

BIOLOGICAL RESPONSE TO SPE EXPOSURES

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ABSTRACT

It has long been recognized that a single solar particle event (SPE) can produce, over a short period of time, exposures on the order of LD₅₀ for humans under normal physiological conditions. It is further recognized that recovery from injury over the period of exposure would greatly increase the chances of survival (dose rate effects) although such effects were left unquantified. In the present report we use the bioresponse model derived from a broad range of animal and human exposure data for evaluation of troop readiness in tactical nuclear warfare to evaluate the biological risk posed by the solar event of 4 August 1972. The astronaut blood forming organ (BFO) exposure in deep space would have been 2.2 Sv (1.6 Gy) in a space suit, 1.8 Sv (1.3 Gy) in an aluminum pressure vessel, and 0.7 Sv (0.5 Gy) in an equipment room compared to an X-ray mortality threshold of 1.5 Gy (assuming high dose rate). We find BFO dose rate effectiveness factors for this SPE on the order of 3 to 4, greatly reducing the mortality risks for this event. There is an approximate 3 percent chance that an even larger event may occur for which exposures could be 2-4 times higher. Assured survival of the astronaut requires added shelter shielding and a warning system for this event. The required mass of the shelter shield can be greatly reduced by using hydrogenous materials such as polymers, water, food, and other biological materials in its construction. Limitations of the current bioresponse model arise from the exposures taking place in the microgravity environment wherein the immune system is already challenged and the effective mortality threshold may be reduced by a factor of two. Such microgravity effects could greatly affect astronaut risks.

INTRODUCTION

Solar cosmic radiation has long been recognized as a serious potential hazard in space operations (Schaefer, 1957). Also, it was recognized that the provision of sufficient shielding to keep exposures at low levels increased the complexity of spacecraft with associated increased risks of mechanical failure; as a consequence tradeoff of radiation health risks with the other mission risks became the rule in early space activity. As a result of the national importance of the Apollo mission to land men on the moon, rather high levels of exposure were allowed in the design process as other risks within those missions were also high and a balance of radiation risks and the other mission risks were assumed (Billingsham et al., 1965). The exposure limits allowed in the design of the Apollo mission were Blood Forming Organ (BFO): 2 Sv, Skin: 7 Sv, Lens: 2 Sv, Hands/Feet: 9.8 Sv respectively. With the development of Skylab, Shuttle, and now International Space Station (ISS), the routine nature of space operations has led to a more conservative view of risk acceptability in space exposures (NAS, 1970). Indeed, the NCRP has recommended the use of low earth orbit (LEO) exposure limits for Shuttle and ISS operations (table 1) as a guideline (NCRP, 1989) to space shield design in deep space exploration (outside the protective geomagnetic field).

An earlier study of the exposures received in deep space operations revealed the 4 August 1972 solar event to be the most important observed event and could deliver a potentially lethal dose within a several hour period (Wilson and Denn, 1976). More recent studies using the earlier data base on exposure estimates evaluated dose rate effects as being an important sparing factor in survivability (Wilson et al., 1997). There are many remaining issues concerning the uncertainty in the associated health risks in space exposures 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 to reduce this uncertainty. In the present paper we will

Table 1. *NCRP Recommended Organ Dose Equivalent Limits (Sv).*

	BFO	Skin	Ocular lens
Career	1-4 ^a	6	4
Annual	0.5	3	2
30 Days	0.25	1.5	1

^aDepending on age and gender

give a relatively complete picture of the exposures which would have been received by an astronaut in deep space for the 4 August 1972 solar particle event and discuss some of the protection-related issues.

SOLAR PARTICLE EVENT PROTECTION

Particles arriving at some remote location from the sun are diffusing through the interplanetary media and show some anisotropy in that the back-scattered particles are absent on the leading edge of the expanding radiation field. Following the first tens of minutes after initial particle arrival, isotropy is usually achieved. We will henceforth assume the radiation fields incident on the spacecraft to be isotropic. The exposure of the BFO and skin due to a monoenergetic source of isotropic protons is shown in figure 1 as a function of proton energy for three typical shield representations assuming aluminum structures (space suit of 0.4 g/cm², pressure vessel of 1 g/cm², and equipment room of 5 g/cm²). The two curves for each organ are the dose equivalent and absorbed dose (upper and lower curves respectively). We 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 do depend on the organ as determined by the mass distribution of the remainder of the astronaut's body. In the present calculation, we use the computerized anatomical man model (CAM) described elsewhere (Billings and Yucker, 1973). The dose varies widely within the body tissues and important distribution effectiveness factors reduce the effects of exposure and need to be included (Wilson, 1975).

We may define a critical fluence level as one in which the exposure is on the order of the exposure limit which requires on the order of 5x10⁸ p/cm² for the BFO and the order of 2x10⁸ p/cm² for the skin and lens. A potentially debilitating event would be about one order of magnitude larger than these critical fluence levels. The energies at which the significant fluence is evaluated depend on the organ and shielding as shown in table 2. Clearly any solar particle event whose fluence exceeds these levels for the specific shielding of the astronaut requires careful consideration. The limiting biological factor will depend on the spectral content of the specific event which differs from event to event.

A recent evaluation of the historic events for the years 1955 to 1986 was given by Shea and Smart (1990). Since 1986 there are the data from the episodes of 1989 during the maximum phase of solar cycle 22 given by Sauer et al. (1990). We have used the IMP data for the August 1972 event (Wilson and Denn, 1976) and careful analysis using the CAM model to show the August 1972 event as the defining event for radiation protection practice (Wilson and Denn, 1976; Simonsen et al. 1992). Only the August 1972 event has the ability to cause a potentially lethal exposure. Clearly the August 1972 event dominates in the range of 70-100 MeV as seen in figure 2 which is most important to the BFO. In addition to the importance of the spectral content the August 1972 event, the dominant portion of the exposure occurred over several hours compared to three days of the October 1989 event for which repair and repopulation will play vastly different roles in affecting tissue response.

