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PROBABLE SOLAR FLARE DOSES ENCOUNTERED ON AN INTERPLANETARY MISSION AS CALCULATED BY THE MCFLARE CODE

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The computer program, MCFLARE, uses Monte Carlo methods to simulate solar flare occurrences during an interplanetary space voyage. The total biological dose inside a shielded crew compartment due to the flares encountered during the voyage is determined. The computer program evaluates the doses obtained on a large number of trips having identical trajectories. From these results, a dose D_p having a probability p of not being exceeded during the voyage can be determined as a function of p for any shield material configuration.

The user of the code selects any number of solar flares considered to be representative of the ones that will occur during future solar active periods (these flares are generally selected from the flares that occurred during the last solar active period 1956 to 1962). The flares are assumed to occur during these periods. The dose at a distance of 1 AU from the Sun from each of these flares behind any shield configuration investigated is input to the MCFLARE code. The code accounts for the dependence of the dose received from a flare on the distance from the Sun according to a $(1/r)^{\alpha}$ variation, where r is the distance from the Sun and the exponent α can be assigned. From trajectory parameters, which are input to the computer program, the distance from the Sun as a function of time during the trip is calculated.

To illustrate the use of the code, a trip to Mars and return is calculated, and estimated doses behind several thicknesses of aluminum shield and water shield are presented.

INTRODUCTION

The protons emitted by solar flares are the most hazardous source of space radiation encountered on an interplanetary space voyage which rapidly traverses the Van Allen belts. To define shielding requirements for biological protection from solar flare protons encountered in manned interplanetary missions, a computer program MCFLARE (ref. 1) has been prepared which uses Monte Carlo methods to simulate solar flare occurrences during the trip and records the total associated biological doses for the trip behind various shield material configurations.

A set of flare events, considered to be representative of those that will occur during future solar active periods, is required. Presently, this set is selected from the flares that occurred during the last solar active period from 1956 to 1962. The flares are assumed to occur randomly during the trip. The doses behind the various shield configurations investigated have to be evaluated for each flare, at a distance of 1 AU from the Sun, by using another computer code such as one of those described in Refs. 2 or 3. (Ref. 4 presents doses from solar flare proton spectra behind two shield materials as calculated by using Ref. 2.) These dose values are input to the computer program MCFLARE. This program provides for including the dependence of the magnitude of the dose received from the flare on the distance r from the Sun. This dependence is taken to be of the form $(r_0/r)^{\alpha}$, where r_0 is the distance between the Sun and the Earth, and the exponent α can be any arbitrarily selected value.

The Monte Carlo sampling procedure (analogous to particle transport Monte Carlo) is used to determine when flares are encountered on the trip, which of the input flares occur, and the total dose obtained from all flares encountered during the trip behind each shield configuration. The computer program tallies the doses obtained for a large number of trips having identical trajectories and from this, the distribution of doses incurred on the mission for each shield configuration is obtained. Each dose distribution determines a dose D_p having the probability p of not being exceeded as a function of p.

METHOD OF ANALYSIS

Any N flare events can be selected as representative of the flare activity that will occur during the space voyage. The doses from each flare at a distance of 1 AU from the Sun behind one or more shield material configurations investigated are input to the computer. Each flare is assumed to occur randomly on the average of once during the solar active period T_{ref}, which is of the order of 2000 days or $5\frac{1}{2}$ years.

Monte Carlo Method to Determine Occurrences of Flares During Trip

Inasmuch as flares are assumed to occur randomly in the solar active period, the probability of any flare occurring in the time interval dt is $(N/T_{ref})dt \equiv \mu\, dt$. Then the probability of no flare occurring for time t is $e^{-\mu t}$ and the probability of a flare occurring in dt at time t is $e^{-\mu t}\mu\, dt$.

In the Monte Carlo method, this probability of flare occurrence in the time interval dt at time t is equated to the probability of selecting a random number in an interval $d\xi$ about ξ. If a random number set uniformly distributed in the interval (0,1) is selected, then the probability of selecting a random number in $d\xi$ about ξ is $d\xi$. Equating these two probabilities, one gets

$$e^{-\mu t}\mu\, dt = d\xi$$

$$\int_0^t e^{-\mu t'}\mu\, dt' = \int_0^{\xi} d\xi'$$

$$t = -\frac{1}{\mu}\ln(1 - \xi)$$

Inasmuch as both ξ and $1 - \xi$ are uniformly distributed in the interval (0,1) an equivalent expression for t which results in the same exponential distribution is

$$t = -\frac{1}{\mu} \ln \xi \tag{1}$$

By selecting a random number from a uniformly distributed set in the interval (0,1) the time between flare events is obtained from Eq. (1).

