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TISSUE DOSAGES FROM ALPHA PARTICLES AND HEAVY NUCLEI IN SOLAR PARTICLE BEAMS IN SPACE

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IN SOLAR PARTICLE BEAMS IN SPACE

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SUMMARY PAGE

THE PROBLEM

Recordings of several flare events indicate that solar particle beams contain, besides protons (H nuclei) and alpha particles (He nuclei), also heavier nuclei. Under conditions of very low shielding, such as the astronaut engaged in extravehicular activity, these nuclei will contribute to the radiation exposure in near-surface regions of the body. For the large flare of November 13, 1960, the rigidity spectra of the H, He, and the medium heavy (C, N, O, F) components have been determined, and it has been found that the three components have rigidity spectra of identical slope with flux ratios of 1 : 1 : 1/60. These data lend themselves to a quantitative evaluation of depth doses in a tissue target behind low shield thicknesses.

FINDINGS

It is shown that identical rigidity spectra of different nuclear species lead to greatly different range spectra with flux ratios depending on the slope of the rigidity spectrum. For the flare of November 13, 1960, flux ratios of 1 : 1 : 1/60 in the rigidity spectra transform into flux ratios of about 1 : 1/2 : 1/1000 in the range spectra for the target surface behind 0. 1 g/cm^2 shielding. The corresponding doses, however, differ by much smaller factors because of the higher Linear Energy Transfer (LET) of heavier particles. The dose rates in the target surface behind 0. 1 g/cm^2 shielding are 85 rads/hour, 65 rads/hour, and 0. 9 rads/hour for the H, He, and medium heavy components, and the corresponding dose equivalents are 108 rems/hour, 263 rems/hour, and 7. 8 rems/hour, respectively, if a Relative Biological Effectiveness (RBE), according to the recommendations of the RBE Committee, up to a value of 10 is assumed. Depth dose gradients in tissue are essentially the same for the He and medium heavy components, yet are substantially smaller for the H component.

In view of the high LET of 960 kev/micron T in the Bragg peak of C nuclei, the depth distribution of the number of enders per gram tissue for C nuclei is also determined in order to allow evaluation of the energy dissipation in terms of the microbeam concept, i. e. , in terms of hit frequencies in the cell population of tissue. A maximum enders frequency of 65 per gram tissue per second for C nuclei is found. It shows the same gradient with depth as the RBE dose equivalent.

In view of the smallness of the dose contribution from medium heavy nuclei, special dosimetric instrumentation that would resolve the LET spectrum up to the Bragg peaks of C, N, O, and F nuclei, i. e. , beyond 1000 kev/micron T, seems dispensable. For assessments of equivalent residual dose from repeated and extended exposures, separate determination of the high LET fraction of total exposure does seem advisable but could be carried out by measuring the combined total high LET energy dissipation beyond a critical threshold LET without resolving the LET spectrum.

INTRODUCTION

Recordings of several flare events during the maximum of the past solar cycle have furnished evidence that flare produced particle beams show essentially the same particle make-up as galactic radiation; that means, they contain, besides protons, alpha particles and heavy nuclei. Though statistics from which quantitative information on flux values could be derived are still comparatively poor, available data indicate that the spectra of the alpha and heavy components seem to obey the same exponential rigidity law as the protons. This finding is of a more general interest inasmuch as it allows establishing the contributions of individual Z components to the total tissue dosage behind various shield configurations.

The following study is an attempt in the just-indicated direction. It analyzes a maximum type flare event with regard to the depth distribution of rad and rem doses for the H (protons), He (alpha particles), and C (carbon nuclei) components behind typical shield thicknesses. From what was pointed out before, it should be clear that main emphasis in this analysis does not rest so much on absolute dose and dose rate as on the relative contributions of different Z components to total exposure in terms of rad and rem doses and on their respective depth dose patterns. Such data would seem of definite interest even at this early stage at which the absolute levels cannot yet very accurately be determined.

