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LINEAR ENERGY TRANSFER SPECTRA AND DOSE EQUIVALENTS OF GALACTIC RADIATION EXPOSURE IN SPACE*

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SUMMARY PAGE

THE PROBLEM

For space missions of long duration, the low-dose, long-term injury to the astronaut from accumulated exposure to galactic cosmic rays is of interest. In assessing the amount of this exposure absorbed doses in rads must be converted to dose equivalents in rems. This conversion poses special problems because a sizeable fraction of the total galactic dose is produced at Linear Energy Transfer (LET) values well above those of laboratory radiations for which radiobiological data on the Relative Biological Effectiveness (RBE) are available. Rather than assume any conservatively high, but basically arbitrary RBE factors for the evaluation of this portion of the galactic radiation exposure, it seems preferable to analyze the LET distributions of the different nuclear components and to compare them individually to standard x-rays. In this way the fraction of the galactic dose that is not amenable to a dosimetric evaluation in conventional terms can be separated and determined as to its absolute amount, the particle type producing it, and its LET distribution.

FINDINGS

The full Z spectrum of the primary galactic radiation was broken down into five classes, protons (H), alpha particles (He), C, Ne, and Ca nuclei. The rigidity spectra for these components as proposed by Freier and Waddington were converted to differential energy spectra and the local LET distributions as they would develop at a depth in tissue of 3 g/cm^2 established by numerical methods. The LET distributions for all five components show the same basic configuration, with an extremely high pointed maximum at minimum LET and a very small pointed second maximum at maximum LET. The LET distribution for protons resembles closely that for Co-60 gamma rays, suggesting an RBE factor well below 1.0. The alpha distribution falls within the LET range of the distribution for standard x-rays, suggesting an RBE of 1.0. For the heavier components, application of the formula of the RBE Committee leads to mean RBE factors of 1.6, 2.9, and 6.6 for the C, Ne, and Ca components, respectively. A total mean value for the full Z spectrum of the primary galactic flux of 1.82 is obtained, suggesting that the very high rem/rad ratios reported by some authors appear unrealistically conservative.

INTRODUCTION

As the stage is being set for manned space missions of longer duration, a more accurate assessment of the accumulated dose from galactic radiation exposure gains interest. In the low inclination, low altitude orbits of present day manned space missions, the galactic radiation exposure is greatly reduced by the magnetic field of the Earth cutting off large sections of the energy spectrum. However, charged particles traveling parallel to the magnetic axis arrive essentially undisturbed. Therefore, the galactic radiation arriving in the vicinity of the Earth within two narrow solid angles about the magnetic axis in the polar regions of the North and South represents the full spectrum and flux as they would be encountered in deep space outside the magnetosphere. Data on the composition of galactic radiation in free interplanetary space thus can be collected with polar orbit satellites and sounding rockets and balloons launched near the geomagnetic poles.

In a preceding report (1), hereafter referred to as Report 36, the rigidity spectra of the various Z components of the undisturbed galactic radiation as they follow from measurements of the indicated type during the past solar minimum were presented and the problems encountered in their interpretation in terms of tissue dosages were discussed. This earlier analysis was essentially limited to an evaluation of absorbed tissue dosages expressed in millirads. The question of their conversion to dose equivalents was dealt with only summarily by breaking down the total ionization into a low Linear Energy Transfer (LET) and a high LET fraction without any attempt to assign specific factors of Relative Biological Effectiveness (RBE) to the various dose components. This simplified treatment seemed entirely acceptable because radiobiological data on long-term damage such as life shortening for different types of radiations likewise merely distinguish between low and high LET radiation without attempting to establish specific RBE/LET relationships.

Another reason principal difficulties are encountered in the determination of actual dose equivalents expressed in millirems derives from the fact that the peak LET values for heavy nuclei of the primary galactic radiation considerably exceed the corresponding maximum values for particle radiations from terrestrial sources such as neutron recoils or alpha particles from internal emitters. This peculiar characteristic of the galactic radiation exposure has prompted some authors (2) to assign very large RBE factors of up to 20 to the dose fractions in question. With regard to the validity of this approach, it should be remembered that, even within the well-investigated LET range of conventional laboratory radiations, RBE factors always are based on certain simplifications and generalizations of experimental data. Their extrapolation into an essentially unexplored LET region would not seem to be a very reliable procedure. Caution is all the more advisable inasmuch as it is well established experimentally that, for most biological reactions to densely ionizing radiations, the RBE factor passes through a maximum in the region about 200 kev/micron T and then reverses its trends in the sense that it decreases with increasing LET.

