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PROBABILITIES OF SOLAR FLARE OCCURRENCE

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Space Flight Center,
Huntsville, Alabama

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ABSTRACT

The primary interest vehicle designers and advanced mission planners have in solar flares is the probability of occurrence of a damaging flare. Obviously then, one must define exactly what is a damaging flare. An environmental model of a "typical" flare is constructed herein, and the probability of occurrence of this or a similar flare is considered. The next step is to then derive an "extreme" model solar flare so that the effects of such a flare on occupants of a nominally shielded vehicle may be derived. Since this report is intended to present only the environmental model, no attempt has been made to estimate the dose accrued for either type flare nor have any shielding calculations been performed.

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W. T. Roberts

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TECHNICAL MEMORANDUM X-53463

PROBABILITIES OF SOLAR FLARE OCCURRENCE

SUMMARY

The primary interest vehicle designers and advanced mission planners have in solar flares is the probability of occurrence of a damaging flare. Obviously then, one must define exactly what is a damaging flare. An environmental model of a "typical" flare is constructed herein, and the probability of occurrence of this or a similar flare is considered. The next step is to then derive an "extreme" model solar flare so that the effects of such a flare on occupants of a nominally shielded vehicle may be derived. Since this report is intended to present only the environmental model, no attempt has been made to estimate the dose accrued for either type flare nor have any shielding calculations been performed.

I. INTRODUCTION

A description of the solar flare environment has been presented by the author in an earlier paper [2], and will not be reviewed in detail here. A few revisions to the "extreme" model flare have been made which will be discussed later. The probability of the occurrence of a solar flare is based upon the binomial law. If p_1 is the probability of occurrence of a solar flare per day and q_1 is the probability of a solar flare not occurring per day, then

$$p_1 + q_1 = 1$$

or

$$q_1 = 1 - p_1.$$

For a mission lasting n days, the probability, P_n, of the occurrence of one or more such flares is derived by

$$P_n = 1 - (1 - p_1)^n.$$

This was the method used to calculate the probabilities in this report. The data used were basically those of Webber [1] for the period 1956-1961. No special calculations were performed to show that the flares tend to "group" in time as evidenced by the July 1959 series, nor was any attempt made to include the time period of the dearth of flares during sunspot minimum. The lack of solar flares at sunspot minimum is well known, but the problem lies in specifying exactly how long this minimum will last. The past sunspot minimum appears to indicate a safe period (for lightly shielded vehicles) of about four years beginning in 1962 and extending through 1965, but to apply this safe period to the next solar minimum would probably not be wise.

A reasonable assumption might be to designate a two-year period centered on sunspot minimum as a safe time zone for lightly shielded vehicles. Since missions to Mars and Venus are not expected to take much over two years, sunspot minimum is the most favorable time period from a solar flare viewpoint. Unfortunately, launch windows for these missions do not necessarily correspond to favorable time periods for solar flares. Whereas launch windows are predictable, solar cycles are not.

In view of the severe flare model used and the time period considered, these results are probably conservative, but nevertheless, they represent reasonable criteria for vehicle design and mission studies.

II. DESIGN FLARE MODEL

A few minor revisions have been made from the model flare presented in the earlier paper [2]. Where, previously, the flux of particles above a certain energy was the highest recorded for individual flares, the flux in this report includes the sums of the series of flares recorded in July 1959. Thus, instead of a flux of 7.5×10^9 (cm^{-2}) with energies above 10 Mev, the maximum particles above 10 Mev is now 1.5×10^{10} (cm^{-2}). In addition, since the February 1956 flare holds up out to very high energies, the energy spectrum for particles over 100 Mev is fitted to that flare spectrum. Using this spectrum, we find that there are still about 1.3×10^8 (cm^{-2}) particles whose energies are equal to or exceed 300 Mev. Since the spectrum is so hard, one should expect that these particles will be exceedingly difficult to shield against. Figure 1 shows this extreme flare model.

Figure 2 shows the flux of particles (with energies greater than 30 Mev) per month throughout the period 1956-1961. One must keep in mind that the particles from these flares were incident at the earth, and were thus recorded. The dashed curve in Figure 2 is the mean monthly solar flux recorded at the National Research Council in Ottawa, Canada.