RIGIDITY SPECTRUM AND RANGE SPECTRUM

Of the few flare events for which flux data on the medium heavy component have been reported, the November 13, 1960 flare is of special interest because it can be considered a maximum type event not only with regard to absolute flux values, but also with regard to the relative shares of alpha and medium heavy nuclei in the total flux. For the reader's convenience, the rigidity spectrum of this flare prevailing at a particular time during the event as reported by Fichtel (1) is reproduced in Figure 1. As seen in the graph, the medium heavy nuclei with the Atomic Numbers Z = 6, 7, 8, and 9 are lumped together to form one flux spectrum. If this compound flux is to be evaluated in terms of tissue dosages behind different shield thicknesses, a specific representative Z number must be chosen because depth doses can be determined only for a specific range/energy relation. The following analysis is based on Z = 6 (carbon) as a representative element of the medium heavy flux. In other words, the computational analysis assumes that the medium heavy class contains exclusively C nuclei with the flux values shown in Figure 1 for the entire class. As will be seen later, the C component contributes only less than 2 per cent to the total rad dose and less than 10 per cent to the total RBE dose equivalent. A detailed analysis of the four components of the medium heavy class, therefore, seems entirely dispensable.

Expressing fluxes of protons and heavier nuclei uniformly in terms of magnetic rigidity is of special interest if clues on the nature of the mechanism of particle acceleration in magnetic fields of the flare itself or in the interplanetary medium are

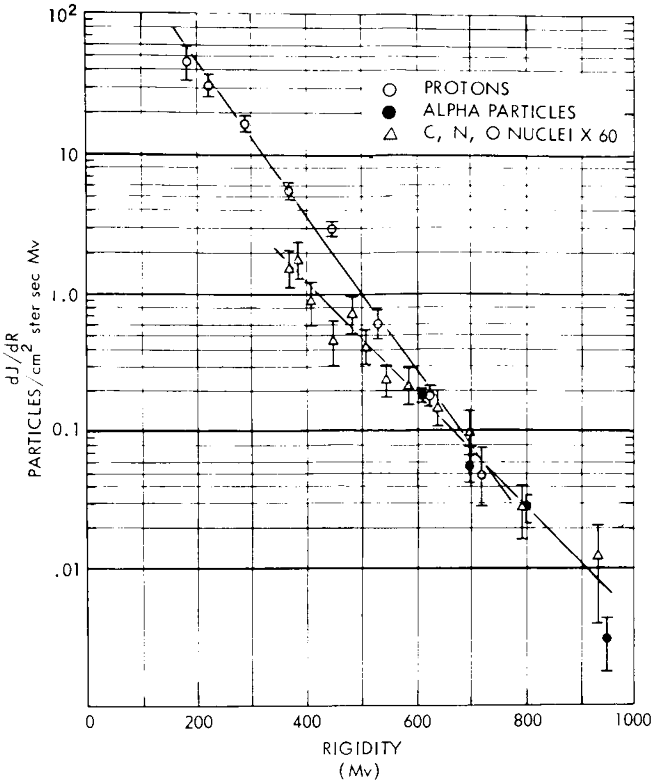

Figure 1

Differential Rigidity Spectrum of Flare Produced
Particles at 1603 UT on Nov. 13, 1960
(Reproduction of Fichtel's original graph)

sought. For assessing tissue dosages behind shields, however, the rigidity spectrum is not a very meaningful way of comparing fluxes of nuclei with a Z/A ratio of 1. 0 (H) to nuclei with a Z/A ratio of 0. 5 (He and C). Since rigidity is momentum per unit charge, a proton and an alpha particle of the same rigidity differ in their momenta only by a factor of 2 whereas their masses differ by a factor of 4. Therefore, their ionization ranges differ by a very wide margin. The finding, then, that the rigidity spectra for the H and He components of a flare beam are identical does not at all mean that that beam contains equal fluxes of H and He nuclei of the same penetrating power.

The basic deficiency of the rigidity spectrum in that it does not allow inferences as to residual fluxes of particles of different Z behind a given shield thickness calls for a better way of presenting component fluxes for mixed beams containing different nuclear species. Most convenient in this respect is the range spectrum since it shows flux directly as a function of penetrating power or range. The conversion of a flux/rigidity plot into a flux/range plot is a routine procedure involving consecutive application of the rigidity/energy and energy/range relationship to the original spectrum. Figure 2 presents the result of this conversion for the spectra of Figure 1.

