Exposure Hazards from Cosmic Radiation beyond the Stratosphere and in Free Space

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IT IS a general characteristic for all kinds of damage to living organisms from ionizing radiation that a latent period is interposed between the radiation exposure and the development of the first manifest symptoms of damage. Even if a lethal dosage is administered to a person, for instance, by a burst of gamma radiation from an atomic explosion, the victim will be little incapacitated for the first hour or even for several hours or a full day until the grave consequences become apparent.

In the range of smaller dosages with correspondingly smaller damage this latent period grows to weeks and months or even years; and at the very end of this scale, in the range of the so-called low-dosage long-term damage, it might even be that the damage defies direct identification entirely and shows up only statistically, for instance, in a general abbreviation of the life-time of test animals dying from apparently unspecific causes.

This fundamental fact has to be kept in mind when we deal with the problem of a possible hazard to health from the primary cosmic radiation. Since the cosmic ray physicists in 1948[1] furnished the direct pictorial evidence for the so-called heavy nuclei component of the primary radiation, we cannot simply extrapolate anymore from our well-established damage curves with the common types of radiation. The heavy nuclei rays have certain features which are entirely novel and apt to endow them with a greatly increased biological effectiveness. This has first been pointed out by C. F. Gell,[2] and the biological significance of the heavy nuclei and of the star phenomenon has much been discussed ever since.[4,5,7,8,9,10 11,12]

Due to the just mentioned circumstances, we do not yet have a clear answer as to the "yes" or "no" or better to the amount of damage which might result from an exposure in the heavy nuclei region. This premise is to be made as a justification for the following discussion of the exposure hazards beyond the stratosphere and in free space when actually only an account can be given of the ionization dosages and the heavy nuclei intensities which might be encountered in these outer regions.

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THE TOTAL IONIZATION

The Shadow Effect of the Earth.—As a prelude to the discussion of the situation in the outer regions a recapitulation of the known data from sea level to the lower stratosphere is worthwhile. Figure 1, taken from a previous report, outlines concisely the distribution of the ionization dosage in the lower regions. The very small sea level dosage of 0.1 mrep/d increases to a maximum of 15 mrep/d at about 75,000 feet altitude. Beyond this altitude a phenomenon occurs which at first looks somewhat paradoxical. The dosage decreases for higher altitudes and finally levels off to a constant value of about 9 mrep/d. Figure 2 gives the continuation of Figure 1 for greater distances from the Earth. The altitude is now plotted on a logarithmic scale. The total range of Figure 1 has shrunk to a small initial part of the whole graph. It is seen that the leveling off to a constant value actually does not hold very long. The ionization dosage increases again this time rather slowly. The second increase mainly is the expression of the shadow effect of the Earth. An observer at sea level on the Earth or at any point in the troposphere is exposed to cosmic radiation only form the upper hemisphere. The lower hemisphere is shielded off by the solid Earth. But in proceeding to higher altitudes the percentage of the full sphere of the sky covered by the Earth decreases and the total incoming intensity increases.

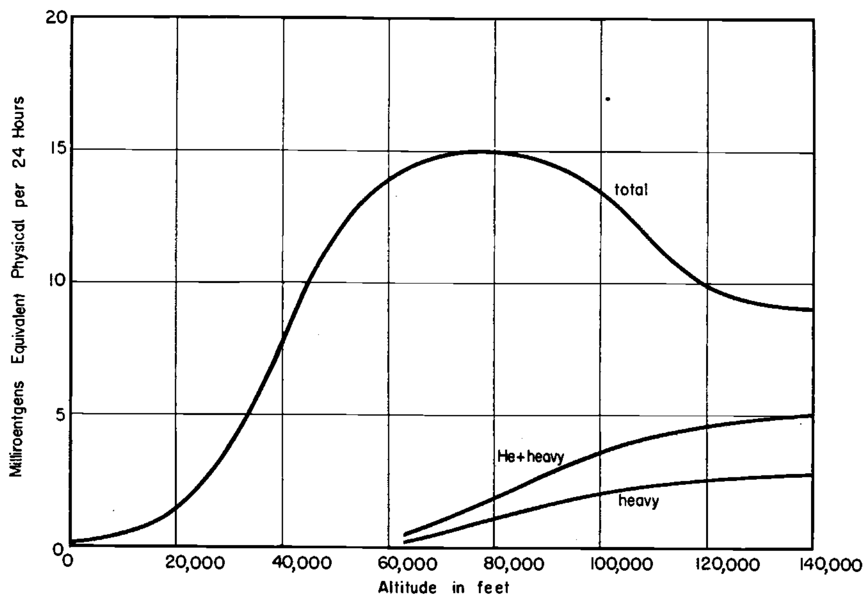

Fig. 1. Ionization dosage from cosmic radiation in the troposphere and stratosphere at higher latitudes.