When an event has occurred, a particular flare of one of the N is also selected by random numbers. The i^{th} flare occurs when a new random number occurs in the interval

$$\frac{i - 1}{N} < \xi \leq \frac{i}{N} \qquad i = 1, 2, \ldots, N \tag{2}$$

Dose values input to the code are calculated by using the methods of Ref. 2, or 3, for each representative flare using the solar flare proton intensity and spectral shape as observed at the Earth. The code permits an effect of the distance from the Sun on the dose (or intensity) received from a flare of the form $(r_o/r)^{\alpha}$ where r_o is the distance from the Sun to the Earth, r is the distance of the spacecraft from the Sun during the flare, and α is an exponent that is assigned.

The code evaluates r for any time during the trip by calculating the mission trajectory from input parameters describing the two transfer ellipses and the total trip time. The first ellipse is the trajectory from the Earth to the planet and the second describes the return trip.

The calculation proceeds as follows: Selecting a random number and using Eq. (1) determines the time in the mission when a flare occurs. Selecting another random number and using Eq. (2) determines the particular flare which occurs. Knowing the time in the mission (and, hence, distance from the Sun) and the particular flare, the dose received through each shield configuration is tallied. The duration of the flare event is then added to the time in the mission when the flare occurred to give the time when the event is over. From a new random number and Eq. (1), the time elapsed until the next flare occurs is calculated, and so on. This procedure is repeated until the total trip time has elapsed. The total dose from all flare events encountered on the trip is determined for each of the shields considered.

Selection of D_p

This procedure is repeated for a large number M of trips of identical trajectory. The code divides the dose range into dose intervals that are 1 dose unit wide and tabulates the number of trips $\Lambda(D)$ during which doses that lie within each dose interval are encountered. The cumulative fraction of the total trips that encounter doses less than the upper dose bound of each interval is also tabulated (this is an estimate of the probability p that a dose equal to the upper dose bound will not be exceeded). From this tabulation, for any specified p, a dose D_p which has the probability p of not being exceeded on the trip can be selected for any shield. The standard deviation of this value from the true value is shown in Ref. 1 to be

$$\sigma_{D_p} = \sqrt{\frac{p(1 - p)}{Mf^2(D_p)}} \tag{3}$$

where M is the number of trips in the group investigated, and $f(D_p)$ is the dose probability density at D_p (which is calculated from the tabulated output). If $\Lambda(D_p)$ is the number of trips contained in the interval in which D_p occurs, $f(D_p)$ is approximately given by

$$f(D_p) = \frac{\Lambda(D_p)}{M}$$

If $\Lambda(D)$ is a widely fluctuating value in the vicinity of D_p, averaged values of $\Lambda(D)$ can be hand calculated from the tabular computer output; $f(D_p)$ is obtained from the averaged value of $\Lambda(D_p)$. Note that for a given p, because $f(D_p)$ is independent of the number of trips, σ_{D_p} varies inversely as $\sqrt{M}$.

To reduce the uncertainty associated with D_p for a given number of trips, the code is written so that the trips constitute a stratified sample for the time-to-first-flare selected in accordance with the exponential distribution $\exp\left[-(Nt/T_{ref})\right]$.

ILLUSTRATIVE EXAMPLE

An interplanetary trip to Mars and return has been evaluated in order to illustrate details of the method and to present some representative shield requirements for such a mission. Water and aluminum were the shield materials considered.

Selection of Flare Events

The flare occurrences during the last solar active period 1956 to 1962 are assumed to be representative of those that will occur during a future active period. Webber in Ref. 5 has compiled a record of these flares, their time-integrated proton intensities, and spectra. From these records, the 20 largest flares, based on proton intensity, were selected (the effect of neglecting the rest of the flares is small for shields considered here). These flares are listed in table I which presents the integrated flux of protons having energies greater than 30 MeV and some constants A and P_o associated with each flare. The spectral shape of each flare is assumed to vary as

$$N > E = A \exp\left(-\frac{\sqrt{E^2 + 1876E}}{P_o}\right)$$

where $N > E$ is the total number of protons per square centimeter with energies greater than E. The values of P_o were obtained from Webber's compilation, and the values of A were calculated to be consistent with flux values of $N > 30$ MeV.

