Theory of Protection of Man in the Region of the Primary Cosmic Radiation

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THE POTENTIAL hazard to humans from exposure to the primary cosmic radiation at very high altitude centers upon the heavy nuclei component of the primary radiation. It is not the total ionization dosage of these rays which creates the potential danger but their extremely high specific ionization.

It has been shown[6,7] that living cells which happen to be in or close to the central core of the ionization column of a heavy nucleus track are exposed in their full cell volume to ionization dosages as high as several thousand roentgens. Moreover, these dosages are administered in times far shorter than one millionth of a second and this circumstance is apt to increase the destructiveness of the heavy nucleus hit further. There is no doubt that such an exposure must be considered an above-threshold injury for the cells affected and that is putting it mildly. However, the percentage of cells of a human organism exposed to such extremely high dosages is very small even in a prolonged stay of many hours in the heavy nuclei region.

If one attempts to assess this novel type of radiation exposure with regard to its damage two questions arise. (1) Is this peculiar type of radiation injury, which severely damages a small percentage of the total number of cells but leaves the surrounding bulk of the tissue unaffected, bearable for all types of body cells? (2) If so, to what extent is it bearable? More specifically, how many hours exposure to heavy nuclei per day can be considered a below-threshold dosage? Present knowledge in radiobiology does not permit a rigorous answer to these questions. Since energy spectrum and mass spectrum of the heavy nuclei cover a wide range, this task of assessing the radiation hazard in quantitative terms is rather complex.

Considering this undecided situation it might seem premature to investigate the problem of protection of humans in the altitude region of the heavy nuclei. However, as will be seen later, the analysis of the relationships involved also furnishes valuable information on how to carry out biological experimentation with heavy nuclei rays most effectively and most economically.

DIFFERENT MECHANISMS OF ENERGY DISSIPATION OF HEAVY NUCLEI AND THEIR BIOLOGICAL SIGNIFICANCE

When heavy nuclei strike living tissue, three different types of hits occur. First, there is the dense ionization column which a heavy nucleus, traveling at medium or high speed, produces

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in the absorber by knocking off orbital electrons from the absorber atoms. Second, after a certain distance which varies statistically, the heavy nucleus will undergo a nuclear collision. This usually results in a complete disintegration of the projectile as well as the target nucleus.

The density of ionization along the trail of a charged particle is proportional to the square of the charge. Thus, if a particle of charge 12 breaks up into three fragments of charge 2 and 6 of charge 1, its ionizing power diminishes from 144 to 18. Furthermore, this greatly reduced ionizing power is no more concentrated in one track, but spreads over nine different tracks, i.e., over many more individual cells. Finally, a biological factor is involved which renders, even in equal tissue volumes, the same total ionization dosage, administered by particles of lesser density of ionization, less effective. Thus, the disintegration represents a degeneration process which greatly reduces the specifically harmful quality of the heavy nucleus, the high rate of energy loss.

The third and most harmful type of hit in living matter is administered by the ionization peak and thin-down part of a heavy nucleus track. This phenomenon can occur only if the residual range of a heavy nucleus when entering the absorber is not too large. Such a nucleus, on its comparatively short range, can escape nuclear collision entirely and spend its kinetic energy exclusively in ordinary ionizations. Close to the end of its path its ionizing power will then grow to an excessively high value. In this terminal section the density and the diameter of the ionization column exceeds by far anything which artificial or natural terrestrial sources of radiation can supply. Cells of living tissue which happen to be in the center of such a thin-down trail are exposed in their full volume to a radiation dosage of several thousand roentgen units.

The relationships governing the frequency of thin-down hits in a target object under different conditions (altitude, latitude, shielding layer) are complex and very different from those holding for the total number of all types of hits. For this reason, the two cases are treated separately in the following discourse. This is all the more logical since both types of hits are also very different in their biological effectiveness.