Superimposed on this phenomenon are influences from the geomagnetic field on the cosmic ray intensity. No exact data, however, are available at present on these effects. It is an open alternative whether the so-called knee in the curve of the cosmic ray intensity at 58° latitude is due to the Sun's magnetic field or due to the absence of any low energy particles in the genuinely "primary" spectrum of cosmic radiation far outside the Earth's magnetic field. Theoretically, the curve of the total ionization as given in Figure 2 should not be altered markedly in either case. However, considering that the just mentioned alternative has no all-covering cogency, one should be prepared for possible surprises and regard Figure 2 only as a lower limit for the ionization dosages to be expected in the outer regions. The controversial issue of the existence or non-existence of the Sun's magnetic field has been described in more detail in a previous report.[12] Additional references are given there. The latest evaluation of the controversy has been well described by Van Allen and Singer.[14]

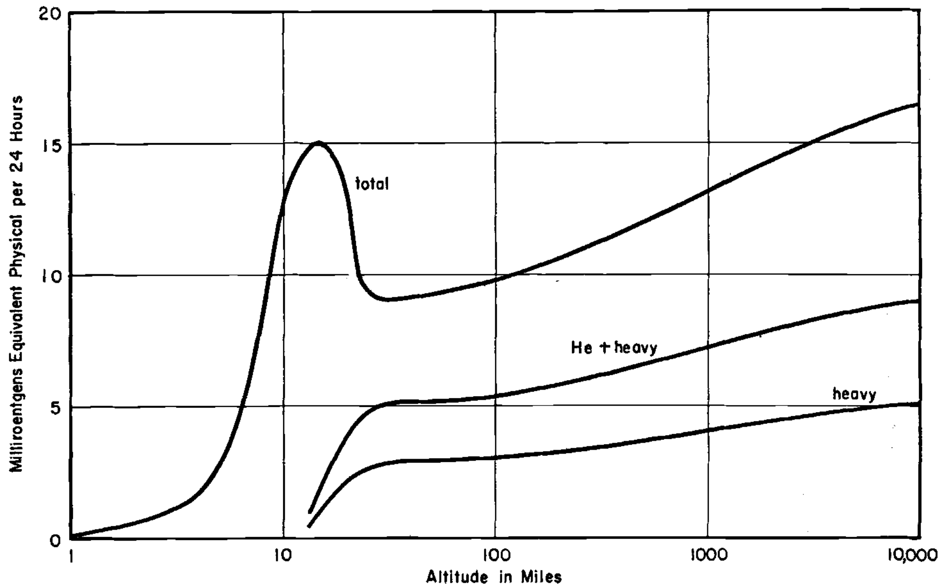

Fig. 2. Ionization dosage from cosmic radiation for distances from 1 to 10,000 miles from the Earth at higher latitudes.

The Transition Effect.—A discussion of the actual exposure hazard of human beings in a ship would be incomplete in a very important detail if limited to a mere presentation of Figure 2. The upper curve in Figure 2 gives the so-called total ionization dosage for living matter. There is, however, one very important restriction. The values of the curve are correct only for an infinitesimally small sample of living tissue floating freely in that region far apart from any additional masses. The values probably will still be correct with a negligible deviation for an object of the size of a mouse. But if we deal with the large mass of any kind of ship, the actual dosage can be expected to be markedly higher.