It has been observed that some of the flares tend to occur in clusters. Table I indicates that such clusters occurred in August 1958, July 1959, November 1960, and July 1961. These four clusters were selected as representative of the clustered flare events that may occur and were assumed to be events of 12-, 8-, 10-, and 8-day durations, respectively. The other nine single flares were each assumed to have a duration of 2 days. During future solar active periods, each of the four clustered events and each of the nine single flare events are assumed to occur randomly with a frequency of once during the active period (taken to be 2000 days).

Doses For Selected Flare Events

Table II presents the doses obtained behind various shield thicknesses from each of these 13 events. These doses were calculated by using the Lewis Proton Shielding Code, described in Ref. 2, and are representative of doses received at the center of a spherical crew compartment having the given shield thicknesses when the vehicle is located at a distance of 1 AU from the Sun. Table II(a) presents the rem doses behind the water shield, and table II(b) the rem doses behind the aluminum shield. The data presented in this table are input to the computer code MCFLARE.

Trajectory

The trajectory selected for the trip is one that requires 556 days for the complete mission (and happens to be one that results in near minimum vehicle weight for a departure date in 1983). The outward journey from Earth to Mars requires 280 days, then there is a 40-day stay at Mars, then a 236-day return trip during which the vehicle approaches within 0.5 AU of the Sun.

Discussion of Results

Figure 1 shows the distribution of dose obtained for a large number of identical trips. The figure presents the rem dose distribution behind 20 g per square cm of water shield obtained from a computer run of 40 000 trips. The effect of distance on dose was assumed to vary as $(1/r)^2$.

In Fig. 1(a), $\Lambda(D)$, the number of trips on which a dose between $D - 1$ and D has been encountered, is plotted against D. A smoothed curve of this distribution $\Lambda(D)$ (obtained by averaging seven values centered about each $\Lambda(D)$) is also shown as a dashed line in this figure.

In Fig. 1(b), $p(D)$ the probability of not exceeding any dose D is shown plotted against D

$$p(D) = \frac{1}{M} \sum_{i=1}^{D} \Lambda(i)$$

where M is the number of trips considered in a computer run. For the case of Fig. 1(b),

$$p(D) = \frac{1}{40\ 000} \sum_{i=1}^{D} \Lambda(i)$$

If D_p is defined as that dose which has a probability p of not being exceeded, then from Fig. 1(b), $D_{0.99}$ for the group of 40 000 trips, occurs in the dose interval between 93 and 94 rem and is selected as the upper bound of the interval, namely, 94 rem.

The dose probability density function $f(D)$ is approximately equal to $\Lambda(D)/M$. At a $D_{0.99}$ of 94 rem, the value of $f(D)$, evaluated by using the smoothed value of $\Lambda(D)$, is

$$f(D_{0.99}) = \frac{26}{40\ 000} = 0.00065/\text{rem}$$

and the standard deviation from Eq. (3) is $\sigma_{D_{0.99}} = 0.77$ rem.

There is a 97.7 percent confidence that the true dose $D^*_{0.99}$ is less than $D_{0.99} + 2\sigma_{D_{0.99}}$; is less than 95.5 rem.

Table III presents values of $D_{0.99}$ determined by using the computer code for rem doses behind various thicknesses (expressed as g/cm^2) of aluminum shield and water shield. These values are presented for both the case where the dose received from a flare event is assumed to vary as $(1/r)^2$ (considered representative of what might be a solar proton diffusion model in space) and for the case where there is no effect of distance (i.e., distance effect, $g(r) = 1$). Also shown in the table are the values of $\sigma_{D_{0.99}}$ associated with each $D_{0.99}$ and the corresponding values of $D_{0.99} + 2\sigma_{D_{0.99}}$.

In Fig. 2 the values of $D_{0.99} + 2\sigma_{D_{0.99}}$ are plotted against shield thickness. In Fig. 2(a), the rem dose is plotted against water shield thickness for cases of $g(r) = 1/r^2$ and $g(r) = 1$. Figure 2(b) is a similar plot of the rem dose behind the aluminum shield. From curves such as Fig. 2, one can select a shield thickness such that on a given mission, there is a probability p of not exceeding an accumulated dose D_p.

These curves indicate how much more effective water is as a shield material than aluminum for shielding against solar flare protons on the basis of grams per square centimeter of material necessary to maintain a given dose level inside the crew compartment. Also shown for this mission is that a $1/r^2$ distance effect on dose received from a flare can have an appreciable effect on shield requirements when the mission trajectory brings the vehicle to within 0.5 AU of the Sun. This result indicates a need for information regarding the effect of position from the Sun on radiation encountered from a flare.

