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MODEL SOLAR PROTON ENVIRONMENTS FOR MANNED SPACECRAFT DESIGN

by Jerry L. Modisette, Terence M. Vinson, and Alva C. Hardy

Manned Spacecraft Center
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SUMMARY

A statistical analysis of the solar proton events occurring during the upper half (1956 to 1961) of the last solar cycle has been made to determine the radiation environment which may be expected for flights outside the protection of the earth's magnetic field. Distribution functions have been derived for both the event size (number of protons) and the spectral parameters for mission durations of 1 to 10^4 weeks. From these distribution functions, model environments are given corresponding to various probabilities of occurrence.

INTRODUCTION

A major hazard to manned space flight outside the protecting influence of the earth's magnetic field is the radiation dose produced by high-energy (20 to 500 Mev) protons emitted by the sun. These emissions are sporadic in nature and vary greatly in the proton fluxes, duration, and spectral characteristics. The emissions, called solar proton events, are associated with solar flares and radio and X-ray emissions from the sun. In addition, there are polar-cap absorption events, fluctuation in the ground-level neutron flux, and magnetic disturbances at the earth.

For the purposes of manned spacecraft design, the important characteristics of a solar proton event are those necessary to calculate the radiation dose: the total (time-integrated) proton flux, the spectrum (energy distribution), and the directional distribution. The flux > 30 Mev for 54 events is available from a compilation of data by Dr. W. R. Webber (ref. 1) and from the forward scatter data of Dr. D. K. Bailey (ref. 2). References 1 and 3 also give flux > 100 Mev for 29 events. Because of the lack of experimental data, the directional distribution is not considered in this paper.

The objective of this analysis is, therefore, to determine the total number of protons and the energy spectrum to be expected during a mission. The number of protons (per cm^2) above 30 Mev is the parameter upon which the event size analysis is based because even for lightly shielded vehicles, protons below this energy do not penetrate. The spectrum is taken to be of the form

$$F(> E) = Ge^{-\frac{P(E)}{P_o}} \tag{1}$$

where G is the event size parameter, $P(E)$ is the magnetic rigidity, and $F(> E)$ is the flux having rigidity greater than P. Therefore, P_o is the spectral parameter on which the statistics are based.

SYMBOLS AND DEFINITIONS

E	proton energy, million electron volts (Mev)
$F(> E)$	number of protons in mission having energy greater than E, protons/cm^2
G	event size parameter, protons/cm^2
N	number of protons
n	number of weeks
$P(E)$	magnetic rigidity, or momentum per unit charge of a particle, million volts (Mv)
P_o	characteristic rigidity (spectrum parameter), million volts (Mv)
$p(> N)$	probability of more than N protons/cm^2 with $E > 30$ Mev
Probability level	the probability that greater than a given number of protons are encountered – used as a parameter in cross-plotting number of protons as a function of mission length

SOLAR PROTON EVENT TABLE

The number of protons (per cm^2) above 30 Mev for 54 events is listed in table I. Forty-three of these events were taken from reference 1 and 11 from the forward scatter data of Dr. D. K. Bailey in reference 2. The data supplied by Dr. Bailey gave the flux > 10 Mev, but for the purpose of uniformity the data have been converted to the flux > 30 Mev by using an average spectrum. The flux > 100 Mev from reference 1 is given for 29 events. In addition, the dates on which the events occurred are listed.

SPECTRUM STATISTICS

From equation (1) and the data in references 1 and 3, the value of P_o can be calculated for 29 events (table II). The number of events with P_o

greater than P is plotted against P_o. This distribution is reproduced from reference 1. With the exception of the February 23, 1956, event, figure 1 shows that the P_o values fit a rectangular distribution with a mean of 97 Mv and extreme values of 50 Mv and 144 Mv.

TOTAL PROTON FLUX STATISTICS

The quantity of interest is the total proton flux during a mission, rather than the total flux for an event because even for extreme events, the maximum dose rate is relatively low. From the table of event sizes (table I), the distribution of total fluxes for a mission could be calculated in two ways. One way would be to calculate separately the distributions of the event size and the distributions of the frequency of occurrence of events. These two distributions would then be combined to obtain the distribution for the total proton flux. A major problem with this approach is the difficulty of writing the proper frequency distribution because of certain apparent irregularities, such as the tendency of events to occur in groups.

Because of the difficulty in obtaining a frequency distribution, the approach adopted in this paper has been to consider each day in the period 1956 to 1961 as a launch date and then to use table I to determine the total number of protons to be encountered (see appendix). Most of the shorter missions do not encounter any protons. For the missions which do encounter protons, the distribution of the number of protons encountered is determined. Since each day is taken to start a new mission, there might seem to be about 2,000 missions in the 6-year period under consideration. This number is deceptive since the missions are not independent because of the overlap. To remove the redundancy in the missions, they are grouped so that the number of missions in each group equals the number of days in the mission.

In figure 2, the distributions of the data for various mission lengths are plotted on normal probability coordinates. For the short missions, the distributions are normal with respect to the logarithm of the number of protons. For longer missions, there are not enough data to determine the distribution with assurance. A normal distribution is assumed, however, as being consistent with the results for shorter missions. It should be understood that the distributions shown in figure 2 are for those missions which encounter protons. The probability of encountering any protons is also shown in the figure. To determine the probability of encountering greater than N protons, it is necessary to multiply the probability of encountering any protons by the probability that an encounter, if it occurs, consists of more than N protons.

From the normal distributions for various mission lengths, the number of protons encountered can be determined as a function of mission length at various probability levels. These functions are plotted in figure 3.

MODEL ENVIRONMENT DEFINITION

In order to define model environment for design purposes, G and P_o from equation (1) must be defined. The spectrum parameter P_o is taken to be 97 Mv, which is the average value from the distribution given in the section of this paper entitled "Spectrum Statistics." The average value is used because the choice of P_o has a small effect on radiation dose as compared with the choice of G and because the effect of variations in P_o on the probability of achieving a given dose level tends to cancel.

The event size parameter G can be determined from figure 3 once P_o, the mission length, and the desired probability level are known. The figure gives $F(> 30)$ so that from equation (1)

$$F(> 30) = G \exp\left(- \frac{P(30)}{P_o}\right) \tag{2}$$

or

$$G = 11.4F(> 30) \tag{2a}$$

The model event as determined by selecting a probability level and a mission length is, therefore, given by

$$F(> E) = 11.4F(> 30) \exp\left(- \frac{P(E)}{97}\right) \tag{3}$$

where $F(> 30)$ is taken from figure 3.

FRACTION OF PROTONS IN ONE WEEK FOR LONG DURATIONS

The curves in figure 3 give the total proton flux to be expected for a mission. For the proper definition of dose limits for the longer missions, it would be desirable to know the manner in which the dose is received during the mission; that is, whether the dose occurs in small amounts over the entire length of the mission or whether the major part comes during one short period of intense solar activity.

The probability distribution for the maximum number of protons to be expected in any week of a mission can be calculated from the distribution for 1 week. If $p(> N)$ is the probability that a week contains N or more protons, given by figure 2, $1 - p(> N)$ is the probability that a week does not contain N or more protons. For n weeks, $\left[1 - p(> N)\right]^n$ is the probability that no week of n weeks has N or more protons, and $1 - \left[1 - p(> N)\right]^n$ is the probability that at least 1 out of n weeks contains N or more protons. This distribution is plotted in figure 4. To a reasonable approximation, the fraction of the total protons occurring in 1 week can be determined from figure 5, which shows the average number of protons for the entire mission and for the maximum week as functions of mission length. It can be seen that the ratio of the maximum week flux to the total mission flux varies from 1 for a 1-week mission to 0.60 for 104-week missions.

