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RADIATION EXPOSURE IN SOLAR PARTICLE BEAMS BEHIND VERY LOW SHIELDING

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BEHIND VERY LOW SHIELDING

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SUMMARY PAGE

THE PROBLEM

The fact that some solar particle beams contain sizeable fractions of alpha particles directs attention to systems of very low shielding because of the lower penetrating power of alpha particles as compared to protons. Though direct measurements of alpha fluxes at very low penetrating powers are missing, estimates of fluxes and spectral configuration can be based on observations of polar cap absorption (PCA) events. Weir and Brown have proposed such an alpha spectrum for very low energies which fits PCA observations well. It seems of interest to evaluate this spectrum in terms of absorbed tissue doses and dose equivalents for very low shielding.

FINDINGS

In near surface regions of a tissue slab behind 0.1 g/cm^2 shielding, the alpha component is the predominant contributor to exposure. At 0.37 g/cm^2 depth, alpha and proton doses become equal and at greater depths, protons take over an increasingly larger share of the total dose. In the tissue surface, the high LET dose fraction accounts, for alpha particles, for 65 per cent of the total rad dose, and for protons, for only 7 per cent. Correspondingly, the local QF and RBE factors for the alpha component are substantially larger than 1.0 in the tissue surface, showing initially a steep and then more gradual drop with depth. These high QF and RBE factors distinguish the alpha component basically from protons and make LET sensors a necessary prerequisite for dosimetric instrumentation if dose equivalents in solar particle beams are to be correctly assessed in systems of low shielding.

Comparative evaluation of the exposure behind a space suit, once taking the variation of shield thickness due to the structural patterns of the various layers of materials fully into consideration and once basing the calculations on the mean thickness, leads, for the flare spectrum investigated, to a difference of only 2 per cent. The mean thickness, therefore, appears an entirely acceptable equivalent in assessing radiation protection of a space suit.

INTRODUCTION

The natural shielding power of vehicle frame, equipment, and space suit provides substantial protection from flare produced particles for the astronaut in space. In cases where he leaves the vehicle, be it in orbit or on the lunar surface, only one of the three components, the space suit, remains as sole protection. Unfortunately, it is the component with by far the smallest shielding equivalent. On the other hand, it is obvious that the probability of an astronaut being caught unexpectedly outside the vehicle by a solar particle beam is quite small. Nevertheless, it seems of interest to attempt a quantitative assessment of the radiation exposure under these extreme conditions. At present, data on the flux fractions of very low penetrating power in solar particle beams are scarce. In fact, what little information there is carries such a large margin of uncertainty that it seems hardly worthwhile to attempt an appraisal of the corresponding radiation dosages. However, it should be realized that two parameters of the radiation exposure in question are of interest: the absorbed dose in rads and the dose equivalents determined by the Quality Factor (QF) or Relative Biological Effectiveness (RBE) according to the Linear Energy Transfer (LET) of the local particle flux. Whereas the first parameter, the rad dose, depends on absolute flux values, QF and RBE depend only on the slope of the range spectrum irrespective of the absolute flux values involved. Estimates of spectral slope for the range intervals in question can be carried out with greater confidence than estimates of absolute fluxes as such.

The problem under consideration appears in a new light since the recent discovery that the alpha component in solar particle beams can reach, in the rigidity spectrum, a flux ratio of one to one to the proton component. Since alpha particles, on a rigidity basis, have a much smaller penetrating power than protons, it is seen that the exposure hazard from flare produced alpha particles is specifically a problem for systems of low and very low shielding and that dose assessments which consider the proton flux alone could seriously underrate the exposure hazard for such systems.

The following discourse is an attempt to investigate what conclusions can be drawn from present knowledge with regard to the exposure from solar particle beams for very low shielding with special consideration of the contribution of the alpha component to the rad and rem doses involved.

