

NASA Technical Memorandum 4229

Space Radiation Dose Analysis
of Solar Flare of August 1989

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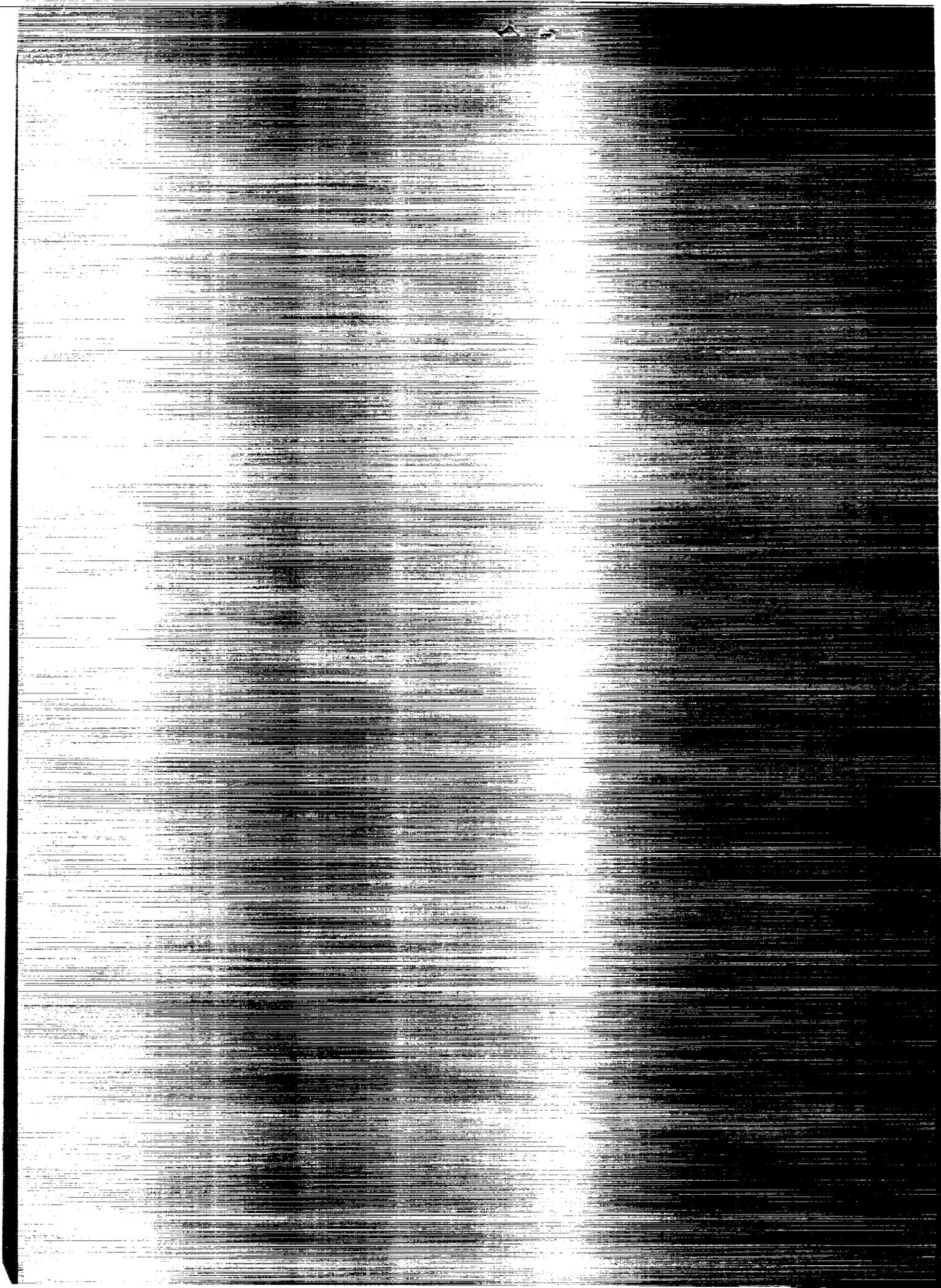
DECEMBER 1990