COMPUTER PROGRAM

Complete data input instructions for the computer program MCFLARE are presented in Ref. 1. The version of the code presented is operational on the Lewis Research Center IBM 7094-II/7044 computer system. Execution times for the examples discussed previously in this report were about 2 minutes per group of 40 000 trips. The MCFLARE code is available from the Radiation Shielding Information Center of Oak Ridge National Laboratory as code package CCC-93.

REFERENCES

1. Lahti, Gerald P.; Karp, Irving M.; and Rosenbaum, Burt M.: MCFLARE, A Monte Carlo Code to Simulate Solar Flare Events and Estimate Probable Doses Encountered on Interplanetary Missions. NASA TN D-4311, 1968.
2. Hildebrand, R. I.; and Renkel, H. E.: The Lewis Proton Shielding Code. NASA TM X-52166, 1966.
3. Kinney, W. E.: The Nucleon Transport Code, NTC. Rep. ORNL-3610, Oak Ridge National Lab., Aug. 1964.
4. Scott, W. Wayne: Estimate of Primary and Secondary Particle Doses Behind Aluminum and Polyethylene Slabs due to Incident Solar-Flare and Van Allen Belt Protons. Rep. ORNL-RSIC-18, Oak Ridge National Lab., July 1967.
5. Webber, W. R.: An Evaluation of the Radiation Hazard Due to Solar-Particle Events. Rep. D2-90469, Boeing Co., Dec. 1963.

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TABLE I. - FLARES (FROM SOLAR ACTIVE PERIOD 1956 TO 1962) SELECTED AS REPRESENTATIVE OF THOSE THAT WILL OCCUR DURING FUTURE ACTIVE PERIODS

[Integral flux above 30 MeV, and spectral constants A and P_o for each flare are tabulated.]

Flare date	N > 30 MeV protons/cm^2	P_o	A, protons/cm^2	
2-23-56	1.0×10^{9}	195	3.4×10^{9}	
1-20-57	2×10^{8}	61	1.0×10^{9}	
8-29-57	1.2×10^{8}	56	8.6×10^{9}	
10-20-57	5×10^{7}	127	3.3×10^{8}	
3-23-58	2.5×10^{8}	64	1.1×10^{9}	
7-7-58	2.5×10^{8}	62	1.2×10^{9}	
8-16-58	4×10^{7}	64	1.7×10^{9}	
8-22-58	7×10^{7}	56	5.0×10^{9}	Clustered flare event
8-26-58	1.1×10^{8}	51	1.2×10^{10}	
5-10-59	9.6×10^{8}	84	1.7×10^{10}	
6-13-59	8.5×10^{7}	[a]48	1.2×10^{10}	
7-10-59	1.0×10^{9}	104	1.0×10^{10}	
7-14-59	1.3×10^{9}	80	2.6×10^{10}	Clustered flare event
7-16-59	9.1×10^{8}	105	8.9×10^{9}	
9-3-60	3.5×10^{7}	127	2.3×10^{8}	
11-12-60	1.3×10^{9}	124	8.9×10^{9}	
11-15-60	7.2×10^{8}	114	5.9×10^{9}	Clustered flare event
11-20-60	4.5×10^{7}	118	3.4×10^{9}	
7-12-61	4×10^{7}	56	2.9×10^{9}	Clustered flare event
7-18-61	3×10^{8}	102	3.1×10^{9}	

[a]Estimated.

TABLE II. - REM DOSES FROM SELECTED FLARE EVENTS BEHIND VARIOUS THICKNESSES OF WATER AND ALUMINUM SHIELD AT 1 ASTRONOMICAL UNIT FROM SUN

(a) Rem dose behind water shield

Shield thickness, g/cm^2					Flare date
10	15	20	30	40	
Dose, rem					
42.10	27.76	20.79	13.03	9.03	2-23-56
1.07	.38	.19	.07	.04	1-20-57
.43	.15	.07	.03	.01	8-29-57
1.20	.65	.42	.21	.12	10-20-57
1.12	.40	.19	.07	.04	3-23-58
1.26	.45	.22	.08	.04	7-7-58
1.03	.35	.17	.07	.04	Aug. 1958 cluster
11.30	4.93	2.67	1.09	.57	5-10-59
.60	.20	.10	.04	.02	6-13-59
49.59	23.68	13.76	6.11	3.36	July 1959 cluster
.84	.46	.29	.15	.09	9-3-60
49.34	26.49	16.79	8.30	4.85	Nov. 1960 cluster
5.48	2.67	1.57	.71	.39	July 1961 cluster

