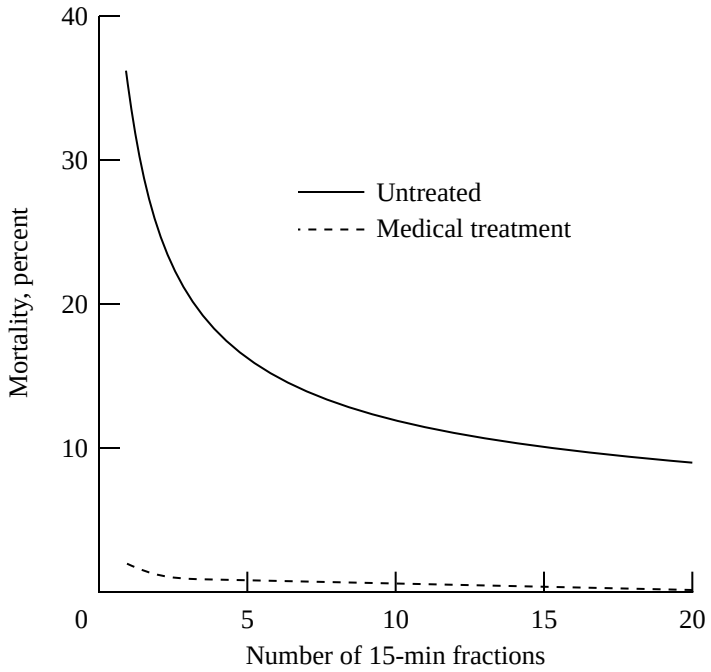


Figure 14. Mortality for hourly fractionated 2-Gy bone marrow dose from 200 kVp X rays as function of number of fractions.

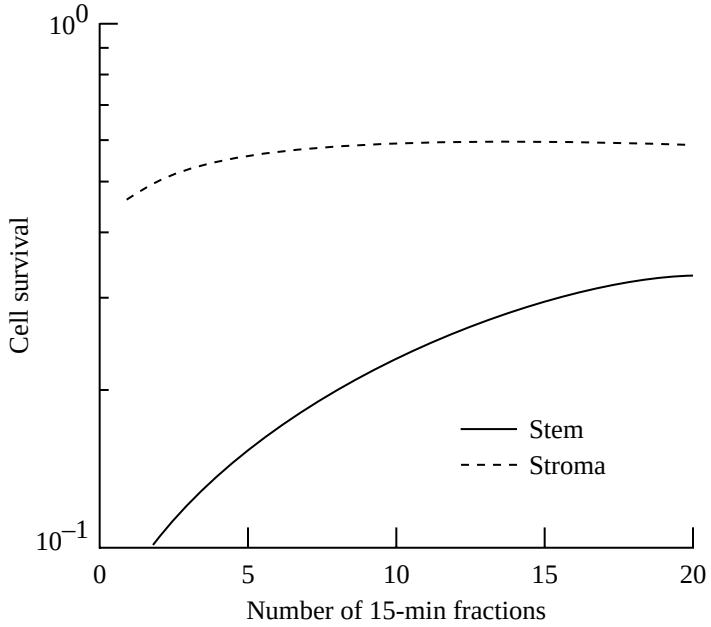


Figure 15. Stem and stromal cell survival at end of exposure period for fractionated 2-Gy total bone marrow dose from 200 kVp X rays.