(NASA-TM-4229) SPACE RADIATION DOSE
ANALYSIS FOR SOLAR FLARE OF AUGUST 1989
(NASA) 9 p

CSSL 03B

N91-14265

H1/93 Unclas
0293212



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National Aeronautics and
Space Administration
Office of Management
Scientific and Technical
Information Division

1990

Abstract

Potential dose and dose rate levels to astronauts in deep space are predicted for the solar flare event which occurred during the week of August 13, 1989. The Geostationary Operational Environmental Satellite (GOES-7) monitored the temporal development and energy characteristics of the protons emitted during this event. From these data, the differential fluence as a function of energy was obtained in order to analyze the flare using the baryon transport code developed at the Langley Research Center, BRYNTRN, which describes the interactions of incident protons in matter. Dose equivalent estimates for the skin, ocular lens, and vital organs for 0.5 to 20 g/cm² of aluminum shielding were predicted. For relatively light shielding (<2 g/cm²), the skin and ocular lens 30-day exposure limits are exceeded within several hours of flare onset. The vital organ (5-cm depth) dose equivalent is exceeded only for the thinnest shield (0.5 g/cm²). Dose rates (rem/hr) for the skin, ocular lens, and vital organs are also computed.

Introduction

The Geostationary Operational Environmental Satellite (GOES-7) recorded a large solar flare during the week of August 13, 1989; both the temporal development and energy characteristics of the emitted energetic protons were monitored. The particle data were transmitted to the NOAA Space Environment Laboratory in Boulder, Colorado. These data are used in the present study to simulate radiation exposure and incurred dose for astronauts outside the Earth's magnetic field, for example, those in transit to the Moon or Mars. This August 1989 flare is chosen for study not only because of the opportunity provided for analysis of a recent data set but also because of some relatively unusual features in the energy spectrum and its time development.

Since extended-duration manned missions into deep space are envisioned for times corresponding to active Sun conditions in solar cycle 23 (AD 2000–2005), detailed analyses of the ionizing radiation environment should be of great value in assessing potential radiation hazards and shielding requirements. The present solar maximum of cycle 22 appears to have begun with relatively high activity; large flares similar to the August 1989 event are expected during the next few years. Thus, the opportunity now exists to work with high quality environmental data, such as that from GOES, in conjunction with accurate transport codes, with the goal of defining shield requirements for extended presence in interplanetary space.

Analysis of Data

The initial particle data consist of the integral proton flux for seven energy values between 1 and

100 MeV at hourly increments over a period of 9 days (216 time points). These data are depicted graphically in figure 1, which shows the flare onset shortly before day 1 of the data period. The data array has been manipulated by several procedures to provide input for a nucleon transport code. The baryon transport code developed at Langley, BRYNTRN, (ref. 1) is used in this analysis to describe the interactions of the incident protons in matter.