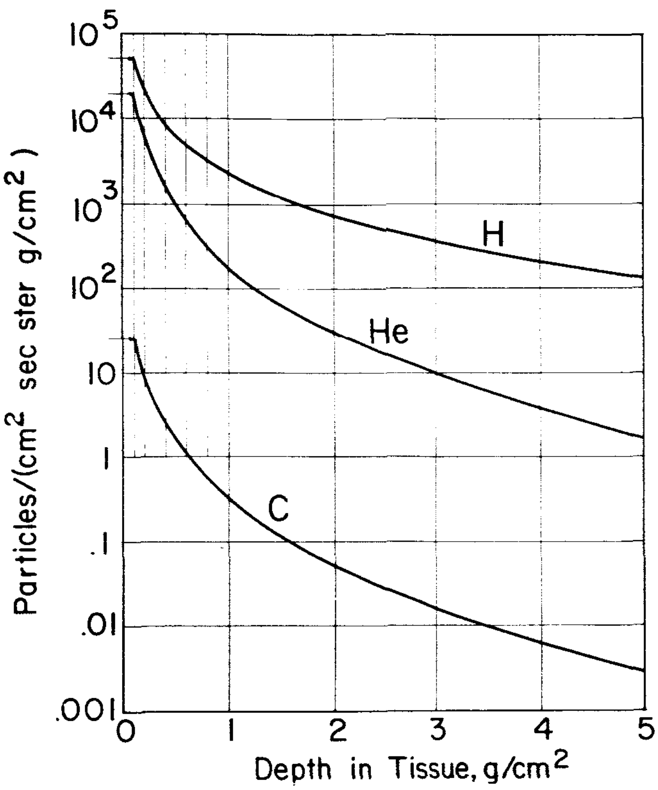

Figure 2

Rigidity Spectra of Figure 1 Converted to Differential Range Spectra

(Note great disparity in abundances of three components in range spectra as compared to rigidity spectra.)

It is seen that, in terms of penetration, the component fluxes differ greatly, with H nuclei showing substantially larger values than He nuclei and these, in turn, larger ones than C nuclei.

The fact that the conversion from the rigidity to the range spectrum involves only the rigidity/energy and energy/range functions of the component nuclear species, i. e., only intrinsic characteristics of the nuclei themselves, might lead to the erroneous conclusion that flux ratios in the range spectra are always the same if the component nuclei show identical rigidity spectra. That this is not the case can be seen from a closer inspection of the formula for the rigidity spectrum. It is usually given as $J = J_o \exp(-P/P_o)$ where J_o and P_o are empirically determined flux and rigidity constants, both varying greatly for different flares and even for different times of the same flare. Even if fluxes are normalized by dividing by J_o, it is seen that the slope of the normalized spectrum still varies with P_o. Now, since the same range corresponds, for particles of different Z, to different rigidities, the flux ratios for given Z components will be different for different P_o values. In other words, the statement that, for a given flare beam, H, He, and C nuclei obey the same rigidity spectrum, does not at all define unique flux ratios for the range spectra.

Freier and Webber (2) have tabulated the constants J_o and P_o for a number of larger flare events. They list a maximum P_o of 300 Mv and a minimum of 50 Mv. It is easily shown that identical rigidity spectra triplets for the H, He, and C components, once for a P_o of 300 Mv and once of 50 Mv, correspond to range spectra triplets with profoundly different flux ratios.

DEPTH OF PENETRATION

The differential range spectra of Figure 2 do not allow quantitative inferences as to the corresponding depth dose distributions of the three nuclear species in the beam since the local energy dissipation at a given depth is not a function of the local particle flux only, but also depends on the local Linear Energy Transfer (LET) spectrum which changes continuously as the beam degrades through absorption. As far as the H and He components are concerned the pertinent relationships already have been discussed in an earlier report (3). As pointed out there, the depth dose distribution in near-surface regions of a tissue target behind low shielding is influenced very little by the macroscopic target geometry and therefore is entirely satisfactorily described by analyzing a semi-infinite slab under 2 pi incidence.

