Tissue Ionization Dosages in Proton Radiation Fields in Space

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SYNOPTIC observations of the intensity and composition of the cosmic ray beam at extreme altitudes and in space during and after the IGY have established the fact that strong additional fluxes of ionizing particles are superimposed, at certain times and in certain regions, upon the so-called quiescent cosmic radiation. Protons, electrons and x-rays have been identified as the constituents of these transitory beams. Similarly as in the quiescent radiation, the protons seem to carry the highest share of the total energy flux. The best known of these radiation fields is the Van Allen Belt. Yet, it is by no means the only high intensity radiation field in space. Similar fields have been observed within the vicinity of auroral displays.

Aside from decay protons of cosmic ray neutrons backscattered from the earth's atmosphere, the single major source for the proton beams in interplanetary space is the solar wind consisting of extremely rarified ionized hyrogen (plasma) ejected from the sun. The ejection rate of these protons from the sun is highly irregular depending on solar activity. Furthermore, wherever these proton beams interact with magnetic fields, be it the solar or telluric field, the galactic field, or fields created by the turbulent motion of the solar wind itself, deflecting, focusing and accelerating forces come into play which produce additional large local and temporal changes of the intensity. From the standpoint of human space travel, then, the question arises what intensities and penetrating powers of the local proton flux might be encountered during a space voyage on a certain trajectory and under certain conditions of solar activity. Several authors have speculated on the electrodynamics of the motion of the solar wind and its interaction with magnetic fields. Others have communicated actual measurements conveying the first direct information on the particle intensities and the energy spectra involved. While present knowledge is still fragmentary in many instances, some general characteristics become already distinguishable. Their implications for the exposure hazard in space flight are of such obvious significance that a detailed evaluation appears of special interest. The following treatise is strictly limited to these radiobiological aspects.

It is a characteristic feature of solar proton beams in space that the flux shows local and temporal variations over a truly tremendous range not only with regard to the total particle intensity, but also with regard to the rela-

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tive shares of particles of different energies. Since the energy directly determines the penetrating power, it is seen that for a meaningful radiobiological evaluation, one must not satisfy oneself with a determination of what, in "terrestrial" terminology, would be called the "air" dose, but must proceed to a quantitative analysis of the intra-target dosage distribution. Indeed, a proton beam of great intensity in the energy range of 10 Mev will not be of particular interest for the radiobiologist since it would have a range in aluminum of only 0.7 millimeters and therefore is not likely to penetrate the wall of a space capsule. Yet, a beam of moderate intensity in the 100 Mev energy interval corresponding to a range in aluminum of 4 centimeters certainly would require close attention from the radiation safety standpoint.

The actual energies encountered in proton beams in extra-atmospheric regions cover the wide range from the gas-kinetic level to many million e-volts. In fact, there is no well defined upper limit of energy since all proton spectra gradually change over, at the upper end, into the ordinary cosmic ray proton spectrum in which individual particles of 10^{18} e-volt energy are not uncommon. This extremely wide energy range corresponds to a similarly wide range of penetrating power. Yet, for a target of the size of the human body shielded by the walls of a vehicle only a certain fraction of the total spectrum is of direct interest. Obviously protons of such low penetration that they will be completely absorbed in the vehicle walls will not have to be taken into consideration. On the other hand, protons of such high penetration that their attenuation in the target is negligible will deliver the same local ionization dosage at all depths within the target and do not require any analysis of the depth of penetration.

With regard to the low end of the spectrum, additional limitations are imposed by instrument factors. In all measurements with balloons, rockets or satellites, a certain unavoidable prefiltration is constituted by instrument casings, vehicle walls, and, for balloons, by the residual atmosphere. As an unfortunate consequence, the exact configuration of the spectrum for very low penetrating powers simply is not known. The analysis of the intra-target dosage field, therefore, cannot be extended below a certain limit. In the following discussion, a minimum value of 2 g/cm^2 has been assumed throughout for the evaluation of all intratarget dosage fields. In other words, this means that a minimum prefiltration of 2 g/cm^2 afforded by the walls of the vehicle or any other interposed protective layer is assumed as always present. It is realized that this is not quite satisfactory for the case of a man freely exposed in a full-pressure suit outside the vehicle since this would correspond to a prefiltration of only 0.2 g/cm^2. Yet present information does not permit a quantitative analysis of this particular case, as just noted.