FLUX VALUES OF SOLAR PROTONS AND ALPHA PARTICLES AT LOW ENERGIES

The combined shielding equivalent of a heat protection and full pressure suit can be as low as 0.1 g/cm^2 of organic material. This thickness corresponds to the range of an 8 Mev proton or a 33 Mev alpha particle. Flux values of solar particle beams for these low energies are usually not determined by direct measurements, but indirectly established from observations of ionospheric absorption in the polar region. Weir and

Brown, in a recent study (1), have shown that extrapolation of the exponential rigidity spectrum for solar protons and alpha particles as proposed by Freier and Webber (2) down to very low energies leads to alpha contributions to ionospheric absorption after large flares of up to 75 per cent and that this assumption fits the observations well. Admittedly, this agreement does not constitute conclusive proof of the validity of the exponential rigidity spectrum as the only correct model in the energy region in question inasmuch as other models could be conceived of which also would fit observation in a quantitative way. However, since the exponential rigidity spectrum at medium and high energies is based directly on flux measurements with emulsions and counters, it clearly deserves preference in the selection of a suitable spectral model for a tentative evaluation of the radiation exposure.

Quite generally, it is an interesting question whether the finding that alpha particles are a regular constituent of solar particle beams and might contribute substantially to ionospheric absorption in polar cap absorption events (PCA) would not seem to call for a revision of all energy or rigidity spectra for flare produced solar particles, which have been based on PCA observations rather than on direct measurements. In this respect, it should be noted that the consequences of a misinterpretation by attributing effects actually produced by alpha particles to protons are quite different for problems of ionospheric absorption on the one hand and for assessing absorbed doses in tissue on the other. For the former, the nature of the ionizing particles is actually of no interest since depth of penetration and QF and RBE factors are irrelevant parameters. For the latter, however, i. e. , for evaluating dose equivalents in tissue, the indicated magnitudes are of decisive importance. It seems questionable whether clues can be established which would allow separate identification of the alpha and proton flux from PCA measurements. At present, anyway, the only possible approach seems to be the indicated extrapolation of the exponential rigidity model.

In determining residual radiation doses as a function of shield thickness, it offers great computational advantages if the flux of the incident beam is expressed in terms of the differential range spectrum. Conversion of the integral rigidity spectrum into the differential range spectrum is a routine matter involving derivation of the integral energy and range spectrum and numerically differentiating the latter. The rigidity spectrum in question (Weir and Brown, l. c. , 1) is described by the formula: $J = J_o \exp(-P/P_o)$ with J_o = 3000 particles/(cm^2 sec sterad) and P_o = 200 Mv. When a rigidity flux ratio of one to one for the proton and alpha component (Freier and Webber, l. c. , 2) is assumed, the indicated conversion leads to the differential range spectra shown in Figure 1. The fact that identical rigidity spectra for protons and alpha particles lead to greatly different range spectra is due to the greatly different range/rigidity functions of the two particle types. The pertinent relationships have been described in more detail in a preceding report (3). The precipitous drop of the alpha to proton flux ratio from the minimum shield thickness of 0. 1 g/cm^2 toward greater depths is striking. At 0. 1 g/cm^2, the differential alpha flux is slightly larger than the proton flux. It drops to 50 per cent of the proton flux at 0. 6 g/cm^2, to 10 per cent at 4.7 g/cm^2, and to 1.0 per cent at 24 g/cm^2. These percentages demonstrate well that the exposure hazard from flare produced alpha particles is of significance only in systems of low shielding. For medium and high shield thickness, neglecting the alpha contribution to the exposure does not introduce a major error in dose assessments. This holds all the more inasmuch as the indicated steep drop of the alpha to proton flux ratio leads to a still steeper decrease of the corresponding ratio of local dose rates because the LET of alpha particles is substantially higher than that of protons.