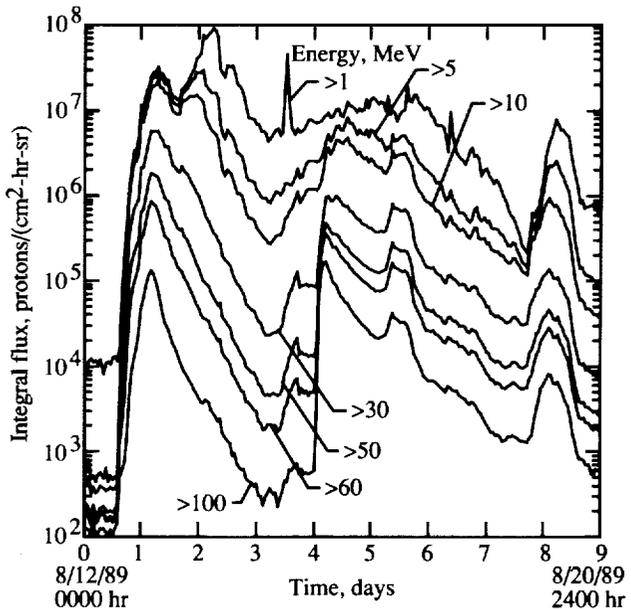
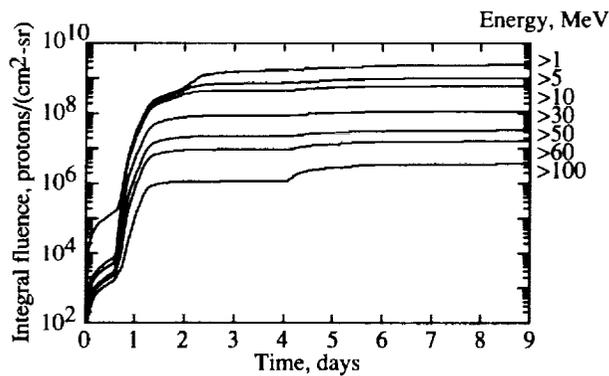


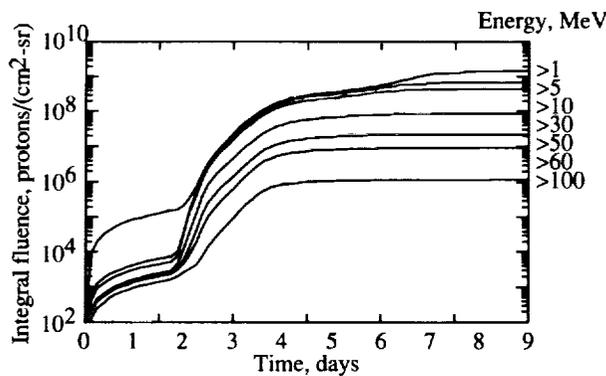
Figure 1. Proton integral flux history for August 1989 solar flare. (GOES-7 data from NOAA Space Environment Laboratory.)

First, a numerical time integration is performed to obtain the integral fluence history. The result is

shown in figure 2(a), along with an expanded plot of the integral fluence time variation at the flare's early development stage (fig. 2(b)). The substantial increase in the fluence of particles with energy greater than 100 MeV is particularly noteworthy at approximately day 4 of the data period. From the time-integrated data of figure 2, the integral fluence can be obtained at each of the seven energy values for selected times during the data period. The energy dependence of the fluence at each of these values is represented by the plotted symbols in figure 3. For this study, the total flare fluence is assumed to occur on day 6.



(a) Cumulative integral for 9-day data period.



(b) Integral fluence for first 3-day period.

Figure 2. Fluence for August 1989 solar flare.

The energy grid used in the transport calculations consists of 25 values of equal logarithmic increments between 0.01 and 2000 MeV. Values of integral fluence for the transport code energy points are obtained by interpolation and extrapolation by assuming a logarithmic variation of integral fluence with energy. Past studies have shown that many flares can be well approximated over widely spaced energy intervals by such a relationship (see ref. 2). The solid lines of figure 3 show the results of the interpolation/extrapolation procedure.