The reason for this phenomenon can best be understood when we direct our attention once more to the region of the lower stratosphere in which the paradoxical reversal in the slope of the ionization curve occurs. In this region the high-energy primarily particles, consisting of protons, He-particles and heavy nuclei, encounter an increasing density of air and undergo collision processes. In these interactions the particle number increases at a high multiplication rate. Due to this increasing particle number the rate at which the energy is turned into ionization per unit mass of air or any other absorber also increases. It is not an actual increase in the total incoming energy flux but only in the rate of turnover of the primary energy into ionization. We call this phenomenon the transition effect. The region of the transition effect is the region in which the equilibrium between the primaries and the secondaries is gradually established. Now, if we place any kind of artificial absorber layer, for instance, a rocket ship, in the path of the primary radiation outside the transition region, local transition effects will develop in the absorber masses of the ship and we will observe a similar increase in the ionization dosage. How large this increase will be depends greatly on the shape and mass of the ship. The multiplication factor for the ionization dosage can for denser materials than air greatly exceed the factor of 2 which holds for the rarified air beyond 75,000 feet and might assume values as high as 4. This phenomenon quite generally has to be kept in mind as soon as we start calculating numerical values of ionization dosages or of any other kind of energy absorption in any region in which the unmodified primary radiation is still contributing to the total intensity. It might be of interest to mention that the air layer from infinity to 75,000 feet in which this dosage increase occurs has a weight of 35 grams/cm.[2] That is the weight of a steel plate of almost 2 inches thickness. Transition effects can even be released by high energy secondaries of cosmic radiation. Therefore, they are not limited to the zone of the atmospheric transition effect beyond 75,000 feet but do occur also in lower regions down to mountain altitudes. Van Allen and co-workers[15] have observed that the ionization dosage under several centimeters of lead or aluminum is increased by a factor of 2 or 3. Only at sea level is the phenomenon entirely absent.

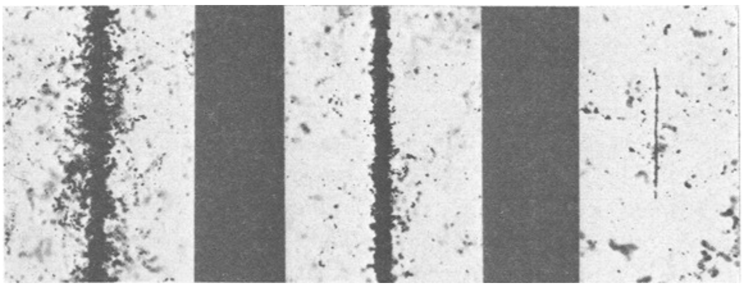

Fig. 3. Microphotograph of two sections of a heavy nucleus track, Z=20, and a thorium alpha track (E. P. Ney and Ph. Freier, University of Minnesota). *Left.* Heavy nucleus of 4,000 million eV energy. *Center.* Heavy nucleus at 400 million eV energy. *Right.* Thorium alpha tract. Total vertical length of the visual field: 58 micra.

THE HEAVY NUCLEI COMPONENT

Radiobiology.—If we now proceed from the discussion of the mere physical facts to an evaluation of their biological significance, we must remember that the exposure hazard in the heavy nuclei region cannot be appraised on the basis of our ordinary concepts. The novel quality of the heavy nuclei, which so far has not been analyzed as to its biological significance, lies in their extremely high specific ionization. Figure 3 might illustrate this. We see an ordinary alpha track and a heavy nucleus of Z-20 in two characteristic phases of its path. All three pictures are taken from the same nuclear emulsion plate at the same magnification.

The left hand picture shows the heavy nucleus track at a point in which the kinetic energy of the nucleus equals 4 billion electron-volts. That sounds at first like a rather high value. In the scale of cosmic radiation, however, it is a rather small value at the lower end of the energy spectrum of the heavy primaries. The nucleus at this point has a speed of 43 per cent of the speed of light and is very close to the end of its path. It is, at the same time, at the peak of its ionizing power and loses its energy at the rate of 500,000 ionizations per 10 micra of living tissue.

The central picture is taken still closer to the end of the same track and shows the nucleus at 400 million electron-volts corresponding to 15 per cent of the speed of light. The energy dissipation is still as high as in the left-hand picture. The right hand picture shows an alpha track of Thorium. Its energy dissipation is smaller than that of the heavy nucleus in the center by about the factor 30.