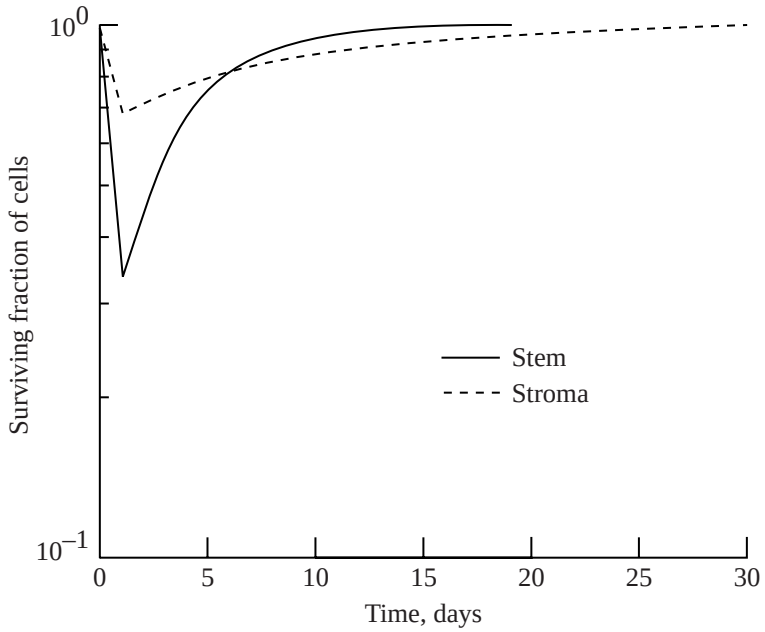
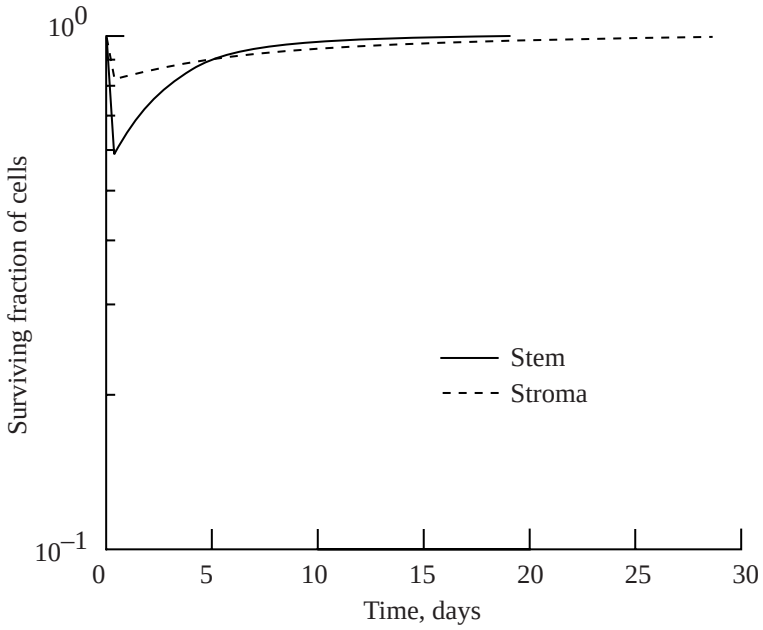
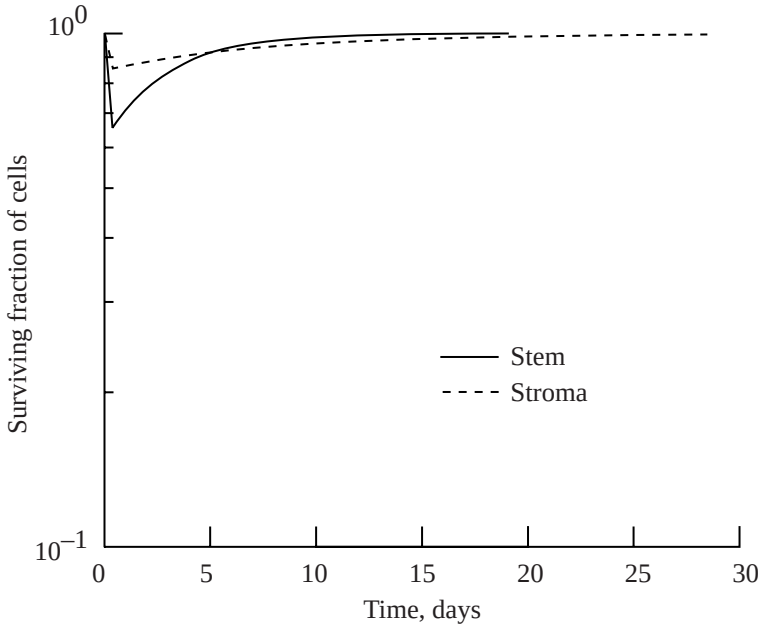


Figure 16. Surviving fraction of stem and stromal cell populations for 20 hourly fractions of 2-Gy total bone marrow dose from 200 kVp X rays showing recovery period.