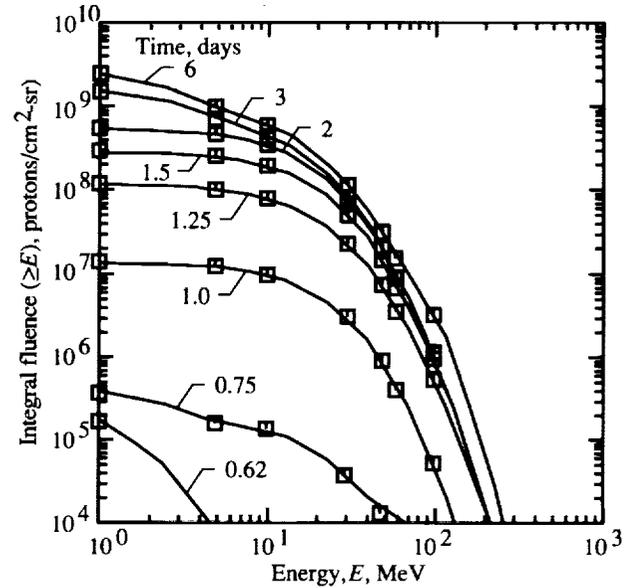


Figure 3. Integral fluence as function of energy for selected times during flare data period. Solid lines are result of interpolation/extrapolation of data symbol points.

Finally, the integral fluences of figure 3 are differentiated by using central differencing to obtain the differential fluence as a function of energy for the selected times (fig. 4). This is the form of the data required as input for the transport code. Also shown is the spectrum of the large flare of August 1972 (ref. 3) which may be compared with the 6-day spectrum of the August 1989 event. The more recent flare

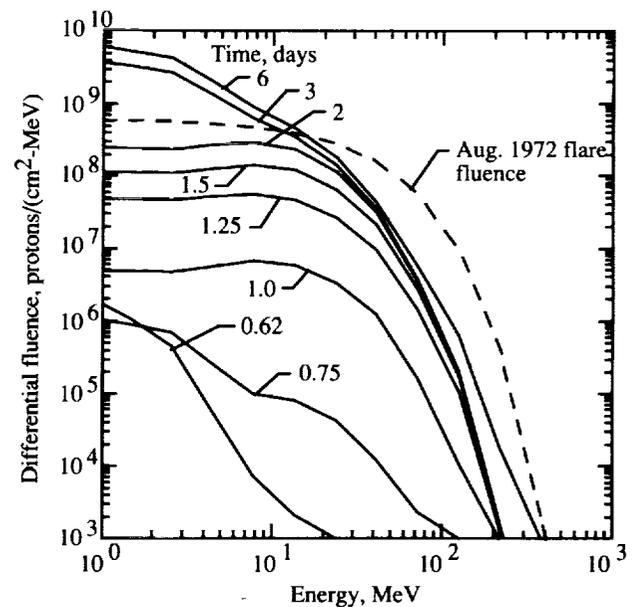


Figure 4. Cumulative differential fluence for flare of August 1989 at selected times and total fluence for August 1972 event.

indicates the production of substantially more particles below energies of about 10 MeV and generally less particles at higher energies relative to the 1972 event. The relative abundance of higher energy particles in the 1972 spectrum causes its dose potential to be larger for shield amounts greater than 1 or 2 g/cm².

Transport and Dosimetry Calculations

The determination of pertinent dosimetric quantities resulting from ionizing radiation requires specific knowledge of the particle flux/energy distribution for each particle type at the location of the dose evaluation. These particle fluxes depend strongly on the types of interactions that occur during propagation through matter as well as on the initial spectrum. In this study, the propagation of the flare particles through an aluminum shield material followed by a simulated human tissue layer is computed. The attenuation of the primary protons, the generation of secondary nucleons, and the heavy ion target recoil contributions are all taken into account. The solution methodology involves the application of a combined analytical-numerical technique to the one-dimensional Boltzmann transport equation. (See ref. 4.) Previous studies have indicated that this code is well-suited to solar flare dose analyses (see refs. 5, 6, and 7.)

Transport calculations are performed for cumulative flux spectra corresponding to days 1, 1.25, 1.5, 2, 3, and 6 of the data period. For each spectrum, the nucleon fluxes emergent from various amounts of aluminum (0.5, 2, 5, 10, and 20 g/cm²) are calculated. In addition, transport through several thicknesses of human tissue (simulated by water) is included in the calculations from which appropriate dosimetric quantities at various depths in the human body can be determined.