It should be emphasized that the limitation of this study to the heavy nuclei phenomenon is merely heuristic. Besides heavy nuclei, the primary cosmic radiation contains protons and He-particles. As a matter of fact, the latter particles are about 100 times as numerous as the heavy nuclei. Adding their contribution to the ionization, one obtains a tissue ionization dosage of 8 milli-roentgen equiv. phys. per twenty-four hours for the primary radiation in toto. It is well established that this dosage increases to a maximum of twice this value due to the multiple production of secondaries if one proceeds to a depth of 75,000 feet altitude into the air ocean. This intensification due to the transition effect in the atmosphere can be expected to be considerably larger in the more compact material of any kind of ship, i.e., considerably larger than two. The total tissue dosage thus might well

TABLE I. NUMBER OF PARTICLES ENTERING A "STANDARD MAN" OUTSIDE THE ATMOSPHERE AT DIFFERENT LATITUDES

Type of Particle	Particle Frequency per Second at Latitudes:			
	55°	50°	40°	30°
Protons	2,650	1,850	970	600
He-Particles	375	280	150	88
C,N,O	19	14	6.8	3.7
Mg-Group	5.0	3.6	1.8	.98
Ca-Group	1.75	1.25	.62	.34
Fe	.83	.61	.30	.16

come close to the full permissible dose of 50 mrep/24 hrs., especially if a larger ship of some thousand pounds of weight is involved. The heavy nuclei hits are administered to the tissue in addition to this general "background" of ordinary ionizing radiation. It stands to reason that these relationships cannot be disregarded in a general appraisal of the biological effectiveness of the primary cosmic radiation. However, a discussion of these aspects is not intonded here.

ALTITUDE AND LATITUDE DEPENDENCE OF THIN-DOWN PHENOMENON

Incident Intensity.—Peters,[5] Freier, Anderson, Naugle, and Ney,[3] and Van Allen and Singer[10] have attempted to describe, from the experimental information available, the energy spectra of the components of the primary cosmic radiation in a concise mathematical form. From their data Table I has been compiled. It gives the number of particles entering a sphere of 75,000 gram weight and specific gravity 1 ("standard man") from all directions at the top of the atmosphere for different geomagnetic latitudes. The figures comprise all *entering* particles regardless of whether they go all the way through or terminate within the body. Our attention here is exclusively directed to the heavy component, i.e., to the elements of the CNO-group and heavier. Moreover, it will be necessary to define how many of these heavy particles do not degenerate in nuclear collisions, but actually travel their maximum range and pass through the terminal ionization peak and the thin-down.

The probability for a heavy nucleus undergoing or escaping nuclear collision strongly depends on its initial kinetic energy. The lowest graph of Figure 1 shows this relationship for nuclei of the CNO-group. It is seen that beyond one Bev per nucleon this probability for nuclear collision is one. No thin-down phenomena will occur beyond that energy. In the range from 1 Bev per nucleon down to 0.1 Bev the probability decreases rapidly to zero. That means below about 0.1 Bev per nucleon no nuclear collision will occur: all particles will pass through the terminal peak and thin-down.

This probability has to be superimposed on the actual energy spectra of the heavy primaries. The uppermost graph in Figure 1 shows the energy spectrum for the CNO-group as it is encountered at the top of the atmosphere and at 55° north. It is entirely sufficient here to show the CNO-group as a representative sample of the total heavy spectrum. For the heavier components the energy distribution is identical. Only the numerical values of the ordinate scale would have to be changed.

The sharp cut-off of the spectrum at 0.3 Bev per nucleon at 55°N is produced by the geomagnetic field which deflects the charged primaries and prevents low energy particles from reaching the earth. This shielding influence is strongly dependent upon latitude and becomes greater for lower latitudes.[1] The second and third graph of Figure 1 give the spectra for 50° 40° and 30°.

By multiplying the ordinates of the actual spectra by the probability of nuclear collision one obtains a reduced energy spectrum which gives the number of particles that will produce thin-down hits. The shaded portions show that such hits occur only at northern latitudes for 50° and higher. In other words, the thin-down phenomenon is limited to the polar region. The shaded part of the spectrum is limited on the left by the shielding force of the geomagnetic field and on the right by the probability of nuclear collision. These two limits overlap at low latitudes, but leave open a small gap from 50° upward. In this narrow energy interval, we observe the thin-down phenomenon upon which the interest of the radiobiologist is centered.

Figure 1 shows the energy distribution only for latitudes up to 55°N and the situation for higher latitudes needs explanation. At 55° we observe the so-called knee in the total intensity of the incoming cosmic ray beam. The intensity levels off at this point to a constant value which seems to be maintained all over the polar region. This contradicts directly the concept of the geomagnetic theory which postulates a continuous marked decrease of the deflecting forces towards higher latitudes and corresponding strong increase in the total intensity.