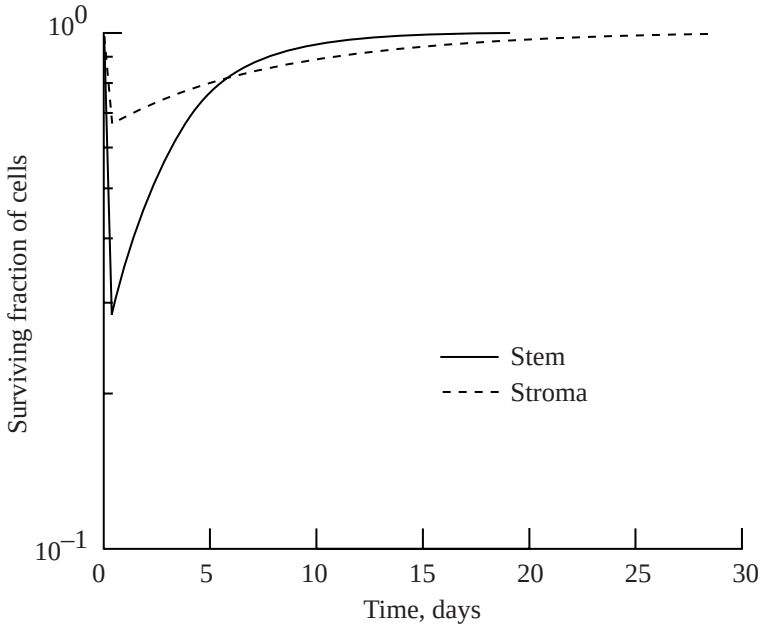


(a) Space suit.

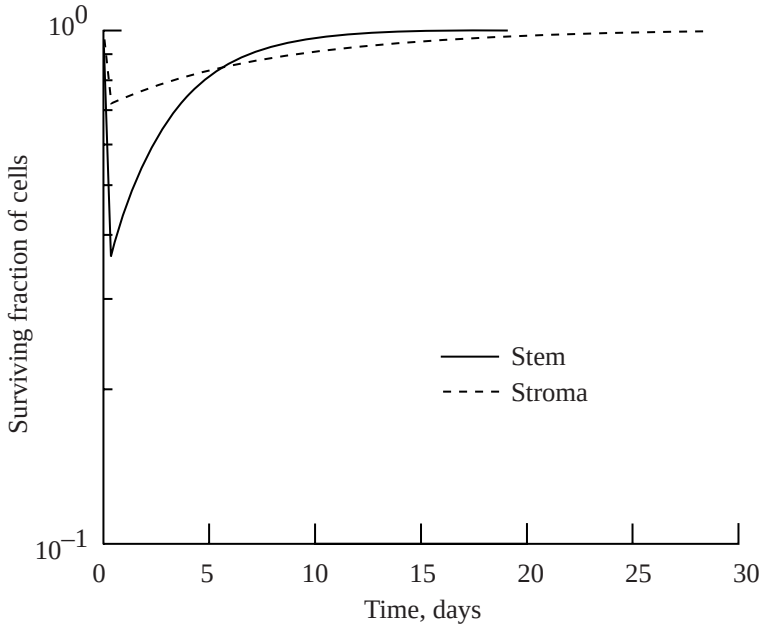


(b) Pressure vessel.

Figure 17. Surviving fraction of stem and stromal cell populations for worst 8-hr exposure during event of August 1972.