The dosimetric quantity of relevance for human exposure is the dose equivalent H (rem), which is evaluated according to

$$H(x) = \sum_i \int_0^\infty \Phi_i(x, E) S_i(E) Q_i(E) dE$$

where Φ_i is the differential flux of particles of type i having energy E at position x , S_i is the stopping power for the propagating particles in the medium, and Q_i is the quality factor which relates the physical deposition of energy to biological damage. For the present study, the quality factors used correspond to those recommended by the International Commission on Radiological Protection. (See ref. 8.)

Astronaut dose limits are established in terms of short term, annual, and career limits for the exposure

of the skin, ocular lens, and vital organs. The current limits are summarized in table I, which has been extracted from reference 9.

Table I. U.S. Astronaut Dose Equivalent Recommended Limits

[From ref. 9]

Astronaut	Dose equivalent recommended limits, rem, for--		
	Career	Annual	30 days
Vital organs	100 400*	50	25
Ocular lens	400	200	100
Skin	600	300	150

*Varies with age and gender.

Analysis of Results

The calculated proton and neutron energy spectra derived from the 6-day flare fluence are shown in figures 5 and 6 after passing through various thicknesses of aluminum. The protons are observed to attenuate rapidly, especially at the lower energies. The neutrons, once generated, are shown to be much more penetrating, particularly at higher energies. Figure 6 indicates that neutron fluxes at energies greater than 70 MeV are actually greater for 20 g/cm² Al than for 0.5 g/cm² Al, since fewer neutrons have been produced in the thinner shield. This

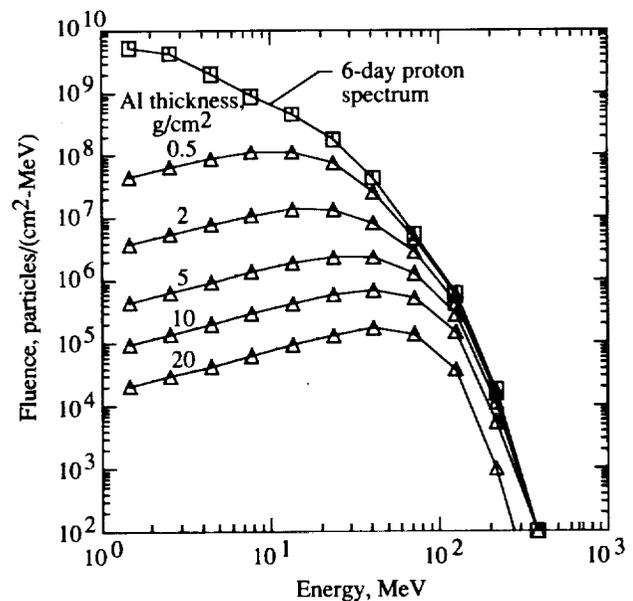


Figure 5. Six-day proton fluence spectrum and computed proton spectra in aluminum.

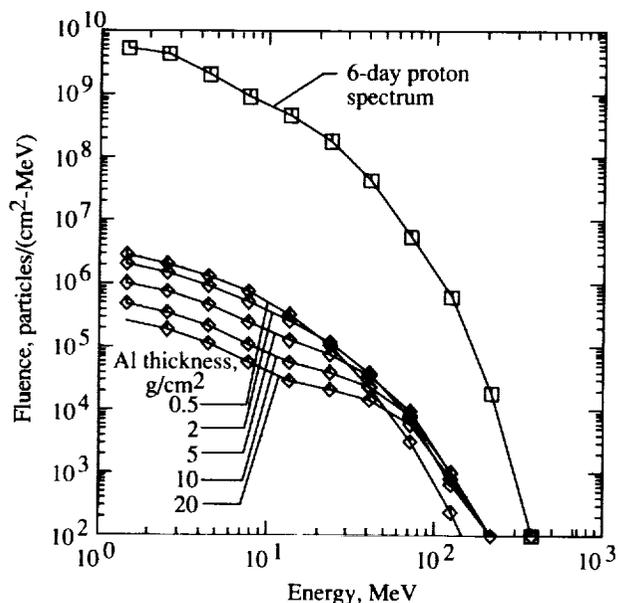


Figure 6. Proton fluence spectrum and neutron spectra in aluminum.