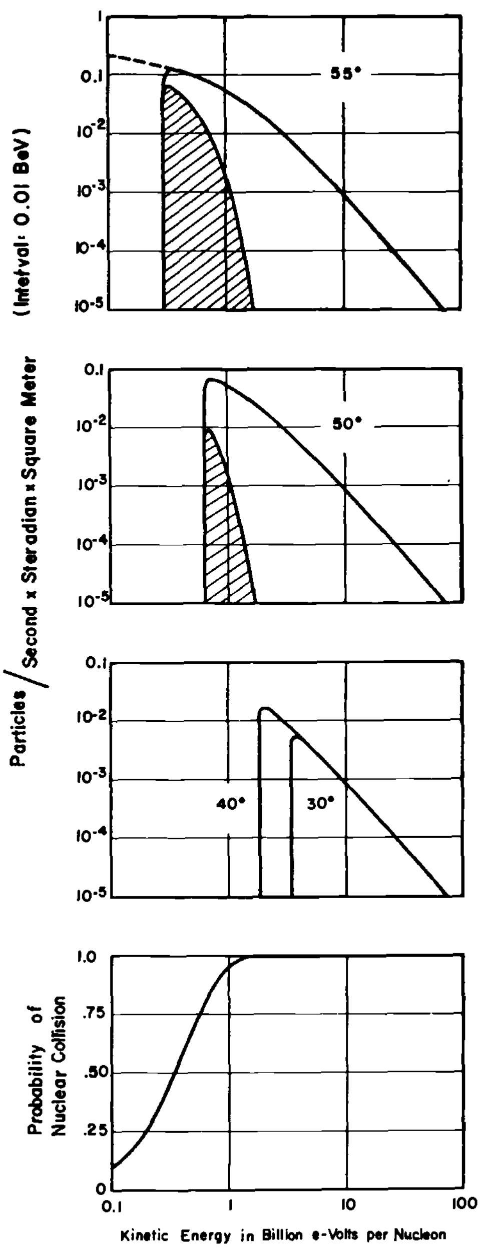

Fig. 1. Differential energy spectrum of the CNO-group of primary cosmic radiation at the top of the atmosphere for different latitudes.

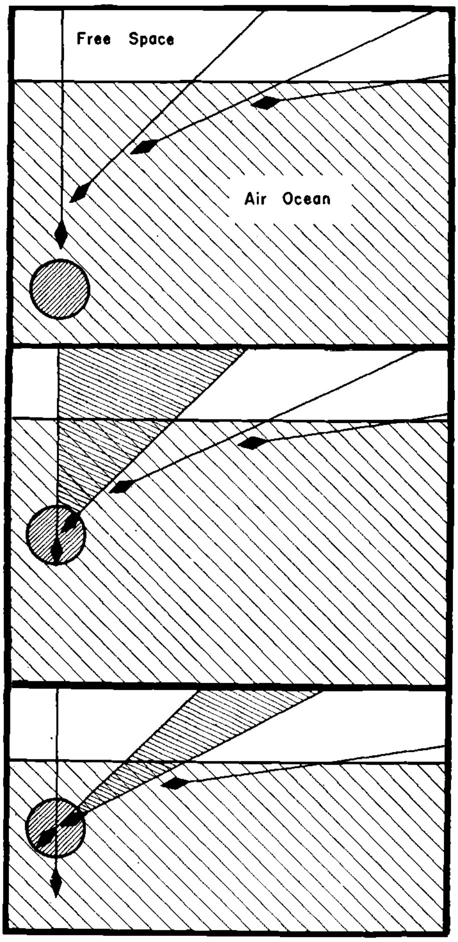

Fig. 2. Limiting angles of incidence for heavy nuclei for producing thin-down hits in a standard sphere.

No satisfactory explanation for this discrepancy is available at present.

Van Allen and co-workers[2] have investigated recently the low-energy end of the heavy spectrum close to the geomagnetic pole by means of balloon-rocket tandems ("rockoons"). Their measurements corroborate and reliably establish the leveling-off. The authors also discuss[2] in detail the theoretical aspects as to the underlying mechanism causing the strange deviation from the geomagnetic prediction in the polar region.

For the radiobiologist, this leveling-off of the intensity and spectral composition at about 55° or 60° has the comforting consequence that the exposure hazard at these latitudes also levels off to a constant value and that the results of biological experimentation with the heavy primaries carried out in the latitude region at 55° to 60° hold for the full polar cap.