In view of these limitations and ambiguities of the RBE concept, it seems preferable, to analyze the LET distributions of the different components of galactic radiation exposure separately, comparing them individually to the LET distribution of standard x-rays as well as to those of densely ionizing particle radiations from terrestrial sources. Such a comparison would furnish a quantitative determination of that part of the galactic ionization dosage which falls outside the LET range for which radiobiological data from laboratory experimentation are available, yet would avoid getting involved in the problematic RBE issue. The assessment of dose equivalents by selecting suitable RBE/LET functions and applying them to the various beam components could still be carried out as a completely separate step if desired.

The following report is an attempt in the indicated direction and strictly separates the two phases of the analysis. It is based essentially on the body of experimental information on the primary galactic spectrum compiled in Report 36. In the presentation of the data, in the present report, rigidity has been changed to kinetic energy in view of the special emphasis on energy dissipation in the present study.

ENERGY SPECTRA OF THE PRIMARY RADIATION AT SOLAR MINIMUM

As explained in more detail in Report 36, the galactic flux is at its maximum at solar minimum. Evaluation of tissue dosages, therefore, would seem of special interest for these conditions. Accordingly, Report 36 reviewed the differential rigidity spectra as they prevailed during the past solar minimum. In converting rigidity of a charged particle to kinetic energy, the charge per mass unit of the particle is a determining magnitude. Since a proton carries one unit of charge per mass unit (A/Z = 1), whereas all heavier nuclei carry one unit of charge per two mass units (A/Z = 2), it simplifies presentation if the energy spectra for protons, on the one hand, and those for all heavier nuclei, on the other, are plotted separately.

The full Z spectrum of the primary galactic beam extends from Z = 1 to essentially Z = 28. Although nuclei of Z numbers greater than 28 have been recorded at rare occasions, their contribution to the total energy fluence is extremely small. For the flux components from Z = 3 to Z = 28 it is customary to formulate experimental data on fluxes in terms of broader Z classes rather than of individual Z numbers. This practice is adhered to because the abundance of some elements is extremely small and because the methodsof identifying Z numbers from pulse heights in ion chambers or counters or from delta ray counts of emulsion tracks carry a certain margin of error. As in Report 36, the Z spectrum from 3 to 28 is broken down in the following analysis into three groups comprising the Z numbers from 3 to 9, 10 to 19, and 20 to 28. As respective group representatives, the elements carbon (C, Z = 6, A = 12), Neon (Ne, Z = 10, A = 20), and Calcium (Ca, Z = 20, A = 40) were selected in the sense that the energy dissipation was evaluated as though the total heavy flux would consist only of C, Ne, and Ca nuclei.

With regard to the spectra of the three groups, experimental information is much less conclusive than that for the alpha component and shows poor statistical significance because of the small absolute flux values. With the assumption that the nature of the acceleration mechanism acting on charged particles in galactic space is electromagnetic, the preferred hypothesis at present is that all nuclear species show rigidity spectra of the same basic configuration. As this proposition holds well for the spectra of protons and alpha particles, its application to heavier components appears to be the best approach for lack of better information. What few experimental data are available on the heavy spectra do not seem to contradict this assumption. As just said, the problem is intimately connected with theoretical concepts about the propagation and absorption of charged particles in the interplanetary medium containing solar plasma and a large scale solar magnetic field. These aspects have been reviewed by Waddington (3).

Figure 1 shows the differential energy spectrum of the galactic proton flux at solar minimum as it follows from the conversion of the corresponding rigidity spectrum communicated by Freier and Waddington (4). Examination of Figure 9 of their report reveals that Freier and Waddington actually propose three alternative model spectra of identical configuration yet with different flux constants. The three spectra reflect three different assumptions of the effective modulating potential of the interplanetary magnetic field. Their graph in question also presents all flux measurements available, yet these are indicated merely as points without attempting to draw a curve of best fit. The spectrum in Figure 1 of the present report is an attempt at such a curve of best fit. Following closely the available experimental information seemed preferable to adopting any of the three theoretical spectra because the actual radiation exposure in space and not the mechanism of particle acceleration is of interest in the present context.

It should be pointed out that the experimental data on the proton spectrum reach down only to a kinetic energy of 30 Mev. The section of the spectrum in Figure 1 below that energy represents a tentative extrapolation. For assessment of tissue dosages the essential fact is that the spectrum shows a large maximum in the 900 Mev energy region, with a differential flux steeply dropping from there on.

In order to convey an idea of the penetrating powers involved, ionization ranges in tissue are indicated in Figure 1 with markings directly on the curve. It is seen from these data that, for systems of low shielding, absorbed doses from primary protons in the body surface will be smaller than for medium or heavy shielding. This is just the opposite of the situation for flare produced or trapped protons where the skin dose increases steeply with decreasing shield thickness because of the steep negative slope of the energy spectra.