type of spectral data is needed to determine corresponding dose equivalent values and has been generated for specific times during the data period. For this study, the relevant dosimetric values for the skin, eyes, and vital organs are taken to correspond to depths in tissue of 0.1, 0.3, and 5 cm, respectively. (See ref. 9.) Figures 7, 8, and 9 show the time history of the cumulative dose quantities for various thicknesses of aluminum shielding. For relatively light shielding ($<2 \text{ g/cm}^2$), the ocular lens and skin 30-day exposure limits are exceeded within several hours of flare onset. However, the vital organ (5-cm depth) dose equivalent limit is exceeded only for the thinnest shield (0.5 g/cm^2) and reflects the influence of the body's self-shielding. The dose increase after day 4 is almost entirely due to the high energy pulse occurring at that time during the data period. (See fig. 1.) Tabular results of the calculations are given in table II.

Note that the transport calculations are performed for normally incident particles on a material slab and that the dosimetric quantities presented here are evaluated accordingly. Because of the large sensitivity of a dose to slab thickness, effects of specific shield geometry are expected to be significant. The data as presented can form a basis for more detailed dose determinations for given shield configurations. The cumulative dose data as a function of time may also be used to infer dose rates (e.g., rem/hr). For manned missions, the dose rate for a given shielding situation would be of importance in estimating the dose that would be incurred over a given time interval. As an example, consider the set of dose values

Table II. Calculated Dose Equivalent Values for Aluminum Shield Layers

Thickness of Al, g/cm^2	Calculated dose equivalent, rem, for time, days, of					
	1.00	1.25	1.50	2.00	3.00	6.00
(a) Skin dose equivalent (30-day limit = 150 rem)						
0.5	41.34	325.13	788.27	1341.8	1678.3	2163.3
2.0	8.80	69.42	151.69	213.65	233.52	298.76
5.0	1.60	13.76	26.64	33.62	35.53	56.87
10.0	0.33	3.11	5.48	6.50	6.81	16.25
20.0	0.02	0.30	0.43	0.44	0.46	3.89
(b) Ocular lens dose equivalent (30-day limit = 100 rem)						
0.5	25.26	194.83	459.58	724.05	844.44	1046.8
2.0	6.39	51.08	109.03	149.48	161.68	212.45
5.0	1.37	11.83	22.72	28.50	30.07	49.43
10.0	0.30	2.81	4.91	5.80	6.07	15.07
20.0	0.02	0.28	0.39	0.40	0.41	3.70
(c) Vital organ (5-cm depth) dose equivalent (30-day limit = 25 rem)						
0.5	0.76	6.77	12.56	15.41	16.21	30.36
2.0	0.48	4.39	7.92	9.55	10.03	21.14
5.0	0.21	2.05	3.49	4.07	4.25	12.04
10.0	0.05	0.64	0.98	1.07	1.11	5.86
20.0	0.004	0.07	0.084	0.080	0.082	1.54

corresponding to a shield thickness of 5 g/cm^2 , which relates to a moderately shielded spacecraft. A spline fit to the cumulative dose and a subsequent numerical differentiation result in the dose rates given as a function of time in figure 10. As might be expected, the dose rates for skin and ocular lens exposures are very similar, and for the first day after flare onset, an average dose rate of about 1 rem/hr is predicted. The vital organ dose rate is decreased substantially by the additional 5-cm tissue layer, but the high energy burst at approximately day 4 enhances the dose substantially in the latter period of the episode.