Frequency of Thin-Down Hits in a "Standard Sphere."—The number of incoming particles passing through the ionization peak and thin-down which has been derived above does not immediately convey information on the exposure of a human being in terms of the number of thin-down hits which actually will occur within the body per unit time. There are three different types of heavy nuclei hits: through-shots, hits which terminate in disintegration stars, and hits which terminate in ionization peaks. In the rarefied air of the heavy nuclei region beyond 70,000 feet altitude, the density of the body tissue is about 55,000 times greater than the density of the ambient air. Therefore, many more particles terminate their tracks within the body than in an equal volume outside of it.

Radiobiologically, this third type of hit, produced by nuclei passing through the ionization peak and the consecutive thin-down (so-called thin-down hits), is of paramount importance. The number of these hits becomes accessible to theoretical calculation if the irregularly shaped human body is replaced by an equivalent of simple geometrical form. For the

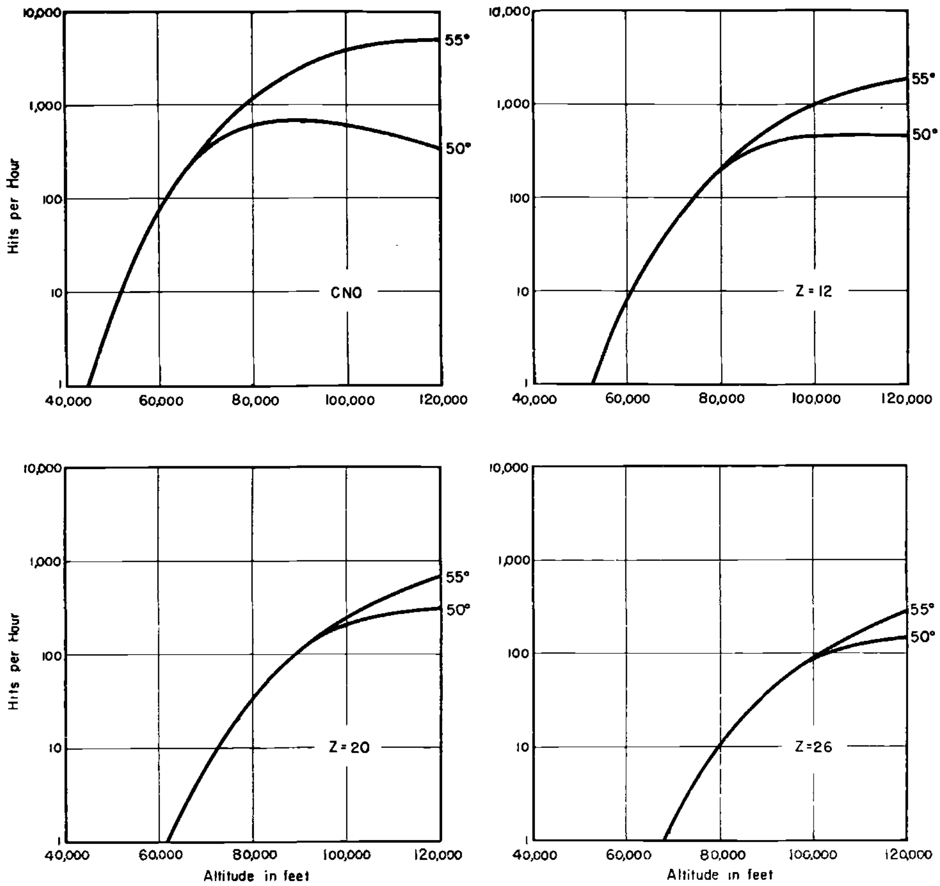

Fig. 3. Number of thin-down hits from heavy nuclei in a "standard sphere" (human body) at different altitudes for 55° and 50° geomagnetic latitude.

present study a sphere of 75,000 grams weight and of specific gravity 1 has been chosen. For this "standard sphere" all relationships can be formulated concisely in equations for which rigorous analytical solutions exist.