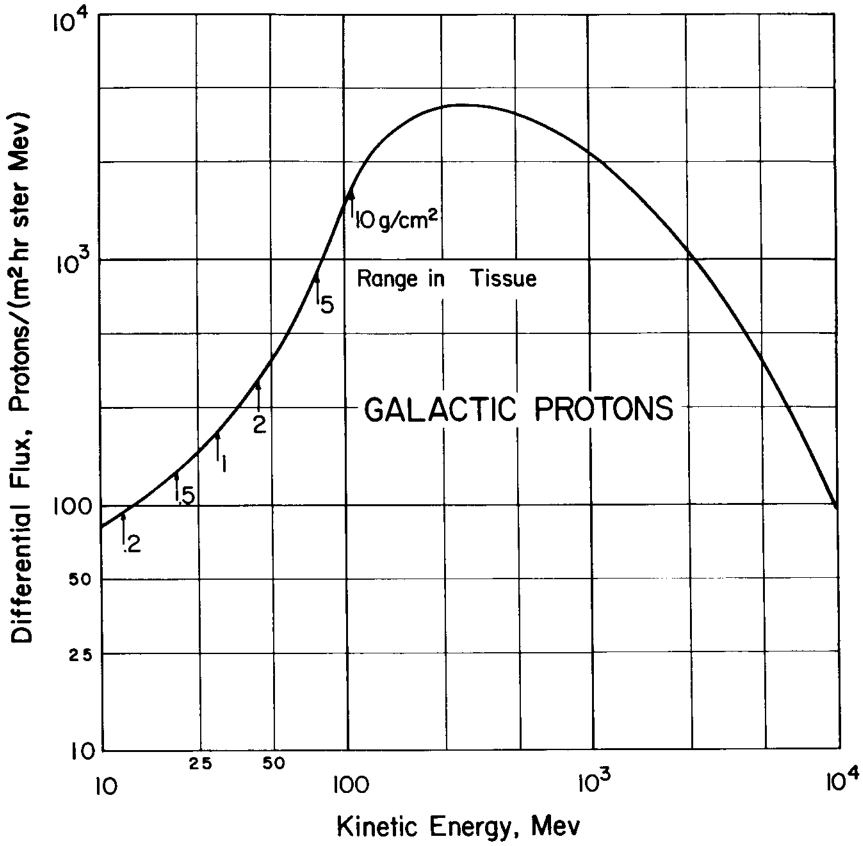

Figure 1

Differential Energy Spectrum of Galactic Protons at Solar Minimum Based on Data of Reference 4

Figure 2 shows the differential energy spectra for all components heavier than protons based on the compilation of all available data on alpha fluxes by Freier and Waddington (l.c., 4) and on the information on component flux ratios of heavier nuclei to alpha particles as proposed by Waddington (l.c., 3) as the best compromise of all existing information. As mentioned before, the rigidity spectra of all heavy components including alpha particles are assumed to show the same configuration. Since all these components, at the same time, have the same A/Z ratio of two, their energy spectra likewise must show the same configuration. That means the spectra of the three heaviest components in Figure 2 actually could be generated from the alpha spectrum simply by shifting the latter vertically downwards until it satisfies the smaller flux constants for the heavier components. The spectra nevertheless have been drawn separately in Figure 2 in order to indicate ranges in tissue in the individual spectra.

