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Interplanetary Crew Dose Rates for the August 1972 Solar Particle Event

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Using the coupled neutron–proton space radiation transport computer code (BRYNTRN), estimates of dose rates of protons in the skin, ocular lens and bone marrow, behind various thicknesses of aluminum shielding, for crews on space missions outside the Earth's magnetosphere, are made for the large solar particle event (SPE) of August 1972. Overall, the August 1972 dose rates are significantly higher than those estimated for any of the events that occurred in August–December 1989. The dose rates in the August 1972 SPE are not low dose rates as specified by the major national and international advisory bodies and committees. © 2000 by Radiation Research Society

INTRODUCTION

Risks to crews of future interplanetary missions from exposures to large solar particle events (SPEs) are a function of the total dose and the dose rate received during the events. Previous estimates (*1–3*) of absorbed doses from the large events of August 1972 and October 1989 indicate that values in excess of 10 Gy are possible for crew members protected only by a spacesuit or thinly shielded spacecraft. Current thinking (*4*), based upon an earlier analysis of the October 1989 event (*5*, *6*), is that dose rates from SPEs are expected to be low, even when the total absorbed dose is large, because of the protracted nature of these events (typical event duration is several days to a week). Recent estimates of dose rates from events that occurred between 1986 and 1993 (*7*) suggest that dose rates from large SPEs are ''low-dose-rate'' events, as defined by various advisory bodies (*8–10*). Very recently, however, it has been noted (*11*) that an earlier analysis (*12*) of the dose-equivalent rates for the large SPE of August 1972 suggest that the dose rates from this event could be much higher than any of the ''low dose rates'' estimated for the events of 1986–1993.

In this communication, we present an analysis of the organ dose rates for the large SPE of August 1972 for crews on missions beyond the Earth's orbit. The calculations of absorbed doses and dose rates are made using the space radiation transport computer code, BRYNTRN (*13*), and a realistic, detailed computerized anatomical model (CAM) (*14*) to represent the actual organ dose and dose-rate distribution. The objective of this analysis is to determine if the August 1972 SPE dose rates are low, as defined by these various advisory bodies.

DOSE-RATE MODEL

The hourly proton fluence values for the August 1972 event are listed in Table 1. Values for the integral fluences J (>30 MeV) and J (>60 MeV), taken from unpublished records of a NASA workshop held several weeks after the event,[2] are parameterized for each time entry using an exponential rigidity function of the form

$$J = J_o \exp(-R/R_o), \tag{1}$$

where R is the proton rigidity (momentum per unit charge) and J_o and R_o are fitting parameters obtained using least-squares regression techniques. Values for J_o and R_o at each time are listed in Table 1. These incident, energetic proton spectra and their reaction products (protons, neutrons, ^2H, ^3H, ^3He and ^4He) are transported through the aluminum shield material and then through an additional quantity of water (assumed to be equivalent to soft tissue) using the BRYNTRN computer code. The calculated absorbed doses as a function of water depth, at each time, are then folded with the body organ self-shielding depth distributions computed from the CAM model to yield dose estimates for each organ. The CAM model is based on a 50th percentile United States Air Force male. The model includes material densities of organs, bone and other body constituents encountered by a particle as it traverses one of the 512 rays, covering the entire 4π solid angle about the organ site. In the version (*15*) of the CAM model used herein, distribution about one site is used to represent the ocular lens, since it is a small, localized organ. For the skin and bone marrow, which are distributed over much of the body, distributions for 33 different sites are averaged to yield the actual organ self-shielding distribution.

Using these computational tools and methods, profiles of organ doses as a function of time are generated for the skin, ocular lens and bone marrow behind each thickness of aluminum shielding considered herein (1, 2 and 5 g/cm^2). Although the profiles vary in magnitude for each organ and shield thickness, they are all well represented by a Weibull functional form

$$D(t) = D_\infty\{1-\exp[-(\alpha t)^\gamma]\}, \tag{2}$$

where $D(t)$ represents the organ dose at time t (time since protons began arriving), D_∞ is the organ total absorbed dose for the event, and γ and α

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[2] Correspondence dated October 24, 1972, from J. H. King (NASA Goddard Space Flight Center) to A. C. Hardy (NASA Johnson Space Center).