BASIC TYPES OF PROTON SPECTRA IN SPACE

Figure 1 shows three representative energy spectra which illustrate well the very wide range of variability encountered in proton fluxes in space. As a comparison, the spectrum of the quiescent cosmic ray beam is also shown.

Even this spectrum exhibits a certain variation inasmuch as the intensity in years of high solar activity during the eleven-year cycle is markedly lower than in years of low activity. The presumable cause of this phenomenon is to be sought in stronger magnetic screening effects at high solar activity.

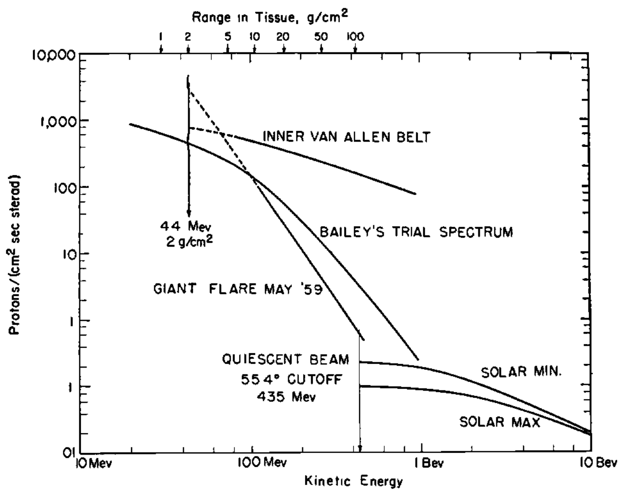

Fig. 1. Integral energy spectra of various proton radiation fields in space. Note enormous intensity of flare 59 spectrum observed at 55.4° magnetic latitude, i.e., in a magnetically forbidden region.

A conspicuous feature of the transitory spectra is the steep drop of the particle intensity toward higher energies. It is most pronounced in the spectrum observed after the giant solar flare of May 10, 1959, as communicated by Ney, Winckler, and Freier.[5] The spectrum is based on balloon observations at 10 g/cm² residual pressure altitude. This means that the spectrum is experimentally verified only down to an energy of 110 Mev. The extrapolation further down to 44 Mev is indicated by a broken line in Figure 1. It has to be realized that the observations have been carried out in Minneapolis at a geomagnetic latitude of 55.4°. As indicated in Figure 1, the geomagnetic cut-off for the ordinary cosmic ray beam at that latitude is 435 Mev. That means that the entire flare-produced proton flux is in a forbidden energy interval and must have been protected from the earth's dipole field by a local field in the plasma cloud in which it was contained.

The counterpart of the flare-produced radiation is the radiation field in the inner Van Allen Belt as recorded by Freden and White.[3] Figure 1 shows that this radiation exhibits a spectrum of considerably smaller slope. This means that the relative share of high energy protons is considerably larger than in the flare spectrum. As a consequence, profoundly different patterns of the intratarget dosage field result for the two proton fluxes.

The two spectra just presented constitute the extremes between which transitional intermediate types of energy distributions might prevail at times and under certain conditions in space. In the attempt to establish a representative mean spectrum which would do justice to all available data, Bailey[2] has proposed what could be called a synthetic spectrum. In its low-energy section it splits up in two models, a Model 1 assuming no geomagnetic influences and a Model 2 assuming partial geomagnetic screening. For the intratarget dosage distribution, the two models differ considerably as will be shown later. In Figure 1, only Model 2 is shown. It differs from Model 1 in the low-energy range below 125 Mev where it shows a less steep slope.

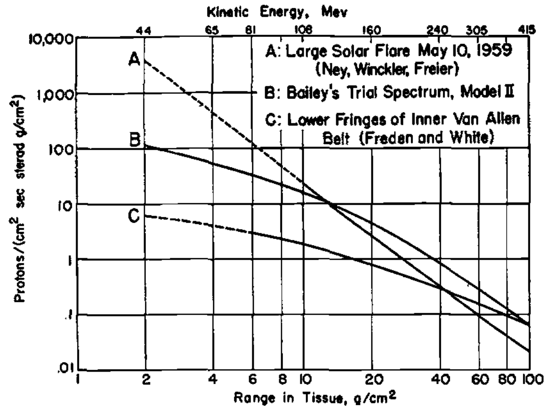

Fig. 2. Differential range spectra of transitory radiation fields in space shown in Figure 1.