Aside from the total fluence, the dose rate is an extremely important parameter. Some somatic threshold doses are observed to double following a factor of ten reduction in dose rate (Langham, 1967). Many large events last for several hours to several days and dose rate dependent factors are expected to be important. The particle intensities of the August 1972 event are shown in figure 3. 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 occurred 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 effects 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 made substantial contributions to the BFO exposure. Clearly the dose rates for specific organs can be quite different depending on the degree of shielding (including the astronaut's tissues) and the spectral content of the event.

Table 2. *Critical Fluence Levels In Astronaut Exposures.*

Organ	Fluence, p/cm ²	Critical Energy, MeV		
		Space Suit	Pressure Vessel	Equipment Rm
BFO	5×10 ⁸	≈ 70	≈ 80	≈ 110
Skin	2×10 ⁸	≈ 20	≈ 30	≈ 75

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 e-folding energy of 26.5 MeV. The resultant data are used to evaluate the particle spectra at specific tissue sites using the BRYNTRN code (Wilson et al., 1989). The protons are transported through the shield and the astronaut's body to the tissue point with the atomic and nuclear processes represented. The BFO environment integrated over the event within the space suit is shown in figure 4. The local tissue environment is complex as a result of the nuclear reactions in the shield and the astronaut's surrounding body tissues. Although the majority of the protons present at the tissue site shown in the figure are those incident on the outer shield surface and transported into the body interior, significant numbers of protons appear as secondaries. 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 (not shown). The neutrons make no direct contribution but 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 data base associated with the HETC or the LAHET Monte Carlo codes. These cross sections are not able to describe the direct production of light ions in collisions with the shield material as found in experimental studies aboard the shuttle spacecraft (Badhwar et al., 1995). The current light ion data base is derived from cluster knockout models for not only the proton and neutron but also light ion induced reactions resulting in very energetic light ion production and light ion breakup calculations (Cucinotta et al., 1996) as required to match shuttle experiments.

The dose and dose equivalent rates for the skin and BFO within a space suit are shown in figure 5. The radiation quality at the skin is variable throughout the event within the space suit. The radiation quality for skin within the equipment room (not shown) is nearly time independent (Wilson et al., 1997). The radiation quality within the BFO depends less on both shielding and time. The dose and dose equivalent rates for the skin and lens (not shown) can be very high (1 to 10 Gy or Sv per hour in a space suit and 1 to 3 Gy or Sv per hour even in a pressure vessel). The BFO exposures are about a factor of ten or more smaller (10 to 20 cGy or cSv per hour in a space suit or a pressure vessel, not shown, and 5 to 7 cGy or cSv per hour in the equipment room, not shown). The total dose and dose equivalent are given for the three critical tissues in table 3. The provision of a shelter with 10 g/cm² of aluminum will provide sufficient shielding to meet the 30 day limits in table 1. The exposure levels within the equipment room or shelter in table 3 can be reduced by large factors by replacing much of the aluminum structure with organic materials of the same total mass as seen in comparing with table 4. Exposures on the lunar surface would be half of the values in the tables as the lunar mass provides a shadow shield over half of the solid angle.

Table 3. *Dose Equivalent And Dose In Critical Body Organs Within An Aluminum Structure During The August 1972 Solar Event, cSv (cGy).*

Organ	Space Suit	Pressure Vessel	Equipment Room	Shelter
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 4. *Dose Equivalent And Dose In Critical Body Organs Within An Polyethylene Structure During The August 1972 Solar Event,cSv (cGy).*

Organ	Space suit	Pressure vessel	Equipment Room	Shelter
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)

The problem of shield design for protection from such events is complicated by the statistical nature of solar particle event occurrence. One's confidence of not exceeding the August 1972 event fluence level above 30 MeV on a one year mission near the next solar maximum is about 97 percent (Feynman et al., 1990). (Note, 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. We suggest that 4 times the August 1972 event be taken as an approximation to the 99.5 percentile annual fluence with the time structure being that most of the particles arrive in a several hour period. A rationale for shield design may be to design for the largest event observed recognizing that it may be exceeded with 3 percent confidence. An event of 4 times the August 1972 event would appear as an accidental exposure not accounted in the design process and one would design medical procedures to cover the possibility of accidental exposure. Exposures at which significant health effects occur have been summarized from various sources by the NAS (Langham et al., 1967) and NCRP (1989) and are shown in table 5. The dose associated with 50 percent mortality (LD_{50}) are affected by the degree of medical support and intensive medical care can greatly increase the chances of survival (NCRP, 1989). As discussed below, the LD_{50} is also affected by the space-related stresses. One can contemplate that the health of the astronaut can be severely impacted in the unlikely occurrence of a 99.5 percentile event or exposures at 4 times the levels in table 3 to be compared with exposure levels at which health effects occur as given in table 5. Clearly a significant probability of early radiation syndrome would result unless dose rate effects are sufficiently important to reduce the risks.

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The design process would be aimed at keeping exposures within acceptable limits as given in table 1. 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 space surrounded, in part, by only 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 particle event. Such a warning could be issued when ten or twenty percent of the critical fluence levels in table 2 are achieved. 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 but even in a pressure vessel as seen in table 3. Alternatively, the design may be to provide protection against the August 1972 event and an improbable more intense event, if it occurs leading to higher than anticipated exposures, would be considered as an accidental exposure.