TABLE 1
August 1972 Solar Particle Event Fluence and Fluence Fitting Parameters

Time (h)		J (>60 MeV) (protons/cm² s)	J (>30 MeV) (protons/cm² s)	R_0 (GV)	J_0 (protons/cm²)
8/4/72	0	13.71	59.17	69.75365	6.553×10^{6}
	1	14.24	71.24	66.22232	1.734×10^{7}
	2	15.09	83.43	63.62680	3.294×10^{7}
	3	16.74	113.70	59.96688	6.345×10^{7}
	4	19.75	159.34	56.29501	1.223×10^{8}
	5	20.96	239.77	51.55716	2.697×10^{8}
	6	19.63	207.47	49.72908	4.111×10^{8}
	7	210.24	556.19	67.70407	1.831×10^{8}
	8	1587.13	4409.54	90.75461	2.957×10^{8}
	9	3842.79	10916.40	95.20613	7.452×10^{8}
	10	7440.54	23938.92	90.48138	2.059×10^{9}
	11	14790.61	49536.59	87.09404	5.055×10^{9}
	12	26590.42	72520.46	93.33001	7.588×10^{9}
	13	40765.27	105079.90	98.73577	1.085×10^{10}
	14	78590.02	186271.15	106.2763	1.549×10^{10}
	15	75511.26	192818.23	107.0231	2.173×10^{10}
	16	77082.05	201237.69	106.8493	2.859×10^{10}
	17	54387.21	151449.77	105.7169	3.451×10^{10}
	18	54073.05	146775.08	105.2528	3.998×10^{10}
	19	51283.32	174584.44	102.0619	4.945×10^{10}
	20	51283.32	174584.44	99.68181	5.921×10^{10}
	21	49046.50	247858.88	93.63999	8.057×10^{10}
	22	28538.20	151035.08	90.67832	9.516×10^{10}
	23	3607.80	18799.27	90.35491	9.702×10^{10}
8/5/72	0	2336.09	12210.73	90.14781	9.823×10^{10}
	1	1637.40	8796.45	89.99469	9.913×10^{10}
	2	2023.18	10868.64	89.80773	1.002×10^{11}
	3	6652.63	29744.57	89.44676	1.029×10^{11}
	4	6875.06	31164.57	89.06971	1.057×10^{11}
	5	2269.48	10497.94	88.94001	1.067×10^{11}
	6	1362.19	6789.60	88.84419	1.073×10^{11}
	7	1212.65	6099.71	88.75739	1.079×10^{11}
	8	1069.90	5277.87	88.68523	1.084×10^{11}
	9	1173.70	5762.93	88.60758	1.090×10^{11}
	10	1211.40	5966.51	88.52726	1.096×10^{11}
	11	1159.62	5668.68	88.45247	1.102×10^{11}
	12	1039.24	5174.83	88.38231	1.107×10^{11}
	13	1061.10	5467.62	88.30427	1.112×10^{11}
	14	891.46	4527.66	88.24151	1.117×10^{11}
	15	820.58	4266.28	88.18038	1.121×10^{11}
	16	813.92	4408.28	88.11355	1.126×10^{11}
	17	692.28	3816.40	88.05452	1.130×10^{11}
	18	584.84	3245.89	88.00405	1.134×10^{11}
	19	545.51	3096.35	87.95464	1.137×10^{11}
	20	497.13	2871.66	87.90795	1.140×10^{11}
	21	441.33	2612.55	87.86433	1.143×10^{11}
	22	413.06	2505.73	87.82144	1.146×10^{11}
	23	375.61	2343.63	87.78020	1.149×10^{11}

are fitting parameters. A detailed description of this fitting method is presented elsewhere (*7, 16*). Once the organ dose–time profiles are parameterized using Eq. (2), they are differentiated in time to yield smoothed, continuous dose-rate curves of the form

$$R(t) = D_{\infty}\alpha^{\gamma}\gamma t^{\gamma-1}\exp[-(\alpha t)^{\gamma}]. \quad (3)$$