Figure 2 depicts some of the geometrical relationships characteristic for this peculiar type of exposure. If we limit the analysis for a moment to heavy nuclei of one atomic number and one energy only it is easily seen that such a nucleus coming in from the zenith or at a small zenith angle will penetrate to greater depth into the air ocean than the same nucleus entering at a large angle. If a standard sphere happens to be in the path of the nucleus a large part of the latter's penetrating power is used up inside the sphere and the total distance traveled will be much shorter. Of course, the graph cannot render this relationship correctly because of the very large density ratio of 55,000 to 1 for body tissue and surrounding air. But the sketch shows correctly that nuclei entering at a large angle will not reach the standard sphere at all. There is a certain cone with the zenith direction as axis within which the nuclei will reach the standard sphere, i.e., will produce thin-down hits in the body. Finally, if the standard sphere is very close to the top of the atmosphere and the penetrating power of the heavy nuclei sufficiently large, it can happen that for a small zenith angle the nuclei will go all the way through the standard sphere (human body) and terminate outside and underneath it. For this case, two critical zenith angles exist defining a double cone within which all incoming nuclei produce thin-down hits within the body.

Actually the heavy component of the primary radiation does not consist of particles of one atomic number and one kinetic energy only, but covers a two-fold continuum comprising all atomic numbers up to at least twenty-six (iron) and several ten powers of kinetic energy. The full quantitative analysis thus grows to a rather voluminous computational undertaking. The mathematical details of this analysis have been described elsewhere.[8] Only the final results are presented here.

Figure 3 gives the number of thin-down hits per hour within the standard sphere (human body) as a function of altitude for the two latitudes of 50° and 55°. The total heavy spectrum is broken down into four components. This separation is useful since, as seen from Figure 3, marked differences exist with regard to the altitudes at which the thin-down hits begin and grow more frequent for the different components.

The most interesting detail of Figure 3 is the latitude influence at extreme altitudes. Whereas the curves for the two latitudes coincide at medium altitudes, it is seen that they split up at extreme altitudes with the number of thin-down hits for 50° latitude being significantly smaller than for 55°. This is caused by the geomagnetic field. Of special interest is the curve for the CNO-group for 50° latitude which shows a maximum for the number of hits at about 85,000 feet altitude. This is due to the circumstance which was mentioned before that the penetrating power of the CNO nuclei at the geomagnetic cutoff energy for 50° latitude exceeds the full diameter of the standard sphere (human body). Therefore, a larger and larger number of nuclei pass all the way through the human body if we approach closer and closer the top of the atmosphere. At 55° latitude, the geomagnetic cutoff energy is smaller. Correspondingly, a larger share of nuclei of lower penetrating power is superimposed upon the spectrum for 50° and the downward slope of the latter to the right of the maximum is encountered.

THEORY OF PROTECTION FROM HEAVY NUCLEI HITS BY SHIELDING

Protection from Thin-Down Hits.—It stands to reason that the residual atmosphere above the standard sphere can be considered as a kind of shielding layer. It is seen, then, from the conclusions drawn in the preceding section, that such an interposed "shielding" layer, at least under certain conditions, can do exactly the op-