Table 5. *Exposure Levels At Which Health Effects Appear In The Healthy Adult (Single, High Dose Rate Exposures)*

Health Effect	Dose of 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} , minimal supportive care	3.2-3.6
LD_{50} , supportive medical treatment	4.8-5.4
Erythema threshold	6.0
Moist desquamation	30.0

The thresholds for erythema is about 6 Sv for prompt exposures (approximately 20 min.). The effects of protraction of the exposure to several hours increases the effective threshold as $T^{0.29}$ for an overall correction factor of 2.4 for the August 1972 event. Even then the exposures in table 3 are likely to cause early adverse skin responses even in a pressure vessel. Aside from this crude analysis we have no detailed models for many tissues as are available for the BFO response developed by the military for field assessment in tactical nuclear warfare (Jones 1981, Jones et al., 1994). There is probably enough data on 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 an order of magnitude larger surface exposure from beta emitters (UNSCEAR, 1988) which is somewhat similar to space exposure distributions (Wilson et al., 1997) as shown in tables 3 and 4. There were no deaths among those whose whole body exposure at Chernobyl was less than 2 Gy. All patients of exposures of the marrow system of doses greater than 2 Gy were given supportive care including isolation, antibiotics, and in extreme cases blood element transfusions and marrow transplants (UNSCEAR, 1988). Radiation-induced skin reaction was a complicating factor in overall treatment (UNSCEAR, 1988). Only one death occurred among the 43 exposed between 2-4 Gy under conditions of intense supportive care. This single death included severe skin injury as a complicating factor (UNSCEAR, 1988).

The diagnostics of the Chernobyl accident relied on biological and physical dosimetry. The blood elements within exposed individuals were monitored within 12 hours of the accident and taken as an indication of the level of exposure. To understand this methodology we show the kinetics of the marrow system in figure 6. The stromal cells reside in marrow cavities and include those populations associated with the yellow marrow or non-hematopoietic marrow. Stromal cells provide cytokine mediated control of marrow, bone and immune system kinetics as well as biochemical signals to other organs. The stem cells attach to the stroma and cytokines are transferred through cell membranes. Stem cells are highly mobile inside the body and circulate in the blood to other, perhaps depleted, sites of the marrow thus aiding survival. During ablative or cytotoxic injury, hematopoiesis may occur in other organs or in normally non-hematopoietic regions of the yellow marrow. The stromal cells provide growth factors which are responsible for the rate of cell propagation among the various 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 the stem and stromal populations will have its ultimate consequences in the peripheral blood. The time course of these peripheral blood elements (specifically the lymphocytes, neutrophils, and platelets) were used to estimate the level of exposure (UNSCEAR, 1988). Kinetic models of the human 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.

The human LD_{50} for bone marrow seems to be about 3 Gy for the atomic bomb survivors (Levin et al., 1992). But the LD_{50} for man can be increased with antibiotics, blood transfusions, and cytokine therapy to about 6 Gy. Intensive medical care including bone marrow or blood stem cell transplant could increase survivability to high levels but such medical procedures themselves carry additional attendant risks (UNSCEAR, 1988) that may be modified by pre-conditioning to the space environment. Conversely Morris and Jones (1988, 1989) and Morris et al. (1993) 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 non-sterile conditions similar to that used for test animals. This estimate would be for a normal gravity environment and may be further reduced by prolonged exposures to microgravity which slows osteogenesis and possibly down-regulate the monocyte-osteoclasts and monocyte-macrophage kinetics. Some data on associations between bone kinetics and immune system function suggest that a 2-fold increased sensitivity may be reached for prolonged weightlessness. The balance between radioresistance from lower dose rates and sensitivity from microgravity/immunosuppression require more realistic time- and effect-dependent models. 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, stress from microgravity, cabin atmosphere... may decrease their radioresistance.

We use the model for early lethality as adapted by Jones (1981) and Jones et al. (1994) to examine the repair/recovery effects in humans due to rather large exposures. Figure 7 shows the probability of death for a 2 Gy dose to the bone marrow by 250 kVp X rays delivered as multiple equal fractions one hour apart. Each fraction was given in a 15 minute exposure. Probability of death can be quite large when received in a single high dose rate fraction (note, Jones estimates that the bone marrow LD_{50} of 250 kVp X rays is 2.15 Gy while that of ^{60}Co gamma rays is 2.95 Gy). It is expected that supportive medical treatment will allow survival as shown in the figure. As the number of fractions are increased, the probability of death drops dramatically to less than 10 percent (even without medical treatment) beyond 15 fractions (or equivalently 15 hours). The stem and stromal cell survival at the end of each fractionated exposure is shown in figure 8. Stem cell survival for the single 2 Gy marrow dose is very low (much less than ten 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 ten 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 and recovery.

Space suit life support systems are limited to eight hours of continuous use. We therefore look at the effects of the worst eight-hour exposure on the biological response. In these estimates we use the dose equivalent with the usual quality factor which overestimates the RBE for repopulation (Jones et al., 1997). The estimated cell populations shielded by a space suit are shown in figure 9 for the August 1972 event. The stem cell population drops to about 58 percent in the space suit with little risk of death. The effects on the cell populations are slight although the accumulated dose equivalent is large and the sparing factor is about a factor of four.

The August 1972 episode was a sequence of three distinct events over an eight day period (fig. 3). The effect of spending the first 50 hours of the event in a pressure vessel is shown in figure 10. 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 will have little effect on mortality. Indeed, the mortality estimate for the first fifty hours is within 10 percent of the mortality of the worst eight hours. Death is not expected for the August 1972 event. If an event twice as large as the August 1972 event occurs (fig. 11) then there is a small risk of death (12 percent) without medical treatment. Depopulation of both stem and stroma cells for a 4 x August 1972 event are 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 good medical practice is followed in which the risk is reduced to 9 percent. These results are summarized in table 6. Again, the use of polymer structures would provide an important safety margin greatly reducing the risks with minimal impact on mission cost. These are extremely improbable events, but if such an event were to occur it is apt to have dire consequences in exposure accidents unless adequate planning is made to provide necessary medical support. Within 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, we have not included any increase in radiosensitivity due to space stress factors or the possible complications arising from injury to other organs, especially the skin. Even so it appears that astronaut survivability will occur with some medical planning in the case of an accidental exposure except in the improbable case of an event 4 times larger than any observed occurs and the exposures are protracted only over a several hour period.