DISCUSSION

Several open or implicit assumptions are made in arriving at the model events. The first of these is the effect of the solar cycle. It has been assumed that only the upper half of the sunspot cycle need be considered. The 54 events recorded during the last cycle occurred during the upper half (1956 to 1961). Because of instrumental limitations, there may be smaller events which were missed. These events, however, would not contribute significantly to the dose. A linear regression fit was made for frequency of occurrence of events as plotted against smoothed sunspot number, and a correlation coefficient of 0.70 was found. A test of the fit for a step function shows the same correlation coefficient. This implies a random distribution over the upper half of the cycle. There is, in fact, some apparent structure to the distribution within the upper half, in that large events seem to occur during the rise and fall. However, the data are not sufficient to allow the specification of this effect, so that a random distribution is assumed.

Another approximation was to consider only the event size in the statistical analysis. The probability of interest is the probability of receiving a given dose. This probability is functionally dependent upon the probability distribution for event size and for the spectrum. An analysis which accounted rigorously for all these dependences would be complex, but more important, the functional dependence of dose on spectrum would also depend on the shielding of the vehicle under consideration. This dependence makes any rigorous environment definition unwieldy in application since it would be necessary to use a multiple iteration; that is, a shielding design would lead to a redefinition of the environment which would then be used for a dose calculation, resulting in redesign of the shielding, which changes the environment, and so forth.

The approach used herein, that of selecting an average spectrum while basing the statistics on the event size, is ideal for design purposes since the dose, for a given shield design, is directly proportional to the number of protons. The question is whether the approximation is justified. The justification is as follows: The observed event size varies over four orders of magnitude as a result of event-size distribution. The variation in P_0, the spectrum parameter, is shown in figure 1. The effect of these parameters on dose is shown in table III. It can be seen that the variation in dose due to event size heavily outweighs the variation due to spectrum for both point dose and depth dose and also for various mission lengths. The low and high values of P_o are the extremes of the rectangular distribution shown in figure 1. The February 23, 1956, spectrum is also included because it did not fit the distribution. In addition, the effects of the variation in the spectral parameter P_o on the dose probability tend to cancel so that basing the statistics on the event size appears to be a reasonable approximation.

In determining the distribution of the parameter P_o, only data for flux of protons greater than 30 Mev and 100 Mev were used. This is the energy range of interest because the thinnest shielding on manned spacecraft is sufficient to stop protons of energy below 30 Mev, while very little dose comes from protons much above 100 Mev. Figure 6 shows the fraction of the dose coming from various energy ranges for a typical lunar vehicle with $P_o = 97$ Mv.

CONCLUDING REMARKS

A statistical analysis of solar proton events occurring during the upper half (1956 to 1961) of the last solar cycle has been made. From the results of the analysis, probability distributions have been derived for the total proton flux during missions of from 1 to 104 weeks duration. Of significance in setting dose limits for long missions is the result that most of the dose received during a mission will be received during 1 week.

The model environments presented can be used for shielding design and reliability analysis of manned spacecraft, keeping in mind the limitations imposed by the assumptions and the uncertainties with regard to future solar activity.

Manned Spacecraft Center,
National Aeronautics and Space Administration,
Houston, Texas, June 27, 1964

APPENDIX

FORTRAN PROGRAM FOR ANALYSIS OF SOLAR PROTON EVENTS

A FORTRAN program for the IBM 7094 was written to analyze the data used in this paper. In the program, every day in the period covered by the data is considered as a possible launch date for a mission. The program examines each day covered by the length of mission which is desired and sums all events seen on that particular mission. After summing the event sizes for all possible missions of the desired length, the program sorts out those missions during which events occurred and computes the mean, variance, and standard deviation of the event sizes, the results being given in log form.

The program then arranges the event sizes in ascending order and computes the sum of the first n events, the second n events, and so on until finally there are m groups (sums) of n events each. The number of groups m is chosen so that it will be the nearest integral number to the number of missions which encounter events divided by the mission length. The program then computes the average of each group, and the mean, variance, and standard deviation of the group averages. Since the number of missions which encounter events divided by the mission length will not be a whole number in most cases, there will be some event sizes left over after grouping. If the mission length does not divide evenly into the number of events, some of the groups are increased to include $n + 1$ events to account for the remainder.

REFERENCES

1. Webber, W. R.: An Evaluation of the Radiation Hazard Due to Solar-Particle Events. D2-90469, The Boeing Co., 1963.

2. Bailey, D. K.: The Detection and Study of Solar Cosmic Rays by Radio Techniques. J. Phys. Soc. Japan, vol. 17, supp. AI, part I, Jan. 1962, pp. 106-112.

3. McDonald, Frank B., ed.: Solar Proton Manual. NASA TR R-169, 1963.

TABLE I.- CALENDAR OF SOLAR PROTON EVENTS FROM 1956 TO 1961

Date	Integrated intensity, protons/cm^2		Source	Date	Integrated intensity, protons/cm^2		Source
	>30 Mev	>100 Mev			>30 Mev	>100 Mev	
Feb. 23, 1956	1.0×10^9	3.5×10^8	Ref. 1	Apr. 10, 1958	5.0×10^6		Ref. 1
Mar. 10, 1956	1.1×10^8		Ref. 2	July 7, 1958	2.5×10^8	9.0×10^6	Ref. 1
Aug. 31, 1956	2.5×10^7	6.0×10^6	Ref. 1	Aug. 16, 1958	4.0×10^7	1.6×10^6	Ref. 1
Nov. 13, 1956	1.1×10^8		Ref. 2	Aug. 22, 1958	7.0×10^7	1.8×10^6	Ref. 1
Jan. 20, 1957	2.0×10^8	7.0×10^6	Ref. 1	Aug. 26, 1958	1.1×10^8	2.0×10^6	Ref. 1
Apr. 3, 1957	5.6×10^7		Ref. 2	Sept. 22, 1958	6.0×10^6	1.0×10^5	Ref. 1
Apr. 6, 1957	3.8×10^7		Ref. 2	Feb. 13, 1959	2.8×10^7		Ref. 2
June 22, 1957	1.7×10^8		Ref. 2	May 10, 1959	9.6×10^8	8.5×10^7	Ref. 1
July 3, 1957	2.0×10^7		Ref. 1	June 13, 1959	8.5×10^7		Ref. 1
Aug. 9, 1957	1.5×10^6		Ref. 1	July 10, 1959	1.0×10^9	1.4×10^8	Ref. 1
Aug. 29, 1957	1.2×10^8	3.0×10^6	Ref. 1	July 14, 1959	1.3×10^9	1.0×10^8	Ref. 1
Aug. 31, 1957	5.3×10^7		Ref. 2	July 16, 1959	9.1×10^8	1.3×10^8	Ref. 1
Sept. 2, 1957	1.4×10^7		Ref. 2	Aug. 18, 1959	1.8×10^6		Ref. 1
Sept. 21, 1957	1.5×10^6		Ref. 1	Jan. 11, 1960	4.0×10^5		Ref. 1
Oct. 20, 1957	5.0×10^7	1.0×10^7	Ref. 1	Mar. 29, 1960	2.7×10^7		Ref. 2
Nov. 4, 1957	9.0×10^6		Ref. 1	Apr. 1, 1960	5.0×10^6	8.5×10^5	Ref. 1
Feb. 9, 1958	1.0×10^7		Ref. 1	Apr. 5, 1960	1.1×10^6		Ref. 1
Mar. 23, 1958	2.5×10^8	1.0×10^7	Ref. 1	Apr. 28, 1960	5.0×10^6	7.0×10^5	Ref. 1
Mar. 25, 1958	7.8×10^8		Ref. 2	Apr. 29, 1960	7.0×10^6		Ref. 1