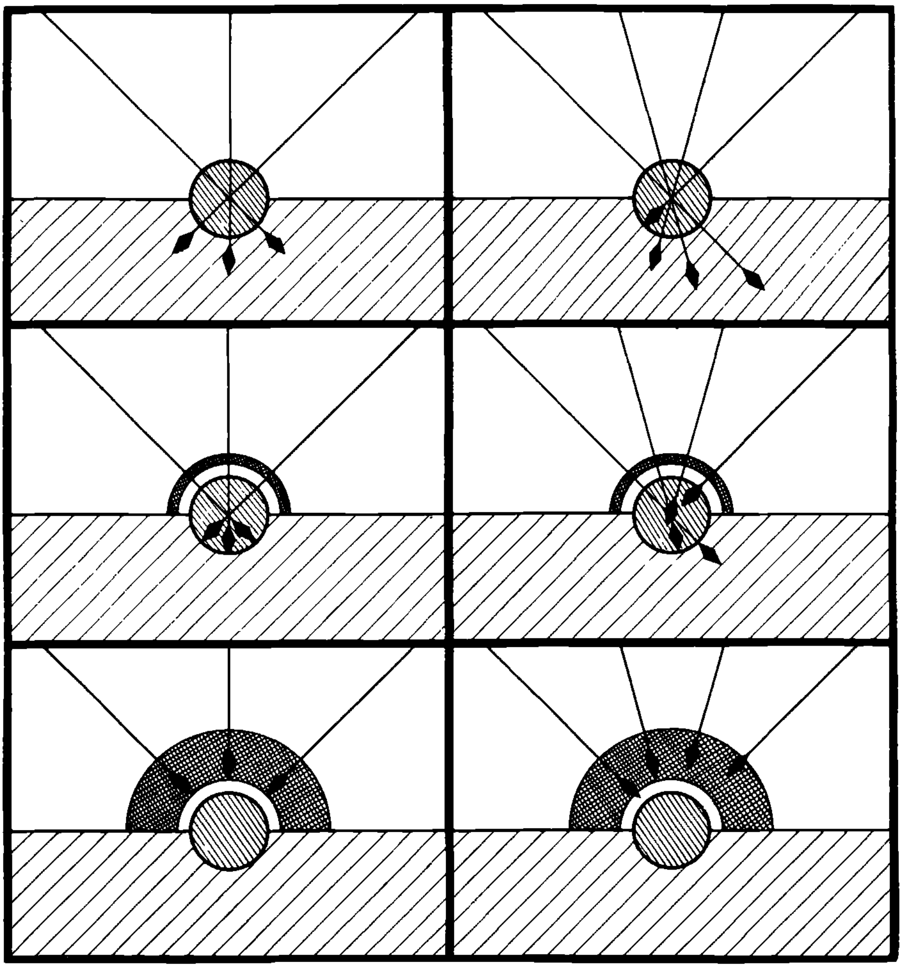

Fig. 4. Protection of a "standard sphere" (human body) from thin-down hits of heavy nuclei by a concentric shielding layer of varying thickness. *Left:* Incident particles are monoenergetic. *Right:* Incident particles have four different energies.

posite from what it is intended to do; it can act as an intensifier.

For the problem of shielding by walls of compact material around the standard sphere we can actually not learn very much from the relationships which describe the shielding influence of the atmosphere. A shielding layer surrounding the space to be protected always acts essentially as a concentric shield. This changes the basic geometry, as is illustrated in Figure 4. Nuclei entering at a large zenith angle now travel very nearly the same distance in the protective layer as those from the zenith. This greatly favors the formation of a maximum in the relevant curve. The left hand part of Figure 4 describes the conditions for incoming nuclei of one range, the right hand part for nuclei of four different ranges. It is seen that concentric shielding yields its protective power only beyond a certain minimum thickness. Below that critical value

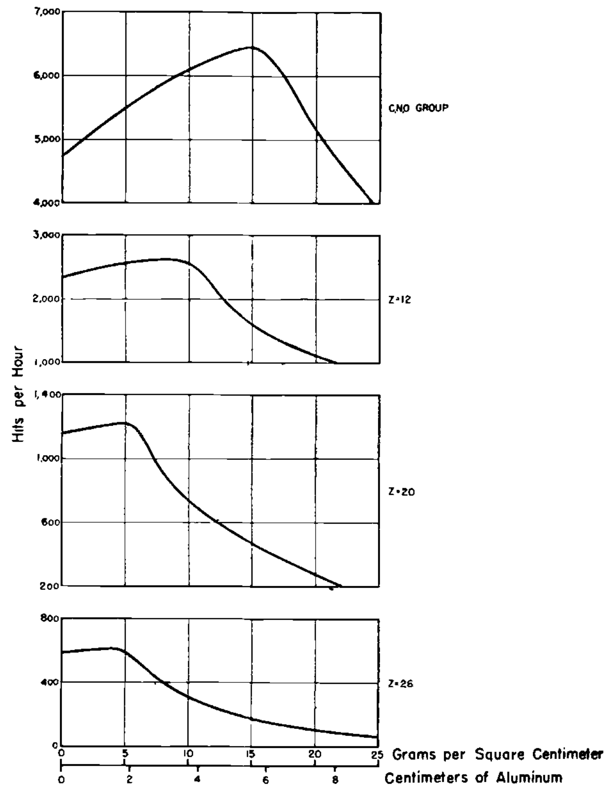

Fig. 5. Number of thin-down hits from heavy nuclei in a "standard sphere" (human body) under concentric shielding layers of varying thickness.

the "shielding" layer acts as an intensifier.