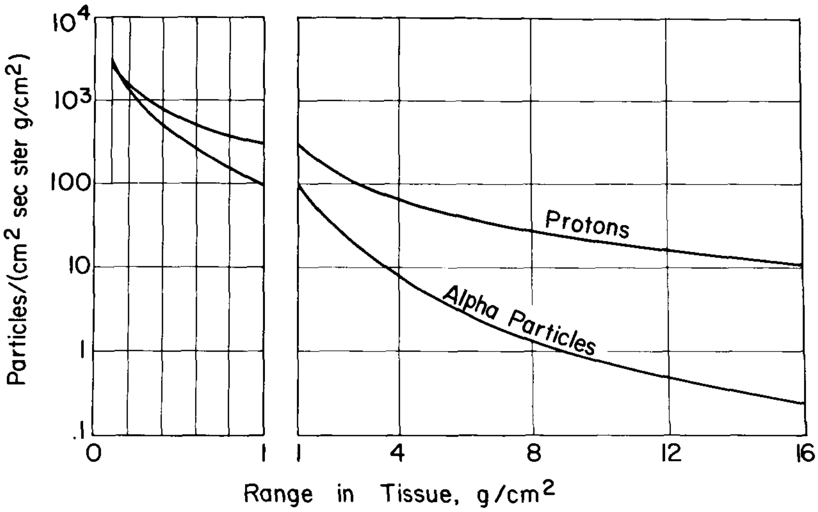

Figure 1

Differential Range Spectra of the Proton and Alpha Component of a Solar Particle Beam

Before the depth dose distribution for the spectrum under investigation is analyzed, a word concerning the geometry of exposure seems in order. As far as is known today, solar particle beams in free space show essentially omnidirectional incidence. Computational analysis of depth dose distributions, therefore, should be based on a geometrical model in which a simplified human torso or tissue phantom is surrounded by a specified shield system and is exposed to the radiation arriving from all directions. However, in the case of very low shielding and for particle beams with a range spectrum of steep negative slope, the local dose in near-surface regions is, for a target of the size of the human body, determined exclusively by particles arriving within the 2 pi solid angle about the local vertical on the body surface as zenith direction. Even within this solid angle the fractional beams arriving from directions near the zenith account by far for the largest part of the exposure in the near-surface layers of the target. In other words, for the purpose of analyzing the initial part of the depth dose distribution for a human target behind low shielding it is entirely sufficient to assume a plane tissue slab behind a plane shield and 2 pi incidence. To be sure, local doses at greater depths within an actual target would depend also on particles arriving from opposite directions. To these doses, however, low range particles from any direction do not contribute at all because of their short ranges. These doses at greater depths are determined exclusively by sections of higher ranges or energies in the incident spectrum for which flux data are more reliable. The pertinent depth dose distributions have been analyzed in an earlier report (l. c., 3).

DEPTH DISTRIBUTION OF ABSORBED DOSES AND DOSE EQUIVALENTS

The analysis of the depth dose distribution for the indicated system of a tissue slab behind a plane shield exposed to particles of 2 pi incidence has been carried out in the following way. The 2 pi solid angle within which particles are arriving was broken down into 20 concentric ring-shaped solid angles of equal size (omega = 2 pi/ 20) around the vertical (zenith) of arrival. For a given depth in tissue, the representative mean distances to be travelled in shield and tissue were determined for each of the 20 solid subangles and the dose contributions for each angle were established by numerical integration of the truncated differential range spectra for each distance. Addition of the 20 contributions furnished the local dose at the given depth. As in the earlier analysis (l. c., 3), the indicated operation was carried out separately for four different doses, namely, the total dose and the fractional high LET dose from the alpha and the proton components. The four resulting depth dose curves are shown in Figure 2. The fractional high LET dose, in these data, is defined as that part of the total dose which is produced at an LET of 25 kev/micron tissue or larger. This particular choice of the critical LET is essentially arbitrary. In a more cautious appraisal one might be inclined to select a lower value, such as 10 kev/micron tissue, which would lead to a larger fractional high LET dose. By reference to the LET/E relationships for protons and alpha particles, the fractional high LET doses in Figure 2 can easily be converted simply by multiplying by the ratio of kinetic energies at 10 and 25 kev/micron tissue.