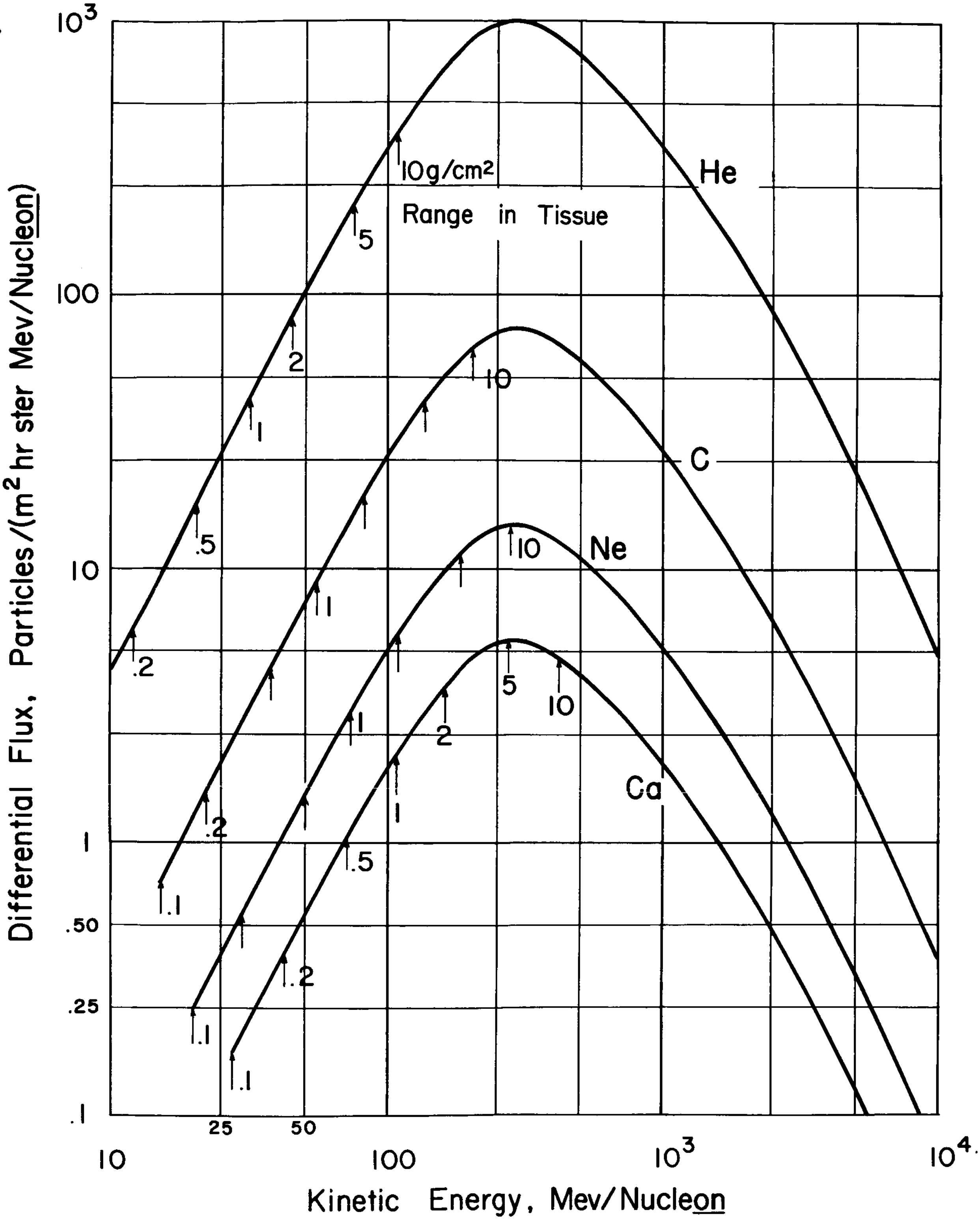

Figure 2

Differential Energy Spectra of Heavy Galactic Particles at Solar Minimum Based on Data of References 3 and 4

The spectra in Figure 2 show, similar to the proton spectrum in Figure 1, a large maximum at comparatively high energy, with the differential flux steeply dropping toward lower energies. Ranges in tissue are again marked directly at the spectra in the same way as for the proton spectrum in Figure 1. It is seen again that, if only the ionization of the primary particles is considered, the tissue doses in the body surface in systems of low shielding will be smaller than for heavier shielding. Speaking about this phenomenon in general, i.e., with inclusion of the proton component, it should be realized that this effect of an increasing local dose with increasing depth is substantially magnified by the production of secondaries of multiple order in nuclear collisions of high energy primaries in the absorbing material.

As far as the heavy primaries are concerned, it is essential to remember that they are broken up, in nuclear collisions, in lighter fragment nuclei, mostly protons and neutrons and some alpha particles, aside from meson production for primaries of very high energies. As all these secondaries including mesons do not show, with regard to their LET spectra, any unique features that would not be known from nuclear radiations of terrestrial sources, it is seen that the analysis of the LET distributions can be limited to the primary components of the heavy flux because only there occur LET values for which dose equivalents cannot be established on the basis of existing radiobiological information. As the further analysis will show, even for the heavy primaries, a substantial part of the energy dissipation falls into the LET region of conventional nuclear radiations and therefore poses no special problem in assessing dose equivalents in millirem.

LET DISTRIBUTIONS OF GALACTIC PRIMARIES

If the energy spectra in Figures 1 and 2 are to be evaluated in terms of LET distributions in tissue, the LET/E relationships of the nuclei involved must be known. For protons and alpha particles, these relationships have been investigated extensively in the laboratory with terrestrial particle sources. Although minor discrepancies still exist, even for these two well-investigated particle types, with regard to the exact LET value in the Bragg peak, the LET/E functions at medium and high energies beyond the Bragg peak are well defined. Both have been presented in earlier reports (5, 6).