Quite contrary to the case of the residual atmosphere with its complicated geometry, the concentric shielding layer is rather simple in its general mathematical treatment. Figure 5 gives the results of the computation carried out again for the four components of the heavy spectrum which have been used before. The slowing down of the heavy nuclei in the shielding material is due to collisions with orbital electrons of the absorber atoms. This process is essentially a function of the number of electrons per gram absorber and thus depends only on the penetrated mass of absorber, regardless what its atomic number, i.e., its chemical composition, may be. Shields of different materials, offering the same weights per unit area, offer the same protection. The abscissae in Figure 5 are, therefore, divided in units of grams per square centimeter and the curves hold for any material. Merely as an example, the equivalent thicknesses of an aluminum shield are also plotted.

It is seen at once that the results are utterly discouraging for any engineer who would like to construct a ship with walls thick enough to protect the crew from thin-down hits of heavy nuclei. All four components show a marked increase of the number of hits for a quite extended range of thickness. The phenomenon is especially pronounced for the CNO component which contributes the largest percentage of hits. For this component the shielding function does not develop until one proceeds to a thickness of 21 grams per square centimeter corresponding to three inches of aluminum or one inch of steel. For the heavier components, the corresponding figures are somewhat smaller but still prohibitively large from an engineering standpoint unless one thinks in terms of a space platform or artificial satellite in which tons of fuel or other materials are to be stockpiled and could be placed around the crew compartment.

The phenomenon that the energy dissipation of a radiation of high penetrating power when entering an absorber increases in the initial layers and passes through a maximum, is a well-known occurrence and is called transition effect. It had already been observed in the early days when the telecurie therapy of cancer with radium gamma radiation was developed. A more modern example, closely related to the topic of this investigation, is the so-called total ionization of the cosmic ray beam which is known to increase to twice the value it has at the top of the atmosphere, if one descends to an atmospheric depth of 75,000 feet altitude.

However, these transition effects differ basically from the phenomenon with which we deal here. These ordinary transition effects are caused by processes of multiple scattering of the primary energy and of multiple production of secondaries in collisions of primary particles. In contradistinction, the transition curve for the number of thin-down hits described above is strictly contingent upon the primary heavy nuclei themselves. Very fortunately, this peculiar type of transition effect is accessible to a complete and rigorous mathematical analysis whereas the ordinary transition effects, owing to their intrinsic multiplicity and irregularity, defy a general analytical treatment except for limited partial solutions and certain approximations.

Protection from Ordinary Hits.—Basically different from the mechanism of the gradual slowing down of nuclei by knock-on collisions is the elimination of nuclei by nuclear collisions. The latter process is a probability event which occurs comparatively seldom depending on the combined cross sections of the projectile and the target nucleus. The cross section of an atomic nucleus varies with the square of its radius; the volume with the third power. This leads to the peculiar consequence that materials of a higher atomic weight offer smaller cross sections for the same weight per unit area of a shielding layer. Hydrogen provides the best weight economy for particle elimination by nuclear collision.

For the actual computation of the

reduction of particle frequencies in shielding layers it is advantageous to use the mean free path for nuclear collision rather than the nuclear cross section. The mean free path for nuclear collision signifies the thickness of material that reduces the number of particles of the incident beam to the fraction 1/e., i.e., to 37 per cent. The mean free path is usually given in grams per square centimeter. The values of this constant for heavy nuclei in different absorber materials are fairly well known and have been critically surveyed by Freier and coworkers[3] and Kaplon and coworkers.[4] On the basis of these data the curves in Figure 6 have been drawn. They show the particle elimination for the lightest (CNO-group) and the heaviest (Fe) component and for three representative substances; paraffin as that solid substance which has the highest hydrogen content known, plastics because they come next to paraffin in hydrogen content and probably will

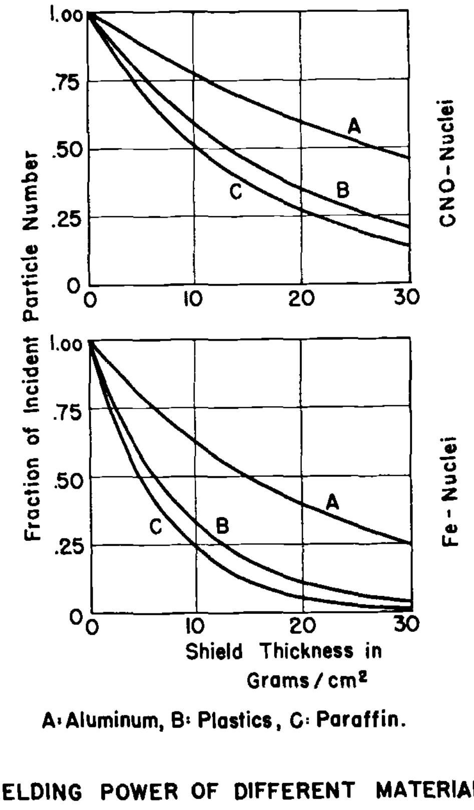

Fig. 6. Shielding factors for paraffin, plastics, and aluminum for ordinary heavy nuclei hits.