CONCLUDING REMARKS

The August 1972 solar particle event is the single most important observed event in relation to the protection of astronauts in deep space in the 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/cm² of aluminum) would have been sufficient to assure survival and a shelter of 10 g/cm² would have maintained exposures within the prescribed 30 day limits in table 1. Even greater protection is provided if large quantities of the usual 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 1) 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/cm² of aluminum. A safety factor 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 so assumed herein) will not be adequate unless additional massive shielding is added. However, the risk of death is small within a 10 g/cm² of aluminum shelter and virtually no risk of death occurs if the aluminum of the shelter is replaced by an equal mass of polymeric materials. Furthermore, the use of an equal mass of polymers for the shelter will reduce astronaut exposures to within a factor of two of the protection standards in table 1. From a practical point of view one may

Table 6. *Expected Mortality (Percent) Without Adequate Medical Treatment For Various Aluminum Shield Configurations.*

Event	Space Suit	Pressure Vessel	Equipment Room	Shelter
Aug. 1972	1) ^a	1	0	0
2 x Aug. 1972	12) ^a	12	0	0
4 x Aug. 1972	87) ^a	88	3	0

^aWorst eight hours

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. Taking this philosophy, the present evaluation of the astronaut response to such improbable high fluence events indicates that a high degree of medical preparedness is required.

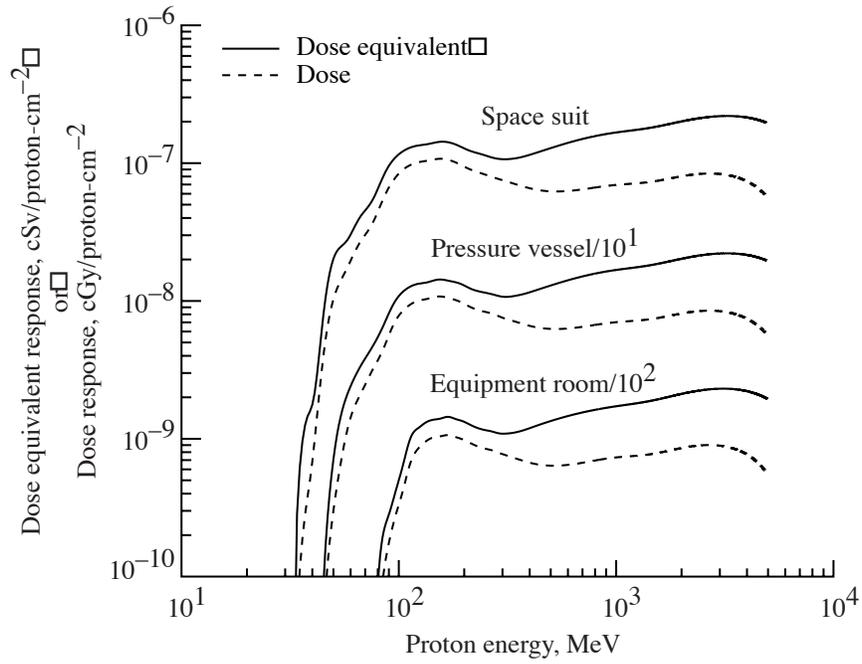
A warning system needs to provide not only information for warning the astronaut to seek shelter but would be required to make assessment of the astronaut health status in the event adequate shelter is not acquired during the event (accidental exposure) or if the shelter is inadequate as a much larger 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 on the range of 20 to 110 MeV with critical fluence levels of 2×10^8 p/cm² for skin and ocular lens and 5×10^8 p/cm² 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 of the current calculations would include direct considerations of these factors instead of adding modifying factors to idealized assumptions as in the present report. Such calculations, plus medical triage based on initial changes in blood counts (e.g., lymphocytes) could contribute significantly to post-exposure therapeutic planning for interdictive measures such as antibiotics, infusion of 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 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 4 times the size of the August 1972 event. This conclusion depends on the adequacy of the present bioresponse model which includes uncertainty due to possible time-dependent impairment of immunity as the mission time increases into many months of weightlessness. However, even within a simple pressure vessel there is a significant risk of death even with good medical practice if such a large event occurs. But, one needs to emphasize that these are very unlikely events and perhaps only require adequate mission operational planning.

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

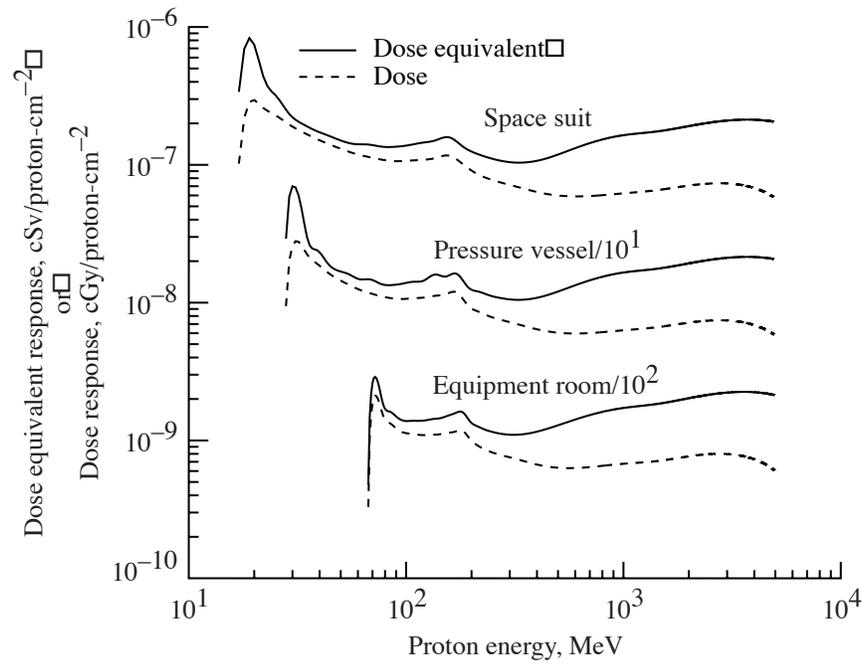
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a. BFO average



b. skin

Figure 1. Dose and dose equivalent in two critical body tissues.