TABLE I.- CALENDAR OF SOLAR PROTON EVENTS FROM 1956 TO 1961 - Concluded

Date	Integrated intensity, protons/cm^2		Source	Date	Integrated intensity, protons/cm^2		Source
	>30 Mev	>100 Mev			>30 Mev	>100 Mev	
May 4, 1960	6.0×10^6	1.2×10^6	Ref. 1	Nov. 15, 1960	7.2×10^8	1.2×10^8	Ref. 1
May 6, 1960	4.0×10^6		Ref. 1	Nov. 20, 1960	4.5×10^7	8.0×10^6	Ref. 1
May 13, 1960	4.0×10^6	4.5×10^5	Ref. 1	July 11, 1961	3.0×10^6	2.4×10^5	Ref. 1
June 1, 1960	4.0×10^5		Ref. 1	July 12, 1961	4.0×10^7	1.0×10^6	Ref. 1
Aug. 12, 1960	6.0×10^5		Ref. 1	July 18, 1961	3.0×10^8	4.0×10^7	Ref. 1
Sept. 3, 1960	3.5×10^7	7.0×10^6	Ref. 1	July 20, 1961	5.0×10^6	9.0×10^5	Ref. 1
Sept. 26, 1960	2.0×10^6	1.2×10^5	Ref. 1	Sept. 10, 1961	3.7×10^7		Ref. 2
Nov. 12, 1960	1.3×10^9	2.5×10^8	Ref. 1	Sept. 28, 1961	6.0×10^6	1.1×10^6	Ref. 1

TABLE II.- CHARACTERISTIC RIGIDITY P_o FOR 29 SOLAR EVENTS

Date	Integrated intensity, protons/cm^2 (a)		Characteristic rigidity P_o Mv
	>30 Mev	>100 Mev	
Feb. 23, 1956	1.0×10^9	3.5×10^8	195
Aug. 31, 1956	2.5×10^7	6.0×10^6	144
Jan. 20, 1957	2.0×10^8	7.0×10^6	61
Aug. 29, 1957	1.2×10^8	3.0×10^6	56
Oct. 20, 1957	5.0×10^7	1.0×10^7	127
Mar. 23, 1958	2.5×10^8	1.0×10^7	64
July 7, 1958	2.5×10^8	9.0×10^6	62
Aug. 16, 1958	4.0×10^7	1.6×10^6	64
Aug. 22, 1958	7.0×10^7	1.8×10^6	56
Aug. 26, 1958	1.1×10^8	2.0×10^6	51
Sept. 22, 1958	6.0×10^6	1.0×10^5	50
May 10, 1959	9.6×10^8	8.5×10^7	84
July 10, 1959	1.0×10^9	1.4×10^8	104
July 14, 1959	1.3×10^9	1.0×10^8	80
July 16, 1959	9.1×10^8	1.3×10^8	105
Apr. 1, 1960	5.0×10^6	8.5×10^5	116
Apr. 28, 1960	5.0×10^6	7.0×10^5	104
May 4, 1960	6.0×10^6	1.2×10^6	127

[a]Data from reference 1

TABLE II.- CHARACTERISTIC RIGIDITY P_o FOR 29 SOLAR EVENTS - Concluded

Date	Integrated intensity, protons/cm^2 (a)		Characteristic rigidity P_o Mv
	>30 Mev	>100 Mev	
May 13, 1960	4.0×10^6	4.5×10^5	94
Sept. 3, 1960	3.5×10^7	7.0×10^6	127
Sept. 26, 1960	2.0×10^6	1.2×10^5	73
Nov. 12, 1960	1.3×10^9	2.5×10^8	124
Nov. 15, 1960	7.2×10^8	1.2×10^8	114
Nov. 20, 1960	4.5×10^7	8.0×10^6	118
July 11, 1961	3.0×10^6	2.4×10^5	81
July 12, 1961	4.0×10^7	1.0×10^6	56
July 18, 1961	3.0×10^8	4.0×10^7	102
July 20, 1961	5.0×10^6	9.0×10^5	120
Sept. 28, 1961	6.0×10^6	1.1×10^6	121

[a] Data from reference 1

TABLE III.- COMPARISON OF EFFECT ON DOSAGE OF VARYING FLUX AND RIGIDITY SPECTRUM

Flux probability	Low P_o = 50 Mv	Mean P_o = 97 Mv	High P_o = 144 Mv	Feb. 23, 1956 P_o = 195 Mv
	Ratio of dose to dose at 0.50 flux, mean P_o			
		(a) Point dose		
		2-week mission		
0.99		0.004		
0.50	0.62	1.0	1.24	1.42
0.01		275.4		
		52-week mission		
0.99		0.05		
0.50	0.62	1.0	1.24	1.42
0.01		19.90		
		104-week mission		
0.99		0.09		
0.50	0.62	1.0	1.24	1.42
0.01		11.50		
		(b) Depth dose (5.0 cm)		
		2-week mission		
0.99		0.004		
0.50	0.14	1.0	1.94	2.78
0.01		275.4		
		52-week mission		
0.99		0.05		
0.50	0.14	1.0	1.94	2.78
0.01		19.90		
		104-week mission		
0.99		0.09		
0.50	0.14	1.0	1.94	2.78
0.01		11.50		