The upper graph of Figure 2 demonstrates strikingly the much steeper drop of the alpha dose as compared to the proton dose in near-surface layers of the target. Immediately in the surface the former is twice as large as the latter; at 0. 4 g/cm^2 depth in tissue, the two doses become equal; and beyond 1 g/cm^2 depth, the alpha dose drops to less than half the value of the proton dose. The steep transition of the absolute dose rate of the alpha component as well as of its ratio to the proton component in the initial layers of the target illustrates the point made in the Introduction that exposure very sensitively depends on the spectral configuration of the incident beam and that this configuration, therefore, has to be defined very accurately for a quantitative assessment of the depth dose distribution. Admittedly, this accurate experimental determination of the spectrum of the incident beam has yet to be accomplished. However, as also was pointed out in the Introduction, the local QF and RBE in the target depend on the spectral slope only and not on absolute flux. The transition of QF and RBE in the near-surface regions of the target can thus be analyzed even if absolute flux values are not accurately known.

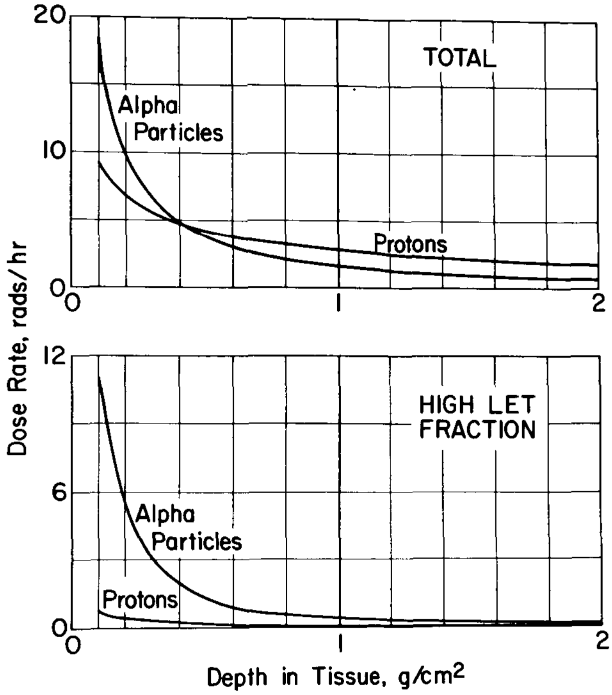

Figure 2

Depth Dose Rates in Semi-Infinite Tissue Slab for 2 Pi Incidence of Particle Fluxes Shown in Figure 1

High LET: $\geq$ 25 kev/micron tissue.

Besides comparing alpha to proton doses, it is also of interest to compare the fractional high LET dose to the total dose separately for the alpha and proton components. The pertinent curves are shown in Figure 3. For better description, percentage doses rather than absolute doses are shown. Special attention is directed to the greatly different ordinate scales of the upper (alpha particles) and lower (protons) graphs. Even for the rather high threshold LET of 25 kev/micron tissue, which actually underrates the high LET dose fraction, that fraction accounts for 65 per cent of the total dose of the alpha component in the target surface, yet for only 7 per cent of the proton component. Radiobiologically, this large difference distinguishes the alpha component basically from the proton component especially if one considers that it will be further magnified if absorbed doses are converted into QF- and RBE-dose equivalents.

As pointed out before, interest in the present context centers on QF and RBE factors rather than on the corresponding dose equivalents themselves. The latter ones will vary greatly for individual flare events, yet the QF and RBE factors and their