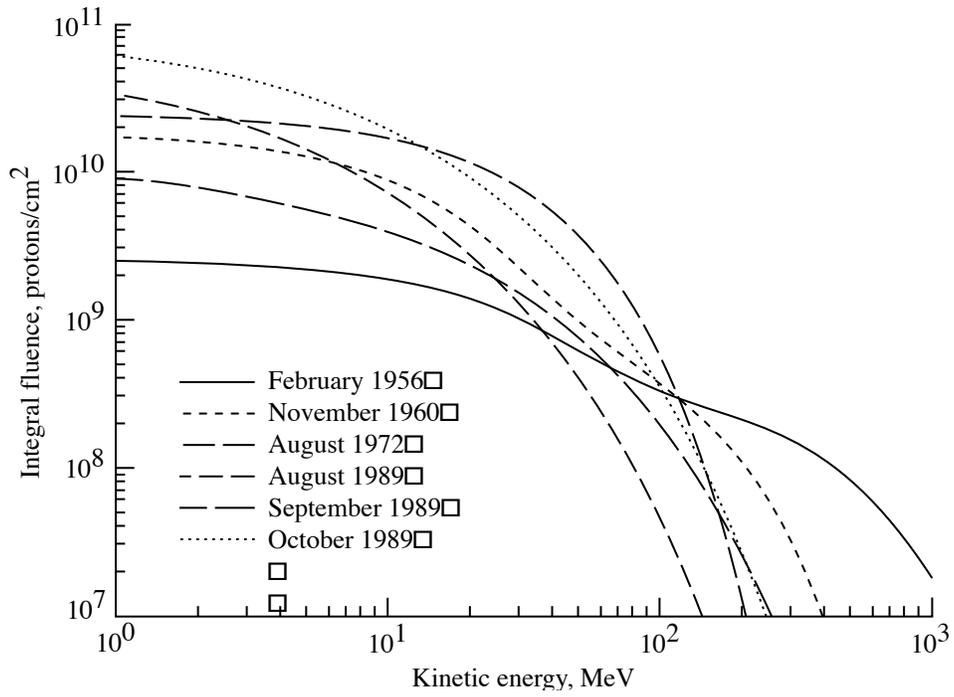


Figure 2. Large solar proton event integral fluence spectra at 1 AU.

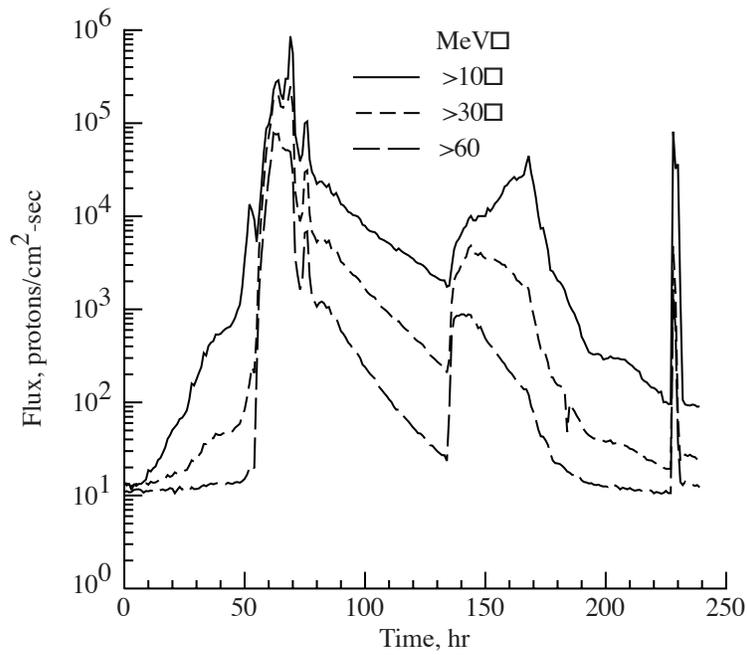


Figure 3. Measured intensities at 1 AU of the 2-11 August 1972 solar event.