(b) Rem dose behind aluminum shield

Shield thickness, g/cm^2							Flare date
10	15	20	30	40	50	60	
Dose, rem							
53.93	37.20	28.77	19.07	14.16	11.15	9.26	2.23-56
2.11	.86	.48	.24	.16	.12	.10	1-20-57
.90	.35	.19	.10	.07	.06	.05	8-29-57
1.73	1.00	.68	.38	.25	.18	.14	10-20-57
2.20	.89	.50	.25	.17	.12	.11	3-23-58
2.48	1.01	.56	.28	.19	.14	.12	7-7-58
2.12	.83	.45	.24	.17	.13	.11	Aug. 1958 cluster
18.98	9.06	5.36	2.59	1.63	1.18	.93	5-10-59
1.25	.49	.26	.14	.10	.08	.06	6-13-59
78.42	40.39	25.19	12.79	8.12	5.86	4.59	July 1959 cluster
1.22	.71	.48	.26	.17	.13	.10	9-3-60
71.89	41.17	27.59	15.09	9.87	7.17	5.61	Nov. 1960 cluster
8.57	4.49	2.82	1.44	.92	.66	.52	July 1961 cluster

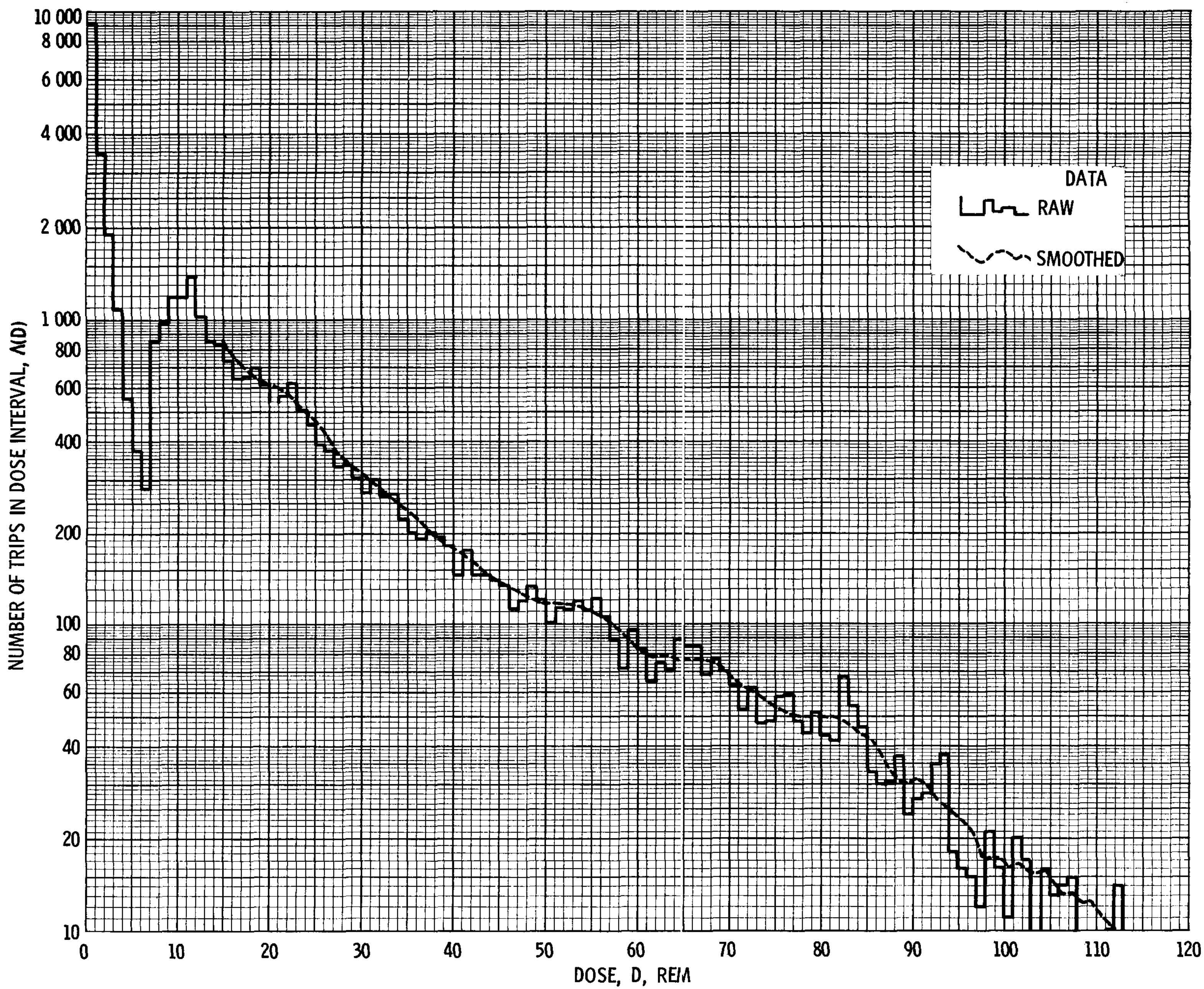
TABLE III. - VALUES OF $D_{0.99}$ AND CORRESPONDING STANDARD DEVIATION BEHIND VARIOUS THICKNESSES OF WATER AND ALUMINUM DETERMINED FROM GROUP OF 40 000 TRIPS