The full Bragg curve for C nuclei covering both sides of the peak has never been measured directly. However, measurements over narrower energy intervals and observations of cosmic ray C nuclei in nuclear emulsions agree reasonably well with theoretical concepts concerning the process of electron capture in the terminal section of the ionization range of an ion with multiple charge. This gradual build-up of the system of orbital electrons toward the end of the ionization range is tantamount to a reduction of the effective nuclear charge of the ion, leading to a similar reduction of the LET and to a corresponding increase of range. The literature has been reviewed recently by Barkas and Berger (4). These authors also list the best available mathematical expression for determining the effective nuclear charge as a function of beta (quotient of speed of ion and speed of light). Applying the data of Barkas and Berger to C nuclei, one obtains the LET/E relationship shown in Figure 3. The corresponding relationships for H and He nuclei used in the present analysis have been presented in earlier reports (5, 6).

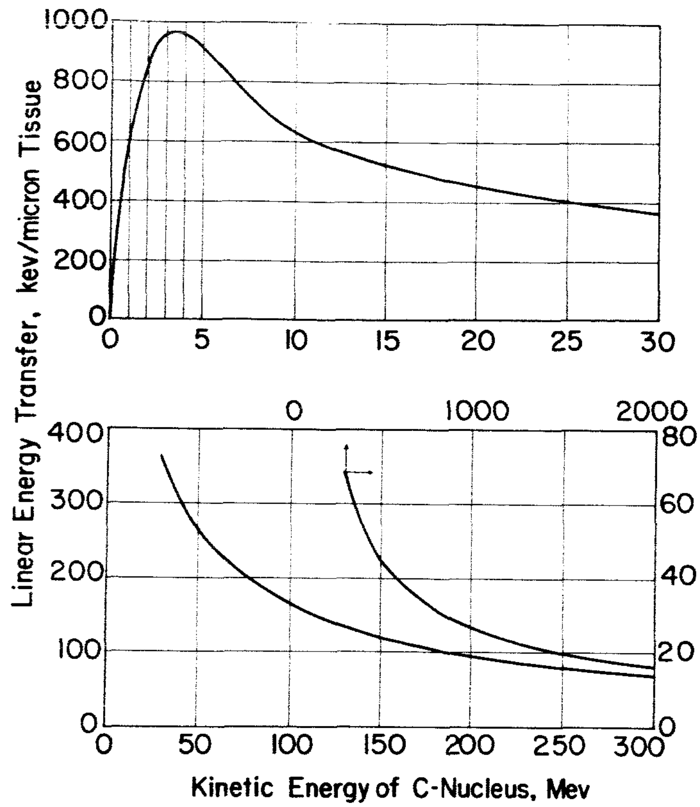

Figure 3

Linear Energy Transfer (LET) of C Nuclei (Z = 6, A = 12) as a Function of Kinetic Energy

Figure 4 shows the dependence of local absorbed dose on depth in a semi-infinite tissue slab assuming 2 pi incidence of a flux showing, for the H, He, and C components, the rigidity spectra of Figure 1 or the range spectra of Figure 2. It is seen that the He component, especially in near-surface regions behind 0. 1 g/cm^2 shielding, contributes a substantial fraction to the total dose. Quite differently, the contribution of the C component is, even in the very surface of the target, negligibly small. The curves of Figure 4 also demonstrate well the much lower penetrating power of the He component as compared to H. Most interesting is the fact that there seems to be very little difference in this respect between the He and C components. This is seen more clearly in the plot of normalized doses shown in Figure 5.