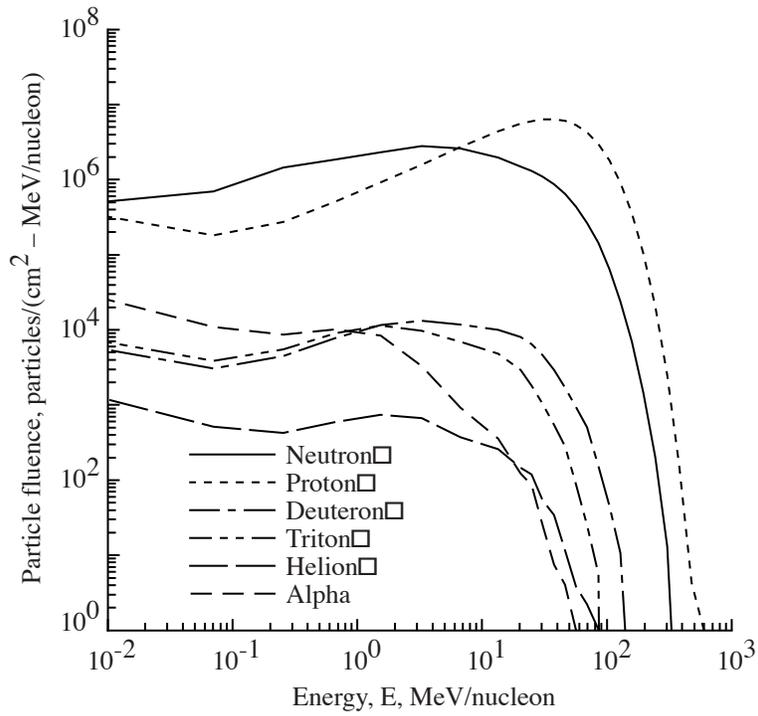
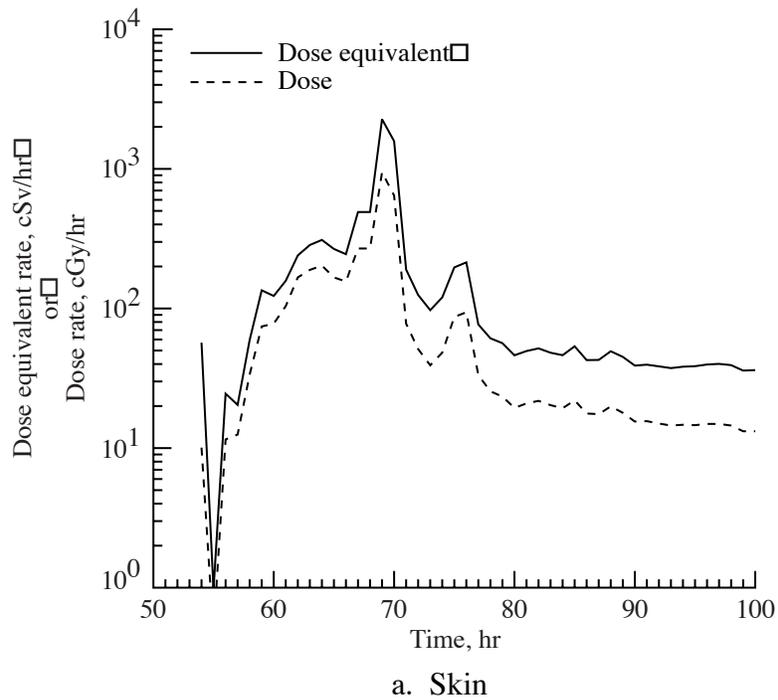
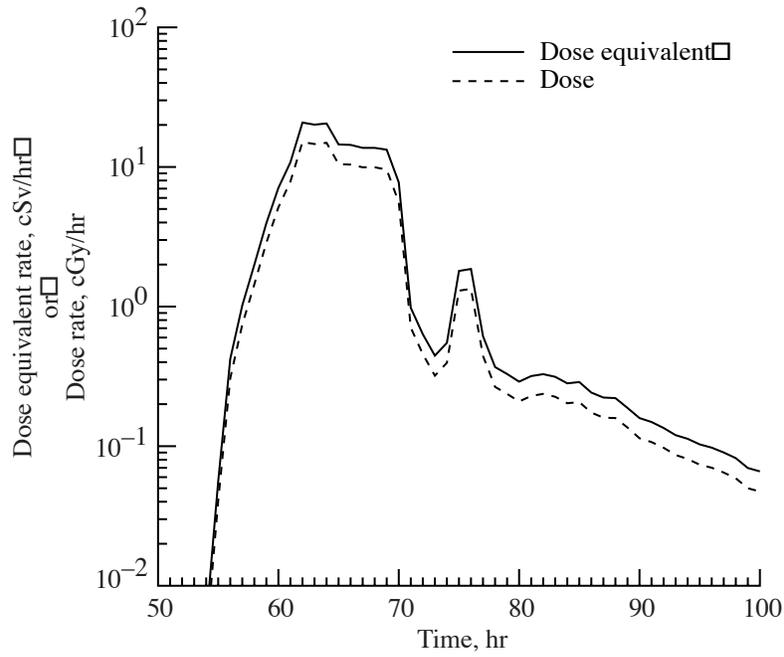


Figure 4. Calculated local average BFO tissue environment within a space suit.





b. Blood forming organ

Figure 5. Calculated skin (a) and blood forming organ (b) dose and dose equivalent rates for the August 1972 solar event within a space suit.