(a) Rem dose behind water shield

Distance effect, g(r)	Quantity	Shield thickness, g/cm^2				
		10	15	20	30	40
		Dose, rem				
$1/r^2$	$D_{0.99}$	254	139	94	55	37
	$\sigma_{D_{0.99}}$	2.0	1.3	.77	.44	.31
	$D_{0.99} + 2\sigma_{D_{0.99}}$	258	141.6	95.5	55.9	37.6
1	$D_{0.99}$	165	90	63	35	23
	$\sigma_{D_{0.99}}$	1.7	1.0	.57	.25	.2
	$D_{0.99} + 2\sigma_{D_{0.99}}$	168.4	92	64.1	35.5	23.4

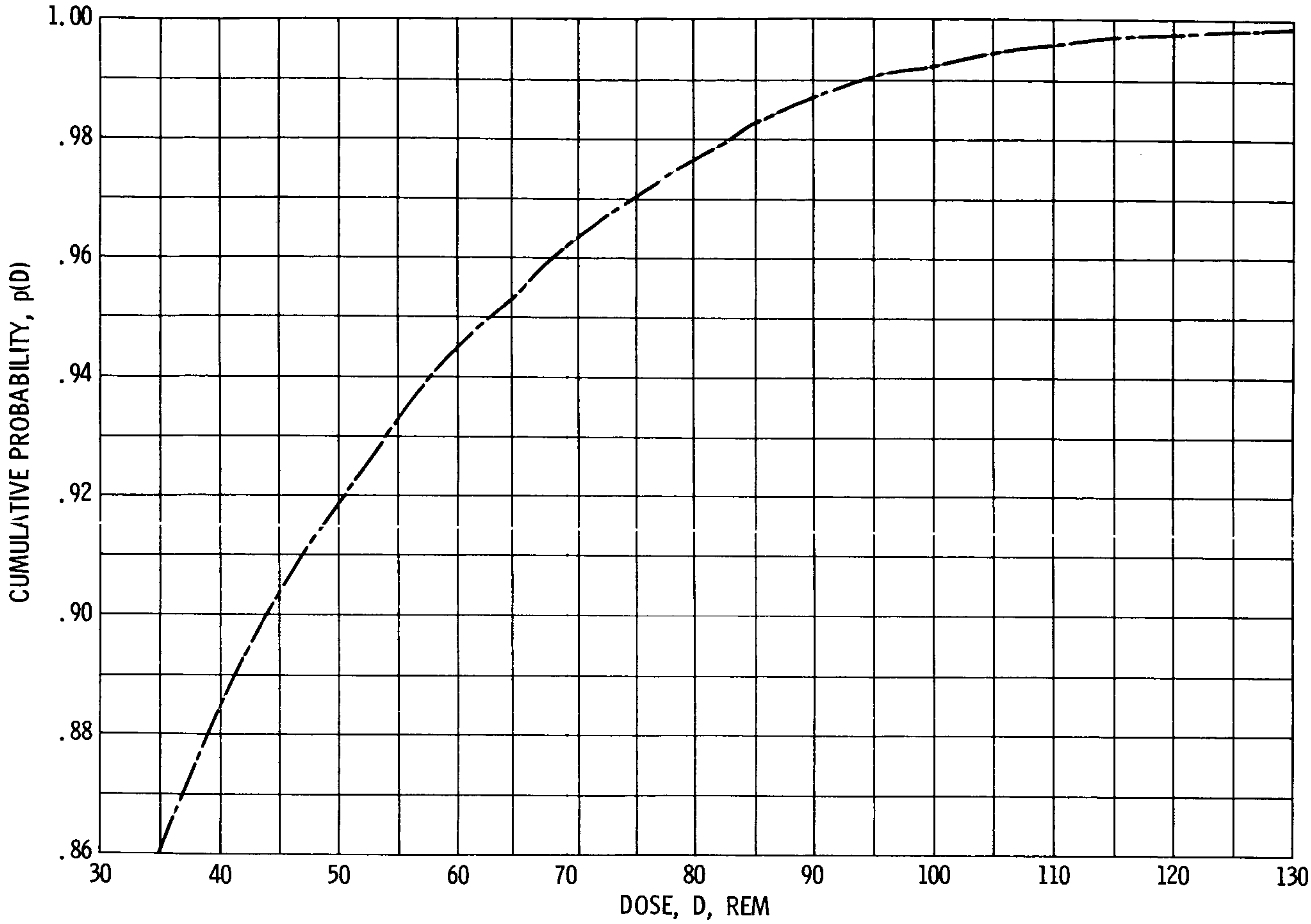
(b) Rem dose behind aluminum shield

Distance effect, g(r)	Quantity	Shield thickness, g/cm^2						