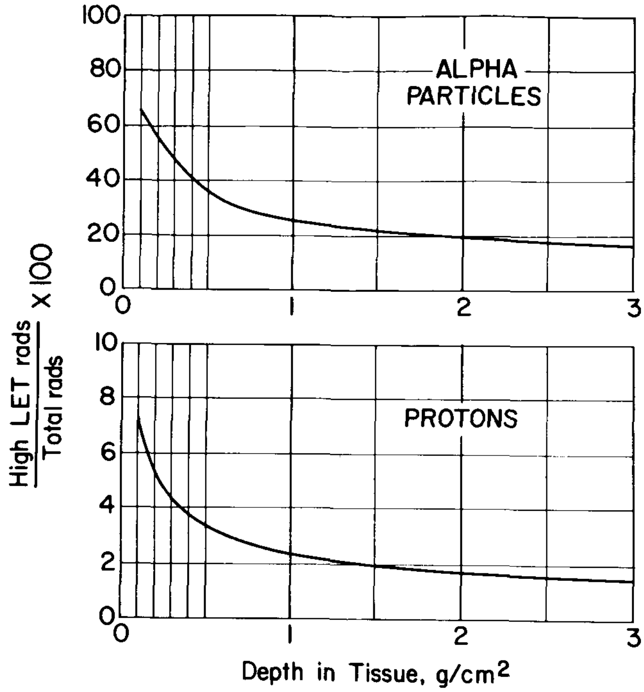

Figure 3

High LET Fractions of Lower Graph of Figure 2 Expressed as Percentages of Total Component Dose

depth distribution in the target do not depend on absolute flux values but on the basic configuration of the range spectrum of the incident beam. The results of the evaluation, therefore, are presented in Figure 4 in terms of the QF and RBE factors. It is seen that QF and RBE for the alpha component are substantially larger than 1.0 especially in near-surface regions of the target, dropping at first steeply and then more gradually as one proceeds to deeper regions. For protons, quite differently, QF and RBE show only a slight increase above 1.0 even in the target surface, approaching 1.0 slowly and gradually toward greater depths. It is interesting to point out that in the target surface behind 0.1 g/cm^2 shielding the alpha component accounts for 88.5 per cent of the total QF dose equivalent and for 82.5 per cent of the total RBE dose equivalent. The pertinent values to be read from the graphs of Figure 2 and 4 are compiled in Table I.

Table I

Absorbed Doses and Dose Equivalents Per Hour in Tissue Surface Behind 0. 1 g/cm^2 Shielding

	Alpha Component	Proton Component	Total
Absorbed dose, rads	17. 4	9. 1	26. 5
QF dose equivalent, rems	109. 3	14. 2	123. 5
RBE dose equivalent, rems	50. 2	10. 7	60. 9

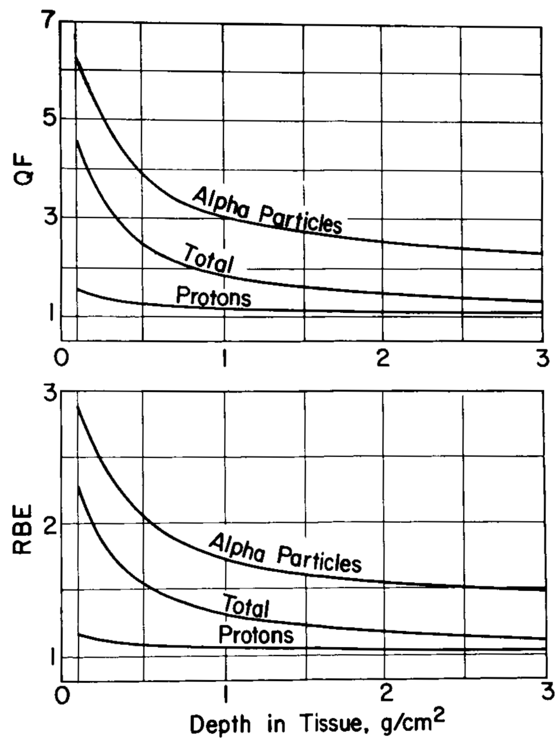

Figure 4

Quality Factor (QF) and Relative Biological Effectiveness (RBE) for Depth Dose Distributions of Figure 2

