GALACTIC COSMIC RAY HEAVY PRIMARY SECONDARY DOSES*

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The free space dose rates from the various components of the galactic cosmic rays can be determined from the particle energy spectra and energy loss data. Depth-dose profiles in material shields or in body tissue are complicated by the nuclear cascade set up in the material by the incident primaries. While considerable work has been done on the proton induced particle cascade, the heavy primary secondary dose from the galactic cosmic rays, which also fragment and cascade, has not been estimated.

In this paper we present the results of a calculation which estimates the heavy primary secondary doses from cosmic ray interaction data. The incident galactic cosmic ray heavy primary spectrum is represented as the sum of helium, nitrogen (M group), magnesium (light heavy), and iron (very heavy) components. The incident iron nuclei are allowed to fragment into lesser Z secondaries, which are assumed to travel in the same direction and start with the same energy per nucleon as the interacting primary. The total emergent particle energy spectra and dose are then presented for the galactic heavy primary spectrum incident on aluminum and tissue slabs. The importance of the fragmentation parameters assumed is also evaluated.

The total dose from the heavy primaries and their secondaries is found to be reduced by only a factor of two in 20 g/cm^2 of shielding.

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We present here a method for the calculation of the secondary particles produced by heavy galactic primaries. The galactic cosmic ray spectrum consists of protons, helium and higher Z elements, all with a similar energy spectrum, but of reduced intensity with increasing Z. As these particles pass through matter, both nuclear interaction and ionization reduce the intensity and energy of the incident spectrum. While the electromagnetic interaction for the particle energies of interest are well understood, and their effects readily calculated, the nuclear interactions lead to complex cascades of secondary particles. While a great deal is known about the cascade products of proton induced reactions, the cascades induced by the higher Z elements of the galactic cosmic rays have received less attention.

The fraction of the yearly free space dose resulting from the various components of the galactic cosmic rays are shown in Table I, as determined from the particle energy spectra given in Reference 1.

In Figure 1, we show the depth-dose profiles for the helium and higher Z particle groups under two assumptions: 1) that only electromagnetic interactions attenuate the flux, and 2) that the particles suffering nuclear interaction are removed from the beam (uncollided particle dose only). The wide range between these estimates indicates a need for further analysis.

TABLE I

Component	Yearly Dose
H (Z=1)	4.6
He (Z=2)	3.5
M ($6 \leq Z \leq 9$)	1.9
LH ($10 \leq Z \leq 14$)	1.3
VH ($26 \leq Z \leq 28$)	1.3
TOTAL:	12.6 rads/ year

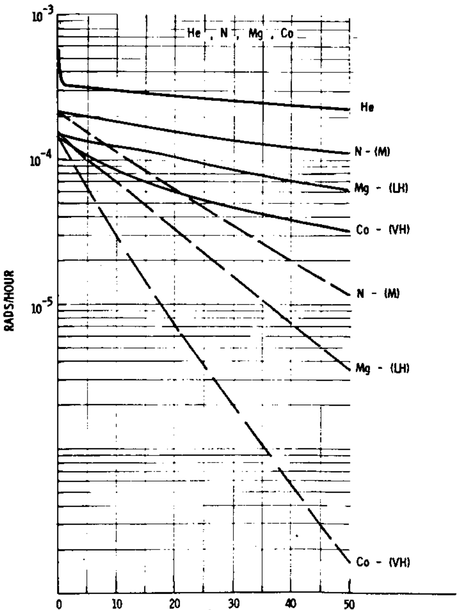

Figure 1: HEAVY PARTICLE GALACTIC DOSES

FORMULATION OF THE CALCULATION

Let ϕ_i (E,x) be the differential number flux of ions of type i at a point x in the absorber. Then it is easy to show that the relation between the incident flux and the flux at a point in the absorber is given by

$$\phi_i(E',x)=\phi_i(E,0)\frac{S(E)}{S(E')}$$

neglecting nuclear interactions.

If we include nuclear interactions, and change variables to energy per nucleon, T, we have

$$(1)\quad \phi_i(T',x)=\phi_i(T,0)\times \frac{S(T)}{S(T')}\exp-\int_T^{T'}\frac{\mu_i(T)dt}{S(T)}$$

where S(T) is the stopping power of the ion of type i and energy per nucleon T. If μ_i is energy dependent, then we have simply $\exp[-\mu_i x]$ for an attenuation factor. The uncollided flux can then be determined at points of interest in the absorber.