DOSE-RATE RESULTS

Calculated organ absorbed dose rates behind 1, 2 and 5 g/cm² aluminum shielding are displayed in Fig. 1. The shielding thickness (areal density) of 1 g/cm² is representative of the protection provided by a typical spacesuit and 5 g/cm² is typical of shielding provided by a manned spacecraft. Values for 2 g/cm² of aluminum shielding are estimated to facilitate comparison between our predicted dose rates and those estimated previously (*7*) using these same fitting techniques for the October 1989 SPE. Table 2 presents the total time during which the organ dose rates exceed some specified value. Table 3 presents the total dose

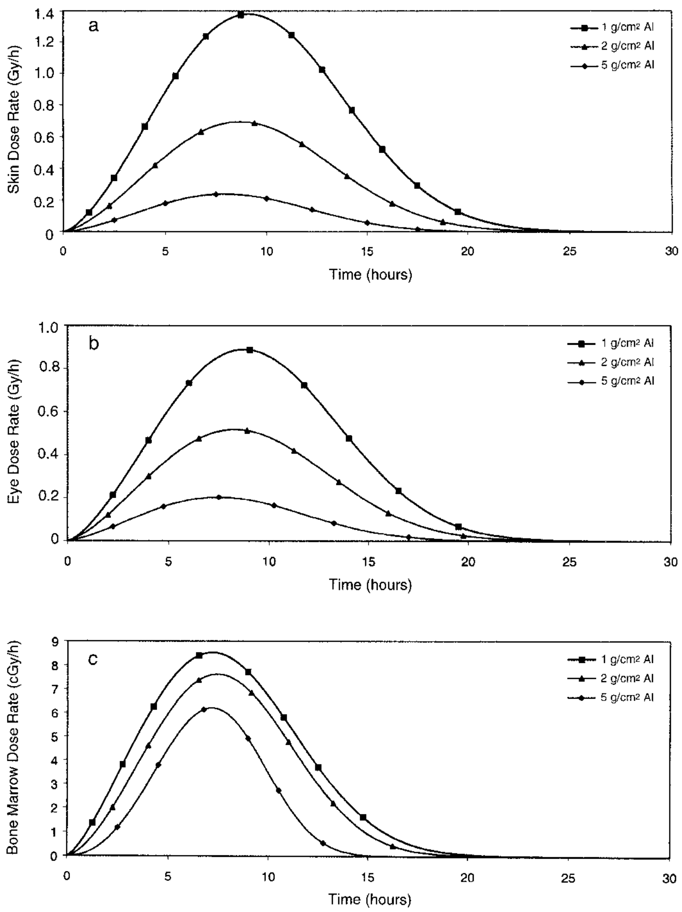

FIG. 1. Absorbed dose rates since event onset for the August 1972 solar particle event for 1, 2 and 5 g/cm^2 aluminum shielding. Displayed are: (panel a) skin dose rate, (panel b) eye dose rate, and (panel c) bone marrow dose rate.

accumulated for each organ during the period that the dose rate exceeds these values.

For a spacesuit (1 g/cm^2), the dose rates are quite high. The skin dose rate peaks at nearly 1.4 Gy/h. Note from Fig. 2 that this is nearly an order of magnitude greater than the peak dose rate for the October 1989 event. In fact, the skin dose rate exceeds the NCRP criterion (*8*) for ''low dose rate'' (0.05 Gy $year^{-1}$ or 0.00057 cGy h^{-1}) for over 31 h during which the accumulated skin dose is estimated to be over 15 Gy. The skin dose rate exceeds the UNSCEAR low-dose-rate criterion (0.1 mGy min^{-1} or 0.6 cGy h^{-1}) (*10*) for nearly 25 h with a cumulative skin dose of about 15 Gy. The ICRP (*9*) low-dose-rate criterion of 0.1 Gy h^{-1} (10 cGy h^{-1}) is exceeded for nearly 19 h with a total skin dose accumulation of 14.8 Gy. Note also that the skin dose rate exceeds 1 Gy h^{-1} for over 7 h with a total skin dose accumulation of over 9 Gy. Although the eye dose rates are somewhat lower than the skin dose rates, with a peak dose rate of 0.9 Gy h^{-1}, the ''low dose rate'' criteria of all three advisory bodies are exceeded for 17 h (ICRP), nearly 24 h (UNSCEAR), and 31 h (NCRP) with cumulative eye doses ranging from 9.4 to 9.6 Gy. For the bone marrow, the dose rates are much lower due to the additional shielding provided by the overlying body tissue. The peak dose rate is 9 cGy h^{-1} and exceeds the low-dose-rate criteria for 25 h (NCRP) and 16 h (UNSCEAR), but not at all for the ICRP criterion. The bone marrow dose accumulated while exceeding the NCRP or UNSCEAR dose-rate criteria is approximately 0.8 Gy. Obviously, spacesuits will not prevent deterministic effects for SPEs as large as the August 1972 event.