Actually, the photographic emulsion gives very little quantitative information with regard to the specific ionization. However, one very significant difference between these three tracks does show up in the microphotographs. That is the difference in the radial spread of the ionization. The heavy nucleus exhibits in both pictures a rather thick central core. In the left hand picture this core is surrounded by what is called the delta ray aura, i.e., an aura of fast electrons knocked out of the atoms which the heavy nucleus strikes on its path. The alpha track, on the other hand, does not exhibit any of these features. Actually, the thickness of the alpha track in the right hand picture is overrendered due to the grain size of the silver bromide crystals.[7]

This large radial spread of the ionization in heavy nuclei tracks is due to their tremendous energy. There is no radiation from any natural or artificial terrestrial source which could be compared to the heavy nuclei with regard to this characteristic.

Since the photoemulsion gives very little quantitative information as to the fine structure of the radial spread of the ionization this author has carried through a theoretical analysis on the basis of the theory of collision. Figure 4 gives as an example the results obtained for a heavy nucleus, $Z = 20$, i.e., for the one of Figure 3. For certain reasons, this analysis can only be carried through in a piecemeal fashion by assuming finite zones for which the total ionization dosage can be derived. This is a rather time-consuming procedure and the process of extending this analysis to all representative types of the mass spectrum of the heavy nuclei is still going on.

There is, of course, the very significant difference between the alpha and the heavy nucleus track with regard to the radial spread of the ionization.

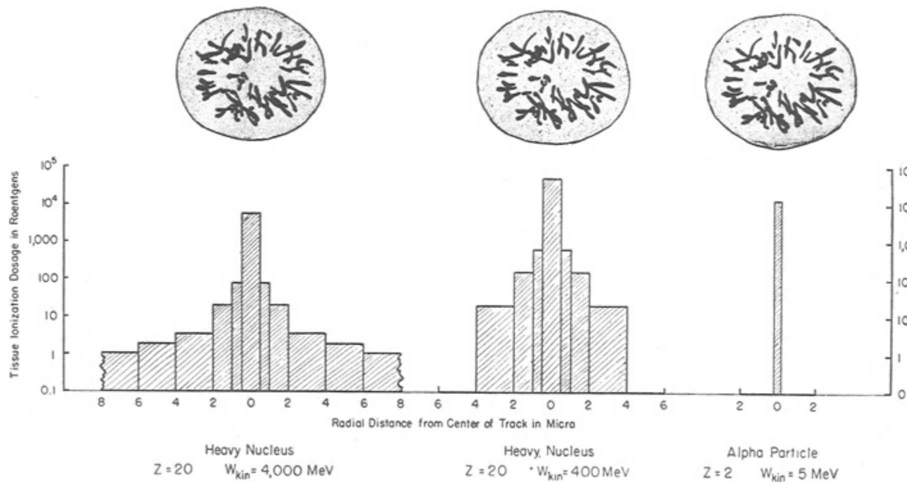

Fig. 4. Radial spread of ionization about heavy nucleus and alpha tracks.

The ionization in Figure 4 is plotted in roentgen units and pertains to the dosage which one heavy nucleus of atomic number 20 and of a kinetic energy of 4 billion eV (left hand graph) and of 400 million eV (center graph) produces in living tissue. It might be emphasized that these very high dosage values must not be overrated. These dosages are administered to very small tissue volumes only. Attention is directed to the right hand graph which gives the situation for an ordinary alpha track. It is seen that in this case the roentgen values are also rather high. But we know that one isolated alpha track does not produce any traceable permanent damage to mammalian tissue. It requires a certain density of such tracks in space and time to do that.

In the upper part of Figure 4 sketches of a human cell with its 48 chromosomes are drawn to scale. In comparing the size of this cell with the histograms one sees that the alpha ionizations produce only a rather narrow trail in the cell whereas the heavy nucleus floods the total cell volume with ionizations. This comparison poses the fundamental question which the radiobiologist has to solve with regard to the heavy nuclei phenomenon. For the first time we encounter a type of radiation in which the single ray produces a zone of primary injury whose diameter is of the order of or even bigger than the living cell. This problem, disregarding now for a moment entirely the practical consequences for aviation, represents a challenging task for basic research in radiobiology.

The computations of the radial fine structure of the ionization do, of course, not contribute directly to the solution of the fundamental radiobiological problem. However, it is useful to have this accurate quantitative information as a baseline in biological experimentation.