Now ions of type i produce secondary ions of type j at points in the absorber at the following rate

$$(2)\quad \frac{d\phi j}{dx}(T',x)=\phi_i(T,x)\frac{No}{M}\,\sigma_i(T)P_{ij}(T,T')$$

where

$\phi_i(T,x)$	is the energy spectrum of ions of type i
$\sigma_i(T)$	is the interaction cross section for ions of type i and energy T
$P_{ij}(T,T')$	**is the fragmentation parameter, giving the probability for an** interaction of type i ions at energy T to produce a secondary ion of type j and energy T'
N_o =	Avogadro's number
M =	the atomic weight of the absorber
$\frac{d\phi_j}{dx}(T',x)=$	the rate at which particles of type j and energy T' are being produced in the absorber at point x

Particles of type j are slowed and attenuated as they pass through the remainder of the absorber and they emerge with an energy related to their initial energy T, and remaining path length in the absorber, X-x, of

$$Rj(T)=Rj(T_f)+X-x$$

and with an intensity reduction of

$$\frac{S(T)}{S(T_f)}\exp[-u_j(X-x)]$$

The emerging flux of type j particles produced by type i primaries is then

$$(3)\quad \phi_j(T_f,X)=\frac{No}{M}\int_0^X\phi_i(T,x)\times \sigma_i(T)P_{ij}(T)\frac{S(T)}{S(Tf)}\times \exp[-u_j(X-x)]dx$$

Now we apply these basic relations to the problem of determining the final penetrating energy spectrum of the galactic heavy primaries and induced secondaries in an absorber. First, we consider a maximum Z of 26, as only a small number of higher Z particles are present in the galactic cosmic ray flux. The penetrating flux of $_{26}$Fe particles at any point in the absorber can be determined by expression (1). Once ϕ_{26} (T,x) is known, then the rate at which lower atomic number particles are being produced at points in the absorber can be determined by expression (2).

The total production rate of particles of type j is given by the following sum

$$\frac{d\phi j}{dx}(T,x)=\sum_{i=j+1}^{26}\phi_i(T,x)\frac{No}{M}\sigma_i(T)P_{ij}(T)$$

where $\phi_i(T,x)$, the total flux of particles of type i, depends on both the incident flux and the accumulated secondary flux.

To determine the penetrating flux of particles, a computer program was developed to evaluate the expressions discussed numerically. This program evaluates the production rates of the secondaries at a set of thickness points in the absorber for a suitable energy grid. Then by sequential transporting the highest Z element through the absorber and determining the production rates for all lower Z elements, we obtain the final penetrating number energy spectrum.

BASIC ASSUMPTIONS USED IN THE CALCULATION

The preceding section has developed the formations used in the calculation of the secondary particles produced by the heavy galactic primaries. Now we discuss the basic assumptions used in this analysis, and some of the resulting limitations in the present calculations.

First we employ the straight ahead, or one dimensional approximation. This can be justified by use of cosmic ray interaction data as discussed in Reference 2 which shows that the heavy fragments emerging from the interaction site are strongly peaked in the forward direction. It is well known that the primary heavy particles suffer little angular deflection while passing through matter.

Second, we use the energy independent overlap cross section model used by Cleghorn, et al. (Reference 3) to fit his cosmic ray emulsion results. It was found that cross sections were essentially independent of energy in the energy range 100 MeV/nucleon to 30 GeV/nucleon. At energies below 100 MeV/nucleon, the higher Z primaries have a small range, but their cross section will probably be underestimated in this energy region.

The fragmentation function, $P_{ij}(T,T')$ represents the least well known quantity required in the calculation. Since the energy dependence of the secondary fragments has not yet been described, we make the simple assumption that T=T', that is the fragments have the same velocity as the primary ion. This assumption is in agreement with an interaction model in which the heavy primary is stripped of some fraction of its mass, and proceeds on with unchanged velocity. Two sets of fragmentation parameters were then used to explore the effects of various assumptions on the final results. In the first approximation, we have used a set of fragmentation parameters which assume one ${}_1H$, one ${}_2He$, and an equal probability of higher Z fragments normalized to conserve Z in the incident heavy primary. This approximation, when coupled to the equal velocity approximation, leads to approximate conservation of energy, neglecting nuclear binding energies and pion formation. The second set of fragmentation parameters are described in the paper by Curtis in these Symposium proceedings.