		10	15	20	30	40	50	60
		Dose, rem						
$1/r^2$	$D_{0.99}$	376	213	146	87	62	48	39
	$\sigma_{D_{0.99}}$	3.3	1.8	1.4	.77	.54	.42	.31
	$D_{0.99} + 2\sigma_{D_{0.99}}$	382.6	216.3	148.8	88.5	63.1	48.8	39.6
1	$D_{0.99}$	250	138	94	58	40	31	25
	$\sigma_{D_{0.99}}$	2.2	1.5	.91	.59	.31	.23	.22
	$D_{0.99} + 2\sigma_{D_{0.99}}$	254.4	141	95.8	59.2	40.6	31.5	25.4



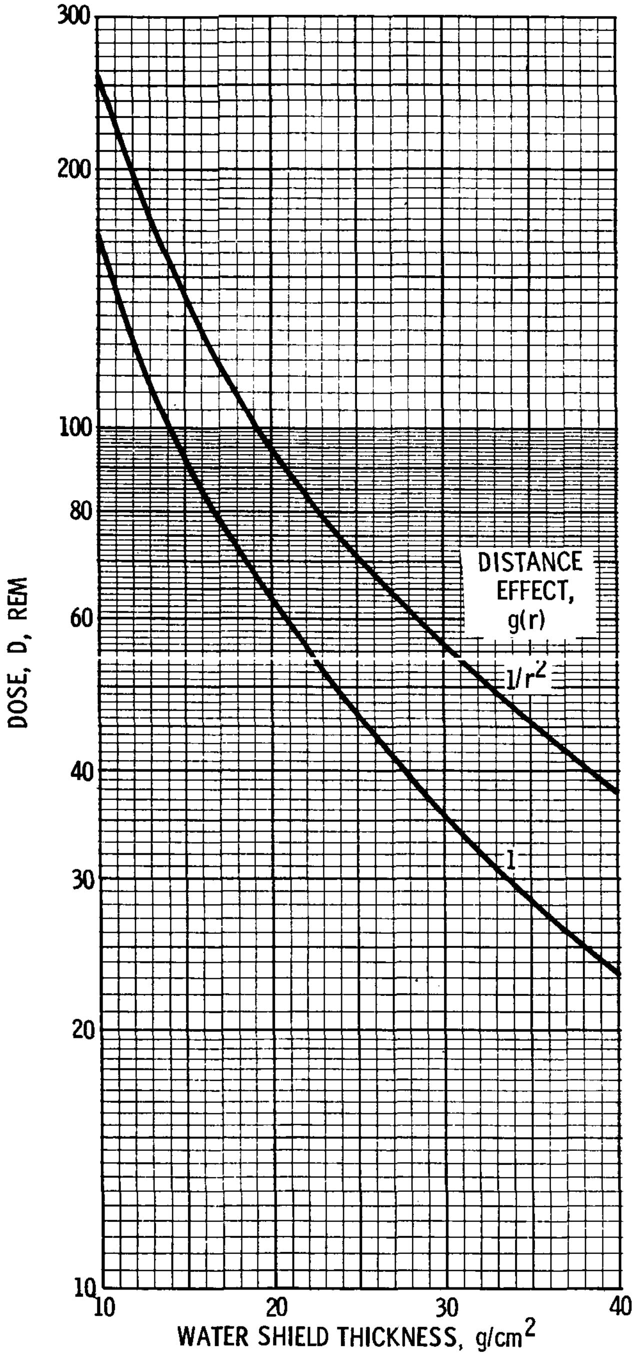
(A) NUMBER OF TRIPS ENCOUNTERING DOSES LYING WITHIN EACH DOSE INTERVAL.