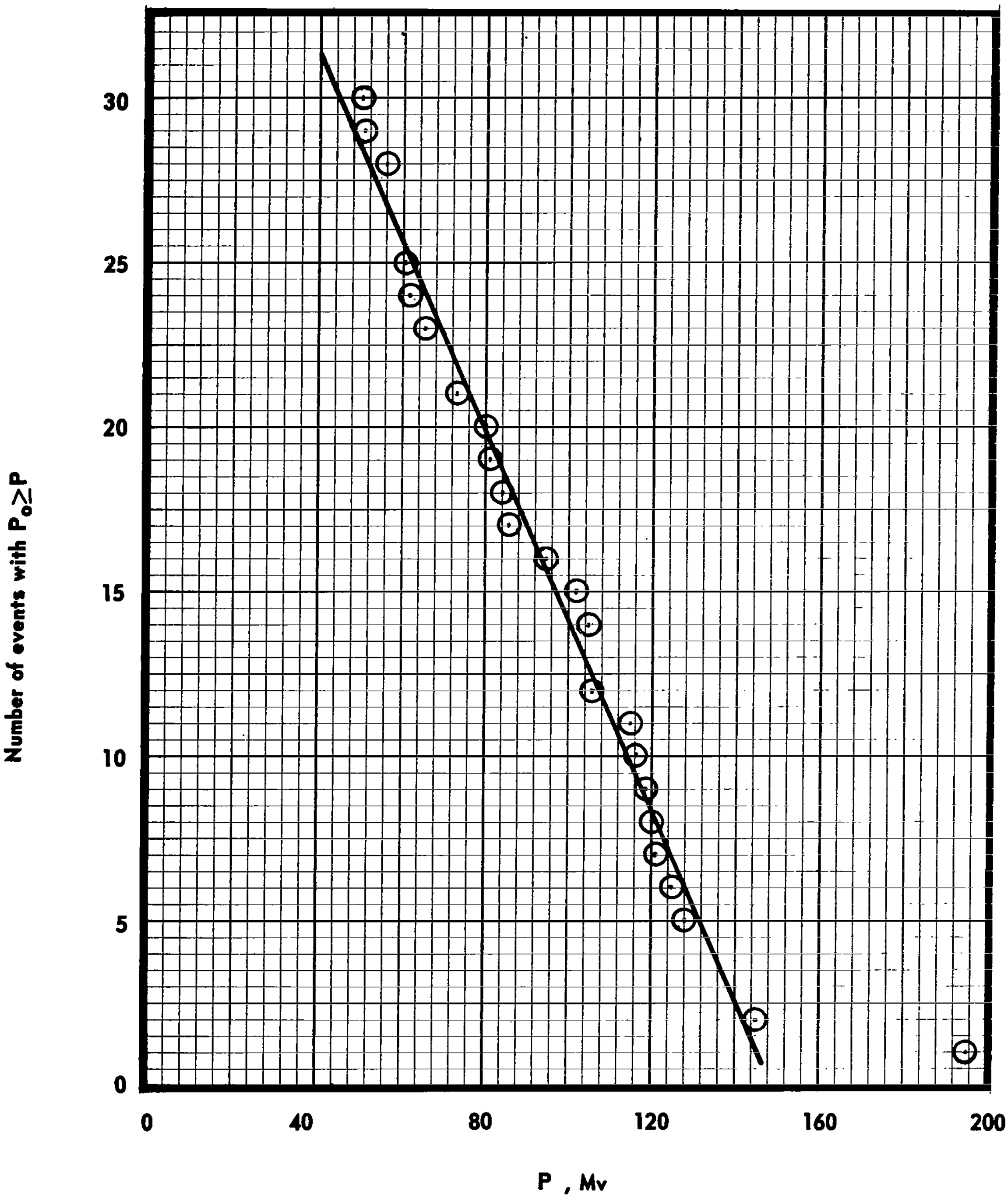
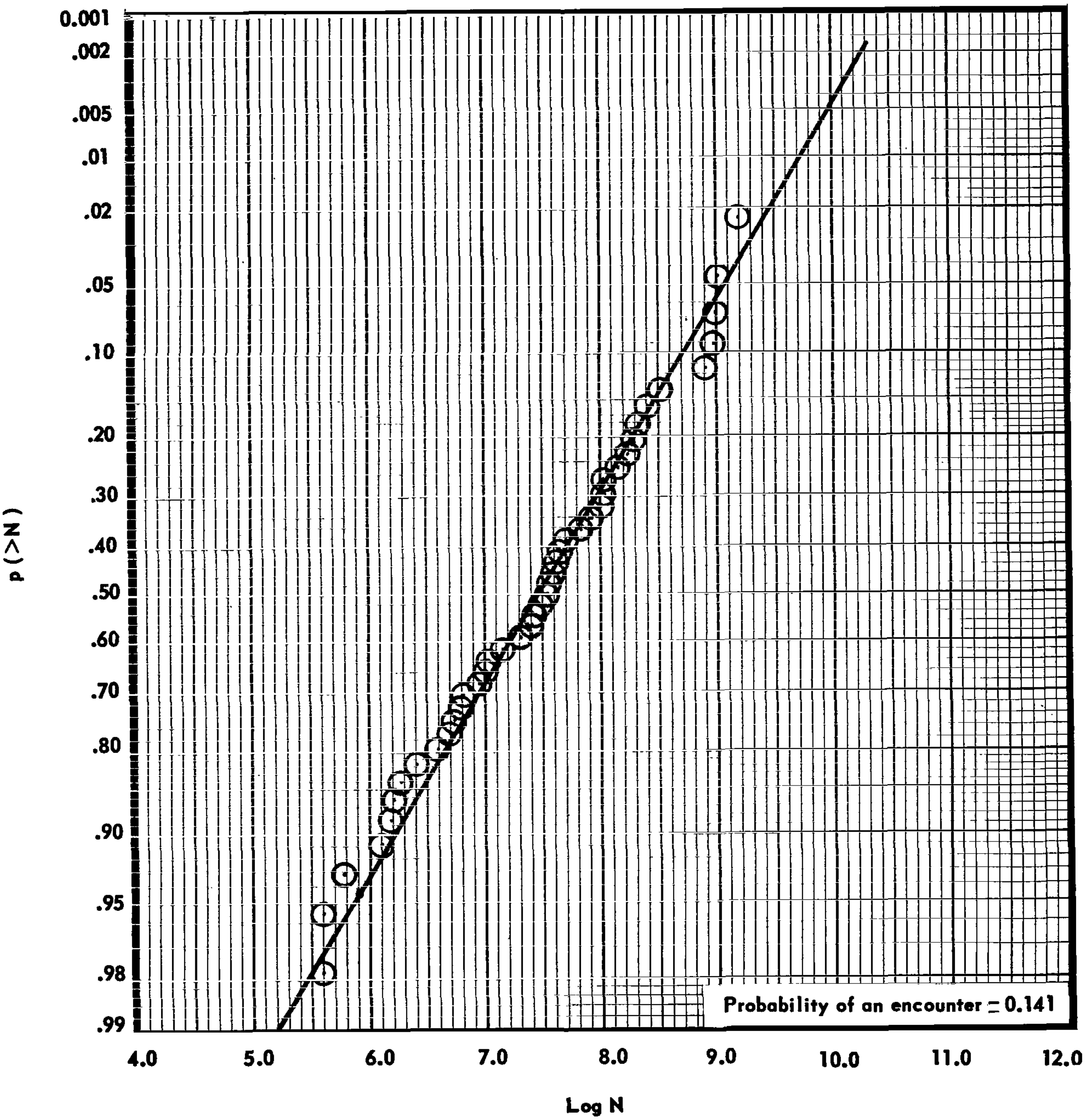
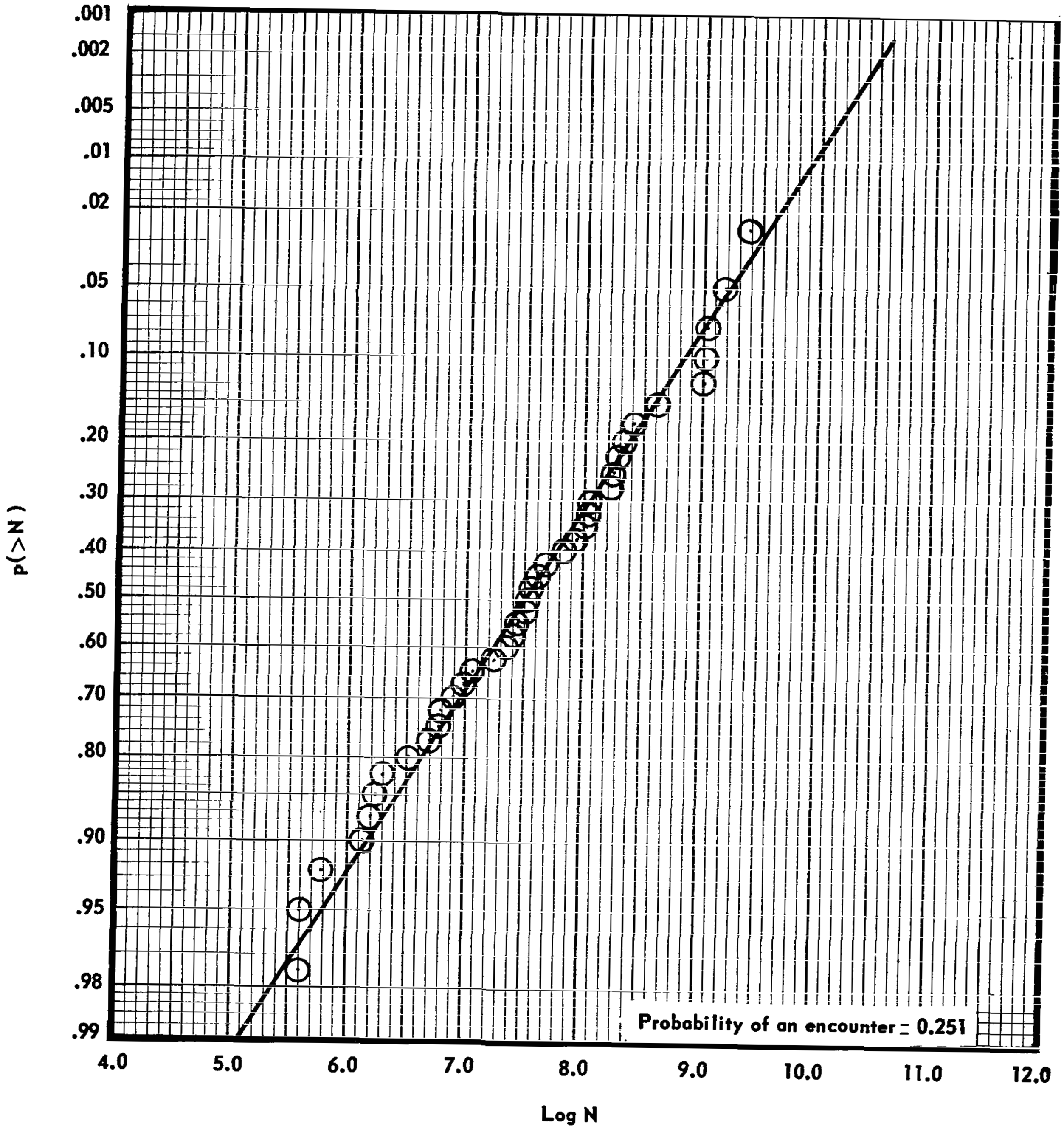