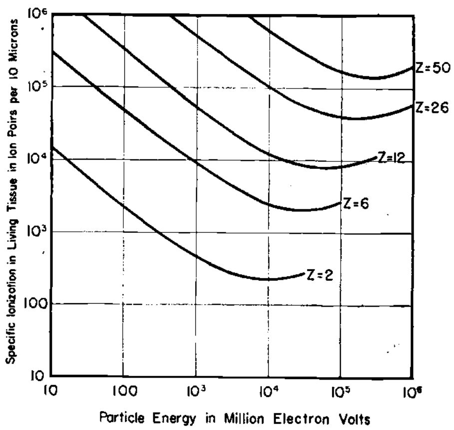

Fig. 5. Specific ionization of heavy nuclei rays in living tissue.

Another field in which such a detailed analysis might be of some help is the study of ways and means to simulate the irradiation conditions of heavy nuclei with laboratory means. C. A. Tobias has made the first suggestion along this line by recommending the use of fourfold ionized carbon nuclei from the cyclotron.[13] Such possibilities of simulating the heavy nuclei have great importance for the economy of biological experimentation. For it makes quite a difference in time and costs whether one can do animal experimentation in the laboratory at sea level or whether one has to do it in the lower stratosphere.

Of decisive importance in the quantitative evaluation of the biological effects of the heavy nuclei component is the fact that the specific ionization of a heavy nucleus depends greatly on its energy. Figure 5 shows this relationship for different representative atomic numbers. It is seen that a high-energy iron nucleus of 100 billion eV, for instance, produces in living tissue 40,000 ion pairs per 10 micra, which is about as much as that produced by an ordinary alpha particle at its peak of ionization. But this value increases considerably for lower energies and the highest possible value, which for iron lies outside our graph, equals more than 2 million ion pairs per cell. This value is reached very closely before the end of the track. From this peak the ionization then drops rapidly to zero when the nucleus picks up its orbital electrons and comes to a complete stop. This terminal end of the track is called the thin-down part. Figure 6 gives an example of such a thin-down part for a nucleus of $Z = 50$. It has been recorded by H. Yagoda with his emulsion chamber method[16] at 105,000 feet in a balloon flight. It is the heaviest track so far recorded.

For an appraisal of what damage such a heavy nucleus ray might inflict upon living tissue it has to be kept in mind that Figure 6 shows the trail of the heavy particle in nuclear emulsion. For tissue all dimensions have to be multiplied by a factor of about 3.5. Furthermore, it has to be taken into account that the full length of the ionization peak is at least twice as long as the part which is depicted in Figure 6. Thus one obtains for living tissue a cylindrical volume of about 15 millimeters in length and 50 micra in diameter which is exposed to the ex-

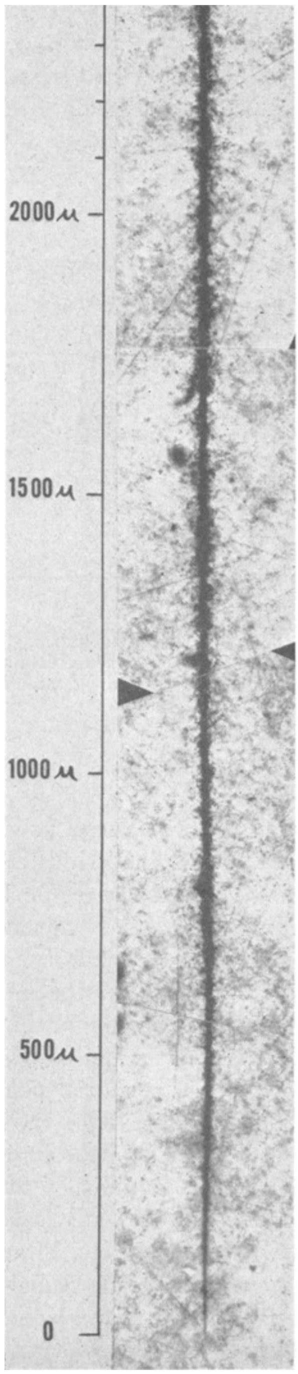

Fig. 6.

ceptionally high roentgen values discussed above. This volume contains about 15,000 cells. That is, of course, an extremely small number in comparison to the more than 1,000 billion cells of the total human organism. The question is only how many such hits can the organism stand in the long run.

The number of these thin-down tracks in an exposed human organism is much smaller than the total number of heavy nuclei hits since not all incoming heavy nuclei are low-energy particles or are slowed down to the thin-down before undergoing nuclear collision. At present, it is not yet possible to give an accurate figure for this especially dangerous type of thin-down hit. The order of magnitude is about 100 per hour for the total organism.