Figure 1. - Distribution of trips encountering doses lying within each dose interval. Rem dose; water shield thickness, 20 grams per square centimeter; 40 000 trips; distance effect varies as $1/r^2$.



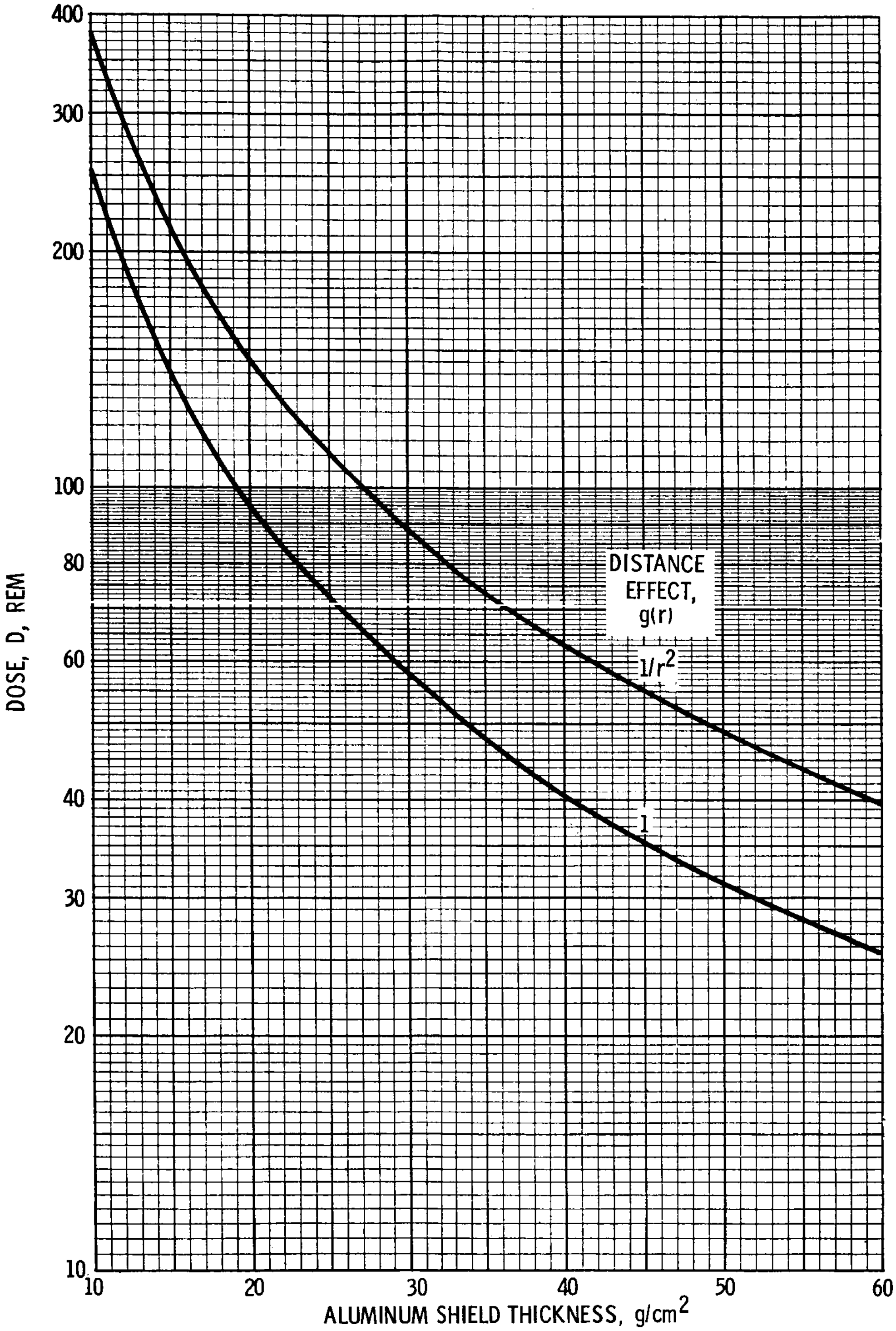
(B) CUMULATIVE PROBABILITY OF TRIP ENCOUNTERING DOSE LESS THAN D.

Figure 1. - Concluded.



(A) REM DOSE BEHIND WATER SHIELD.

Figure 2. - Values of $D_{0.99} + 2\sigma_{D_{0.99}}$ for various thicknesses of water and aluminum shields, and for cases of distance effect varying as $1/r^2$ and no effect of distance. Number of trips, 40 000.



(B) REM DOSE BEHIND ALUMINUM SHIELD.

Figure 2. - Concluded.