Integral energy spectra such as those shown in Figure 1 are not very meaningful for the radiobiologist who prefers to classify radiations with regard to their penetrating power since the intratarget dosage distribution depends on it. The analysis of this distribution is most easily carried out on the basis of the differential range spectrum. Since the range-energy relationship is well investigated for protons and has been tabulated repeatedly, for example, by Sternheimer,[9] the conversion of the integral energy spectrum into the differential range spectrum is a routine matter. The resulting spectra are shown in Figure 2. Special attention is directed to the logarithmic ordinate scale comprising an intensity interval from 1 to 1 million lest the reader, in a perfunctory inspection, gains the impression that the spectra are basically alike because of the apparently quite similar slope. Actually they differ profoundly as a closer comparison of corresponding particle intensities at various ranges will reveal. However, for full comprehension of what these differences mean in terms of the total body radiation burden, the dosage distribution within a human target must be analyzed.

THE INTRATARGET DOSAGE FIELD FOR THE BASIC TYPES OF SPECTRA

The basic procedure of how to compute the dosage distribution for a given differential range spectrum has been described before[7] and the results for the proton beam in the inner Van Allen Belt presented. The particular target selected in the earlier report will also be used in the following analysis. It is a spherical tissue volume of 52 cm. diameter corresponding to 75 kg. weight. While this is a crude approximation of the human body, the well defined geometrical form has the advantage of simplifying greatly the geometry of an incident omnidirectional beam and of demonstrating more clearly the important features of the depth dose pattern. Figure 3 amplifies the earlier evaluation[7] by adding to the one prefiltration thickness of 2 g./cm.^{2} the depth dose curves for 4, 6, 8 and 12 g./cm.^{2} prefiltration. A conspicuous feature of these data is the much stronger influence of the prefiltration on the target entrance dose than on the depth dose in the center of the target. Whereas the former drops from 0.23 to 0.105 rep./hr. that is, i.e., by 55 per cent for an increase of 10 g./cm.^{2} in prefiltration, the latter drops from 0.98 to 0.75 rep./hr., that is, i.e., by only 24 per cent. This indicates the substantial increase of the penetrating power as the radiation beam reaches more deeply into the target.

Figure 4 presents the intratarget dosage fields for all four proton spectra under discussion. At the upper left, three selected curves from the graph in Figure 3 are shown again. The dissected graph at the upper right shows the corresponding three curves for the flare-produced protons flux, and the two lower graphs pertain to the two models of Bailey's trial spectrum. The extremely small penetrating power of the flare-produced radiation as compared to the Van Allen radiation is striking. These two spectra seem to represent the limiting cases of a very

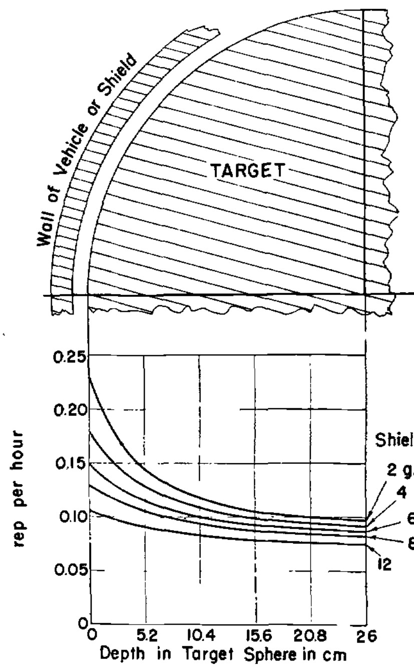

Fig. 3. Depth dose curves for a spherical tissue phantom of 52 cm. diameter (75 kg. weight) exposed to the proton beam in the lowest fringes of the inner Van Allen belt. Intensity in center of belt is about 500 times larger, yet depth dose pattern is not known.

hard and a very soft type of proton radiation, whereas the two models of Bailey's spectrum, shown in the lower part of Figure 4, occupy an intermediate position. The two latter spectra, at the same time, demonstrate the large influence of the geomagnetic cut-off and emphasize the importance of an accurate determination of the low-energy of the spectrum.