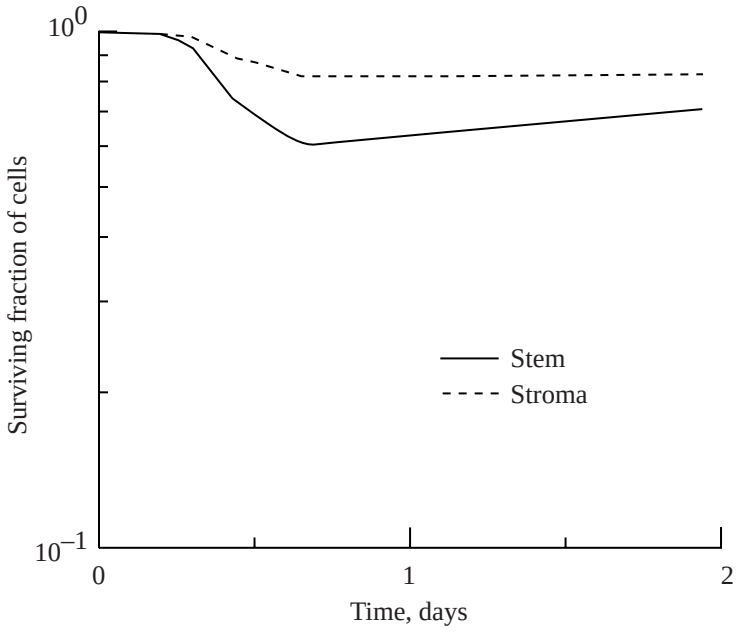


(a) Space suit.

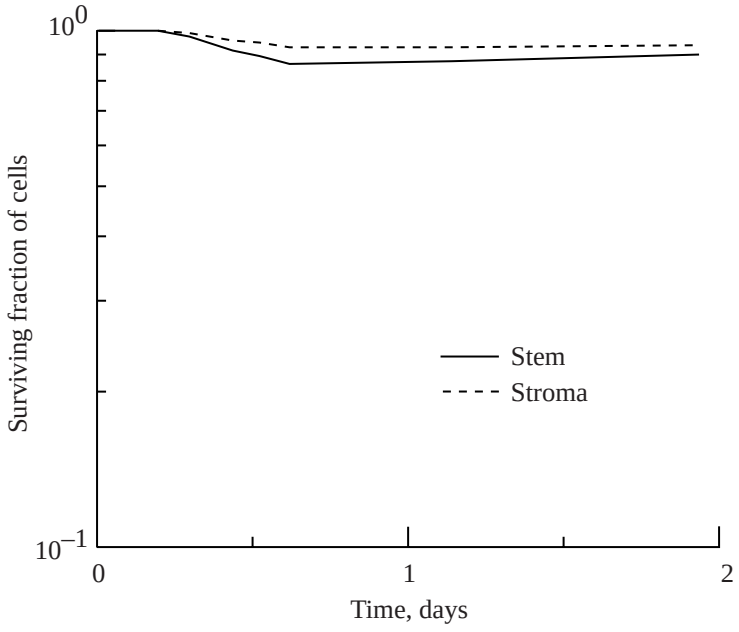


(b) Pressure vessel.

Figure 18. Surviving fraction of stem and stromal cell populations for worst 8-hr exposure during event two times that of August 1972.