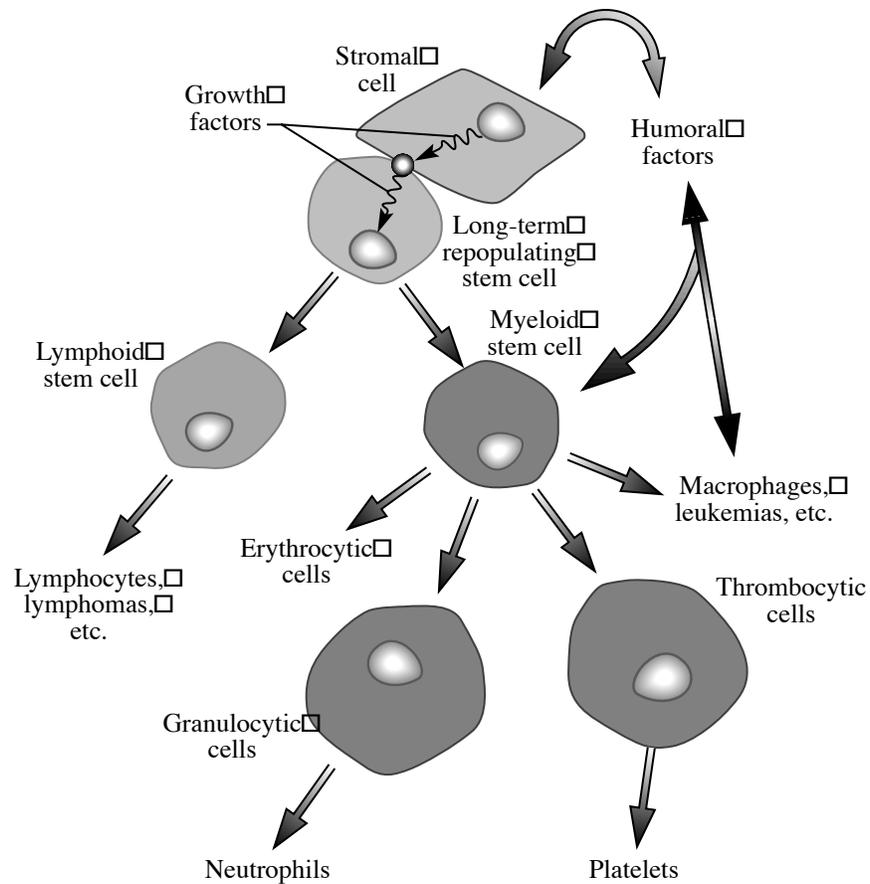


Figure 6. Cell populations and humoral factors controlling the peripheral blood elements.

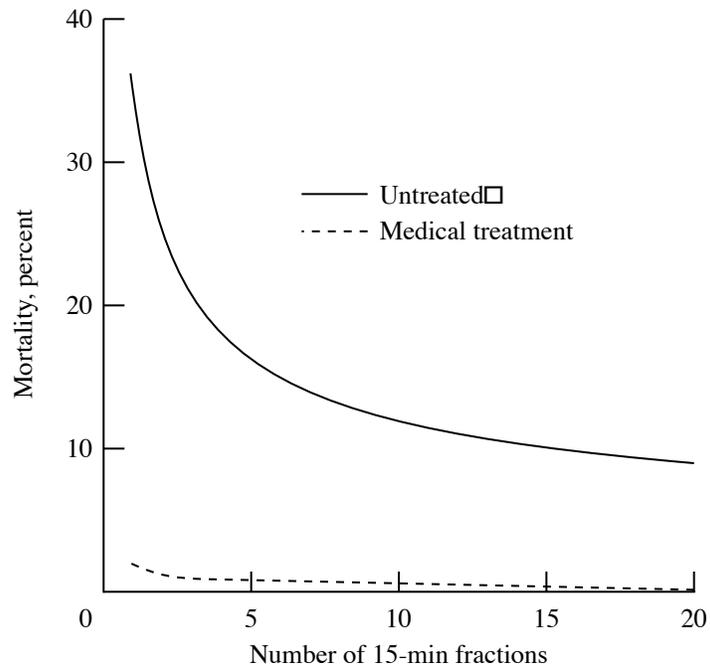


Figure 7. Mortality for an hourly fractionated 2 Gy bone marrow dose from 250 kVp x rays as a function of the number of fractions.

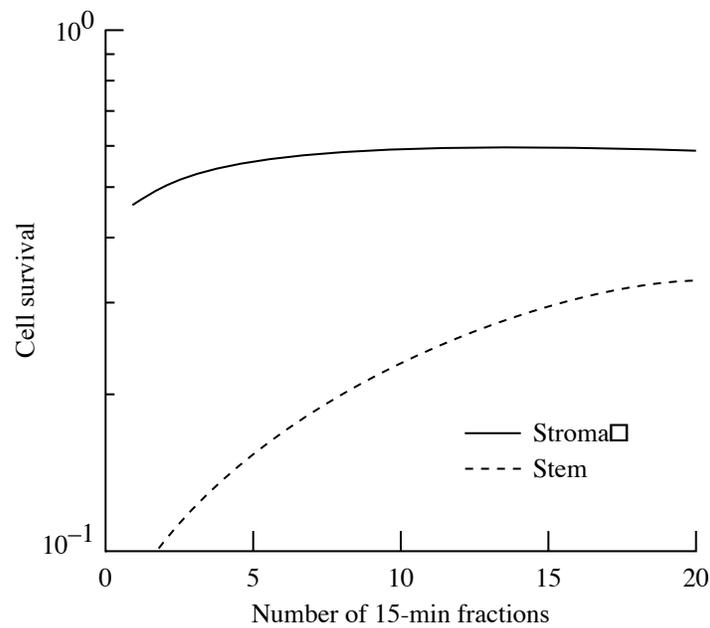


Figure 8. Stem and stromal cell survival at the end of the exposure period for a fractionated 2 Gy total bone marrow dose from 250 kVp x rays.

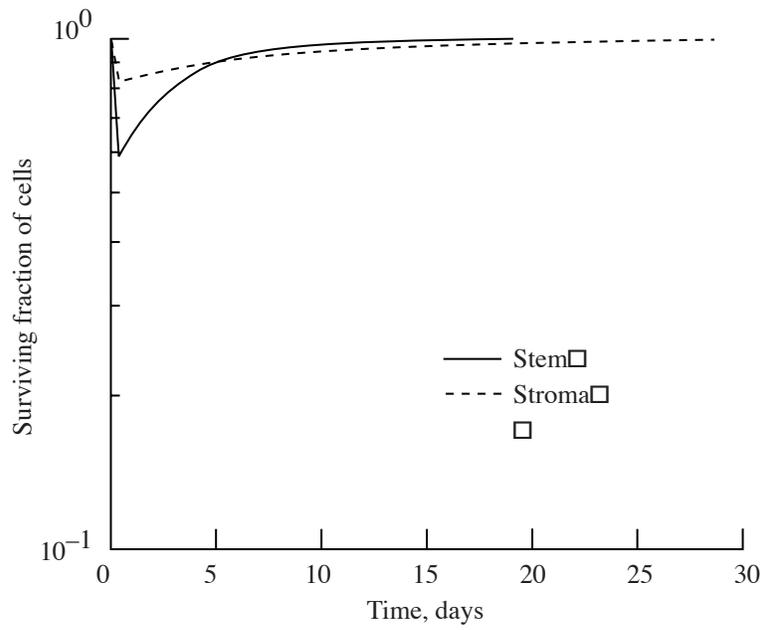


Figure 9. Surviving fraction of the stem and stromal cell populations for eight hour exposure in a space suit for the August 1972 event.