For a complete dosimetric analysis, absorbed doses in rads have to be expressed in rem dose equivalents. As pointed out in an earlier report (l. c. , 6) this conversion encounters principal difficulties already for the He component inasmuch as official recommendations (7) provide specific Relative Biological Effectiveness (RBE) and

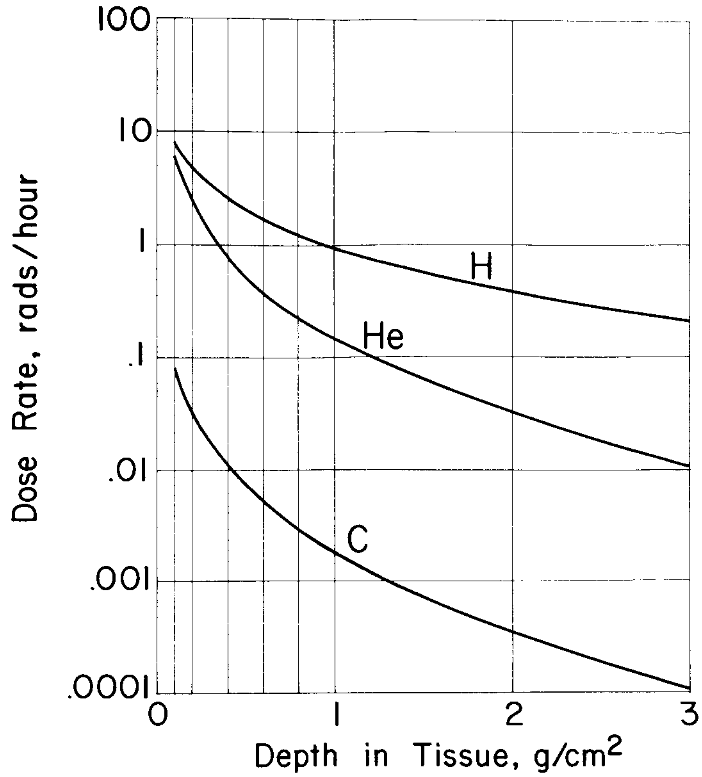

Figure 4

Depth Distributions of Rad Dose Rates in Semi-Infinite Tissue Slab for 2 pi Incidence of Solar Particle Beam Showing Flux Spectra of Figures 1 and 2

Quality Factor (QF) factors only up to an LET value which falls considerably short of the maximum LET of He nuclei in the Bragg peak. For C nuclei, this discrepancy assumes proportions which would leave almost the entire energy dissipation undetermined. This gap is all the more difficult to bridge even with a crude estimate inasmuch as experimental radiobiological data indicate that in the general vicinity of 200 to 200 kev/micron T the RBE passes through a maximum and drops substantially toward high and very high LET values. As a conservative but otherwise entirely arbitrary way out of this difficulty, an RBE/LET relationship has been adopted which follows the official recommendations up to the LET of 150 kev/micron T and then saturates at the constant value of 10 for the entire remainder of the LET scale of C nuclei. The relationship is shown in Figure 6. It is felt that this compromise avoids, on the one hand, the gross exaggeration which a linear extrapolation of the formula of the RBE Committee (l. c., 7) up to the maximum LET of 960 kev/micron T for C nuclei would constitute, yet, on the other hand, it can be considered conservatively high since it does not allow for the re-decrease of the RBE in the upper part of the LET scale.

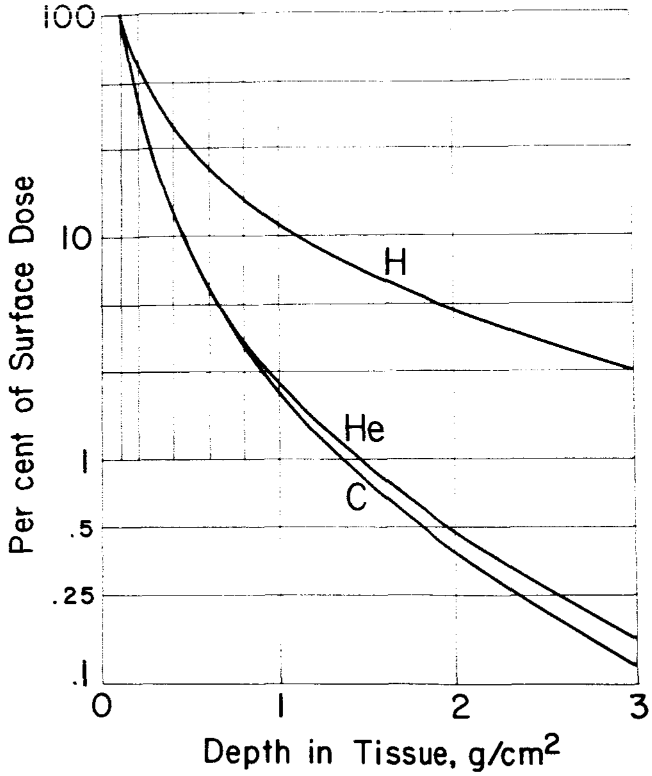

Figure 5

Normalized Depth Distributions of Rad Dose Rates
Shown in Figure 4

(Note small difference in depth of penetration between He and C components and much larger depth of penetration of H component.)