Figure 1.- Distribution of P_o, rigidity spectrum parameter.



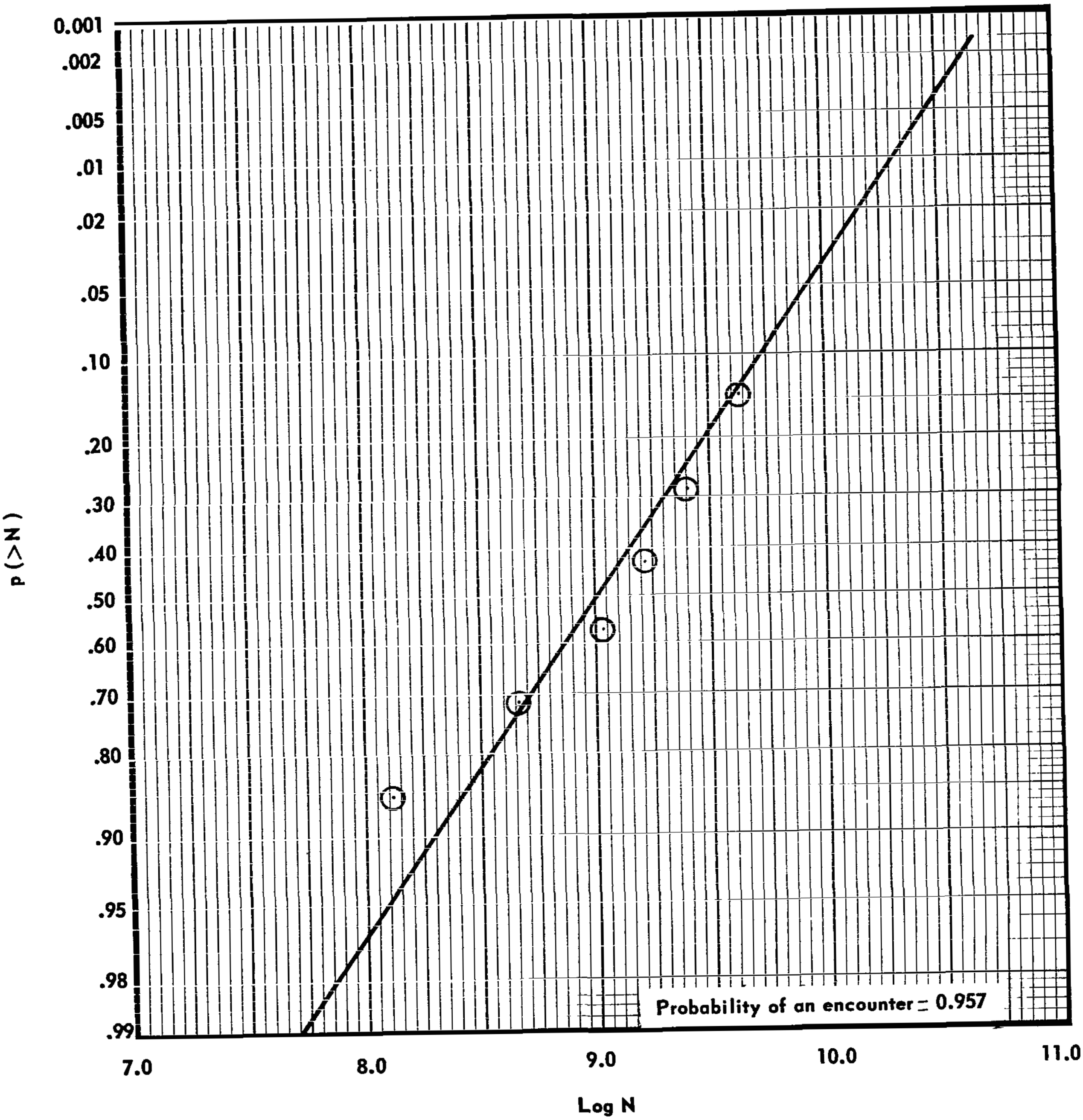
(a) 1-week mission.

Figure 2.- Probability that an encounter consists of more than N protons/cm^2.