be greatly preferred in aircraft design, and aluminum as a basic construction material for aircraft. It is seen from Figure 6 that the weight requirements are again prohibitively high, though this time no transition effect occurs, but the shielding factor monotonically increases from zero thickness.

CONCLUSIONS

It seems too early to enter into a discussion of the radiobiological consequences of the data presented. With regard to the quantity of damage from heavy nuclei to living tissue, our knowledge at present is most fragmentary. Thus, the definition of a permissible exposure to be given in number of thin-down hits per day, is still a task for the future. The compliance with such an official permissible dosage, whatever its numerical value might be, will only be possible by restricting the daily or weekly exposure time in the heavy nuclei region. This permissible exposure time will vary greatly with altitude and latitude and will have to be calculated on the basis of the statistics of thin-down hits for the various components.

For a concrete answer to all these problems it will be necessary to expose living animals, preferably mammals, to the heavy nuclei region. It is with regard to such experimentation that the results presented here have an immediate practical significance. If in such a high altitude exposure a maximum number of thin-down hits in the animal body is to be obtained, it will not suffice to expose the animal capsule indiscriminately to as high altitude as possible. The number of thin-down hits in the target body depends on the size of the animal, the thickness of additional absorber layers to be superposed, and on the type of nucleus to be studied. Altitudes and latitude of the exposure are additional factors to be considered.

The theory presented is of special importance for rocket flights in which the test animal is carried clear of the atmosphere. For instance, a small animal without superposed intensifying absorbers will escape thin-down hits entirely in a rocket flight at 50° latitude. The incoming nuclei will penetrate the animal body at high and medium high energy and reach their terminal section below at greater depths of the air ocean.

To be sure, this phenomenon will not occur in balloon experimentation with its present ceiling altitude of about 10 millibar. At this air pressure, the residual atmosphere provides already a moderating layer of a thickness beyond the optimum so that any additional absorber above the specimen will always reduce the number of thin-down hits. This circumstance is indicative for the fact that the present-day balloon is still a rather imperfect vehicle for biological experimentation since it just reaches the lowest fringes of the heavy nuclei region.

SUMMARY

The potential hazard to humans from exposure to the primary cosmic radiation in flight at extreme altitudes centers upon the heavy nuclei component of the primary radiation. Along the tracks of heavy nuclei in living matter very high local radiation dosages are administered to the cells, though the overall total body exposure

stays well below the permissible level. These high local ionization densities reach excessively large values in the terminal sections of the tracks (so-called thin-down parts).

Working from the assumption that the damage from thin-down hits to living tissue is much greater than from ordinary heavy nuclei hits, the frequencies of thin-down hits per hour in a "standard man" are calculated for all altitudes and latitudes and for all components of the heavy spectrum. It is shown that thin-down hits occur only at northern latitudes of about 50° and higher where the deflecting power of the geomagnetic field is small enough to admit low-energy heavy nuclei to the Earth.

The problem of protection from thin-down hits by shielding is investigated. It is shown that insufficiently thick shielding layers can act as intensifiers and actually increase the number of thin-down hits. The relationships between the thickness of the shielding layer and the number of thin-down hits are presented in graphs. They show that the weight requirements for efficient shielding from thin-down hits are prohibitively high.

The shielding of ordinary heavy nuclei hits in a protective layer is due to nuclear collisions and thus obeys different laws. The shielding power depends on the atomic composition, materials of small atomic weights being more effective Therefore, substances with a high hydrogen content offer the best weight economy. The shielding factors for paraffin, plastics, and aluminum are computed and presented in graphs. The weight requirements are again prohibitively high.

Thus, protection of man from heavy nuclei hits seems possible only by limiting the exposure time. Quantitative data for it cannot be yet established since no information is available as to the damage of a single hit and to the number of hits that can be considered a below-threshold exposure for the different body tissues.

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