The distinction between RBE and QF as proposed by the RBE Committee has not been adopted in the present study. It seemed preferable to limit the evaluation to the RBE formula of the Committee with the indicated extrapolation. Inspection of the LET/E relationship for C nuclei in Figure 3 shows that a major part of the energy dissipation of C nuclei takes place at LET values by far exceeding the common types of laboratory radiations for which good experimental data on RBE factors are available and the recommendations of the RBE Committee are intended. To extrapolate the QF formula of the Committee with its large margin of safety to the high LET levels in question would seem quite unrealistic.

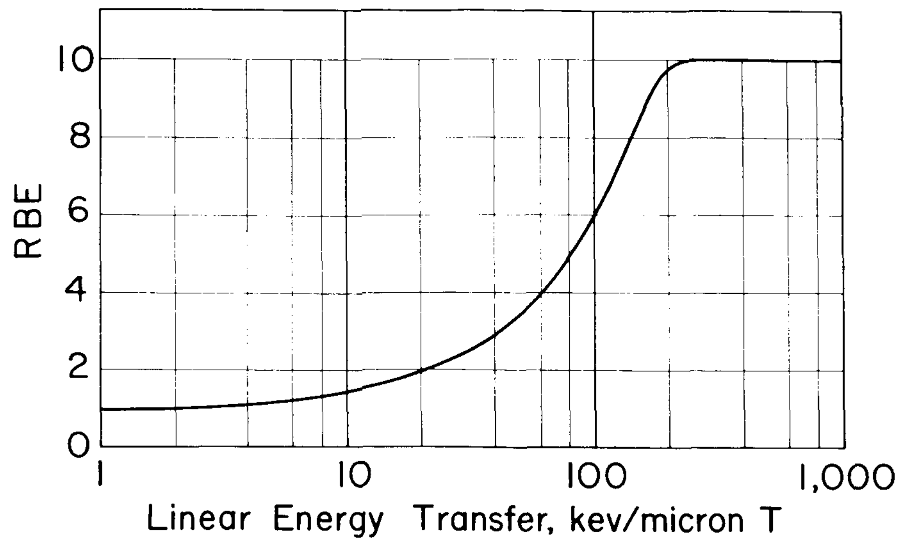

Figure 6

Relative Biological Effectiveness (RBE) as a Function of Linear Energy Transfer (LET)

(Up to 150 kev/micron T curve follows formula of RBE Committee; section beyond is arbitrary extrapolation.)

Figure 7 shows the rad dose data of Figure 4 converted to RBE dose equivalents using the RBE/LET function of Figure 6. It is interesting to see that the He component now moves up to first place as contributor to total dose in the target surface down to a tissue depth of 0. 2 g/cm^2 (0. 3 g/cm^2 total thickness including 0. 1 g/cm^2 shield). The dose contribution of the C component is enlarged by a factor of almost 10, yet still remains well below the 10 per cent level of total dose at all depths.

It seems worthwhile mentioning that the dose fractions from the H and He components show, for the spectrum of the flare event under investigation in the present study, a basically different ratio from that for the flare spectrum of Weir and Brown (8) analyzed in an earlier report (l. c., 3). For the latter spectrum, the He component was found to produce a substantially larger surface dose than the H component on the rad level whereas Figure 4 of the present report shows a slightly smaller rad dose from the He component in the target surface. This difference between the two flare spectra demonstrates well the point made earlier that two flare beams, either one showing identical H and He rigidity spectra, yet of different slope, i. e., of different P_o, do not show equal flux ratios of H to He in their respective range spectra. As pointed out in the earlier report, the Weir and Brown spectrum has a P_o of 200 Mv. Fichtel's spectra for the H and He components (Figure 1 of this report) correspond to a P_o of 78 Mv. As mentioned at the end of the preceding section, the synoptic survey of Freier and Webber (l. c., 2) lists a maximum P_o of 300 Mv and a minimum of 50 Mv.