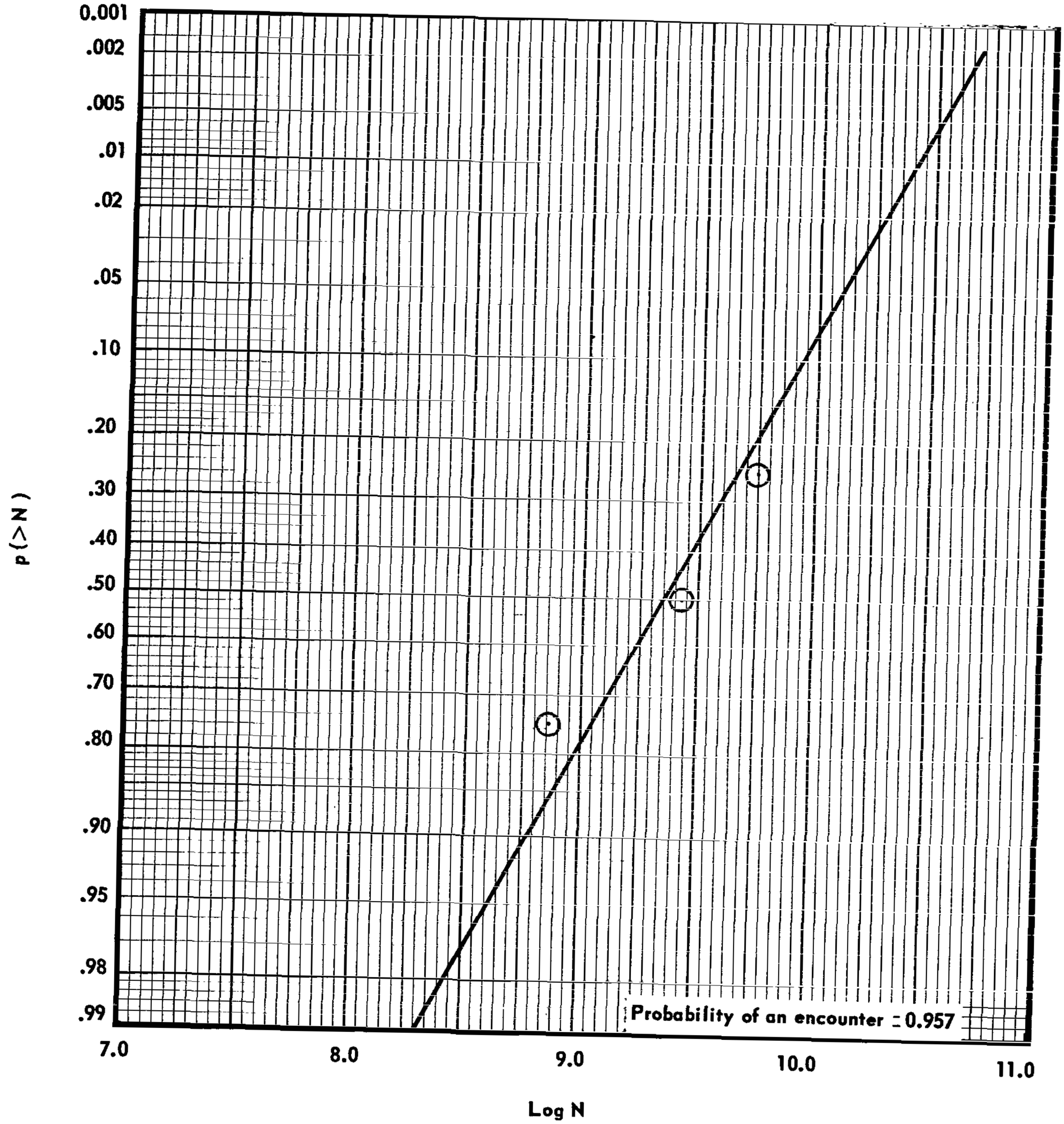
(b) 2-week mission.

Figure 2.- Continued.



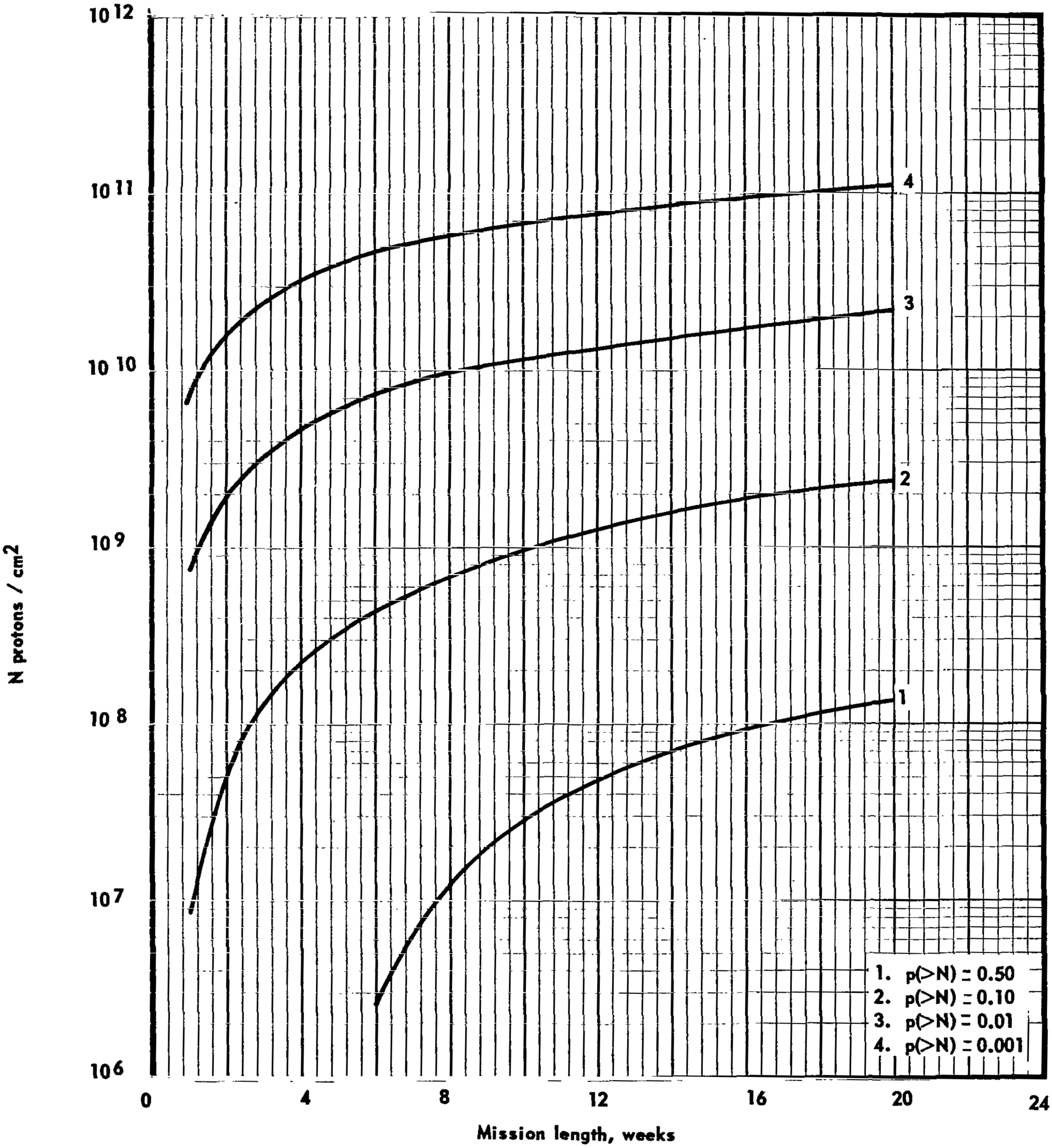
(c) 52-week mission.

Figure 2.- Continued.