EFFECT OF SHIELD INHOMOGENEITY

In assessing the shielding equivalent of compound shield systems such as a space suit made up of various layers of different materials with each layer in itself again showing structural inhomogeneities, the question arises whether the shielding properties are adequately described by the mean thickness usually quoted in g/cm^2. It is obvious that for a material of the indicated kind the mean thickness, i. e., the average weight per unit area of, for instance, 0. 15 g/cm^2 does not necessarily mean that 0. 15 gram of material are evenly spread over 1 cm^2. For a complete description of the shielding properties, the shield thickness distribution rather than the mean shield thickness must be known. For a space suit in particular these relationships seem of special significance under conditions where the suit provides the only protection, i. e., when the astronaut leaves the ship in free space or on the lunar surface. It seems of interest to analyze the error involved if the exposure from a solar particle beam, for these conditions, is assessed for the mean thickness rather than for the thickness distribution.

For a system like a space suit, a simple and accurate way of determining the shield distribution would seem to be direct inspection of cross sections of the various layers and measurement of the local variations of thickness of the compound materials and their superpositions. Data of that kind do not seem to be available, at least not in a form amenable to establishing the thickness distribution. Dance, Edens, Farmer, and Johnson (4) determined the distribution in question for the pressure suit used for the Mercury missions by analyzing the attenuation of high energy protons. They found that the mean shielding equivalent of 0. 094 g/cm^2 is actually due to a distribution extending from a minimum of 0. 052 g/cm^2 to a maximum of 0. 136 g/cm^2. Since this distribution reaches well below the minimum of 0. 1 g/cm^2 for which the range spectrum used in the present study is determined, a fictitious distribution has been assumed which closely resembles, with regard to width and configuration, the one of the Mercury suit, but is about 50 per cent heavier. It is shown in the lower graph of Figure 5. The solid curve in the upper graph shows the high LET dose fraction for the alpha component over the same range scale as the lower graph. In other words, this curve is the section from 0. 11 to 0. 19 g/cm^2 of the corresponding curve in Figure 2 shown at higher resolution and with a linear ordinate scale. It is seen that the slope of the spectrum varies quite noticeably even within the narrow range interval of the distribution. The broken straight line in the upper graph of Figure 5 represents a fictitious range spectrum of constant slope equal to the slope of the actual spectrum at the mean of the distribution, i. e., at 0. 15 g/cm^2. It can be shown, using elementary concepts of statistical mathematics, that the residual dose behind a complex shield system exhibiting a thickness distribution rather than constant thickness is identical to the dose behind an equivalent uniform shield of mean thickness provided that the attenuation characteristic of the incident radiation over the full range interval of the distribution is linear, i. e., is a straight line in a linear coordinate system. For radiations showing nonlinear attenuation, substitution of the mean thickness for the actual distribution will lead to a different dose and no general equivalent constant thickness can be established.

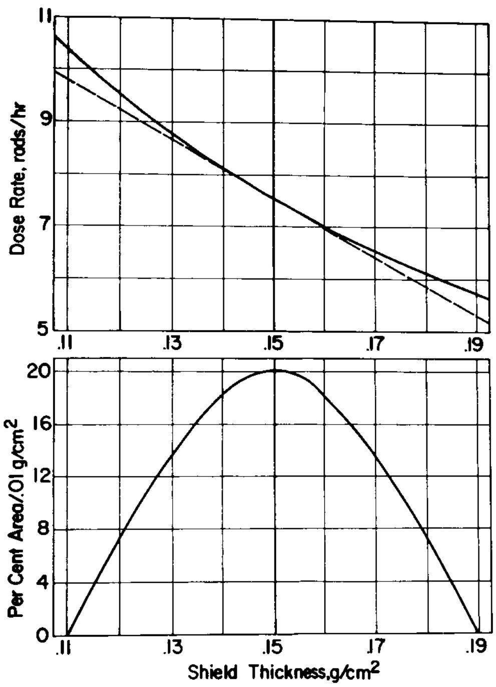

Figure 5

Shield Thickness Distribution for Combined Heat Protection and Pressure Suit (Lower) and Residual Dose Rate of High LET Fraction of Alpha Component (Upper)

Solid line in upper graph is actual depth dose rate curve. Broken line denotes slant of actual dose rate at 0. 15 g/cm^2 demonstrating nonlinearity of actual curve.