Inside a typical aluminum spacecraft (5 g/cm^2), the organ dose rates are significantly lower, but remain high enough to warrant concern about deterministic effects. Peak dose rates are 21 (skin), 20 (eye) and 6 cGy h^{-1} (bone marrow). The NCRP low-dose-rate criterion is exceeded for 27 h (skin), 28 h (eye), and 17.5 h (bone marrow) with cumulative organ doses of 2.3, 2.0 and 0.4 Gy, respectively, during the time that the dose rate exceeds 0.00057 cGy h^{-1}. The UNSCEAR low-dose-rate criterion is exceeded for 19 h (skin and eye) and 11 h (bone marrow) with cumulative organ doses of 2.3, 2.0 and 0.4 Gy, respectively. The ICRP low-dose-rate criterion is not exceeded for the bone mar-

TABLE 2
Total Time that the Organ Dose Rate Exceeds the Specified Dose Rate Value for the August 1972 Solar Particle Event

Dose rate ($cGy\ h^{-1}$)	Time (h) Skin 1	Skin 2	Skin 5	Eye 1	Eye 2	Eye 5	Bone marrow 1	Bone marrow 2	Bone marrow 5
0.00057[a]	31.5	30.0	27.0	31.0	30.0	27.7	25.5	23.0	17.5
0.6[b]	24.5	22.5	18.9	23.6	22.0	18.8	16.1	14.7	10.8
1	23.7	21.6	17.9	22.7	21.0	17.7	14.8	13.4	9.7
5	20.7	18.1	13.4	19.4	17.3	13.0	8.0	6.5	3.5
10[c]	18.9	16.1	10.3	17.4	15.0	9.6			
50	12.6	7.1		9.6	2.4				
100	7.3								

[a] NCRP (1980) low-dose-rate limit (0,05 Gy $year^{-1}$) (*8*).
[b] UNSCEAR (1993) low-dose-rate limit (0.1 mGy min^{-1}) (*10*).
[c] ICRP (1991) low-dose-rate limit (0.1 Gy h^{-1}) (*9*).

TABLE 3
Total Organ Doses Accumulated during the Period in Which the Dose Rates Exceed the Specified Values

Dose rate ($cGy\ h^{-1}$)	Cumulative dose (Gy)								
	Skin			Eye			Bone marrow		
	1	2	5	1	2	5	1	2	5
0.00057	15.0	7.2	2.3	9.6	5.4	2.0	0.8	0.6	0.4
0.6	15.0	7.2	2.3	9.6	5.4	2.0	0.8	0.6	0.4
1	15.0	7.2	2.3	9.6	5.4	2.0	0.8	0.6	0.4
5	15.0	7.1	2.1	9.5	5.3	1.8	0.6	0.4	0.2
10	14.8	7.0	2.0	9.4	5.1	1.6			
50	13.1	4.4		7.2	1.2				
100	9.2								

row, but is exceeded for the skin (10 h) and eye (9.6 h). The organ doses accumulated during this time are 1.9 (skin) and 1.6 Gy (eye).

A comparison of skin dose rates for the August 1972 and October 1989 events, behind 2 g/cm² aluminum shielding, is displayed in Fig. 2. Clearly the dose rates for the 1972 SPE are much higher; however, the October 1989 SPE cumulative dose was comparable to the August 1972 dose because of the protracted nature of the October 1989 event.

Low dose rates defined by advisory bodies are related to stochastic effects. Unfortunately, information about the dose rate at which the effect on specific tissues for deterministic effects is reduced is unsatisfactory. A dose rate of 1 Gy h^{-1} is a high dose for $LD_{50/30}$ and bone marrow cell killing. However, the precise relevant dose rate for deterministic effects in other tissues is less clear.

