SOLAR COSMIC RAY HAZARD TO INTERPLANETARY AND EARTH-ORBITAL SPACE TRAVEL*

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Abstract

This paper describes a statistical treatment of the radiation hazard to astronauts due to solar cosmic ray protons. While several similar studies have been conducted in the past, objections to the use of this approach to determining shielding requirements have been raised due to the limited number of solar proton events for which data are available. More recent data are incorporated into the present analysis, including events from 1956 to 1969, in order to improve the accuracy of the predicted mission fluence and dose. The effects of the finite data sample are discussed. Also, an attempt is made to present a unified and consistent view of the solar cosmic ray proton hazard and to justify the application of a statistical approach for mission planning.

Mission fluence and dose versus shield thickness data are presented for mission lengths up to 3 years during periods of maximum and minimum solar activity; these correspond to various levels of confidence that the predicted hazard will not be exceeded.

Introduction

The occurrence of solar cosmic rays (SCR) has been recognized for almost 30 years, and accurate, detailed measurements are available from the last 14 years. **Charged particles, mostly protons, but including alpha particles and small numbers of heavier nuclei, are emitted by the sun and travel through interplanetary space. The resulting** hazard to manned space vehicles created by the solar cosmic rays is the subject of this paper.

Many aspects of the SCR radiation protection problem warrant continuing study. A comprehensive theoretical understanding of the origin of solar cosmic radiation has not been developed, nor is one to be expected shortly. Attempts to predict solar proton events over periods of several days have met with some success, but the long-range prediction of events is not yet possible.[1] Without adequate predictions of the occurrence and the intensity of events, prior evaluation of the radiation hazard to space travel cannot be made.

A model has been developed by Baker, et al.,[2] that predicts the total intensity of an event from spectral data measured early in the event. For earth-orbit missions, such a model would allow astronauts to abandon a mission and return to earth to avoid receiving the full dose from a dangerously large event. While the prediction is of too short a range to allow escape of the crew of a lunar or interplanetary mission, it does provide early warning of the occurrence of a large event. In this case, the mission operating plan could provide for locating the crew inside a small but relatively heavily shielded biowell to reduce the dose received, and possibly provide for premature termination of the mission to escape anv additional dose from subsequent events.

Aside from the problems of evaluating the radiation source, the mission criteria for the hazard caused by the SCR environment require further refinement and more definiteness; at present, both the acceptable and incurred risks are ill-defined. The concept of allowable doses to astronauts should be considered in a much more general sense than has been common in the past. As described by Kelton,[3] the level of risk acceptable for an astronaut due to radiation exposure should be assumed to be at least as great as that accepted by persons pursuing normal occupations. Also, the dose criteria should be expressed statistically, with corresponding levels of confidence that the chosen risk to the well being of the astronauts and to the performance of the space mission will not be exceeded. This approach to specifying allowable doses is consistent with the present statistical treatment of the SCR environment; it allows the total problem of SCR hazards to be handled in a self-consistent manner and in a manner consistent with conventional mission reliability considerations.

Because long-term predictions of SCR events cannot be made, an alternative approach to space vehicle shielding design must be used. Several studies have been conducted that statistically treat the SCR events observed during the maximum portion of the 19th solar cycle, 1956 to 1961, to predict the SCR fluences expected to be encountered in the future.[4-12] In spite of the fact that a statistical approach is the only objective way to predict events that cannot be predicted from a detailed knowledge of basic causal mechanisms, the application of the results of such studies has not been universally accepted. The major objections against using these statistical results arise from the limited sample of data available on past events. It should be remembered, however; that while some aspects of SCR events for which sufficient knowledge is not now available may become known during cycles 20, 21, and subsequent cycles; the important proton event parameters (i. e., fluence distribution, frequency of occurrence, and energy spectrum) will not be determined with significantly better statistical accuracy than is now available. Thus, the long-term SCR hazard predictions for the high confidence levels appropriate for mission planning cannot be expected to improve much until data from perhaps the next 50 or 100 years have been recorded. Clearly, a rational and consistent

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approach to the evaluation of the SCR proton hazard to space travel is needed, not only before manned interplanetary systems have been designed and operated, but also before we can reasonably expect to actually observe the somewhat extreme SCR environments we must be prepared to encounter during long missions.

One primary purpose of this report is to evaluate the statistical approach to estimating the SCR radiation hazard, using presently available data. Previous studies will be discussed, with more recent event data in mind. A second objective is to present mission-integrated fluence and dose results corresponding to various levels of confidence that the design criteria will not be exceeded on missions of up to 3 years duration.

The results of previous statistical treatments can be classified into two groups, according to the maximum possible event fluence assumed: either (1) infinite, or (2) the largest event previously observed. Most of these studies have used a statistical sampling technique to determine the distribution of mission fluences or doses. If the predictions include only event fluence values from observed events, such as those of Webber, [4] the mission fluence probability decreases rapidly to zero for fluences larger than that of the largest event. This phenomenon is unrealistic, however, since no evidence exists that no events can occur larger than any yet observed, the period of observation having been approximately 15 years.

A more reasonable approach to accounting for as yet unobserved events is to extrapolate the observed probability distribution of event fluence to include larger events with small, but nonzero probability. The accuracy of this approach depends upon the strength of the observed distribution correlation. Such an extension of the observed event data was introduced by Modisette, et al., [5] using a normal distribution in the logarithm of fluence (log-normal). That work and the study of Synder [10] produce consistent predictions, although Modisette treats the distribution of fluences and Synder treats doses. The present calculations, involving the numerical integration of compound probabilities, will be shown to lead to predicted doses about a factor of 2 higher than either of those studies, mainly due to differences in the event fluence distributions used.

Data from 84 SCR events were used in this work, 74 of which occurred during periods of maximum solar activity. Except for predictable distortions at the extremes of the sample distribution, which are inherent in any finite size sample, the event fluences follow a log-normal distribution extremely well. Because of the strength of this correlation (i.e., every data point is consistent with the log-normal function) over more than three decades of event fluence, and because of the lack of contrary evidence, the log-normal distribution must reasonably be assumed to hold for future events, as well as for those previously observed.