No direct measurements of the LET in the Bragg peaks of the three heaviest components in Figure 2 have been reported. However, the basic mechanism of electron capture of a multiple-charged nucleus in slowing down is well enough known to allow a satisfactory theoretical determination of the LET/E relationship at low energies. An exhaustive literature survey on the subject has been conducted by Barkas and Berger (7). The LET/E functions for C, Ne, and Ca nuclei shown in Figures 3, 4, and 5 have been computed with the approximation formulae proposed by these authors. For kinetic energies exceeding the abscissa scales in the graphs the LET can be obtained from that for protons by applying the square law of charge, remembering that a proton of kinetic energy E has the same speed as any heavy nucleus of kinetic energy E per nucleon. The LET of the heavy nucleus is then simply Z^2 times that of the proton.

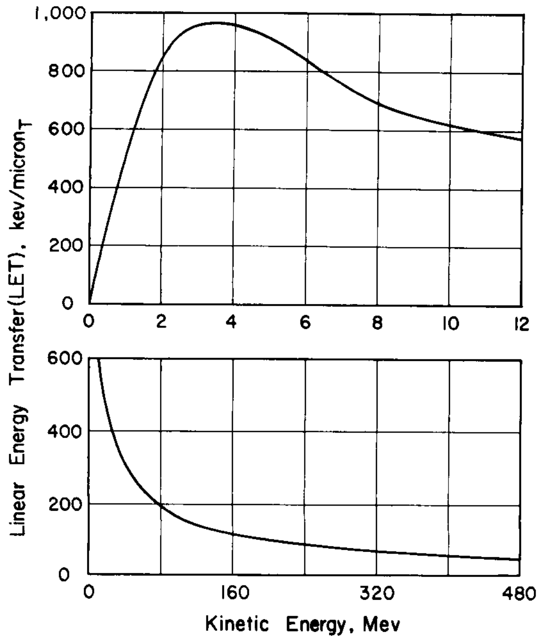

Figure 3

LET/Energy Function for C Nuclei Based on Data of Reference 7

To obtain energy per nucleon, divide abscissa values by 12.