A more concise description of the different quality of the four types of proton beams can be given by express-

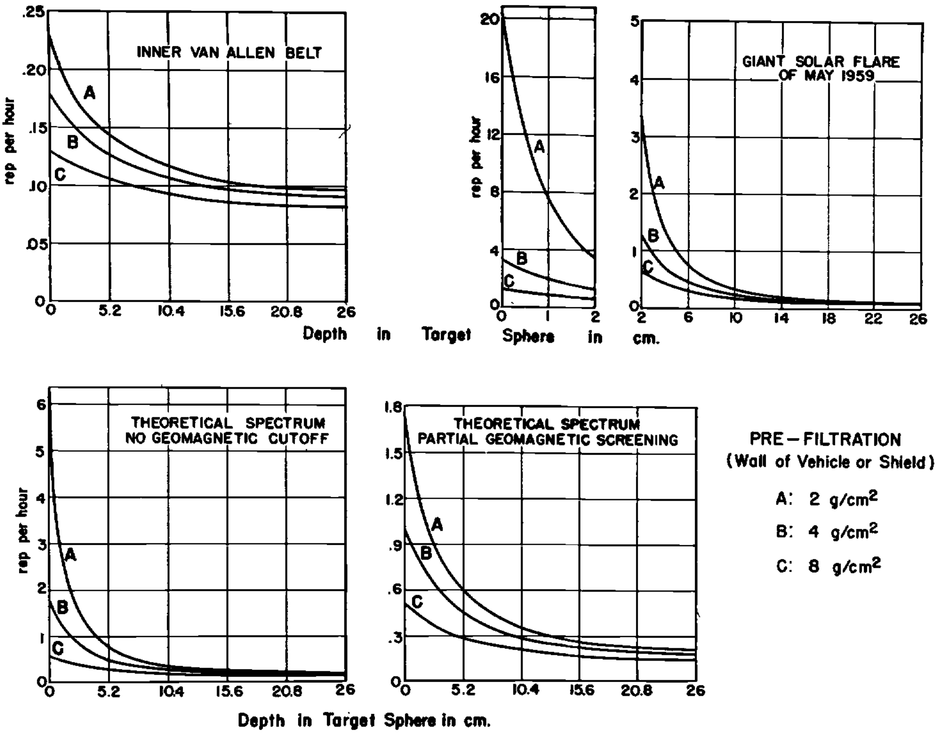

Fig. 4. Depth dose curves for same phantom as in Figure 3 for four basic types of proton radiation fields in space.

TABLE I. PERCENTAGE DEPTH DOSES* FOR DIFFERENT PROTON RADIATIONS IN SPACE

Type of Radiation	Prefiltration		
	2 g/cm²	4 g/cm²	8 g/cm²
Flare-produced radiation	0.6%	2.9%	10%
Bailey's spectrum model 1	3.6%	10%	26%
Bailey's spectrum model 2	12%	19%	29%
Inner Van Allen belt	42%	51%	64%

*Shown is dose in center of target used in Figures 3 and 4 expressed in per cent of surface dose for various prefiltration thicknesses.

ing the depth dose in the center of the target sphere in per cent of the surface dose. Table I gives the pertinent values. The spectra are listed in order of increasing penetrating power. The horizontal lines in the table show the hardening effect of prefiltration and the vertical columns the comparative hardness of the different beams.

Though the different penetration and the effect of prefiltration seems well described in Table I, it holds only for the particular spherical target used in Figures 3 and 4. Obviously, a more general method of designating the quality of a given proton beam would be desirable. Besides the percentage depth dose, the half value layer (HVL) is often used in medical dosimetry. For a heterogeneous radiation beam in particular, the change of the HVL is sometimes denoted by giving the first, second, and third HVL. The discontinuous change in such a tabulation of consecutive HVL's is, of course, an artifact. More appropriately, the HVL concept should be used differentially by expressing the instantaneous attenuation at a given depth as an exponential function and by deriving the HVL corresponding to the local coefficient of attenuation.

Figure 5 shows in its lower graph such a HVL curve for 250 kv x-rays in lead as a representative example of

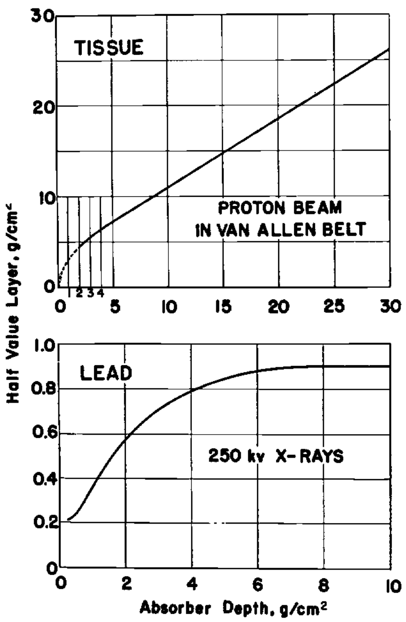

Fig. 5. Half value layer transition for conventional x-rays and for proton beam of inner Van Allen Belt. Note complete absence of saturation effect in Van Allen radiation.