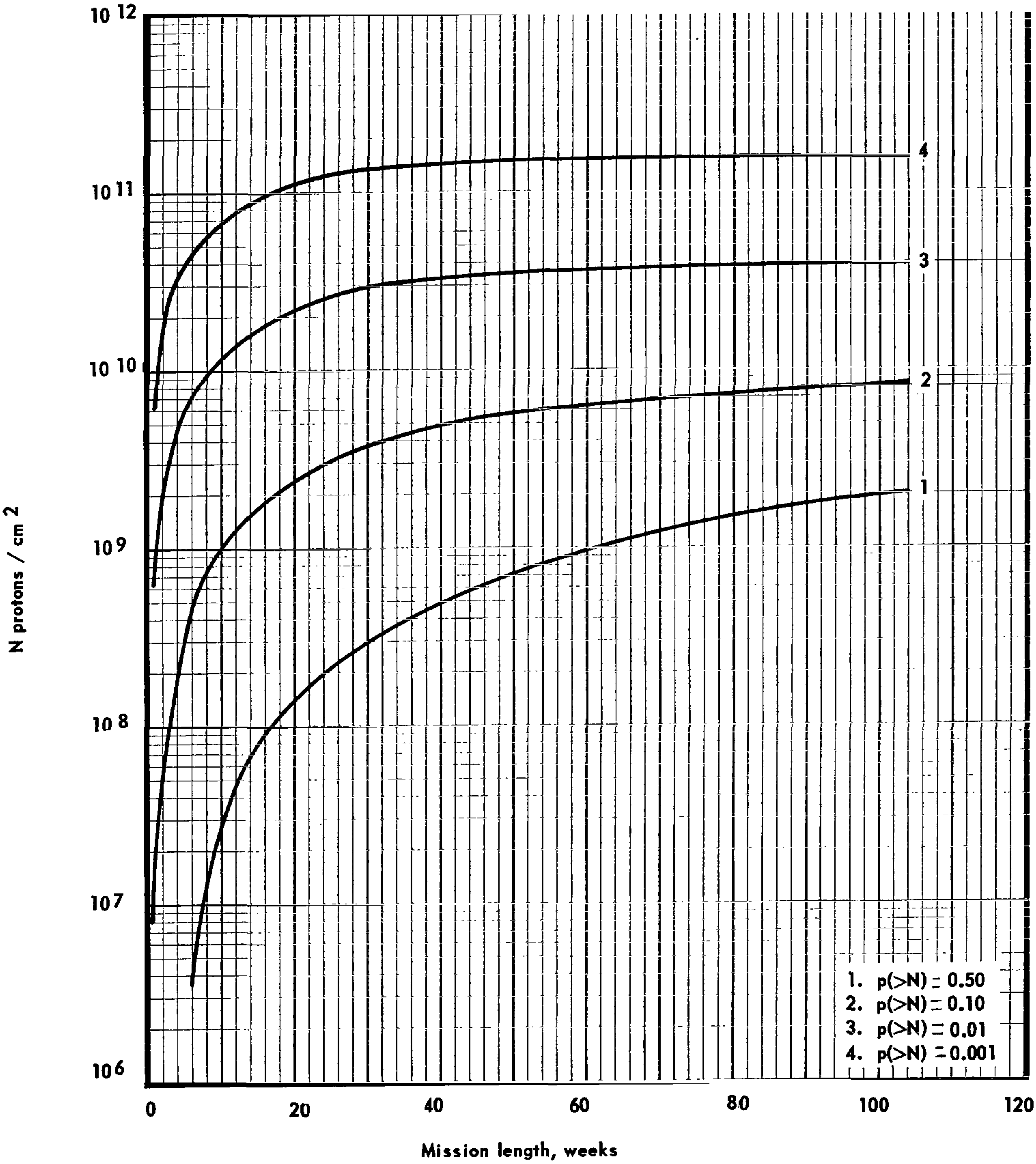
(d) 104-week mission.

Figure 2.- Concluded.



(a) Mission durations from 1 to 20 weeks.

Figure 3.- Variation of number of protons/cm^2 with mission lengths at four probability levels.



(b) Mission durations from 1 to 104 weeks.

Figure 3.- Concluded.

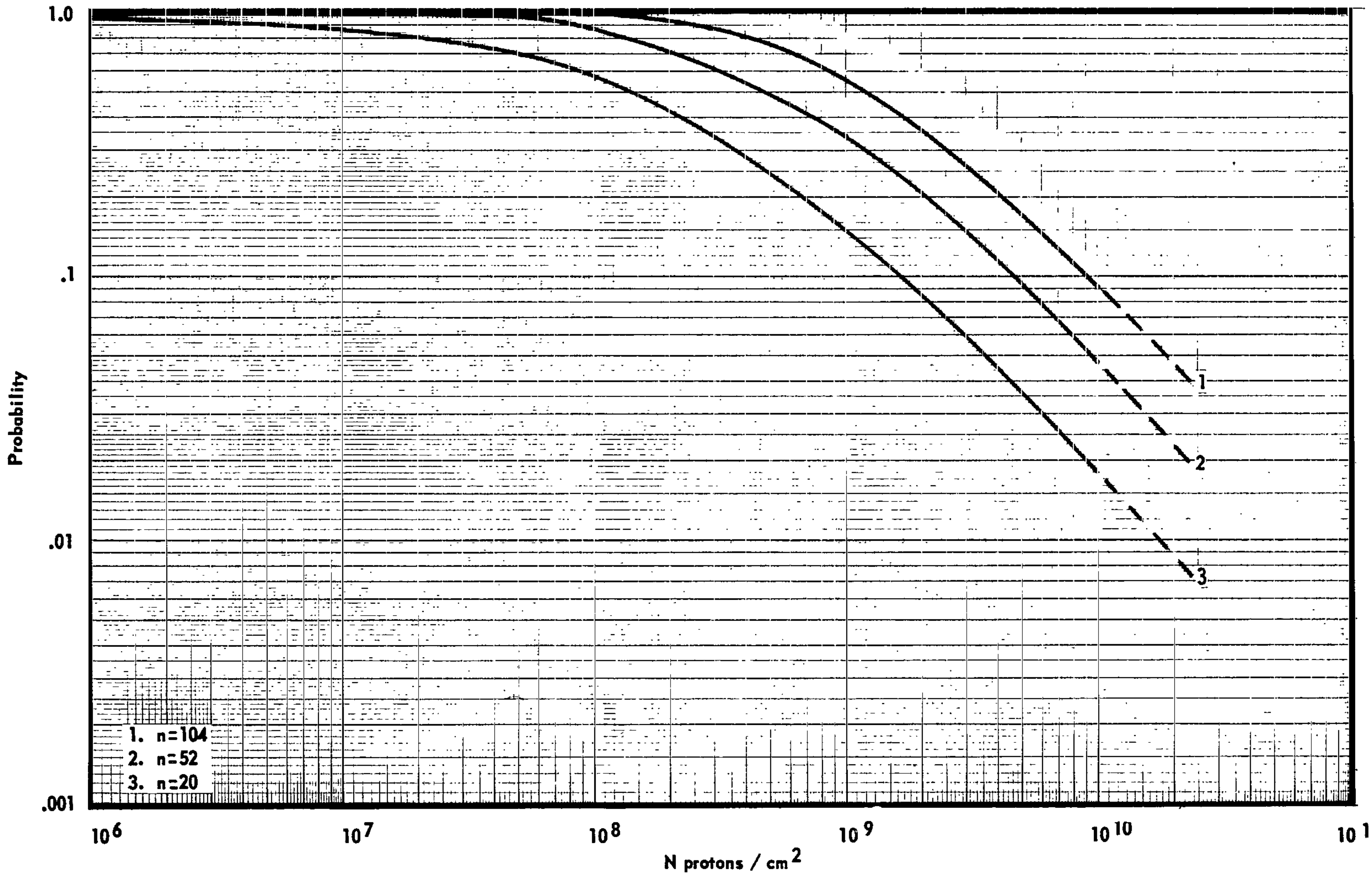


Figure 4.- Probability of encountering $\geq N$ protons/cm^2 in 1 week during a mission of n weeks.