This shows that the dose ratios for the H and He components as found in the present study and the earlier report for the spectra of Weir and Brown and of Fichtel do not encompass the full variability for flare spectra in general.

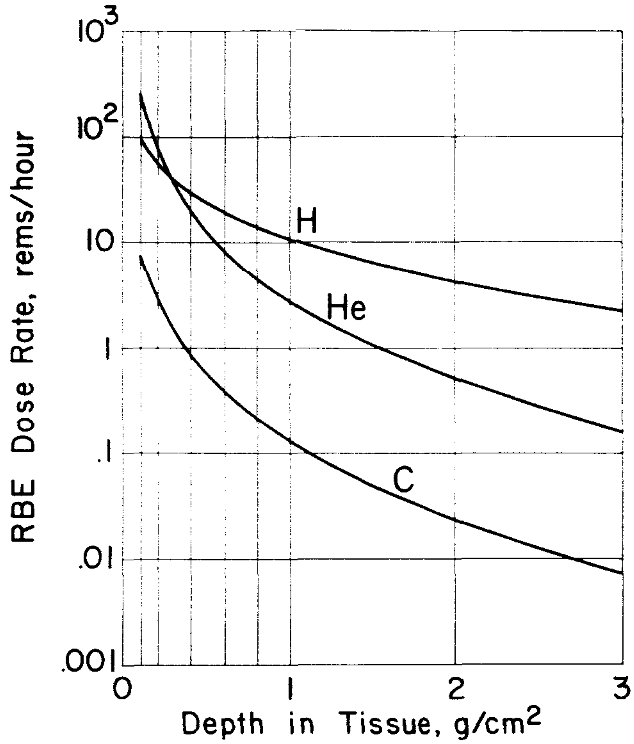

Figure 7

Depth Distributions of RBE Dose Equivalents Obtained by Applying RBE/LET Function of Figure 6 to Data of Figure 4

(Note strong preponderance of He component in tissue surface.)

If dose contributions of heavy nuclei are discussed, the controversial issue of the "microbeam" effectiveness of individual ionization trails of these nuclei in tissue comes up. A critical survey of the various opinions stated by radiobiologists on this problem is beyond the scope of this treatise. A brief remark, however, seems in place concerning the dosimetric implications of the microbeam concept. With specific reference to the passage of a single particle of high LET, the report of the RBE Committee points out that the RBE concept cannot be applied when the concept of radiation "dose" itself fails (l. c., 7). At present, no generally accepted proposal for a dosimetric characterization of a microbeam irradiation exists. Whether such a unit for a quantitative measure, that would equal or at least approach the general validity and usefulness of the roentgen unit, can ever be found seems questionable. Existing attempts, such as fractional cell lethality or the kilogram-roentgen, fall far short of this goal.

If the scope of investigation is limited strictly to physical parameters, a complete dosimetric analysis of a microbeam irradiation is furnished with the number of "enders," i. e. , of heavy nuclei reaching the end of their ionization range per gram tissue. For a given nuclear species, this number allows a determination of the amount of local energy dissipation and its micro-spatial distribution in cellular tissue. The number of enders is useful even for H and He nuclei if a more detailed analysis of their LET distribution is desired. In view of this general applicability of the enders count to dosimetric evaluations, it seems worthwhile to determine the enders count for the C nuclei of the flare spectrum under investigation as a function of depth in tissue. The results are shown in Figure 8. It is interesting to see that, contrary to H and He