Both sets of fragmentation parameters are assumed to be independent of the primary particle energy, a conclusion that is consistent with the results of Cleghorne.

Finally, the calculations have neglected the interactions of primary and secondary ions with hydrogen. While the results of Bertini's internuclear cascade calculation can be applied to this problem by a proper transformation of rest frames this has not yet been incorporated in the calculation. The results given for tissue thus neglect the fragmentation induced by hydrogen.

RESULTS

Typical results of this calculational method have been developed with the assumptions discussed. First, using the VH group heavy particle spectrum presented in Reference 1, depth dose profiles for a unidirectional beam of particles incident normally on a slab of water and aluminum are shown in Figures 2 & 3. The total tissue dose, the ${}_{26}Fe$ (VH) dose, and selected lower Z secondaries are shown. For H_2O, the two sets of fragmentation parameters are represented by (1) solid lines and (2) dotted lines. We see the expected rise and more gradual fall of the secondary dose components.

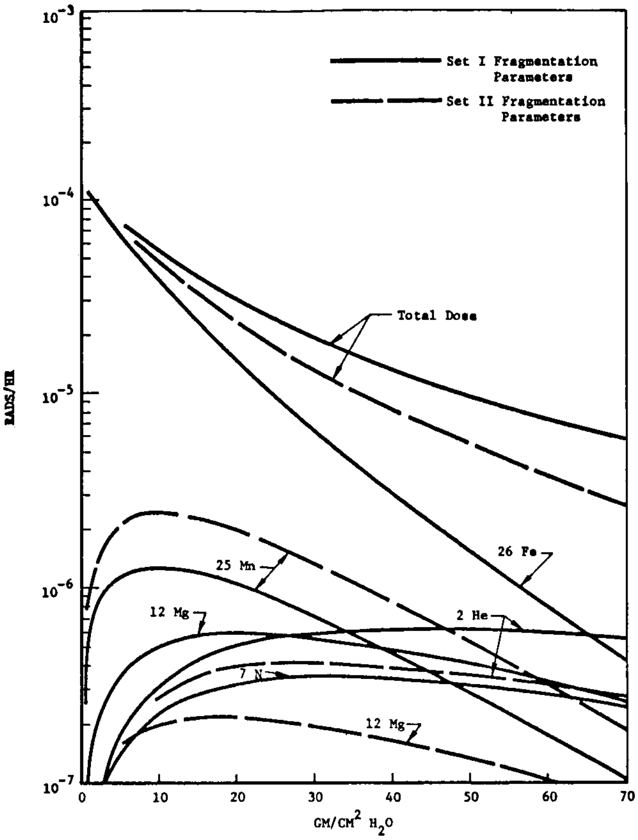

Figure 2: HEAVY GALACTIC PRIMARY VH GROUP DOSE

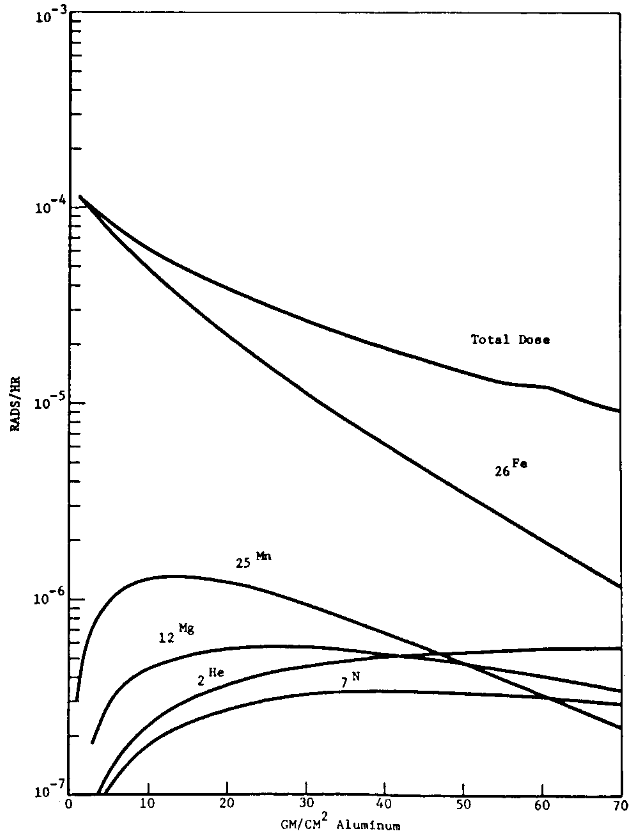

Figure 3: HEAVY GALACTIC PRIMARY VH GROUP

With the complete GCR spectra, as represented by VH, LH, M and Helium components, the results are as shown in Figure 4.