The frequency of occurrence of SCR events is less certain than the fluence distribution. From the data of cycle 19 alone, an average of nine events per year were observed at solar maximum. However, cycle 19 was perhaps an unusually active cycle and, as estimated by Synder, [10] assuming cycle 19 to be the most active of 20 cycles, the average frequency might be closer to five per year. This value is consistent with the data now available for cycle 20. However, the significant point is that this variation in event frequency has only a slight effect on the predicted doses for the range of confidence levels of interest, since, as Synder points out, the doses corresponding to high confidence levels are dominated by the contribution of a single large event, rather than of numerous small events. The assumption that cycle 19 is the largest of 20 cycles results in a reduction of only 40 percent in predicted does for 1-year missions during cycle 19 to those during an average cycle of five events per year, for a confidence level of 99 percent.

A calculation of the SCR proton energy spectrum, by sampling from available event data, was included in this work. As one would expect for long missions, the calculated spectrum is very close to the average spectrum of all the events used. This results from the fact that a long mission involves a significant portion of the total time during which event data have been measured. The spectrum calculated for short missions at high confidence levels departs from the average at high energies. This deviation from an average spectrum results from the dominant contribution of the largest high energy SCR event observed. Hence, the amount of deviation depends on the particular event data sample presently available. For this reason, and because of the fact that the deviation in spectrum occurs only at energies too high to significantly affect the dose behind practical shield thicknesses, the average spectrum is assumed applicable, independent of mission length and confidence level. This generalization greatly simplifies the results and their application without introducing significant error.

The data discussed thus far; the SCR proton event fluence, frequency, and energy spectrum for events during solar maximum; have been determined well enough to make reliable predictions of mission fluence and dose for missions during solar maximum. The data for solar minimum events are much less certain, since only 10 events have been observed. Because the data sample is too limited to establish a general distribution, and because there is no evidence to the contrary, the variance of the event fluence distribution and the average energy spectrum were assumed equal to the values determined for solar maximum. Thus, only the mean event fluence and the event frequency were determined from the solar minimum data. Because the predicted mission hazard is sensitive to the event fluence distribution, the solar minimum results must be considered as rough estimates. The estimated hazard during solar minimum is less than that for solar maximum by factors of 10 or greater.

Alpha particles have sometimes been observed in appreciable numbers during SCR events. However, alpha particle data are available for only a few events. Webber [7] reports proton-to-alpha particle fluence ratios varying from 1 to 100. The energy spectrum of the alpha particles appears to follow an exponential rigidity spectrum with nearly the same rigidity parameter value as that of the protons. The data shown by Webber indicate that the large proton-to-alpha ratios are correlated with very large rigidity values. These data imply an average ratio between 1 and 2. The alpha particle data do not appear to warrant a thorough analysis of that component of the radiation hazard at this time. It would appear that the best way to handle the SCR alpha hazard is to use the solar proton rigidity spectra and fluence data described here, and to relate it to the SCR alpha environment as an estimated proton-to-alpha ratio.

Solar Cosmic Ray Data

Proton fluences measured during SCR events during the 19th and 20th solar cycles were collected; the extensive tabulation of data presented by Weddell and Haffner [9] forms the major part of the data used. Only those values reported as measured data were used, the estimated numbers being disregarded. This source provided information on events between 23 February 1956 and 23 October 1962. Data on several other events were located in the tables published by Webber [8] and by Modisette, et al.,[5] which referenced the work of Bailey.[13] The fluence values for the event of 12 November 1960 were taken from the detailed study of that event done by Masley and Goedeke.[14] Data for 20th cycle events from 1966 to 1969 were taken from the work of Masley, Goedeke, and Satterblom.[15, 16]

The event integral fluence data are given in Figure 1 for particles with energy greater than 10, 30, and 100 Mev. The integral energy spectrum for each event was assumed to follow an exponential in particle rigidity. This assumption of a rigidity parameter p_o is based on correlations originally done by Freier and Webber.[17]

The integral energy spectrum is given by

$$\phi\,(>E) = A\,\text{Exp}\left[\frac{-p\,(E)}{p_o}\right] \qquad (1)$$

where the rigidity p(E) of a particle with charge ze, kinetic energy E, and rest mass energy $m_o c^2$, is the momentum per unit charge and is given by

$$p(E) = \frac{1}{ze}\sqrt{E\,(E + 2\,m_o c^2)} \qquad (2)$$

The constants A and p_o are also given in Figure 1. They were determined separately for energies above and below 30 Mev because p_o was found to be significantly less between 10 and 30 Mev than between 30 and 100 Mev.

The events occurring during the period of minimum solar activity, September 1961 through July 1966, are noted with asterisks in Figure 1. A marked reduction can be seen in both the size and frequency of events as opposed to the events during solar maximum.

The distribution of event fluence, integral above 30 Mev, was constructed for the events given in Figure 1 by arranging the events in the order of decreasing fluence. For several events for which the fluence above 30 Mev was not available, it was estimated using Equation (1) and the fluence above 10 Mev. For this calculation, a rigidity of 75 Mv was assumed. Events for which no data are available at either of these energies were disregarded. The resulting fluence probability distribution is presented in Figure 2 for solar maximum events.

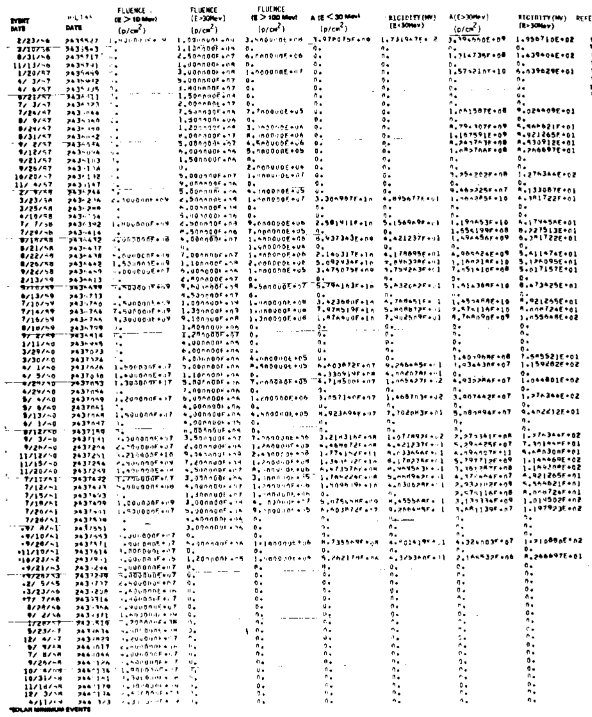

Figure 1. Basic Solar Cosmic Ray Proton Event Data

The distribution of solar maximum event fluences includes data from 72 events. Because of the finite number of data points, the distribution is necessarily distorted near both ends, including perhaps the last 5 or 10 percent of the events. The distortions manifested in the figures are typical of finite samples and do not indicate a deviation from the true distribution which has evidently reached equilibrium in Figure 2 between 10^7 and 10^9 protons/cm^2. In addition, the data for the smallest events are less reliable than for large events because it is more likely that small events occurred unrecorded before sufficiently sensitive instrumentation was available to detect them. Figure 2 exhibits these features, distorting the distribution from a log-normal, which it follows very well over two full decades in fluence, in the middle portion. Thus, there would appear to be little question about the degree of correlation when these factors are considered. The straight line shown in the figure is a log-normal distribution fit to the data points in the middle portion, between 6×10^6 and 1×10^9 protons/cm^2. For this distribution, the mean fluence is 2.7×10^7 protons/cm^2 and the variance is 1.32 in the logarithm, which corresponds to a standard deviation of a factor of 14 in fluence.