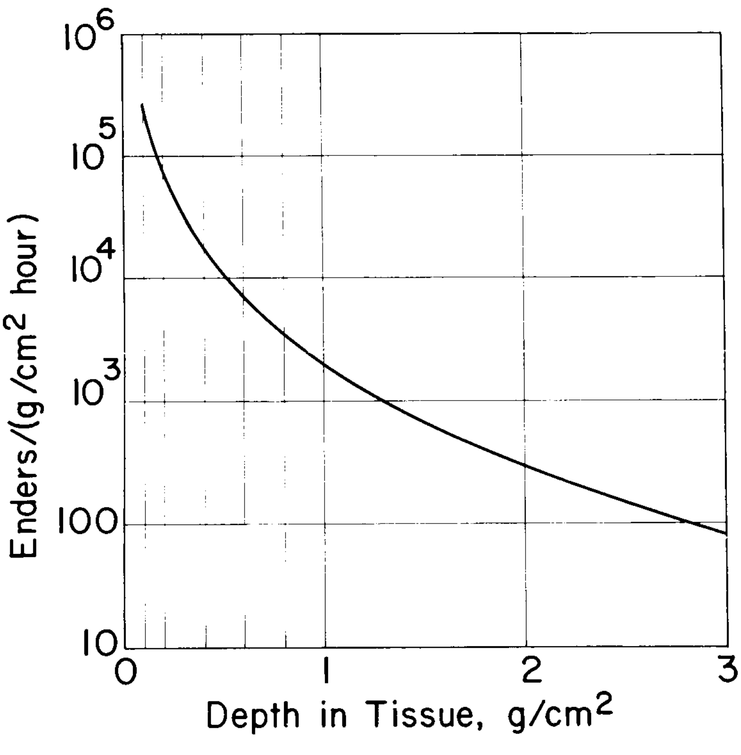

Figure 8

Depth Distribution of C Nuclei Reaching End of Ionization Range in System Described in Figure 4

nuclei, the enders count for C nuclei does not show a substantially larger depth gradient in tissue than the total ionization dosage of the C component. An interpretation of the data on the enders count in terms of tissue damage shall not be attempted here. The extremely small number of cells traversed by C nuclei even in the tissue surface in an exposure of several hours is easily seen from the data of Figure 8. It is a different question, however, whether the resulting tissue damage does not differ from the damage of the same energy dissipation per unit tissue volume spread evenly over all cells as would result from exposures to x- or gamma rays.

DISCUSSION

As far as the exposure hazard to the astronaut is concerned, most important is the finding that the dose contribution from components heavier than He does not significantly increase the combined exposure from the H and He components. This is true not only for the rad dose, but also for the RBE dose equivalent. Exception has to be taken to this statement if the high LET fraction of the total exposure is to be evaluated separately as would be the case in assessments of long-term damage, for instance, by establishing the Equivalent Residual Dose (ERS) from accumulated career or lifetime exposures. To be sure, even in such cases the components heavier than H would have to be considered only for those exposures to solar particle beams which caught the astronaut engaged in extravehicular activity (EVA) since the shielding equivalent of any larger ship would widen the gap between the dose levels from the H as compared to the He and heavier components to a point where the latter ones become insignificant contributors. Obviously, the probability of EVA coinciding with the arrival of a solar particle beam is remote.

In view of this extremely low risk factor, instrumentation which would analyze the LET spectrum up to the Bragg peaks of C, N, O, and F nuclei seems dispensable. For all practical purposes it would appear that only a "high pass" type LET discrimination is needed. Such instrumentation would be comparatively simple as only the combined total of the high LET energy dissipation of all nuclear species beyond a critical threshold LET would have to be measured. For assessments of ERS, such bulk determination of the high LET fraction of total exposure without resolving the detailed configuration of the LET spectrum should be sufficient.

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Recordings of several large flare events indicate that solar particle beams contain, in addition to H and He, also heavy nuclei. For the November 13, 1960 flare in particular, complete rigidity spectra for H and He and C, N, O, F nuclei have been reported. Evaluation of these spectra in terms of tissue depth doses behind 0. 1 g/cm^2 shielding shows that, while the He component contributes substantially to exposure in near-surface regions, the dose fraction of the medium heavy component remains, even in the tissue surface, on the level of a few per cent. In view of the smallness of this contribution, it seems unnecessary to extend the spectral resolution of LET sensors up to the Bragg peaks of medium heavy nuclei (1000 kev/micron T).

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