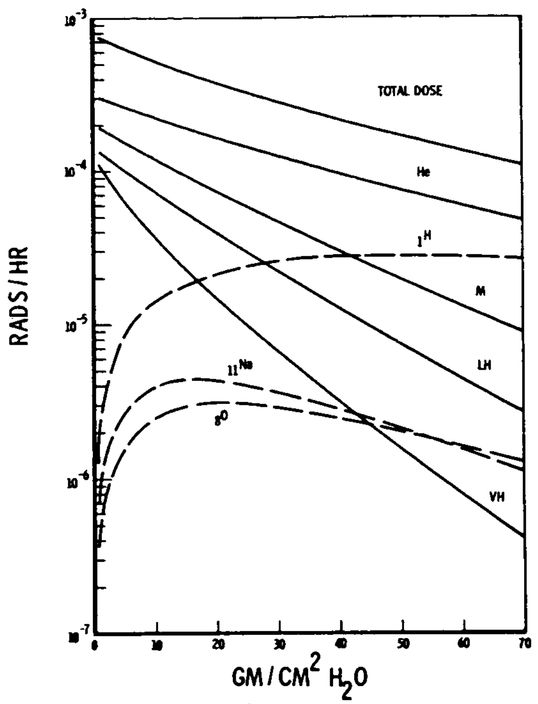

Figure 4: HEAVY GALACTIC PRIMARY TOTAL DOSE

Meyer (Reference 4) has reviewed the galactic cosmic ray data available up to 1969, and has presented an estimate of the intensity of all the heavy primary components below $_{26}$Fe. From this compilation we have calculated the total depth dose profiles in water for incident primaries $_2$He to $_{26}$Fe, and presented the results in Figure 5.

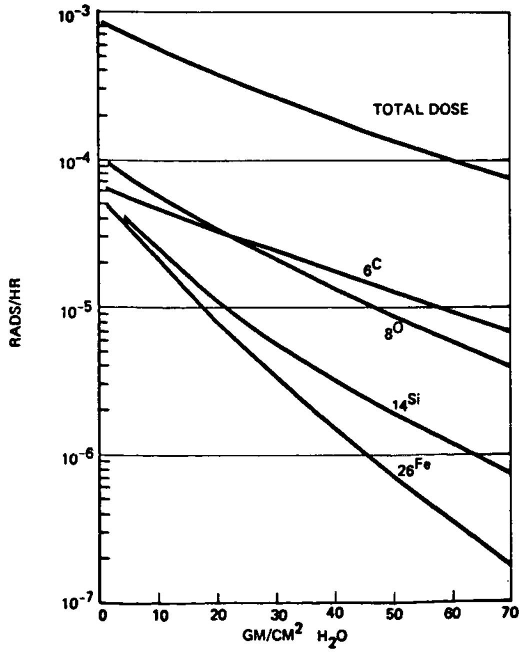

Figure 5: HEAVY GALACTIC PRIMARY TOTAL DOSE Separate Spectra, Excluding Proton Dose

CONCLUSIONS

The results presented indicate the general nature of the total depth-dose profiles we can expect in tissue and aluminum absorbers. Uncertainties in the fragmentation parameters lead to significant changes in the total dose, as well as the dose distribution among the secondary components. Further work in defining the fragmentation parameters and incorporation of the hydrogen interaction results for tissue would improve these dose estimates.

While only dose results are presented in this paper, the penetrating particle energy spectra are also calculated, and can be used to examine the LET spectra for further study of the biological implications of the galactic cosmic rays.

REFERENCES

1. S.B. Curtis and M.C. Wilkinson, "Study of Radiation Hazards to Man on Extended Missions" NASA CR-1037, May 1968
2. S.B. Curtis, W.R. Doherty, and M.C. Wilkinson, "Study of Radiation Hazards to Man on Extended Near Earth Missions", NASA CR-1469, December 1969.
3. T.F. Cleghorne, P.S. Freier, C. J. Waddington, Canadian Journal of Physics, 46, 5572 (1968).
4. P. Meyer, "Cosmic Rays in the Galaxy", Annual Reviews of Astronomy and Astrophysics, Vol. 7, Page 1, 1969.