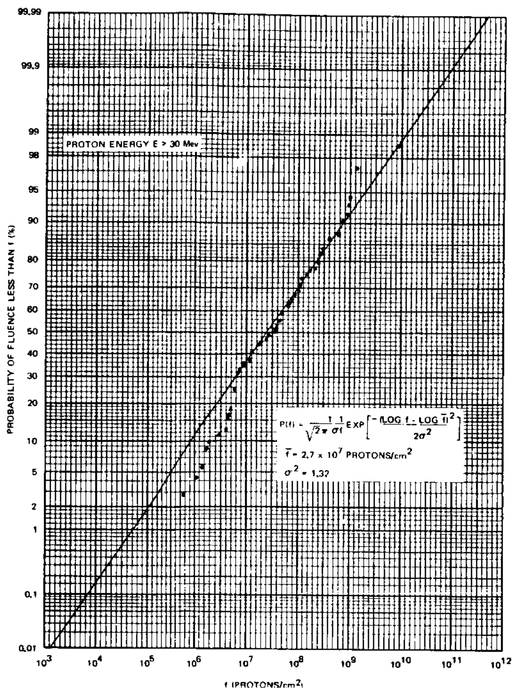

Figure 2. Distribution of Solar Cosmic Ray Proton Event Fluence During Solar Maximum

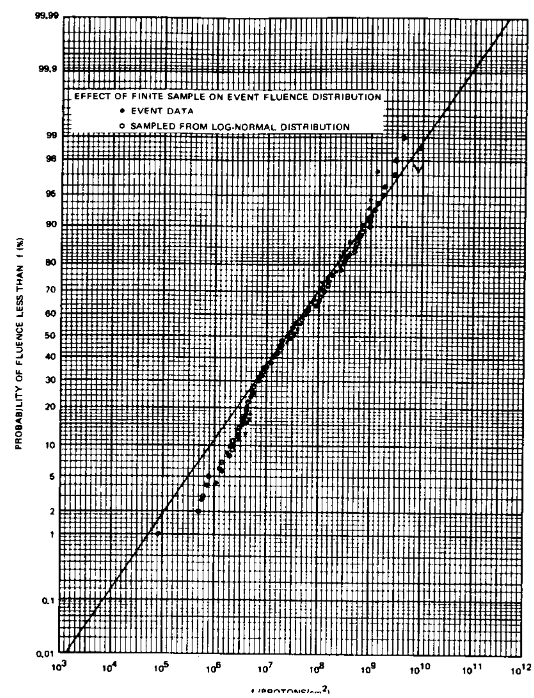

Figure 3. Effect of Finite Sample on Event Fluence Distribution

This variance is slightly larger than one would obtain if all the data points shown in Figure 2 were equally weighted in determining the log-normal fit, thus including the finite sample distortion in the fit. However, the difference in variances between the two possible log-normal distributions would lead to only a factor of 2 difference in fluence at a probability of 0.999. The detailed study by Masley and Goedeke of the 12 November 1960 event tends to support the larger variance, which was used in this study. This choice of variance is the source of the factor of two disagreement between the present results and those of Modisette, et al., and Snyder, as previously mentioned.

Figure 3 presents a clear demonstration of the distortions caused by the finite number of points in the event data sample. A similar number of fluence values were sampled randomly from this equilibrium log-normal distribution. These values, arranged by magnitude, are shown by the open circles plotted in Figure 3, which also shows the event data and the log-normal distribution previously shown in Figure 2. Clearly, the distortions in the sampled points occur at precisely the same fluence values and have the same magnitude as the distortions present in the SCR event data. Thus, the distortions in the observed event fluence distribution, which at first sight seem to indicate a failure of the log-normal distribution or to lead to large uncertainties in the proper value of the variance, are actually in agreement with the chosen equilibrium distribution.

Data from only 10 events are available to construct the distribution for solar minimum. For this reason, the derived parameters of the log-normal distribution are quite uncertain; therefore, since there is no known reason to assume otherwise, the variance is assumed equal to that for solar maximum. The mean fluence for solar minimum is 7.8 x 10^6 protons/cm^2.

The distribution of rigidity values, p_o, for the events of Figure 1 were constructed both for particles with energy below 30 Mev and for particles with energy above 30 Mev. The low-energy points were calculated from events for which integral fluences were available at 10 Mev and 30 Mev, and the high-energy points were calculated from data at 30 Mev and 100 Mev. Since spectral data were available for only two events, which occurred during solar minimum, no separate distribution could be constructed, and that of solar maximum is assumed to apply. The average values of the rigidity parameter p_o are 72.4 Mv below 30 Mev and 91.1 at higher energies.

Modisette, et al., found a uniform frequency of SCR event occurrence to correlate with the data of the maximum portion of cycle 19. The correlation of the data with smoothed sun-spot number, which might be a more intuitive frequency variation, was not better than with a constant frequency. Because of this result, the lack of additional data that would modify these conclusions, and the fact that Snyder showed that the results are insensitive to the event frequency, a step function was used to describe the event frequency. The average frequency value for each half of the solar cycle was determined by the total number of events and total time span during which they were observed. The value for solar maximum is 0.0247 per day and for solar minimum, 0.00548 per day.

In summary, whatever fine structure that may exist in the periodicity of SCR proton events, the scatter of data does not allow a statistically significant resolution of them to be made. The only statistically significant frequency variation is the contrast between the average frequencies during solar maximum and solar minimum. To provide practical and reliable information in the context of mission planning, any predictable higher frequency modes must be defined rather precisely, although nothing is gained for them to be defined much more precisely than the gross parameters describing SCR activity. At this point the precision of the gross parameters (i.e., average frequency, fluence distribution, and spectral distribution) are limiting the accuracy of the predictions.