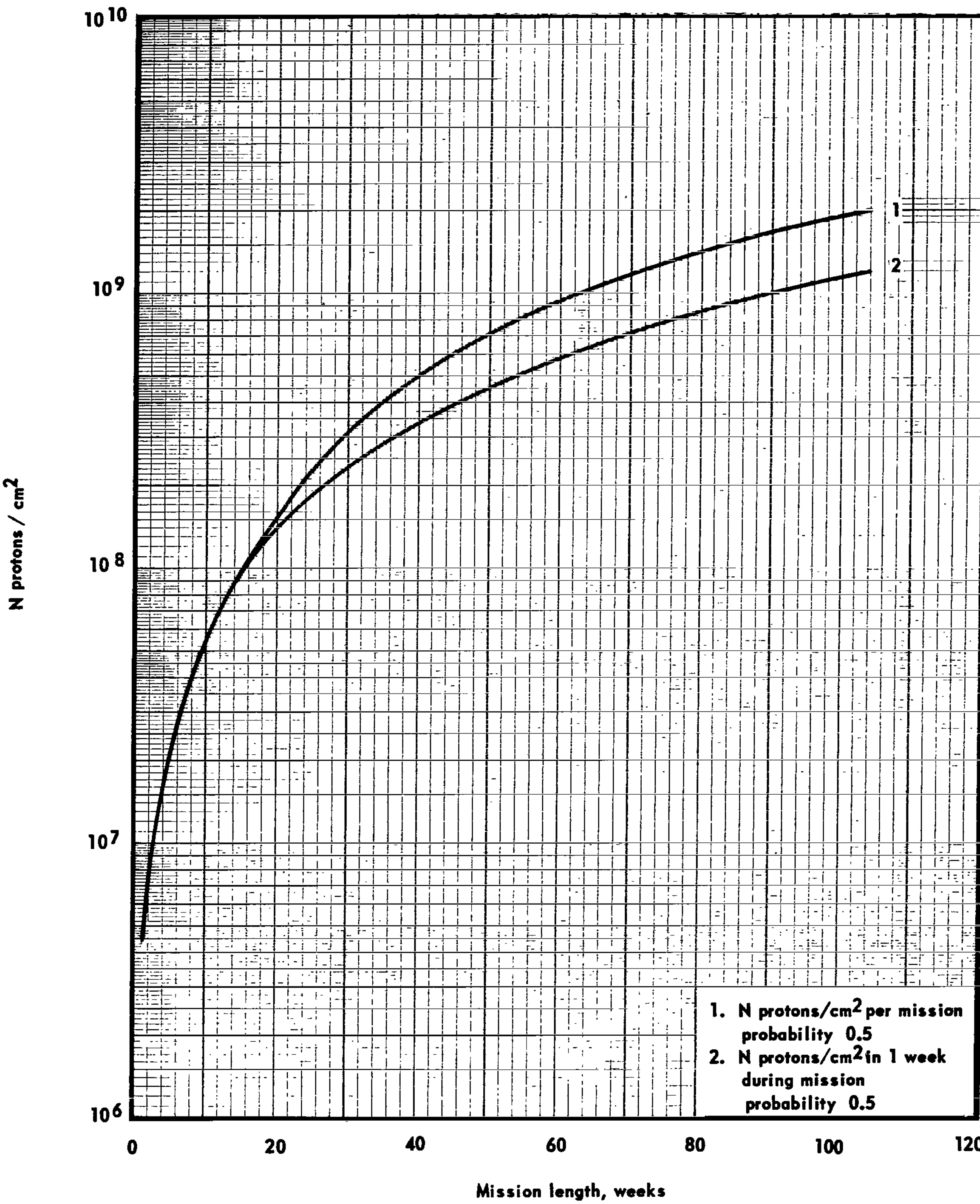


Figure 5.- Number of protons/cm^2 encountered per mission and in the maximum week during the mission (0.5 probability level).

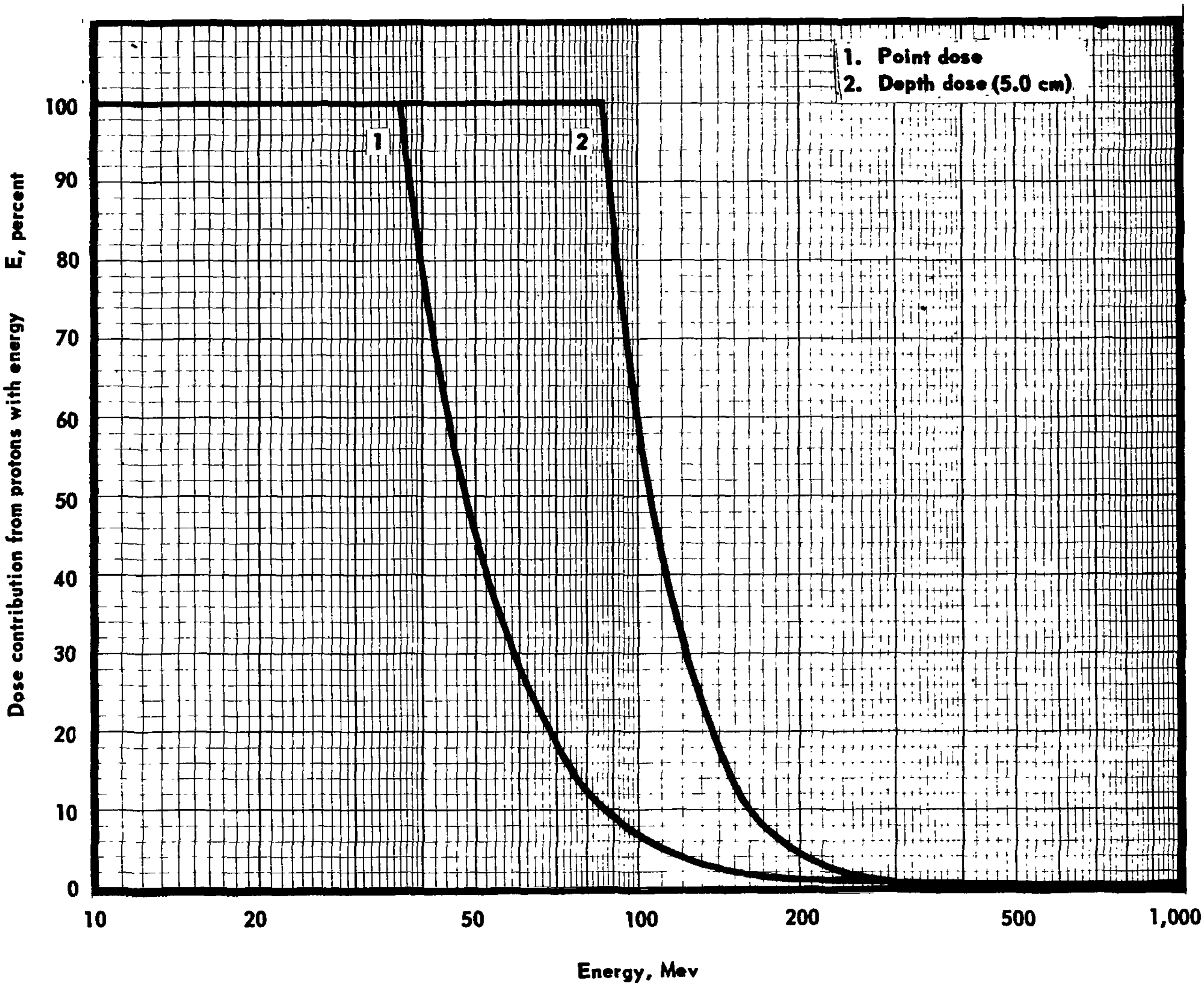


Figure 6.- Dose contribution from protons with energy greater than E plotted against E (P_o = 97 Mv).

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