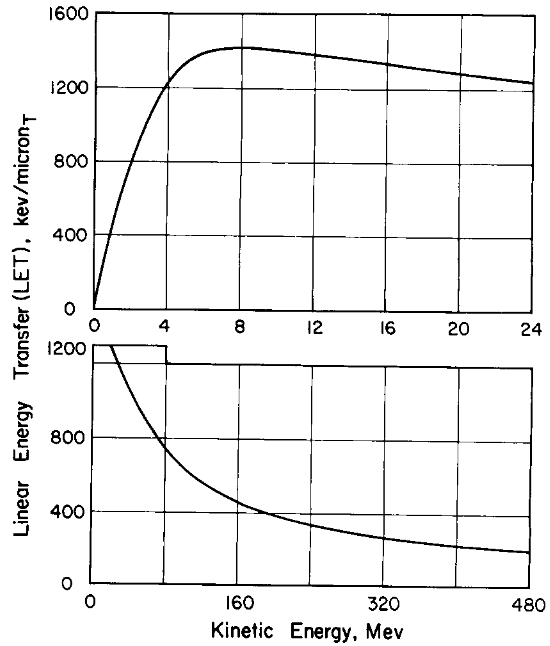

Figure 4

LET/Energy Function for Ne Nuclei Based on Data of Reference 7

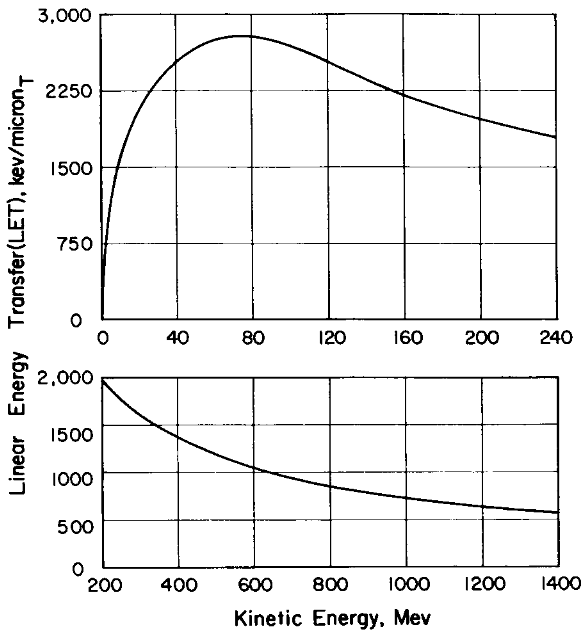

Figure 5

LET/Energy Function for Ca Nuclei Based on Data of Reference 7

The maximum LET, the so-called Bragg peak, for any kind of ionizing particle occurs at very low energy shortly before the particle reaches the end of its ionization range. Since the energy spectra of the primary galactic radiation outside the magnetosphere shown in Figures 1 and 2 are continua without any sharp cutoff at the low or high energy side, the LET distributions will extend at all depths in a shield or target from the Bragg peak maximum to the relativistic minimum. In other words, width and location of the distribution on the LET scale for a given type heavy nuclei will not change as the beam is gradually attenuated. As the radiation penetrates more deeply into the shield or human body, changes do occur in the configuration of the distribution curve within the just-defined invariant limits. However, these changes are quite moderate since the energy spectra in Figures 1 and 2 do not change much if the small differential fluxes at low energies are removed from the beam by absorption. It seems sufficient, therefore, to analyze the LET distribution for one depth, which can be selected arbitrarily as long as it remains at the left side below the maxima of the fluxes in Figures 1 and 2. The following analysis was carried out for 3 g/cm^2 which fulfills the indicated requirement and at the same time would seem a good estimate for the inherent shielding of a larger vehicle.

Since the LET distributions for most radiations, x- or gamma as well as nuclear, extend over a rather wide range on the LET scale, it has become customary to use plots with a log LET abscissa scale normalizing the total area under the distribution curve to unity. For more details on this technique the reader is referred to an earlier report (8) or directly to the publications of Howard-Flanders (9) or Burch (10) or to the review in NBS Handbook 78 (11). Since, in the present context, the LET distributions of galactic primaries are analyzed for the express purpose of comparing them to standard x-rays, the LET distribution of the latter radiation should be introduced first. The upper graph of Figure 6 taken from a study of Cormack and Johns (12) shows this distribution. It is seen that the graph covers the wide LET interval from 0.40 to 35 kev/micron T. Also plotted in the same graph is the RBE/LET relationship as it follows from the formula recommended by the RBE Committee of the International Commission of Radiation Protection (13). Realizing that x-rays of 200 kv by definition represent the standard radiation for which the RBE is 1.0, one sees the principal difficulty of establishing, from the wide LET distribution for standard x-rays, a precise numerical relationship between RBE and LET.

Of special interest is the "spike" at the right end of the standard LET distribution. It represents the energy dissipation in the terminal sections of electron tracks where the LET increases very steeply to its maximum as the electron comes to rest. Similar spikes occur also in nuclear radiations provided the energy spectrum has no low energy cutoff, i.e., begins at zero. For a nuclear radiation the spike represents in the same way as for electrons the energy dissipation in the Bragg peak at the end of the particle track where the LET steeply increases to its maximum.

The lower graph of Figure 6 shows the LET distributions for the five components of the primary galactic radiation. Due to the fact that the bulk of the flux for all components is of high and very high energies, the LET distributions center heavily on the minimum value. At the minimum LET itself the energy dissipation grows so large that its graphical presentation on a linear ordinate scale poses difficulties; therefore, merely the stumps of the extremely high and sharply pointed maxima are drawn in Figure 6, with arrows pointing in the direction of each maximum. The left flank of the maximum is absolutely vertical since the energy dissipation at the minimum LET drops discontinuously to zero. The right-hand flank forms a very small but finite angle with the vertical, and this angle sensitively depends on the LET/E function near the minimum LET. The absolute value of the energy dissipation at the maximum can be easily computed if one remembers that the total area under the distribution curve must equal unity. However, this absolute value of the maximum is of no special significance radiobiologically.

It is essential to realize that the LET distributions of Figure 6, those for standard x-rays, and for the galactic particles as well are normalized. That means the ordinate values are adjusted in such a way that the areas under all LET distributions are equal. Only such normalized curves allow direct quantitative comparisons of fractional doses at given LET values. The absolute dose fractions in millirads/24 hours for the five components cannot be read from the lower graph in Figure 6. They are listed in Table I together with other basic information on the galactic primaries.