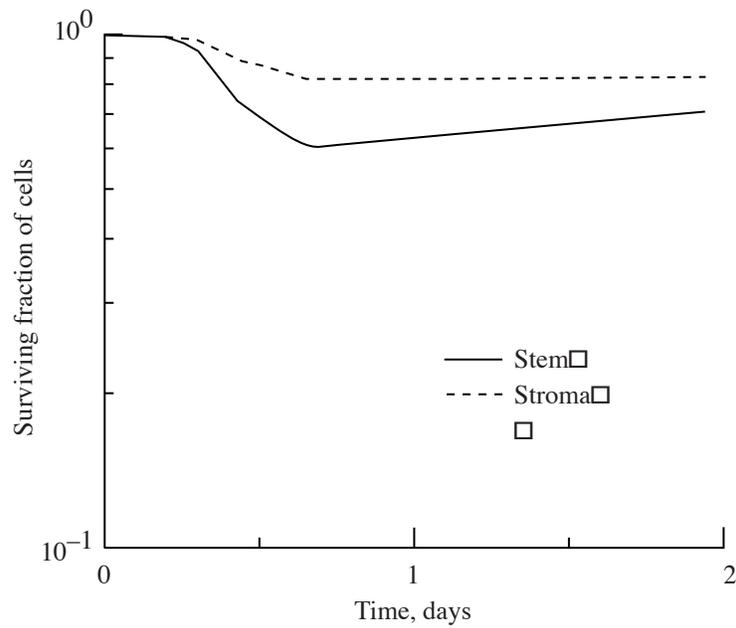
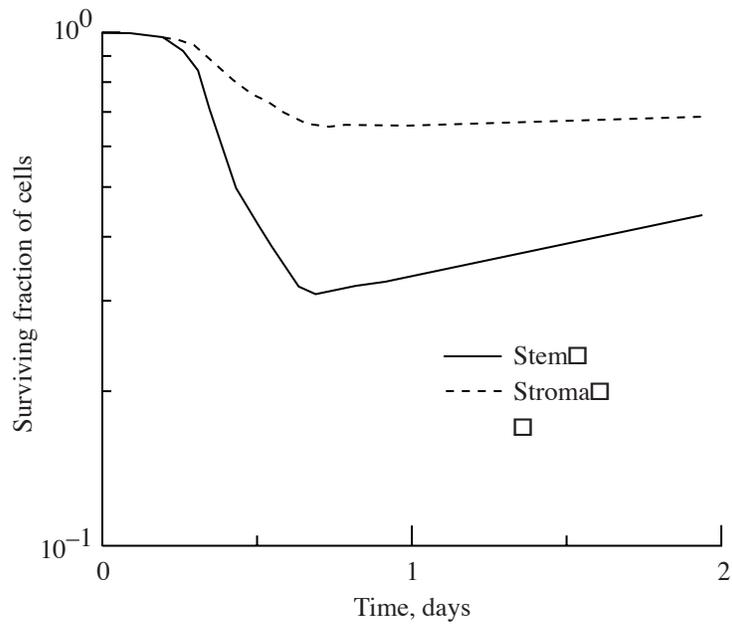
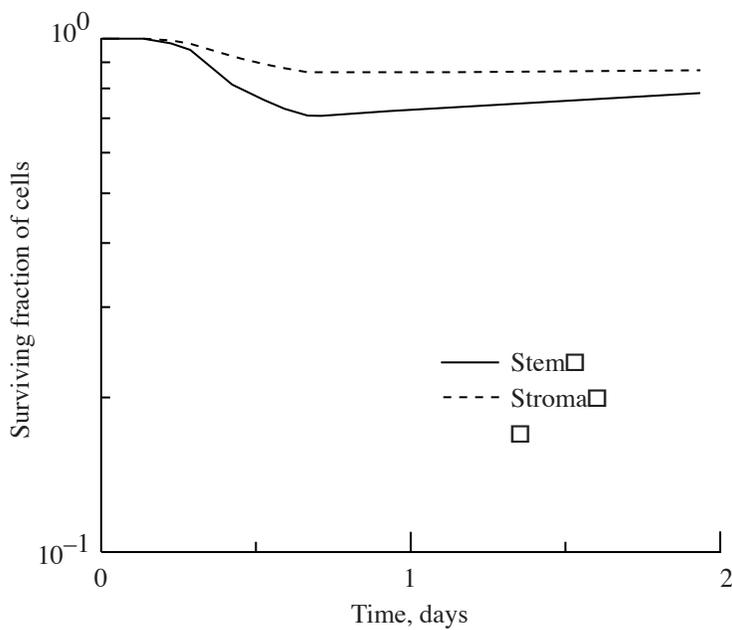


Figure 10. Surviving fraction of the stem and stromal cell populations for exposure in a pressure vessel for the August 1972 event.



a. pressure vessel



b. equipment room

Figure 11. Surviving fraction of the stem and stromal cell populations for exposure in a pressure vessel (a) and equipment room (b) for the 2 x August 1972 event.