POSSIBLE ACUTE EFFECTS

Exposure of interplanetary crews to absorbed doses and dose rates at the levels estimated in this work are likely to result in acute health effects manifesting in an exposed crew. Other analyses of potential dose-rate effects from large SPEs, using particular dose–response models, have been published elsewhere. One such analysis by Wilson *et al.* (*17*) used response models developed by the U.S. military for nuclear warfare (*18*) to investigate the response of

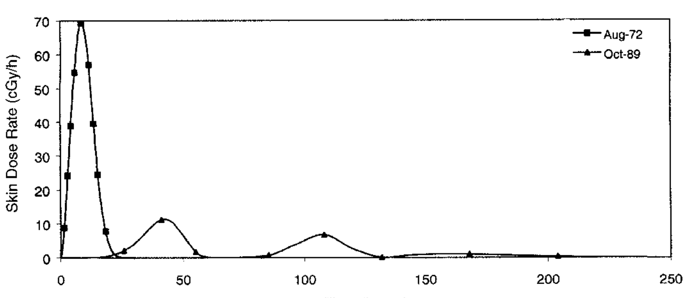

FIG. 2. Comparison of the predicted skin dose rates for the August 1972 and October 1989 SPEs, as a function of time since event onset, behind 2 g/cm² aluminum shielding.

the blood-forming organs (BFO) from the 1972 event. Other analyses have been carried out by Curtis *et al.* using the lethal–potentially lethal response model (*19*). We have chosen for this work to consider possible acute effects from the August 1972 SPE by using RBE values to relate proton dose effects to those observed for γ-ray exposures. Unfortunately, predicting specific effects is hampered by the paucity of RBE data for protons at these energies and dose rates. Improving the ability to predict specific effects from SPE proton exposures requires new data on the actual RBE values at these dose rates and energies. Assuming that the bone marrow doses and dose rates are representative of whole-body exposures, cumulative doses of the order of 0.4–0.8 Gy, delivered within a day inside a spacesuit or typical spacecraft, may produce some hematological responses including blood count changes and possibly nausea or vomiting (*20*). Here we assume an RBE of 1 for acute exposures to SPE protons. For the skin, which receives the highest doses and at the highest dose rates in a spacesuit, doses of 15 Gy will produce erythema. Assuming an RBE of unity, up to 20% of the exposed crewmembers could experience moist desquamation (*20*). Epilation is also likely to occur. Inside a spacecraft shielded with 5g/cm² of aluminum, skin doses of ~2 Gy could produce mild erythema in some individuals. Other acute skin effects are unlikely inside a spacecraft with 5 g/cm² of shielding.

For the doses and dose rates estimated for the eye, possible acute responses include (*20*) early erythema of the lid skin (at doses from 4–6 Gy), early edema and keratitis in the cornea (at 10 Gy), and lens cataracts (at 2–10 Gy). For crewmember exposures when protected only by a spacesuit, all of these effects could be manifest. Inside a spacecraft, however, only cataract formation would be of concern.

Concerning the diversity and severity of possible acute effects from interplanetary crew exposures to SPEs similar to the large event of August 1972, it appears to be obvious that some type of "storm shelter", with at least 10–20 g/cm² aluminum thickness, is needed to adequately protect the crew. Although this recommendation is not new to this work, its appropriateness is clearly supported by the results reported herein. In previous work (*2*) it was demonstrated that 10 g/cm^2 of aluminum will lower organ doses to 0.7 Gy or less and 20 g/cm^2 of aluminum will lower them to 0.1 Gy or less.

SUMMARY

Using the space radiation transport code, BRYNTRN, and the CAM model for the human body geometry, absorbed dose and dose-rate estimates for the bone marrow, ocular lens and skin of astronauts on manned interplanetary missions have been made for one of the largest solar particle events ever observed. The estimated organ dose rates are quite high and exceed the low-dose-rate criteria of the major national and international advisory bodies. Consequently, the combination of high doses and high dose rates delivered to crews by solar particle events of the magnitude and duration of the August 1972 event is likely to produce significant acute effects, which could be mission- or even life-threatening unless a heavily shielded space is provided for use by the crew. There is, however, a clear lack of RBE data for deterministic effects from protons at the energies and dose rates relevant to exposures from this event that hampers a precise analysis of the potential effects on exposed crewmembers.

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