the normal type of HVL transition as it is found with collimated beams of x- or gamma rays. It is seen that the HVL increases in the initial layers of the absorber and then levels off to a constant value. The upper graph in Figure 5 shows the HVL of the proton beam in the inner Van Allen Belt based on the data of Freden and White (l.c.). The profound difference from the ordinary type of transition curve is clearly seen. For the Van Allen radiation the HVL never levels off to a constant value indicating that the spec-

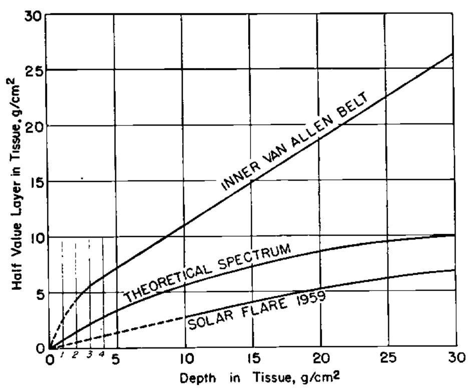

Fig. 6. Half value layer transition for three basic types of proton radiation fields in space.

trum is a continuum of infinite extension toward higher energies. In Figure 6 the same graph is reproduced again and shown together with the corresponding curves of the flare-produced and the Bailey Model I radiation. The very large heterogeneity of the radiations in question as well as their individual differences seem well described in this way.

CONCLUSIONS

In proceeding from the dosimetric analysis to a discussion of the radiobiological implications concerning radiation hazards, one should realize that for the type of proton radiations under discussion, a characterization of the total body radiation load by one simple and precise rep. or rep./hr. value is not possible. Obviously the same skin dose of, for example, 20 rep./hr. administered once by a radiation of the flare-produced type and once in the Van

Allen Belt, represents a profoundly different radiation burden for the total body. The volume dose expressed in gram-rep or kilogram-rep as suggested by Mayneord[4] would clearly show this great difference in the actually administered total ionization energy in both cases. On the other hand, a serious objection against this method of designating the radiation load must be raised in view of the particular configuration of the dosage fields under discussion. We mean the fact that the volume dose does not *per se* convey information on the maximum local dose. Especially with regard to the type of the flare-produced radiation and, to a lesser degree, to the Bailey Model I type, this implies the danger that an objectionably high skin dose is not recognized behind an acceptable volume dose.

It must also be pointed out that existing official regulations concerning the maximum permissible dose seem inadequate if they are to be applied on proton radiation fields in space. The current recommendations of the National Committee on Radiation Protection[6] distinguish only radiations that have HVLs larger or smaller than 5 centimeters of soft tissue and a third category with a HVL of less than 1 millimeter tissue ("radiation of extremely low penetrating power" Rule 3). Whether this will suffice in dealing with the proton beams in space seems questionable. Especially if one visualizes emergency conditions in space flight which might demand trespassing the official Maximum Permissible Dose by a large margin, one realizes the need for more elaborate recommendations which would more sharply point out the actual danger level for acute damage for the different types of proton spectra. Such recommendations would also have to contain specifications on how to carry out the dose determination. A possible suggestion in this respect would be to monitor the tissue-equivalent dose inside the vehicle for 0.1 g./cm.^{2}, 1 g./cm.^{2}, and 10 g./cm.^{2} prefiltration. The first value should be expressly connected to the exposure of the eyes specifying at what dose rate level a lead glass visor for local protection should be put on. The readings of the second and third monitor would serve to appraise the total body radiation burden. Eventually these measurements would have to be integrated with a determination of the beta and gamma doses from electrons and protons which probably in all cases accompany the proton flux. Since the near future is likely to augment greatly our knowledge of these phenomena from recordings of satellites and deep space probes now in orbit, a more specific discussion should be deferred until this information is available.