Although during this period mean monthly solar flux values vary widely, the form of the curve is easily discernible. Both the months of July 1959 and November 1960 indicate the occurrence of exceedingly large flares. In July 1959 there were three exceptionally large flares, and in November 1960 there were two very large flares. By comparison, the February 1956 flare appears to be only one of three moderately large flares. However, the energy spectrum for this flare is much harder or flatter than any other large flare. As a result, this February 1956 flare has more particles with energies exceeding 100 Mev than any other flare on record.

The design model flare is shown in Figure 3. This model was constructed by assuming an envelope which exceeded the flux-energy spectra of all but thirteen flares recorded. Thirteen were chosen for several reasons. First, the probability of occurrence of this type of flare is not extremely steep over relatively long mission lengths. Second, shielding for this flare spectrum will probably prove reasonable for most missions. Third, the high energy spectrum tends to be reasonably hard, thus providing the conservatism necessary in specifying a solar flare model. Figure 4 is a graph of the probability of occurrence of a flare equal to or greater than this flux energy spectrum during an extramagnetospheric mission lasting n days.

III. MISSION CONSIDERATIONS

When should the solar flare be considered in mission planning? Although vehicles in low earth orbits which have inclinations less than about 55 degrees will probably never have to consider the solar flare as a direct radiation hazard, there are effects caused by the solar flare which will be of concern to even low earth orbiting vehicles. These effects include the enhancement and extension of the Van Allen radiation zones.

Lunar missions must certainly consider solar flare radiation. The lunar surface is not protected by an extensive atmosphere which could absorb the incoming particles nor is it protected by an appreciable magnetic field which could deflect incoming particles. It is probable that the lunar surface will be subjected to about the same atmosphere environment as that found in interplanetary space. It is possible that some measurable atmosphere exists, but this atmosphere would be extremely tenuous. The same statement may be made about the magnetic field on the moon.

The moon itself would offer some shielding at a given site depending on the sun-moon-site angle and the angle subtended by the lunar surface itself.

Since interplanetary missions will be subjected to the direct radiation of the solar flare, ways must be found to reduce the radiation dose as much as possible. It has been suggested that a small but heavily shielded area be included where personnel could remain during the occurrence of large solar flares. This might also serve as a sleeping area for these astronauts. Another possibility is that interplanetary missions traveling at distances greater than 1 astronomical unit from the sun might encounter a less severe flare environment, because of dispersion and increased loss of energy of the particles themselves. For instance, since it is fairly certain that the solar constant varies as $1/R^2$ due to dispersion, unless the particles are controlled decisively by the solar magnetic field, it is to be expected that solar flares will exhibit this same relationship.

It was mentioned earlier that vehicles in low earth orbit and at low inclinations would not be subjected to the direct solar flare environment. Vehicles in polar or near polar orbits will, however, spend some time outside the protection of the magnetic field. Near the magnetic poles, the lines of force are approaching perpendicular to the earth's surface; thus, the $\bar{V} \times \vec{B}$ term in the force equation approaches zero and the particles are allowed to flow in uninhibited by the magnetic field. For this reason, manned vehicles in polar orbit should have either a well defined abort capability or sufficient shielding to reduce the dose to acceptable limits. The acceptable dose criteria here should also be more strict since termination is possible for this type of mission.

The final type of mission which will require consideration of the solar flare as a radiation hazard is the high altitude earth orbital mission. The geomagnetic field boundary is determined by the energy of the solar wind being balanced by the magnetic field energy. When a solar flare occurs, the solar wind energy is enhanced and the geomagnetic field boundary then is deflated. Another way of looking at the problem is to consider the rigidity of the solar flare particles. Rigidity, P, is given by

$$P = \frac{pc}{ze} ,$$

where

p = particles momentum,

c = speed of light,

e = charge on an electron, and

z = the atomic number of the particles.

The distance a particle can penetrate into the magnetic field is directly proportional to the rigidity of the particles. The cutoff rigidity, P_c, for particles is a function of the magnetic field itself.

$$P_c = 14{,}900 \cos^4\lambda \text{ in million volts,}$$

where λ is the geomagnetic latitude.

$$P_c = 14{,}900\ (R/L)^2,$$

where R is the geocentric radial distance to the dipole field coordinate, L. Thus, for instance, a satellite at synchronous orbit on the sunward side of the earth would be exposed to almost all of the higher energy solar flare particles.