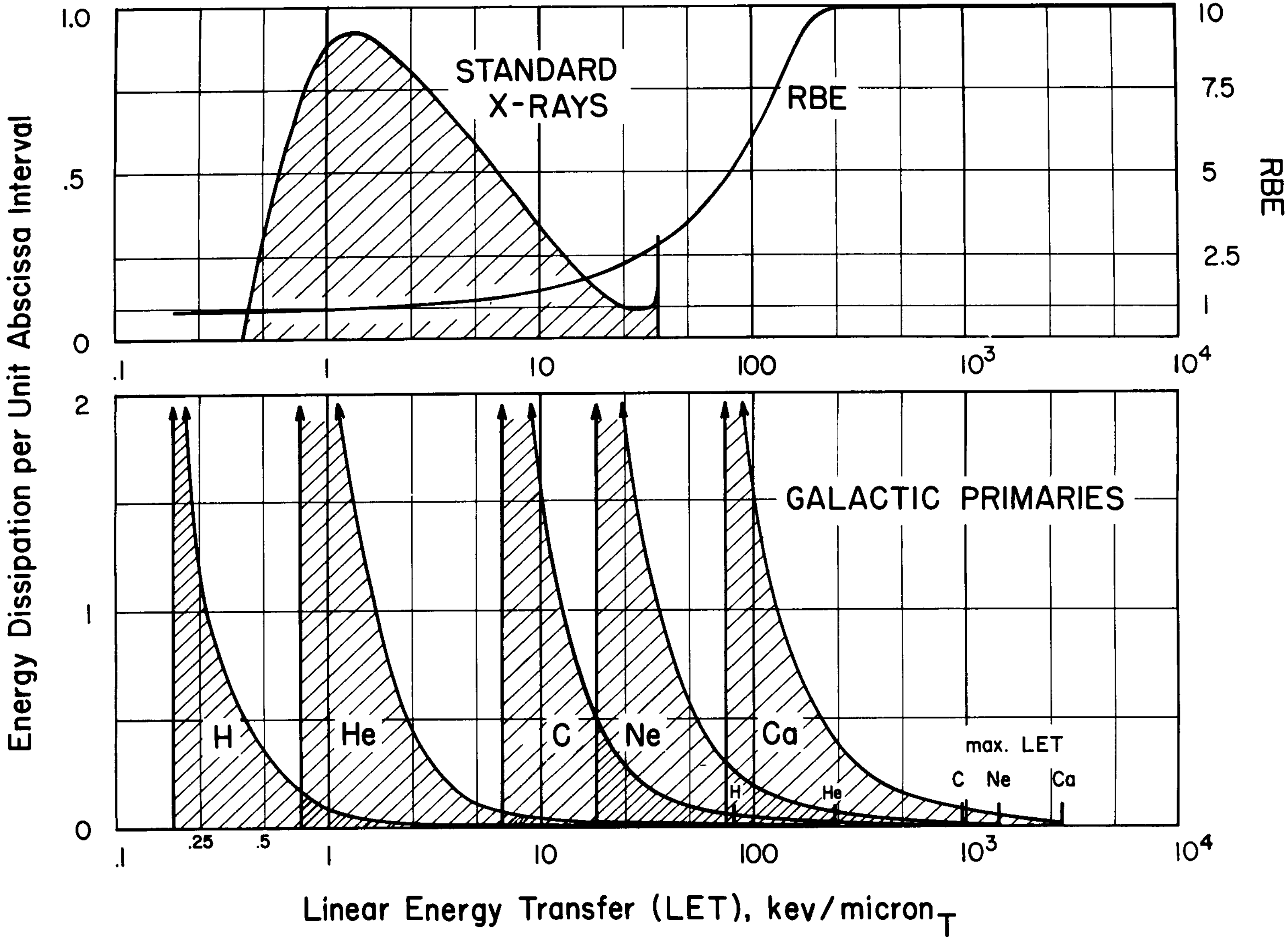

Figure 6

LET Distributions of Standard X-Rays (Reference 12) and of Heavy Galactic Primaries in Tissue and RBE/LET Function

Table I

Dosimetric Data on Primary Galactic Radiation

Element		H	He	C	Ne	Ca
Atomic Number Z		1	2	6	10	20
LET,	Minimum	0.18	0.73	6.6	18	73
kev/micron T	Maximum	85	240	964	1420	2790
Ionization dose, millirads/24 hours		5.3	3.2	2.0[a]	1.1[b]	1.6[c]
Mean RBE[d]		0.75	1.00	1.59	2.86	6.64
Dose equivalent, millirems/24 hours		3.98	3.20	3.18	3.15	10.62

a: For Class Z = 3 to 9; b: For Class Z = 10 to 19; c: For Class Z = 20 to 28.
d: Computed from LET distribution with RBE formula of the RBE Committee of the ICRP.