Method of Calculation

Many of the statistical studies of SCR proton dose done previously use some form of sampling from available event data. Because the calculations are restricted to tallying only from events actually observed since 1956, they are based on a small enough body of data that the upper limit in event size has almost certainly not been observed. The use of a log-normal distribution to extrapolate the mission fluence distribution removes this restriction to fluence values already observed and removes the distortions at the ends of the distribution, which are also caused by the finite sample. However, for missions longer than about 6 months, this procedure becomes uncertain because each mission history then includes a significant portion of the total number of data available, and the distorted ends of the distribution consequently tend to converge toward the center. For example, in the limit of an 8-year mission, there is only one mission history possible and therefore no distribution of fluence results. For this reason, an alternative technique, the compound probability method, was developed to calculate mission fluence distributions from the generalized log-normal event fluence distribution directly. Because relatively long missions are of primary interest, the energy spectrum to be encountered can be assumed equal to the average spectrum from all events, with a rigidity of 72.4 Mv at energies below 30 Mev and 91.1 Mv above that energy. The analysis is then performed for fluences with greater energy than 30 Mev. Data corresponding to any other energy may be readily calculated using the average spectrum.

Contributions to the mission fluence are separated according to the number of events occurring, m. The mission fluence probability distribution is given by a sum over these components.

$$P(<f,\ T) = \sum_{m=o}^{\infty} P_m(<f)\ P(m,\ T) \qquad (3)$$

The probability of encountering m events during a mission of duration T is given by the Poisson distribution as

$$P(m,\ T) = \frac{e^{-\omega T}(\omega T)^m}{m!} \qquad (4)$$

where ω is the average event frequency.

The probability that the total fluence summed over m events is less than f, $P_m(<f)$, is calculated from the distribution $P_1(<f)$, which is given in Figure 2. The probability density function g for a single event is obtained by differentiation.

$$g_1(f) = \frac{d}{df} P_1(<f) \qquad (5)$$

The density for the sum of two events is given by the product of the probabilities of single event fluence values, s and f-s, summed over all possible values of the intermediate variable s.

$$g_{2(f)} = \int_o^f ds\ g_1(s)\ g_1(f-s) \qquad (6)$$

The calculations are performed by doubling the orders of convolution

$$g_{2m(f)} = \int_o^f ds\ g_m(s)\ g_m(f-s) \qquad (7)$$

The integral distributions are then calculated from the density functions.

$$P_m(<f) = \int_o^f ds\ g_m(s) \qquad (8)$$

These distributions are interpolated to obtain probability values for all intermediate values of m at fixed fluence levels. The mission fluence distributions are then evaluated using Equation (3), obtaining for each fluence value the confidence level, or probability that the fluence will not be exceeded.

Fluence and Dose Probability Distributions

The results of the fluence probability distribution calculations for various mission lengths are presented in Figures 4 and 5, for solar maximum and solar minimum. These data represent the total probability, including missions during which no events occur. These distributions are recommended for use in determining the SCR proton fluence for mission planning.

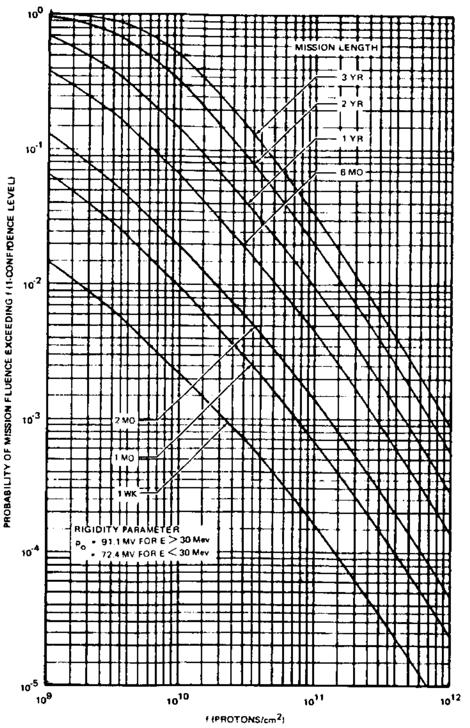

Figure 4. Fluence Distributions for Missions During Solar Maximum

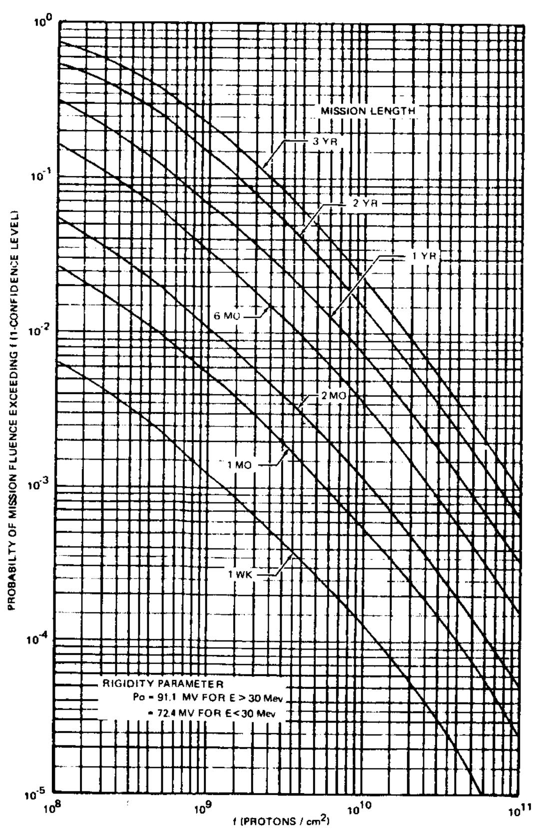

Figure 5. Fluence Distributions for Missions During Solar Minimum

The variation of these distributions with the average event frequency can be evaluated easily, since the product ωT, the average number of events during a mission, is the actual parameter used in the Poisson distribution, Equation (4). Figure 6 shows the fluence distribution for solar maximum as a function of ωT, for several levels of confidence. As discussed previously, the average event frequency has been estimated to be nine events per year (which was used in generating all data presented in this paper), or perhaps as low as five events per year. From the data given in Figure 6, this range of frequencies results in changes in the predicted fluence of less than a factor of 2 for mission durations greater than 6 months.