IV. PROBABILITY OF FLARE OCCURRENCE

For planning missions and for vehicle design, it is well to know the probability of occurrence of a particular type of solar flare. Figures 5 and 6 provide this information for various single flare particle fluxes. The probability of occurrence, p, of at least one flare with a flux equal to or exceeding N is given in these two figures. There is no relation between the probabilities and a particular flare spectrum, but notice that Figure 5 is calculated for a flux of particles with energies equal to or exceeding 30 Mev, whereas, Figure 6 is calculated for a flux of particles with energies equal to or exceeding 100 Mev. From these graphs, one may obtain reasonable figures for various mission lengths versus probabilities of occurrence.

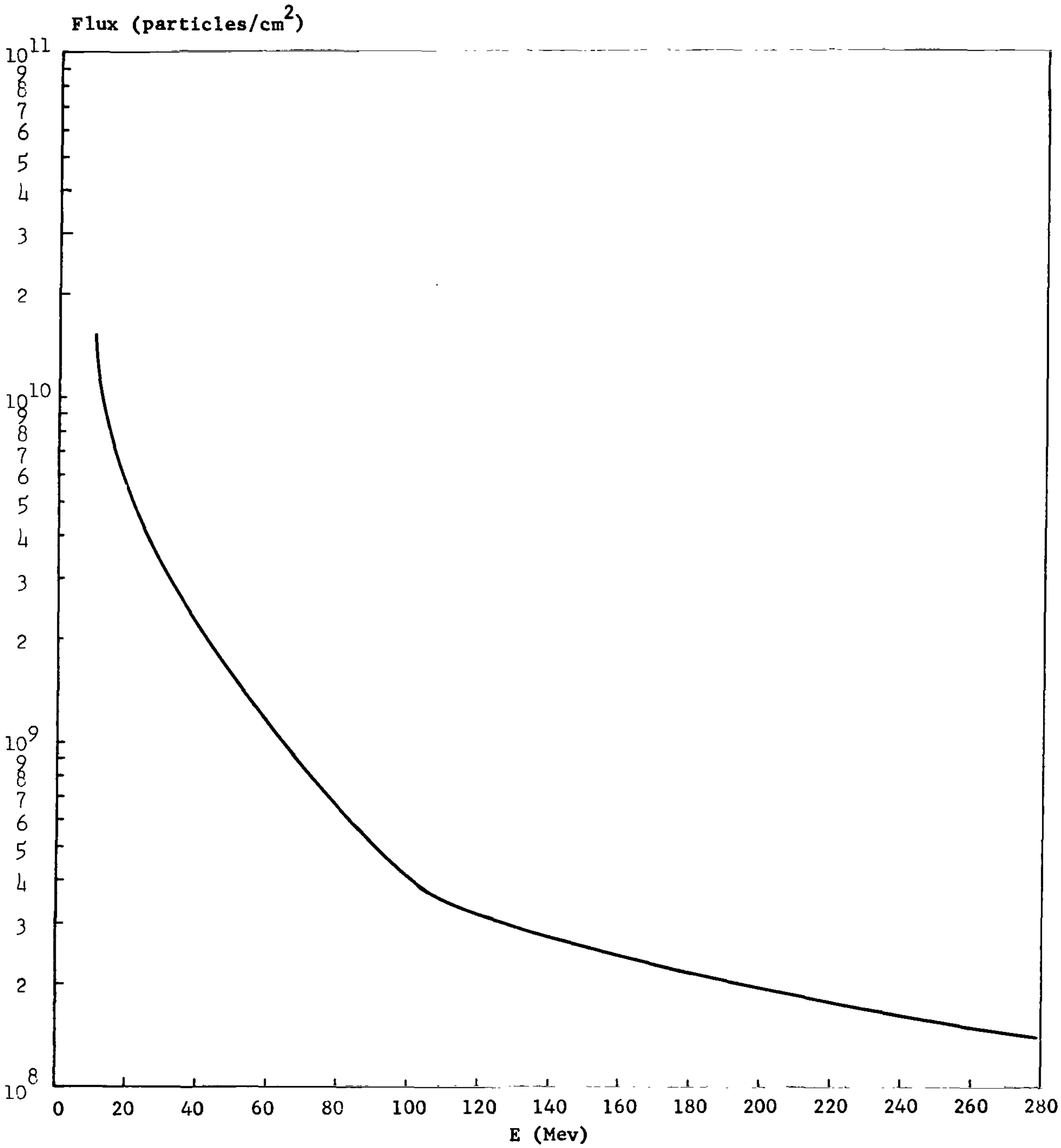

Figure 1. Extreme Flare Model

$N(>E) \cong 4.26 \times 10^{11} E^{-1.45}$

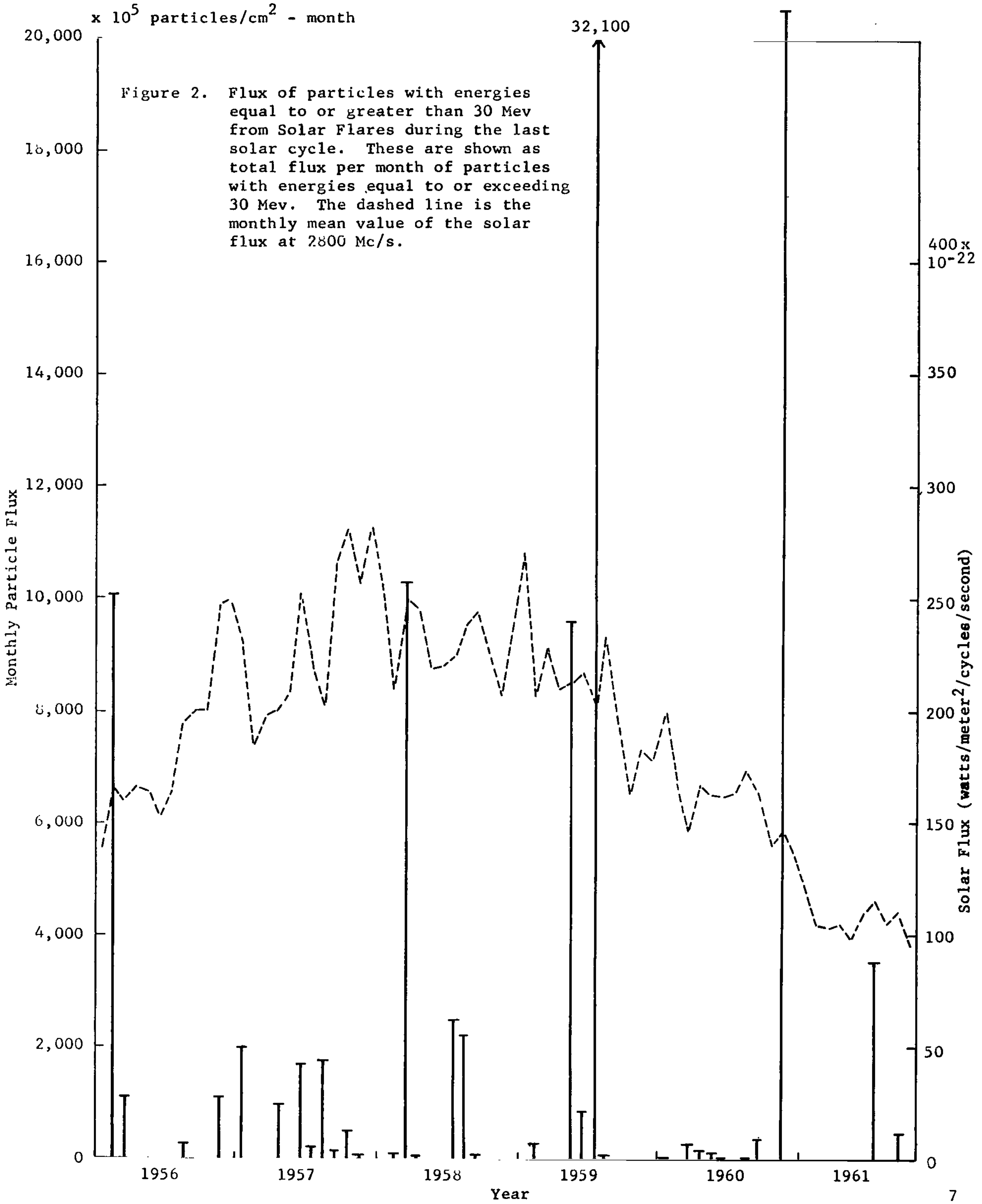

Figure 2. Flux of particles with energies equal to or greater than 30 Mev from Solar Flares during the last solar cycle. These are shown as total flux per month of particles with energies equal to or exceeding 30 Mev. The dashed line is the monthly mean value of the solar flux at 2800 Mc/s.