Influence of the Geomagnetic Field on the Heavy Nuclei Component.—A most important consequence for the exposure hazard from thin-down hits derives from the influence of the geomagnetic field on the primary cosmic radiation. This field prevents low-energy primaries from reaching the earth in the equatorial belt, but they do enter the upper atmosphere at higher latitudes. Since these latitude-sensitive, low-energy primaries constitute the component which furnishes the thin-down particles the latter ones are limited to northern latitudes. At 58°, between 20 and 30 per cent of

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Fig. 6. Ionization peak and thin-down part of a heavy nucleus track of $Z = \sim 50$ (tin) recorded at 105,000 feet and 55° N latitude with the emulsion chamber method, by Herman Yagoda, Laboratory of Physical Biology, National Institutes of Health.

all incoming heavy nuclei go through the thin-down[3]. Below 30° not one thin-down phenomenon has been recorded so far. This means that the cle energy, or better, of particle momentum. The momentum p_{max} is the limiting value below which particles can enter only from certain directions.

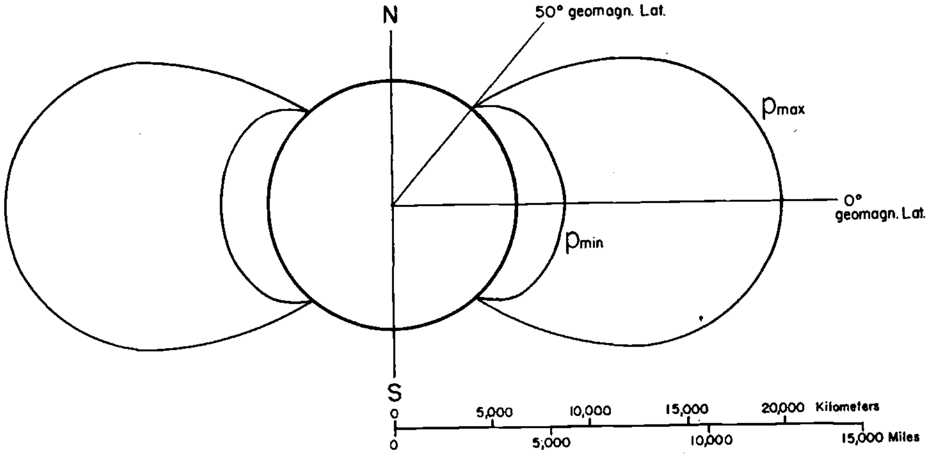

Fig. 7. Zones of exclusion of low energy cosmic ray primaries around the earth. Particles with momentum less than p_{max} can enter the outer toroid only from certain directions. Particles with momentum less than p_{min} cannot enter the inner toroid at all. P_{max} and p_{min}: limiting momenta for 50° latitude.

exposure hazard can be expected to be considerably higher at northern latitudes. This is, to repeat, not only due to the considerably higher total ionization dosage in that region but even more so due to the limitation of the thin-down phenomenon to that region.

It is intriguing to attempt an analysis of how far this characteristic latitude limitation of the thin-down phenomenon extends into the regions beyond the stratosphere. Considering the complete lack of information as to the origin of cosmic radiation and its genuinely "primary" spectrum[14] such analysis, of course, can be merely speculative.

The theory states that at any given latitude the conditions for the entrance of a particle from outer space are delimited by two critical values of parti-

The momentum p_{min} is the limiting value below which particles cannot enter at all. If we assume now tentatively that 50° is the critical latitude at which the thin-down region begins, the theory permits us to calculate the geometrical locus for lower latitudes for which the same limiting momenta hold. Figure 7 shows the results. The toroid for the momentum p_{min} is rather narrow in the equatorial plane and equals only 40 per cent of the radius of the Earth. The p_{max} toroid, i.e., the zone for which a diminished intensity of the critical particle energy holds is of somewhat larger size. Its width in the equatorial plane equals 2.14 Earth radii. This again is not very much from the standpoint of space travel.