The dose corresponding to the fluence probability distributions was calculated as a function of aluminum shield thickness using the CHARGE code.[18] The dose curves presented are point doses to a water target at the center of a spherical aluminum shell of varying thickness. Because the proton energy spectrum has been assumed to have a shape independent of mission length, confidence level, and solar activity; all dose results can be scaled from a single calculation.

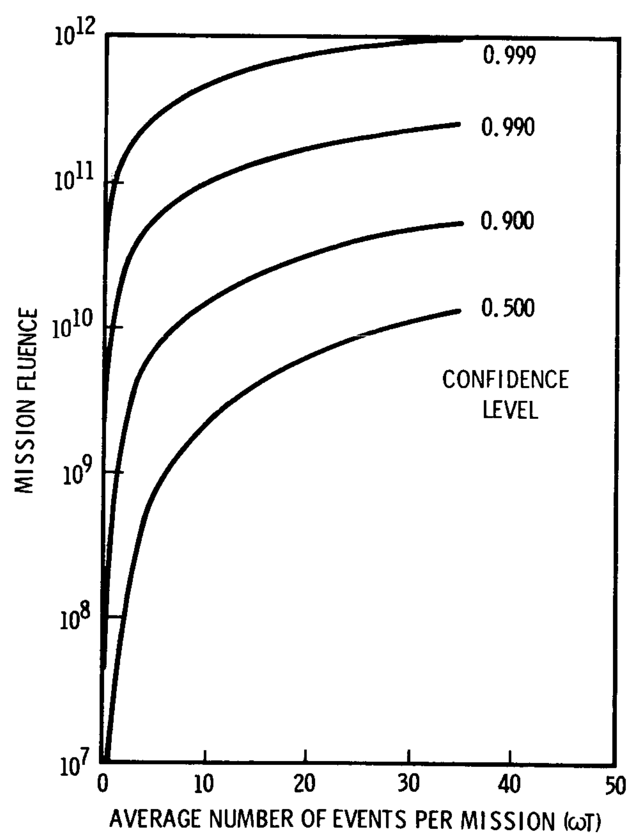

Figure 6. Combined Effect of Event Frequency and Mission Length on Mission Fluence

Figures 7 and 8 present the dose for 1-year missions as a function of shield thickness for several confidence levels, during solar maximum and solar minimum. Comparison of these two figures shows that the ratio of solar maximum dose to solar minimum dose varies with confidence level, from 10 at 0.999 to 70 at 0.500.

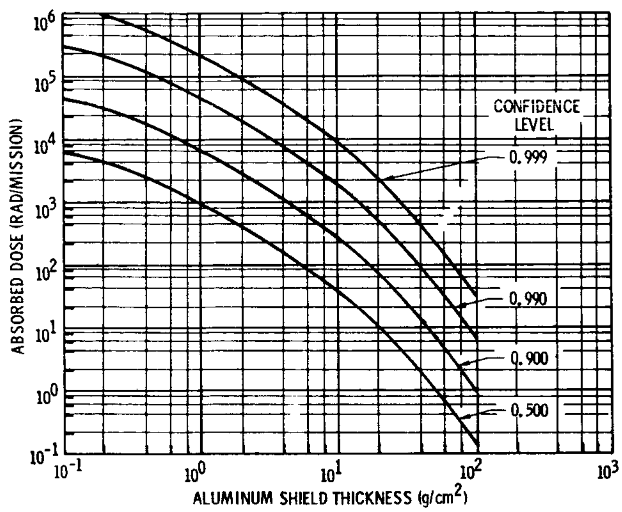

Figure 7. Solar Cosmic Ray Proton Dose for 1-Year Missions During Solar Maximum

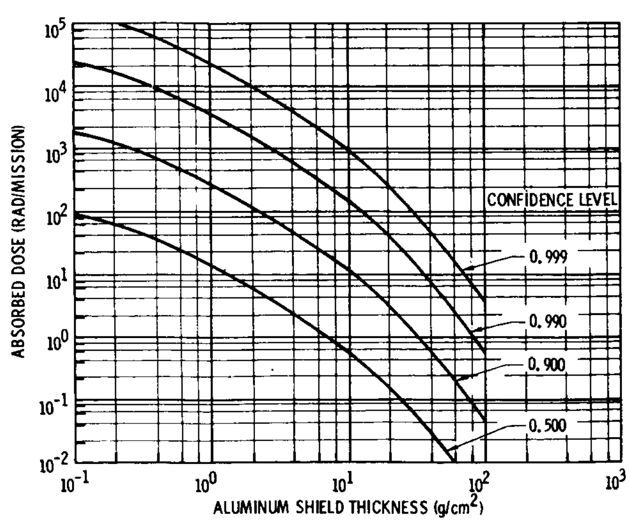

Figure 8. Solar Cosmic Ray Proton Dose for 1-Year Missions During Solar Minimum

The variations of dose with mission duration are presented in Figures 9 and 10 for solar maximum and solar minimum, respectively. These figures give the factor by which the 1-year dose must be multiplied to obtain the dose for any mission length up to 3 years. One set of curves describes each half of the solar cycle because of the single energy spectrum used. Over the range of mission durations shown, the difference between Figures 9 and 10 is only 30 percent or less. Therefore, because of the greater reliability of the solar maximum results, they can also be used for solar minimum, as a good approximation.

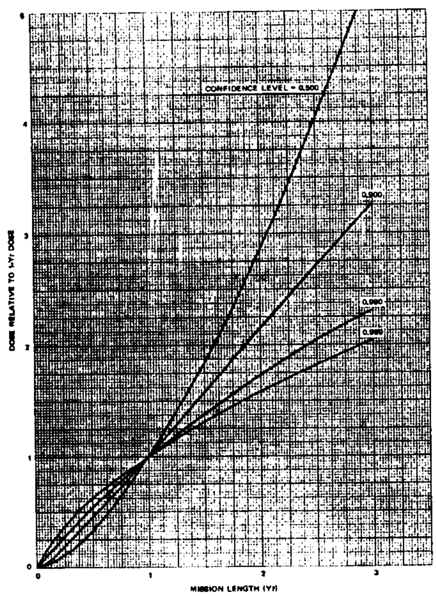

Figure 9. Variation of Solar Cosmic Ray Proton Dose with Mission Length for Solar Minimum Missions