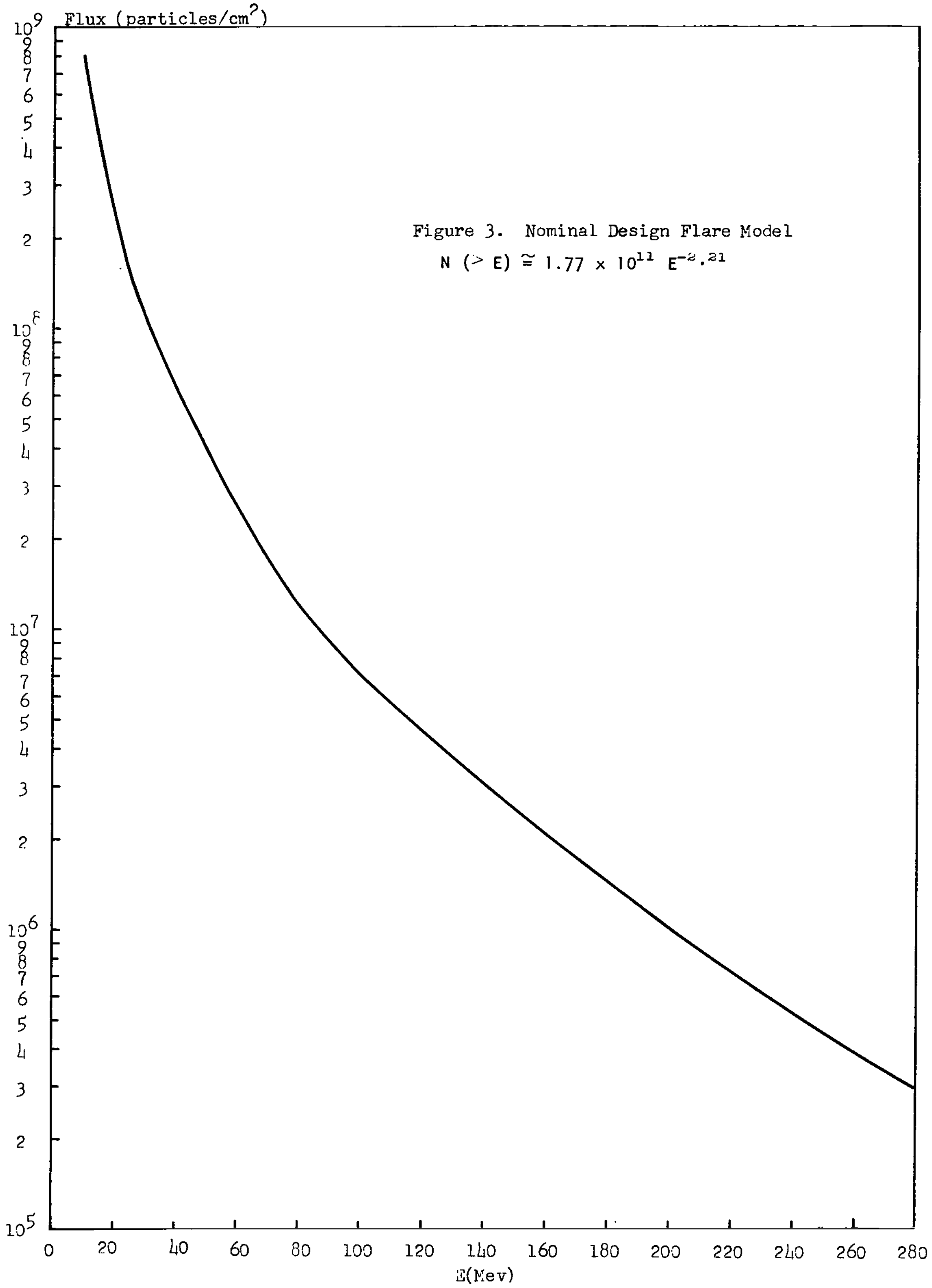

Figure 3. Nominal Design Flare Model

$N(>E) \cong 1.77 \times 10^{11}\ E^{-2.21}$

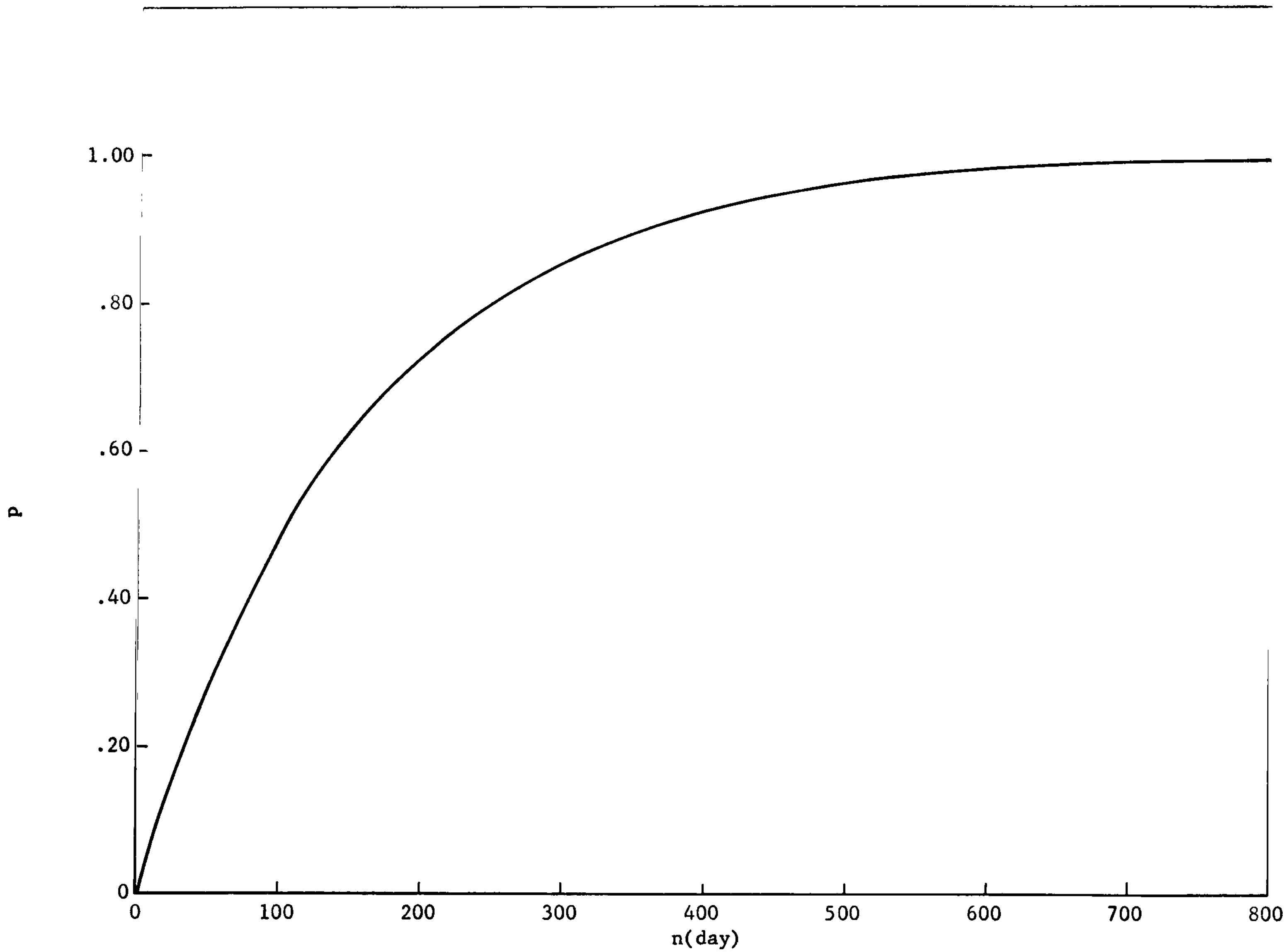

Figure 4. **Probability of occurrence of a flare during a mission lasting n days whose flux in any energy internal equals to or exceeds the model design flare.**