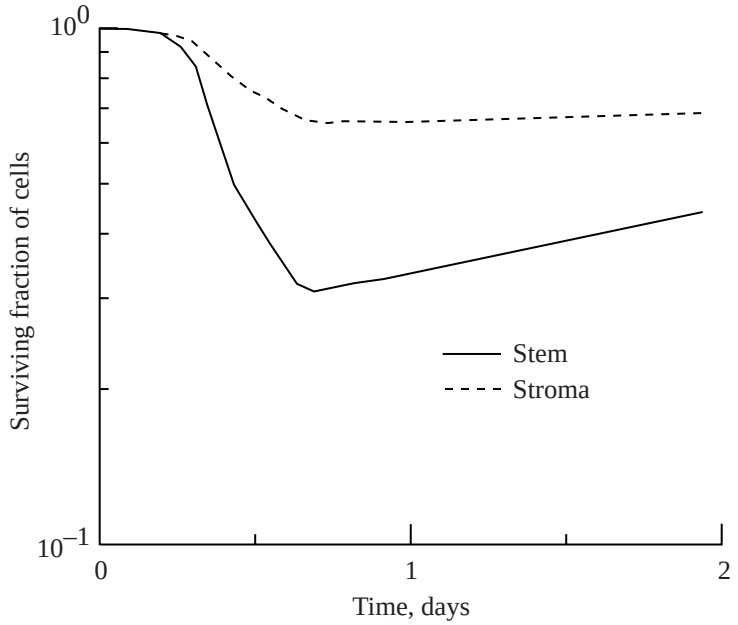


(a) Pressure vessel.

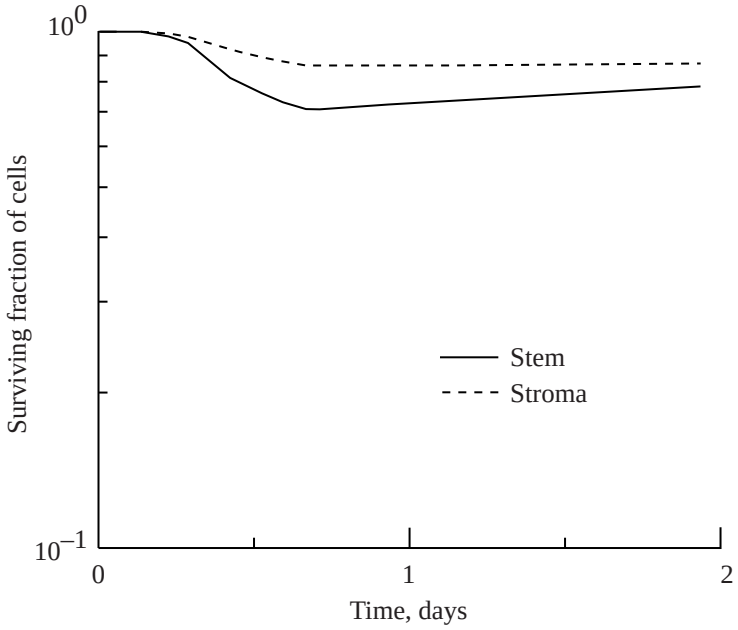


(b) Equipment room.

Figure 19. Surviving fraction of stem and stromal cell populations for exposure during event of August 1972.

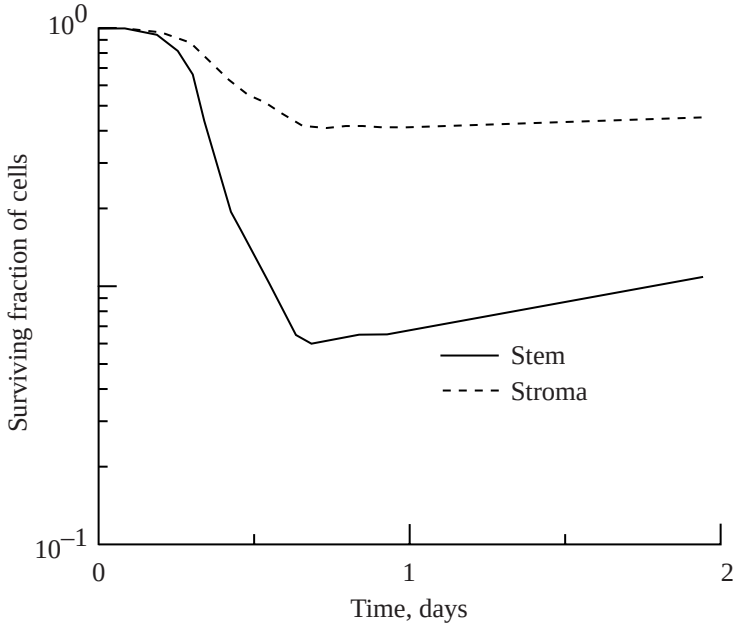


(a) Pressure vessel.