The thickness distribution in Figure 5 is symmetrical; i. e. , the descending branches to the left and right of the maximum are mirror images and the mean thickness coincides with the thickness at the maximum. It might be mentioned in passing, though this is irrelevant to the present study, that also for any asymmetrical distribution the mean thickness furnishes, for radiations with linear attenuation, the correct exposure. According to the laws of statistics, the mean for an asymmetrical distribution is defined as the value dividing the area under the distribution curve into two sections of equal and opposite first moments.

Since the attenuation characteristic of the flare spectrum of Figure 1 was shown, in Figure 5, to be nonlinear, it is of interest to determine the error that will arise if the mean thickness is substituted for the distribution. A closer examination of the four components of the total exposure in Figure 2 in the range interval from 0. 11 to 0. 19 g/cm^2 reveals that the fractional high LET dose of the alpha component shows by far the highest degree of nonlinearity. Therefore, the error in question should be largest for this component. Breaking down the range interval of the distribution into 20 subsections and evaluating and adding their individual contributions to the exposure leads to a dose rate of 7. 72 rad/hr behind the shield, whereas the corresponding dose rate computed for the mean thickness of 0. 15 g/cm^2 is 7. 57 rad/hr. This represents a difference of only 2 per cent and justifies the simplified approach of using the mean thickness. As just pointed out, the corresponding errors for the other three components of exposure will even be smaller. It can be concluded, then, that for a space suit with a shield distribution shown in Figure 5 and for spectra of the type shown in Figure 1 the shielding properties are very satisfactorily described by the mean equivalent thickness.

DISCUSSION

Radiobiologically, the most interesting result of the foregoing analysis is the finding that for very low shielding the tissue dose from a solar particle beam in near-surface regions of the target is predominantly determined by the alpha component. Furthermore, a large fraction of this alpha dose, contrary to the proton dose, is produced at a high LET leading to QF and RBE factors substantially larger than 1. 0. These factors, in turn, were seen to undergo a similarly steep drop as that of the absorbed dose itself. As a consequence, the rem dose equivalents, i. e. , the products of absorbed dose times QF or RBE, will show a still more precipitous drop. In fact, the depth gradients of the alpha rem doses, in near-surface regions of the target, are so large that actual measurements of the local dose or the local LET spectrum with conventional dosimetric instrumentation seems a difficult task almost requiring microsensors.

Even more problematic is the radiobiological interpretation of the peculiar dose distribution in near-surface regions of the body in terms of radiation damage. As far as the rad-dose distribution is concerned, a limited analogy exists with cases of beta ray damage from fallout deposits on human skin (5). The initially high and then steeply dropping QF and RBE factors, however, constitute an entirely new feature which is not paralleled in the fallout exposure. It seems quite difficult to simulate, with laboratory sources, this particular characteristic of flare produced alpha particles. Such simulation would be equally useful for design and testing of dosimetric equipment as well as for studies of radiation effects with biological specimens.

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13. ABSTRACT

Outside the vehicle the astronaut is protected from radiation merely by his space suit with a shielding equivalent of about 0. 1 g/cm^2. Evaluations based on a spectral model for a solar particle beam suggested by Weir and Brown show that the skin dose for such low shielding is due predominantly to the alpha component of the flare beam. Sixty-five per cent of this alpha skin dose is produced at a high LET corresponding to a QF of 6 and an RBE of 3. The alpha dose itself, as well as QF and RBE, drops much more steeply with increasing depth in tissue than the proton dose. Analysis of the thickness distribution of a space suit due to the structural inhomogeneities shows that substituting the mean for the actual distribution introduces an error of only 2 per cent in the surface tissue dose behind the suit materials. The findings indicate that a correct assessment of exposure in solar particle beams behind low shielding requires LET sensors in addition to instrumentation for measuring total rad doses.

Security Classification

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