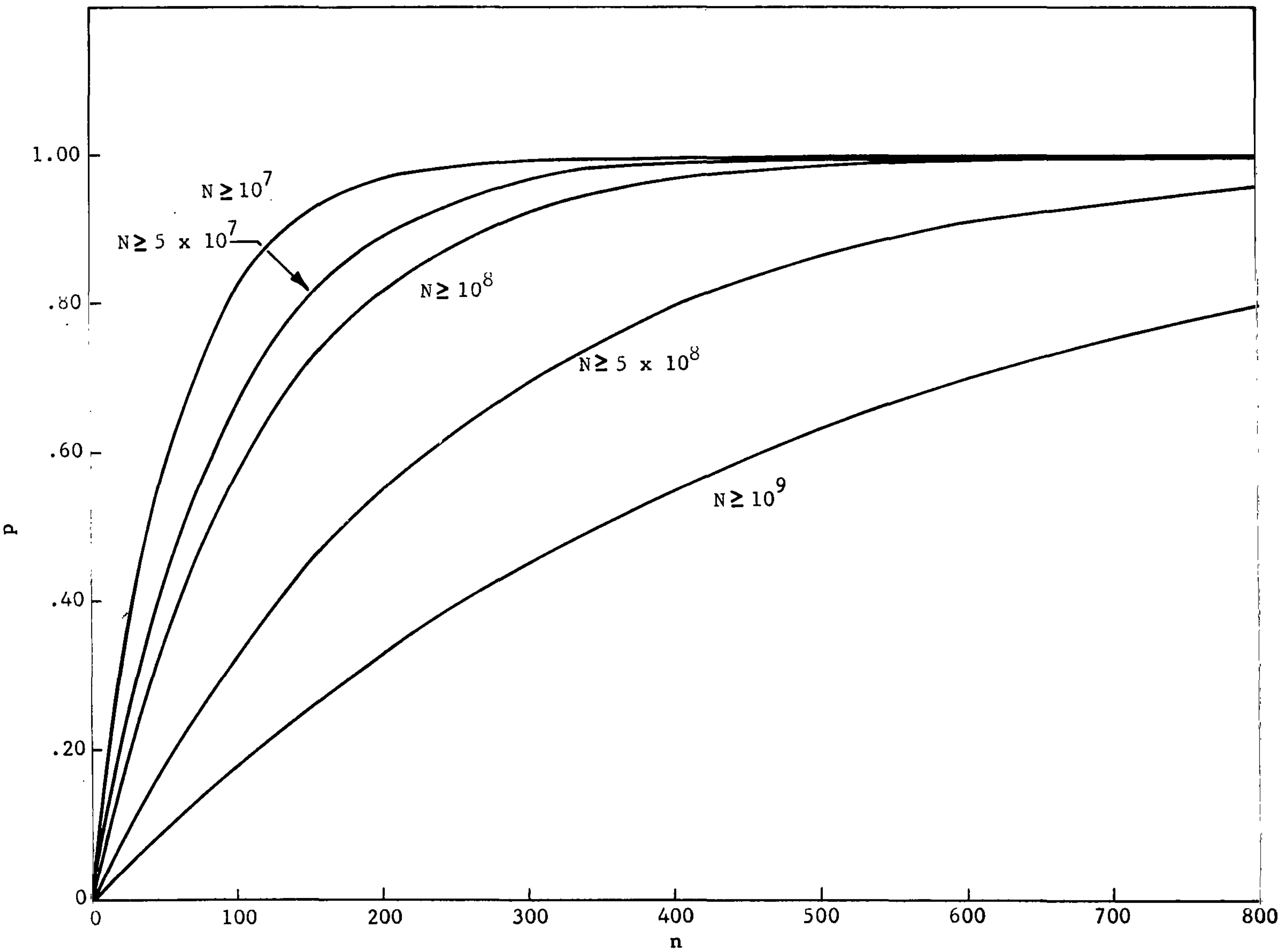

Figure 5. Probability p, in a mission lasting n days, of the occurrence of one or more solar flares with flux greater than or equal to N with energies greater than or equal to 30 Mev.