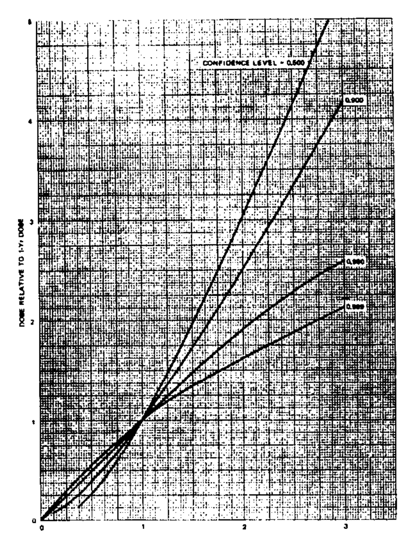

Figure 10. Variation of Solar Cosmic Ray Proton Dose with Mission Length for Solar Minimum Missions

The dose equivalent was also calculated as a function of aluminum shield thickness. The proton quality factors were taken from ICRP recommendations (19) and the dose conversion factors for the maximum neutron dose in a 30-cm slab of tissue were taken from Irving, et al.(20) and Zerby and Kinney.(21) Figure 11 presents the average quality factor, for the average SCR proton spectrum, as a function of shield thickness. The dose equivalent for various confidence levels for missions of varying length can be evaluated by using the data given in Figure 11, together with absorbed dose data presented previously.

Figure 12 presents the ratio of absorbed dose due to alpha particles to that due to protons, assuming a proton-to-alpha particle fluence ratio of unity. The alpha particle integral energy spectrum was assumed to follow an exponential in rigidity, with the same rigidity parameter as the proton spectrum, as reported by Webber.(4) The SCR alpha particle absorbed dose may be estimated using these data, the proton absorbed dose data previously presented, and an assumed proton-to-alpha particle fluence ratio. An estimate for the particle ratio was made using the distribution given by Hill, et al., (6). Values between 1 and 2 were obtained, which indicate that the alpha particle dose is negligible in comparison with the proton dose for shield thicknesses greater than 5 g/cm^2.

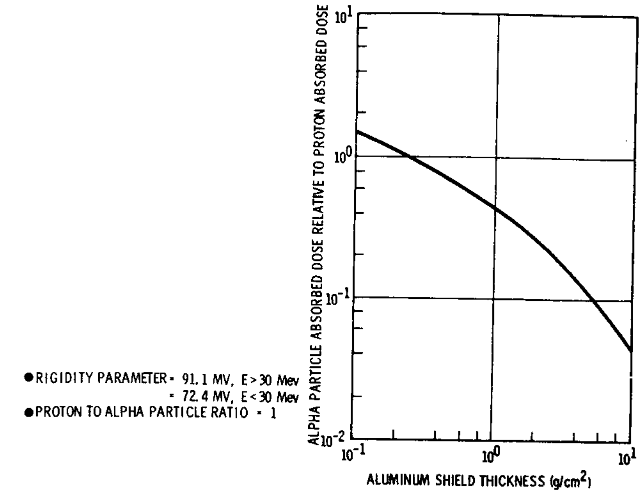

Figure 12. Ratio of Alpha Particle Dose to Proton Dose for Particle Ratio of Unity

Figure 13 shows a comparison of the results of the mission fluence distribution calculations with the results of previous studies. The present results give fluences larger than those of Modisette, et al., (5) by a factor of 2 over most of the range of probability. The results of Webber(4) are also in reasonable agreement with the present work for low confidence level values. However, at the high confidence level values of interest, the agreement is quite poor. The Webber study did not include an extrapolation to account for exceptionally large SCR events, and hence his results show a rapid increase of confidence level to unity, with a maximum event fluence of about 4 x 10^9 protons/cm^2.

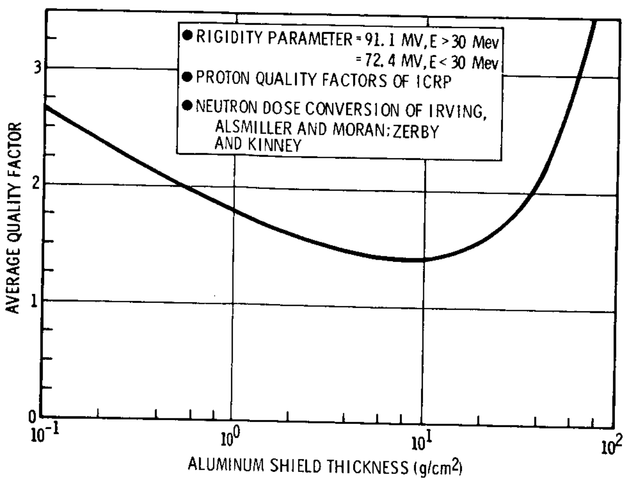

Figure 11. Average Quality Factor as a Function of Aluminum Shield Thickness

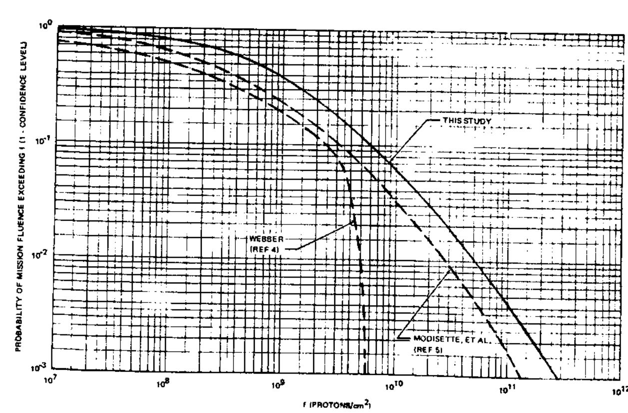

Figure 13. Comparison of Fluence Distributions for 6-Month Missions During Solar Maximum

Figure 14 shows a comparison of doses with results of Snyder[10] and Burrell, et al.,[12] for 1-year solar maximum missions and a confidence level of 0.900. The Snyder data were originally presented as dose equivalent, and were modified for purposes of this comparison using the quality factor data given in Figure 11. The Snyder dose is about a factor of 3 lower, as are the results of Burrell, et al., for shield thicknesses between 5 and 50 g/cm^2.