It does have bearings on the project

of an artificial satellite of the type which has been suggested by W. von Braun. The altitude of 1,000 miles for that satellite is, as we see from Figure 7, in the equatorial belt still in the protected zone in which no thin-down nuclei are likely to occur. However, a trajectory in the equatorial belt is in conflict with the practical purposes of such a space platform. These purposes, whatever they might be, can best be fulfilled if the plane of the orbit is meridional or nearly meridional to the Earth, for in a meridional orbit the satellite would pass through the zenith of all points of the Earth. But, at the same time, its maintenance crew would be exposed, for a certain percentage of the time, to the thin-down region around the magnetic axis. Since short duty periods entailing frequent relief of the crew would be costly these radiation safety aspects might become a factor to be considered in a project of that kind.

Looking at space travel from a more general standpoint, it is seen that the protective power of the magnetic field of the Earth to exclude low-energy heavy nuclei is limited to a rather small zone. That holds two-dimensionally for the surface of the Earth and the very thin layer above it in which man travels today and is doing experimentation with pilot balloons and rockets. But it also holds three-dimensionally when man is preparing to travel in space.

CONCLUSIONS

It might be emphasized once more that all conclusions drawn in this report with regard to regions beyond 120,000 feet altitude are hypothetical. As long as there is no unequivocal information on what actually causes the "knee" in the intensity and spectral composition of the primary radiation at 58°N any extrapolation as to the conditions in the outer regions will be guess work. The situation is especially unfortunate for the problem of a possible exposure hazard since for the biological effectiveness paramount importance rests on the low energy part of the primary spectrum, and it is just this part about which our knowledge is most fragmentary.

To augment information heavy nuclei recordings at extreme altitudes at or close to the geomagnetic northpole are needed. A rocket flight for this special purpose is being organized by J. A. Van Allen for the summer of 1952. Such recordings promise to yield the basic decision with regard to the existence and the influence of the solar magnetic field. Besides this crucial information, more and better data are urgently needed on the intensity and energy distribution of the heavy nuclei, especially with regard to the latitude dependence.

It might be pointed out again, at this occasion, that the interests of the physicist in cosmic ray research quite generally differ greatly from those of the radiobiologist. Since the former's task—gaining a better understanding of the nuclear forces—greatly surpasses in importance the latter's task which anticipates future developments not yet clearly visible, it is entirely just that cosmic ray research places the main emphasis on the physicist's work. Very often, however, it requires only a minor change or addition in the physicist's experimentation to render the prospective results highly useful for the radiobiologist. Under this special consideration the physicists among the readers are urged to pay special attention to the section on the heavy nuclei component (radiobiology) in this discourse.

SUMMARY

The ionization dosage from cosmic radiation increases from its sea level value of 0.1 milliroentgen-equivalent-physical per twenty-four hours to a maximum of 15 mrep/d at 75,000 feet for northern latitudes. It then decreases and levels off to a value of 9 mrep/d which is reached at about 140,000 feet. At larger distances from the Earth the ionization dosage can be expected to increase again to twice the last mentioned value due to the gradually vanishing shadow effect of the Earth.

The actual ionization dosages in larger absorber masses (airplanes, rocket ships) will be considerably higher due to the transition effect. The multiplication factor which equals about 2.0 for the rarified air at 75,000 feet altitude will be substantially larger for denser materials.

The main contribution to a possible exposure hazard in the outer regions comes from the heavy nuclei component due to the extremely high specific ionizations of these particles. It is especially the so-called thin-down part and the preceding ionization peak of the low-energy particles which have to be considered most harmful. A unique characteristic of the heavy nuclei is the large radial spread of the ionization. A numerical analysis is given for this radial spread in the ionization peak and thin-down part of a nucleus $Z=20$. In the central core the dosage goes up to values beyond 10,000 roentgen units. However, the number of cells exposed to such extreme radiation dosages is very small. It amounts to about 15,000 cells per heavy nucleus hit. A human organism exposed to the full heavy nuclei intensity will receive about 100 such hits per hour. No appraisal of the biological significance of this entirely new type of radiation exposure can be given at present.

The deflecting influence of the geomagnetic field excludes low-energy primaries from the equatorial belt. The thin-down phenomenon is limited to northern latitudes. The exposure hazard, therefore, can be expected to be substantially greater in the polar cap.

For larger distances from the Earth it can be theoretically derived that the equatorial zone of total exclusion of low-energy heavy nuclei extends to about 1,000 miles altitude and the zone of partial exclusion (i.e., of the gradual build-up of the full intensity) to about 8,000 miles altitude.

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