Discussion

For the large solar flare of August 1989, the comprehensive proton flux data provided by the GOES-7 energetic particle monitor have provided an opportunity for detailed analysis and prediction of potential dose and dose rate levels to astronaut crews in deep space. The analysis has indicated that an event of this type could be very hazardous to those having inadequate shielding. However, the general spectral characteristics of the

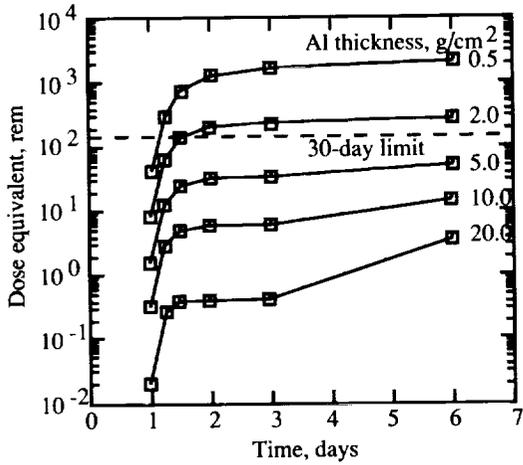


Figure 7. Time variation of predicted skin dose equivalent behind aluminum shield layers.

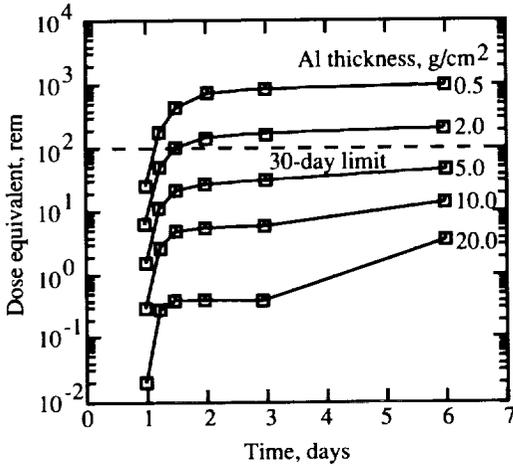


Figure 8. Time variation of predicted ocular-lens dose equivalent behind aluminum shield layers.

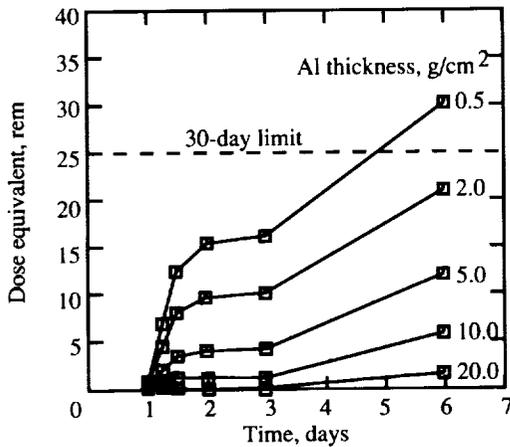
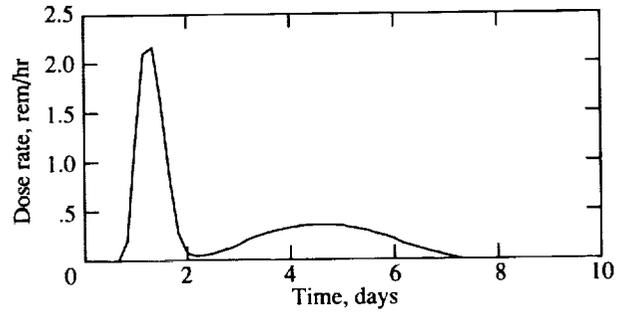
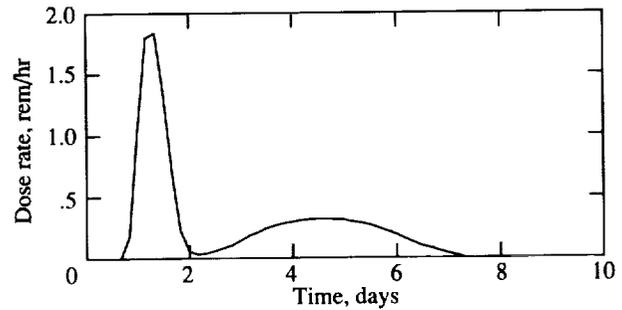