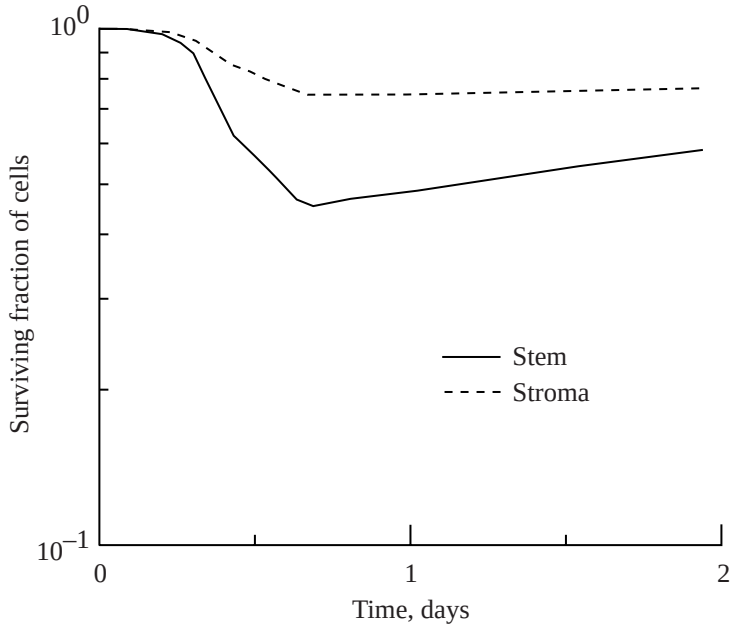


(b) Equipment room.

Figure 20. Surviving fraction of stem and stromal cell populations for exposure during event two times that of August 1972.



(a) Pressure vessel.



(b) Equipment room.

Figure 21. Surviving fraction of stem and stromal cell populations for exposure during event four times that of August 1972.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	October 1997	Technical Paper

4. TITLE AND SUBTITLE
Exposures to Solar Particle Events in Deep Space Missions

5. FUNDING NUMBERS
WU 199-45-16-11

6. AUTHOR(S)
John W. Wilson, Judy L. Shinn, Lisa C. Simonsen, Francis A. Cucinotta, R. R. Dubey, W. R. Jordan, T. D. Jones, C. K. Chang, and M. Y. Kim

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
NASA Langley Research Center
Hampton, VA 23681-2199

8. PERFORMING ORGANIZATION REPORT NUMBER
L-17616

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA TP-3668

11. SUPPLEMENTARY NOTES
Wilson, Shinn, Simonsen, and Cucinotta: Langley Research Center, Hampton, VA; Dubey and Jordan: Old Dominion University, Norfolk, VA; Jones: Oak Ridge National Laboratory, Oak Ridge, TN; Chang: Christopher Newport University, Newport News, VA; Kim: NRC-NASA Resident Research Associate at Langley Research Center, Hampton, VA.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified–Unlimited
Subject Category 93
Availability: NASA CASI (301) 621-0390

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The physical composition and intensities of exposures to solar particle events of sensitive astronaut tissues are examined under conditions approximating an astronaut in space. Response functions for conversion of particle fluence into dose and dose equivalent are used to establish significant fluence levels and the expected dose and dose rates of the most important events from past observations. The BRYNTRN transport code is used to evaluate the local environment experienced by sensitive tissues and is used to evaluate bioresponse models developed for use in tactical nuclear warfare. The present results will help to clarify the biophysical aspects of such exposure in the assessment of relative biological effectiveness (RBE) and dose rate effects and their impact on the design of protection systems for the astronauts. The use of polymers as shielding material in place of an equal mass of aluminum would provide a large safety factor without increasing the vehicle mass. This safety factor is sufficient to provide adequate protection if an event a factor of 2 larger than has ever been observed occurs during the mission.

14. SUBJECT TERMS
Solar particle event; Deep-space missions; Blood-forming organs (BFO); Dose equivalent; BRYNTRN

15. NUMBER OF PAGES
43

16. PRICE CODE
A03

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	