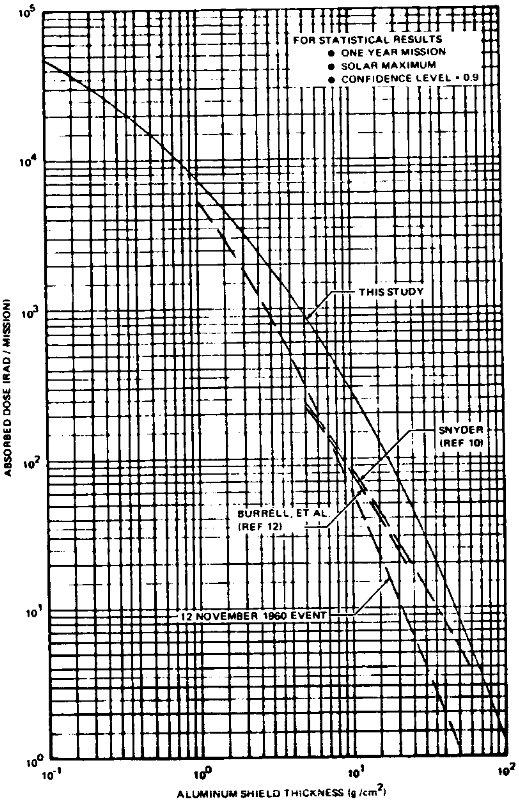

Figure 14. Comparison of Model Solar Cosmic Ray Event Doses

Figure 14 also shows the dose calculated from the largest SCR event available, that of 12 November 1960, as defined by Masley and Goedeke.[14] Dose criteria are sometimes applied using either the assumption that one large event such as this will occur per mission on short missions, or the assumption that such an event will occur with a given frequency (e. g., one per year). The figure demonstrates that such an approach has an associated confidence level of less than 0.900 for 1-year missions, and small shield thicknesses, which would increase for 30-day missions to almost 0.990. For 3-year missions, the confidence would decrease to almost 0.500. Because of the difference between the energy spectrum of the 12 November 1960 event and the average energy spectrum, these estimates are sensitive to shield thickness and the confidence would be much less at thicknesses greater than about 5 g/cm^2. Therefore, it would appear that using the statistical approach to evaluate shield requirements represents a considerable improvement over the use of a single large event, because of this large range of confidence levels associated with the single event. In fact, the degree of validity of the nonstatistical approach for a given set of conditions and assumptions, can be evaluated only by comparing it to the results of a consistent statistical analysis. There is no other known objective basis for comparison; thus, it would seem that there is little merit in this or similar nonstatistical approaches, at our present level of knowledge.

All data presented so far have been for free space (i. e., away from the influence of the geomagnetic field and mass of the earth) at one astronomical unit (AU) from the sun. In order to facilitate use of the results presented above for application to earth-orbit missions, a calculation was performed of the dose received in 200-nautical-mile circular orbits.

The orbit-averaged proton fluence was calculated from the free-space fluence presented above, for several values of orbit inclination, using the OGRE code.[22] These calculations include the reduction in fluence due to earth shadowing and the cutoff based on a detailed model of the geomagnetic field, including both the field during solar quiet, and the perturbation caused by a large SCR event. The cutoff data used are based on observations made during the 12 November 1960 event.[23] Including the geomagnetic field perturbation leads to significantly less overall reduction of the free-space proton fluence at moderate to high orbit inclinations than one corresponding to the unperturbed field during solar quiescence. Therefore the resulting dose values can be considered typical of situations involving large events (i. e., high confidence levels), but is conservative for smaller events.

The ratio of absorbed dose in orbit to that in free space is presented in Figure 15 for the solar quiet field and Figure 16 for the perturbed field, as a function of shield thickness. Because the geomagnetic field and earth shadowing effects vary slowly with altitude, these data are applicable for orbits of up to several hundred nautical miles. Since a single energy spectrum is assumed, independent of mission duration and confidence level, only a single calculation of orbit-averaged fluence is necessary for each orbit inclination.

Conclusions

Solar cosmic ray proton fluence and dose have been determined statistically from the event data available from cycles 19 and 20 (1956 to 1969). For a mission of specified duration occuring in free space near one astronomical unit from the sun, the fluences corresponding to various confidence levels have been presented. Also, corresponding dose data have been presented that allow estimating free-space and low earth-orbit shielding requirements needed to meet a specified mission dose criterion. These data are recommended as a consistent and rational approach to mission planning from the standpoint of solar cosmic ray hazards.

While the number of SCR events for which data are available is not large, enough data are available so that many conclusions about the SCR environments for future space missions can be drawn with reasonable confidence. The event fluence probability distribution and event frequency during solar maximum are determined reasonably well; their statistical quality is not likely to change for some time because of the weight of additional observations necessary to effect a significant change. The variance of the fluence distribution could be taken as slightly smaller than that used, if the data from all events were given equal weight, rather than ignoring the characteristic finite-sample tails of the observed distribution. However, this would only reduce the mission fluence by a factor of 2 for a confidence level of 0.999, which the comparisons show would lead to results nearly equal to those of Modisette, et al., and Snyder. The relatively large intensity from Masley and Goedeke analysis of the 12 November 1960 event tends to support the larger variance used.

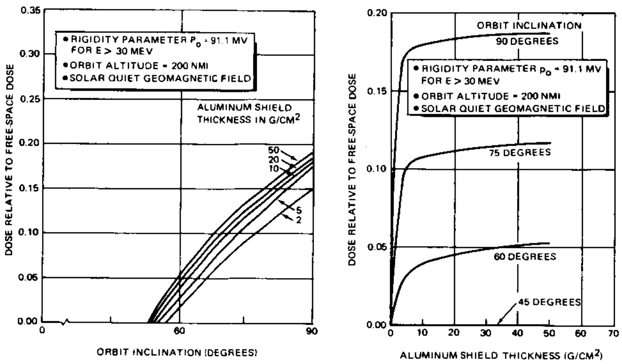

Figure 15. Variation of Solar Cosmic Ray Proton Dose with Aluminum Shield Thickness and Circular Inclination for Solar Quiet

The event frequency of 0.0247 per day may be larger than typical future values, since cycle 19 was apparently an unusually active cycle. Just how unusual it is cannot be established at this time; the correlation of SCR intensity and sunspot number is too weak to provide reliable information. (19) The data from cycle 20 alone give 0.0137 per day, or an average of five events per year. This value was arrived at by Snyder, using a binominal distribution and assuming cycle 19 to be the most active of 20 cycles (as would be indicated by average sunspot number alone). However, it has been shown in this study that the results are not sensitive to a change in frequency, because the mission fluence and dose are dominated by the contribution of a single large event. For example, the effect of the reduction in event frequency from 0.0247 to 0.0137 per day produces only about a 40 percent reduction in dose at a confidence level of 0.999 for 1-year missions.