With regard to radiation injury to the eye, a few details are worth remembering. The element of highest radiosensitivity is the lens. It is protected toward the outside only by about 3.5 millimeters of other tissues (Aqueous, cornea, tear fluid) and is known to be much more sensitive for radiation than skin in general and to suffer irreparable damage (radiation-induced cataract) from comparatively small exposure. It seems wise to remember that once before, in the early post-war years which saw the rapid development of modern nuclear technology, irreparable damage has been inflicted upon the eyes of cyclotron workers from "surprisingly low" neutron doses as first reported by Abelson and Kruger.[1] It seems also useful to remember that neutrons inflict their damage to tissue mainly through recoil protons released locally. This fact in particular should demonstrate how very specifically the earlier experiences bear on the new problem which also involves protons.

The intricacy of the pertinent relationships is best demonstrated in a concrete example. If we visualize an astronaut in a capsule protected by a vehicle wall of ¾ inch of aluminum flying through the lower fringes of the Van Allen Belt, the lenses of his eyes are protected by an additional 3.5 millimeters of tissue as mentioned above. This additional filtration reduces the dose to the lens to about 94.5 per cent of the skin dose inside the ship. By closing his eyes, the man could further reduce the dose to the lens to 93 per cent, and by squeezing the eyes to about 90 per cent. In an auroral proton field under the same conditions the corresponding figures are 67 per cent, 59 per cent, and 47 per cent, respectively. It is obvious that in the first case, that is, in the Van Allen Belt closing the eyes and squeezing is not of much advantage, whereas in the auroral radiation field a substantial reduction of the radiation load on the lens would be accomplished. Still more drastic figures are obtained if we visualize the man as freely floating outside the ship in a full pressure suit with his eyes merely protected by 3 millimeters of plastic visor of the helmet. Exact numerical data for this particular case cannot be established at present, since, as has been pointed out before, the range spectra for these very small thicknesses are not known. Yet the increasing steepness of the spectrum toward smaller ranges indicates that the entrance dose will grow disproportionately faster for lower prefiltration than the depth dose at any point within the target.

The special problem of dose determination for very low prefiltration is further complicated by the fact that electrons and associated bremsstrahlung superimpose their ionization upon that from protons. As has been mentioned above, quantitative data on those constituents are not yet available. The general relationships concerning their attenuation in various materials have been presented before.[8] Specific design features must await more detailed experimental information.

SUMMARY

Powerful additional radiation fluxes are superimposed on the ordinary cosmic ray beam at certain times and in certain regions of space. They seem to be correlated to solar activity. Besides the well known Van Allen Belt, such beams have been observed during and after large solar flares in connection with aurorae. Protons, electrons and x-rays have been identified as constituents of these fluxes. For a possible exposure hazard to man, interest centers on the protons because of their high intensity and depth of penetration.

The energy spectra of these various proton beams in space differ considerably from each other. Four representative spectra have been selected for a detailed analysis of the intratarget dosage distribution in the human body. These are the proton radiation in the

inner Van Allen Belt, the proton radiation after the giant solar flare of May 10, 1959, and two theoretical spectra suggested by Bailey and based on a synoptic evaluation of observations.

After conversion of the integral energy spectra into differential range spectra, the intratarget dosage field for a spherical tissue volume of 52 cm. diameter (75 kg. weight) and for various thicknesses of prefiltration is analyzed. The depth dose in the center of the target is found to change from 0.6 per cent of the skin dose for the flare-produced radiation at low prefiltration to 64 per cent for the radiation in the Van Allen Belt at high prefiltration. The extreme heterogeneity of each individual type of radiation and the great differences between them make it impossible to determine the radiation burden for a human target in terms of a general total body dose in rep or rem. Quotation of the integral dose in kg rep or kg rem, though of somewhat better descriptiveness, implies the danger that, especially for the flare-produced radiation, an objectionably high skin dose remains hidden behind an apparently low integral dose.

The classification of penetrating powers provided for in the recommendations of the National Committee on Radiation Protection seems inadequate for application to proton radiations in space. More detailed rules should be established in order to furnish the astronaut with reliable and concise criteria for determining the danger threshold for acute radiation injury. As a tentative solution, dose measurements inside the capsule behind 0.1 g./cm.^{2}, 1 g./cm.^{2}, and 10 g./cm.^{2} are suggested. The first of these three dose values would have special significance for the danger threshold for the lens of the eye since it is protected only by about 3.5 millimeter of superimposed tissue and shows for radiation-induced cataract a much higher radiosensitivity than skin in general.

Superimposed intensities from electrons and associated bremsstrahlung complicate the dose determination for low prefiltration. Quantitative data on these components are not available.

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