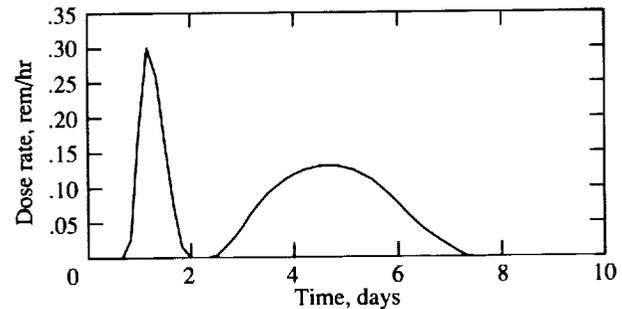
Figure 9. Time variation of predicted vital organ (5-cm depth) dose equivalent behind aluminum shield layers.



(a) Skin.



(b) Ocular lens.



(c) Vital organs (5-cm tissue depth).

Figure 10. Predicted dose rate variation during August 1989 flare behind 5 g/cm² aluminum shield.

flare are such that moderate shielding is capable of reducing incurred doses to acceptable levels. Although the total episode duration was slightly over 1 week, the high dose rates at early times indicate the necessity of active flare alert instrumentation. In addition, figure 1 shows a rather steady persistence of high total particle flux for days 1 to 5 as indicated by the 1, 5, and 10 MeV integral flux curves. This high total flux is coupled with bursts of the high energy component (days 1 and 4; 30–100 MeV). These features emphasize the need for active dosimetric instrumentation capable of spectral discrimination, since substantial reductions in total flux may not reflect a corresponding decrease in high energy flux which is of

greatest significance for vital organ dose. Such detectors could enable an astronaut to determine when adequate protection exists in a moderately shielded area as opposed to, for example, a storm shelter.

Although the August 1989 event is not among the most potentially dangerous flares (ref. 6), it is of the type which may occur more frequently than those in the category of the 1972 flare. The present analysis clearly indicates that, even for 5 to 10 g/cm² of equivalent shielding, a flare of the August 1989 vintage can contribute substantially to the established longer term annual and career dose limits. Detailed analyses of solar flare spectra during the remainder of the current solar maximum period will be of great value in providing reliable radiation protection systems for future long-duration manned missions.

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October 18, 1990

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Report Documentation Page

1. Report No. NASA TM-4229		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle Space Radiation Dose Analysis for Solar Flare of August 1989				5. Report Date December 1990	
				6. Performing Organization Code	
7. Author(s) John E. Nealy, Lisa C. Simonsen, Herbert H. Sauer, John W. Wilson, and Lawrence W. Townsend				8. Performing Organization Report No. L-16812	
				10. Work Unit No. 326-22-20-50	
9. Performing Organization Name and Address NASA Langley Research Center Hampton, VA 23665-5225				11. Contract or Grant No.	
				13. Type of Report and Period Covered Technical Memorandum	
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546-0001				14. Sponsoring Agency Code	
				15. Supplementary Notes John E. Nealy, Lisa C. Simonsen, John W. Wilson, and Lawrence W. Townsend: Langley Research Center, Hampton, Virginia. Herbert H. Sauer: National Oceanic and Atmospheric Administration, Boulder, Colorado.	
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17. Key Words (Suggested by Authors(s)) Solar flare protons Space radiation exposure			18. Distribution Statement Unclassified--Unlimited		
Subject Category 93					
19. Security Classif. (of this report) Unclassified		20. Security Classif. (of this page) Unclassified		21. No. of Pages 7	22. Price A02