Contrary to conditions for electrons, where the LET reaches its maximum at the very end of the particle track, the maximum LET occurs for nuclear particles a very short distance before the end (2 micra T for protons, 46 micra T for Ca nuclei) and then drops steeply to zero. As the exact shape of this final descent of the LET to zero is not known, the exact height of the spike at the upper end of the LET distribution remains uncertain. For this reason the spikes in the lower graph of Figure 6 are drawn with the same arbitrary height for all five components. Accordingly, the spikes should be interpreted merely as denoting the position of the steep terminal rise of the curve on the LET scale. A quantitative assessment of the extremely small fraction of the energy dissipation at the maximum LET would require a separate and entirely different approach. The fractional dose at the maximum LET represents radiobiologically an essentially unknown quantity best described dosimetrically with the term "microbeam." As this problem has been discussed repeatedly (14) and no new viewpoints or experimental evidence have been produced so far, it shall not be taken up again here.

CONCLUSIONS

If we proceed now to the crucial point of the entire analysis, the interpretation of the five LET distributions in the lower graph of Figure 6 in terms of dose equivalents, we see immediately that a large part of galactic radiation exposure falls into the region of low and very low LET values. For the proton component in particular the bulk of the energy dissipation takes place at LET values even below the lowest LET of standard x-rays. In fact, the LET distribution of galactic protons closely resembles the one for Co-60 gamma rays. This is to be expected since for both radiations a large part of the energy dissipation is produced by relativistic particles of single charge. Since LET depends only on charge and speed, but not on mass, there is no difference in the energy loss between electrons and protons of the same speed.

Since Co-60 gamma rays show a markedly smaller RBE than standard x-rays, the same statement would hold also for primary protons of the galactic radiation because of the close similarity of the LET distributions. It must be mentioned in this connection that the RBE curve in the upper graph of Figure 6, drawn according to the formula of the RBE Committee, shows conservatively high RBE values, especially in the region where LET values are lower than those of standard x-rays. As shown by Ashikawa and colleagues (15) and also by Kurlyandskaya (16), the RBE of protons in the 600 to 700 Mev energy region corresponding to the LET values in question is well below the minimum value of 0.9 which follows from the formula of the RBE Committee. Depending on the particular type of radiation injury used as criterion, RBE values of 0.6 to 0.9 have been reported. It is seen, then, that the proton contribution to the total dose from galactic primaries should be assigned an RBE well below 1.0.

Proceeding to the alpha component, one sees from Figure 6 that the bulk of the energy dissipation falls well within the LET limits of standard x-rays, assuring that for this dose contribution an RBE of 1.0 is appropriate. The picture changes as we proceed to heavier components. For C nuclei, a sizeable portion of the energy dissipation extends into the LET region for which the RBE factor exceeds 2.0. If the mean RBE for the absorbed dose from the C component is computed by numerical methods from the LET and RBE curves, a value of 1.56 is obtained. The corresponding mean RBE values for Ne and Ca nuclei are 2.86 and 6.64, respectively. Weighing these mean RBE values for the individual components according to their respective shares in the total dose and using a mean RBE of 0.75 for the proton contribution, one arrives at an over-all mean RBE of 1.82 for the total dose from galactic primaries. This value might appear unexpectedly low in the light of other estimates in the literature. The discrepancy is due mainly to the fact that in the present analysis a ceiling value of 10 for the RBE was used whereas in other estimates values up to 20 have been assumed. Justification or preference for either value is largely subjective and any argument seems pointless. It is felt that main emphasis should be placed on the LET distributions themselves rather than on dose equivalents. The LET distribution describes the energy dissipation of a radiation in rigorous terms, and comparing it with the distribution for standard x-rays or any other type of radiation for which radiobiological data are available identifies that part of the total energy dissipation that cannot be assessed in common dosimetric units. It would appear that this approach avoids misleading impressions which the quoting of a clear-cut dose value in millirems/day yet based on an entirely arbitrary RBE factor might produce.

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13. ABSTRACT

In assessing the astronaut's exposure from galactic cosmic rays on space missions of long duration conversion of absorbed doses to dose equivalents is required. Since a large part of the dose contribution from heavy primaries is produced at Linear Energy Transfer (LET) values beyond the range for which radiobiological data are available, it seems preferable to analyze the LET distributions themselves and to compare them to standard x-rays rather than to assume arbitrary values for the Relative Biological Effectiveness (RBE). The local LET distributions in tissue are found to be extremely skewed, with a large maximum at the relativistic minimum LET. Lined up on the LET scale, they cover the very wide interval from 0.18 to 2790 kev/micron T as compared to an interval from 0.4 to 35 kev/micron T for standard x-rays. Applying the RBE formula of the RBE Committee of the ICRP and a saturation value of 10 leads to a grand mean RBE of 1.82 for the total absorbed dose of 13 millirads/24 hours from primaries.

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