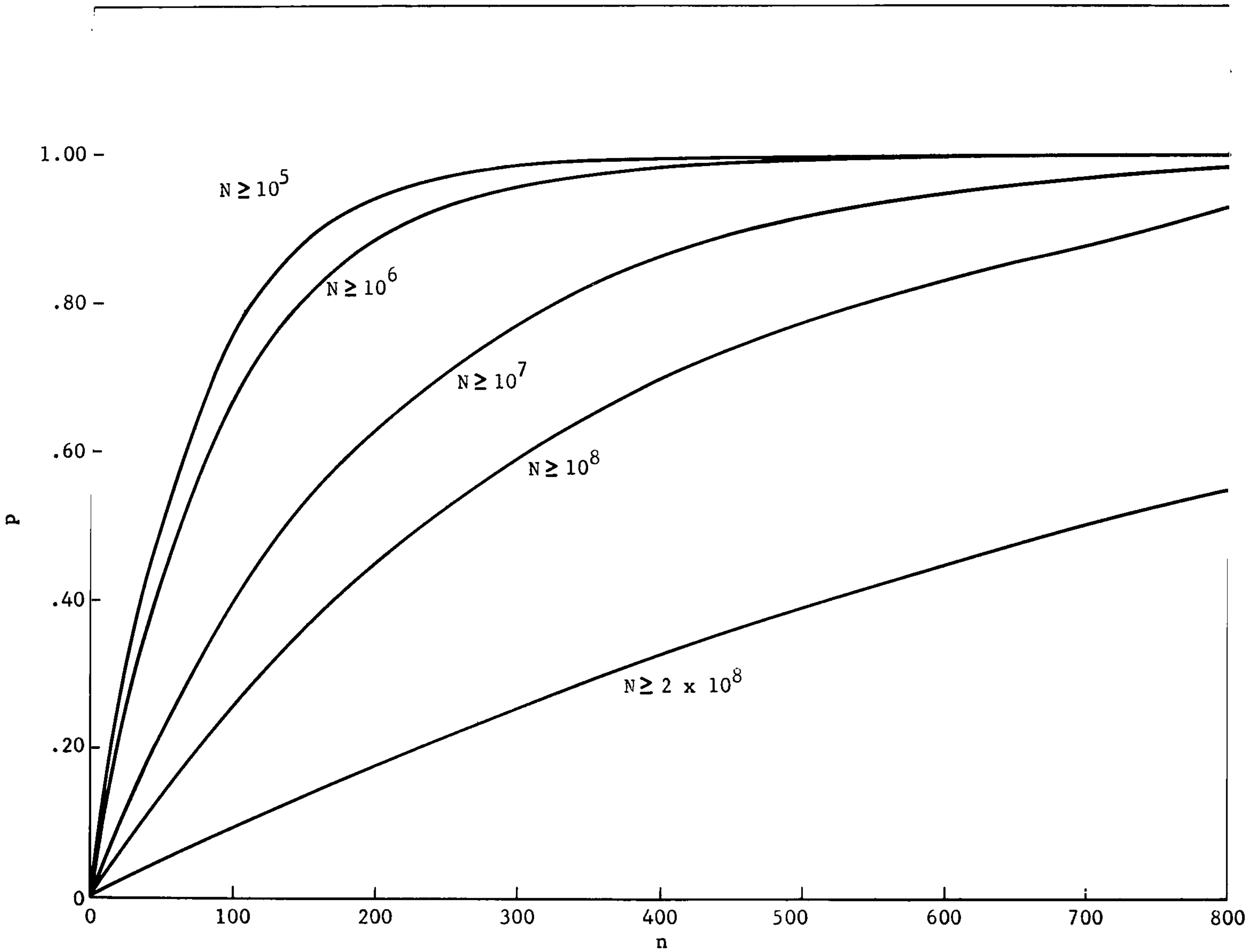

Figure 6. Probability p, in a mission lasting n days, of the occurrence of one or more flares with flux equal to or greater than N with energies equal to or greater than 100 Mev.

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The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

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