While the fluence distribution and event frequency are quite uncertain for solar minimum, similar statistical analyses were performed as for solar maximum. However, because of the relative uncertainty in the solar minimum results, and their similarity to those for solar maximum, a justifiable approximation for mission planning is to use the solar maximum data for solar minimum with the fluences and doses reduced by a factor of 10. Similarly, the SCR alpha particle environment can be approximated by assuming Figures 4 and 5 to apply for a proton-to-alpha ratio of 1 to 2, and assuming the rigidity spectrum to be the same for alpha particles as for protons. The alpha particle dose will be negligible compared to proton dose, for shield thicknesses greater than 5 g/cm^2.

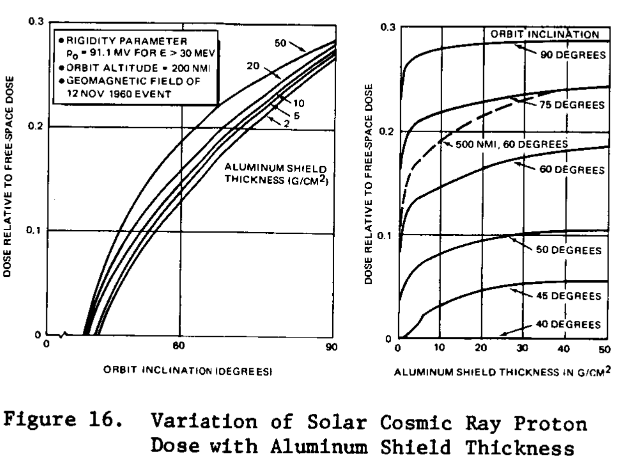

Figure 16. Variation of Solar Cosmic Ray Proton Dose with Aluminum Shield Thickness and Circular Orbit Inclination for Solar Active

The statistical approach to the evaluation of the solar cosmic ray hazard represents a significant improvement over the use of a single model event. As demonstrated in this study, the assumption that one large event such as the one observed on 12 November 1960 will occur on a 1-year mission during solar maximum has an associated confidence level of less than 0.9 for small shield thicknesses, decreasing to almost 0.5 at 10 to 20 g/cm^2 of aluminum. For longer missions, the confidence level decreases further. There is, in fact, little reason to use any nonstatiscal approach, since the only means available to evaluate the validity of such treatments for a given set of mission conditions is to compare it with the results of a consistent statistical analysis.

References

1. "Ionospheric Forecasting," NATO Advisory Group for Aerospace Research and Development, AGARD CP 49, January 1970.

2. Baker, M. B., R. E. Santina and A. J. Masley, "Modeling of Solar Cosmic Ray Events Based on Recent Observations", AIAA Journal, 7, 2105, November 1969.

3. Kelton, A. A., "Radiation Guidelines for Manned Space Vehicles—A Review with Recommendations," Douglas Aircraft Company, SM-47749, July 1965.

4. Webber, W. R., "An Evaluation of the Radiation Hazard Due to Solar Particle Events," The Boeing Company, D2-90469, December 1963.

5. Modisette, J. L., T. M. Vinson, and A. C. Hardy, "Model Solar Proton Environments for Manned Spacecraft Design," Manned Spacecraft Center, NASA TN D-2746, April 1965.

6. Hill, C. W., W. B. Ritchie, and K. M. Simpson, Jr., "Data Compilation and Evaluation of Space Shielding Problems: Radiation Hazards in Space," Lockheed Nuclear Products, ER 7777, Volume III, April 1966.

7. Roberts, W. T., "Probabilities of Solar Flare Occurrence," NASA TM X-53463, May 1966.

8. Webber, W. R., "An Evaluation of Solar-Cosmic-Ray Events During Solar Minimum," The Boeing Company, D2-84274-1, June 1966.

9. Weddell, J. B., and J. W. Haffner, "Statistical Evaluation of Proton Radiation from Solar Flares," North American Aviation, SID 66-421, July 1966.

10. Snyder, J. W., "Radiation Hazard to Man from Solar Proton Events", Journal of Spacecraft and Rockets, 4, 826, June 1967.

11. Lahti, G. P., I. M. Karp, and B. M. Rosenbaum, "McFLARE, A Monte Carlo Code to Simulate Solar Flare Events and Estimate Probable Doses Encountered on Interplanetary Missions," Lewis Research Center, NASA TN D-4311, February 1968.

12. Burrell, M. O., J. J. Wright, and J. W. Watts, "An Analysis of Energetic Space Radiation and Dose Rates," George C. Marshall Space Flight Center, NASA TN D-4404, February 1968.

13. Bailey, D. K., "The Detection and Study of Solar Cosmic Rays by Radio Techniques", J. Phys. Soc. Japan, 17, Supp. AI, Part I, 106, 1962.

14. Masley, A. J. and A. D. Goedeke, "A Complete Dose Analysis of the November 12, 1960 Solar Cosmic Ray Event", Life Science and Research, North Holland Publishing Company, 1963.

15. Masley, A. J. and A. D. Goedeke, "1966-67 Increase in Solar Cosmic Ray Activity", Can. Journal of Phys., 46, 1968.

16. Masley, A. J. and P. R. Satterblom, "A Discussion of Solar Cosmic Ray Activity Near Sunspot Minimum", Proceedings of the 11th International Conference on Cosmic Rays, Budapest, Hungary; McDonnell Douglas Astronautics Company, MDAC Paper WD-1070, November 1969.

17. Frier, P. S. and W. R. Webber, J. Geophys. Res., 68, 1605, 1963.

18. Yucker, W. R. and J. R. Lilley, "CHARGE Code for Space Radiation Shielding Analysis," McDonnell Douglas Astronautics Company, DAC-62231, April 1969.

19. "Permissible Dose from External Sources of Ionizing Radiation", NBS Handbook 59, 1954.

20. Irving, D. C., R. G. Alsmiller, Jr., and H. S. Moran, "Tissue Current-to-Dose Conversion Factors for Neutrons with Energies from 0.5 to 60 Mev," ORNL-4032, 1967.

21. Zerby, C. D. and W. E. Kinney, "Calculated Tissue Current-to-Dose Conversion Factors for Nucleons Below 400 Mev", Nuclear Instruments and Methods, 36, 125, 1965.

22. Baker, M. B., "Geomagnetically Trapped Radiation," Douglas Aircraft Company, SM-47635, October 1964.

23. Baker, M. B., "Geomagnetically Trapped Radiation", AIAA Journal, 3, 9, 1965.