Limitations on Space Flight due to Cosmic Radiations

Newly discovered radiations dictate vehicle design and orbit of future manned space flights.

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One of the factors which may severely limit man's operation in space is the presence there of various ionizing radiations. Until very recent years the possibility of putting men in outer space seemed so remote, and the radiations there appeared so weak, that the problem was largely ignored. However, with the development of rocket systems capable of placing satellites in orbit around the earth and with the prospect of placing manned satellites in orbit in the near future, the problem of radiation hazard is both a real and an immediate one.

Cosmic rays have been known and studied for many years. Mainly originating outside the solar system, they consist of atomic nuclei accelerated to very high velocities (*1*). They are present in the vicinity of the earth only in very small numbers and until very recently have been of only theoretical interest to biologists.

When the first American satellite (1958 Alpha, Explorer I) went into orbit on 31 January 1958, there were instruments aboard which gave an indication of a very high radiation field outside the earth's atmosphere; this finding was definitely confirmed when the next satellite was placed in orbit. It was soon found that the radiations involved were quite different from the cosmic rays, and it appeared that the intensities were great enough to be a real hazard for manned space vehicles.

Thus an interest was created in these radiations and the effect they might have on a man in space. Since the newly discovered radiations differ so completely from cosmic rays, in both physical and biological aspects, it will be best to discuss them separately.

Van Allen Radiation Belts

Since their discovery these radiations have been very intensively studied. Within a year it was found that the radiations consist almost entirely of electrons and protons and are confined largely to two zones surrounding the earth, with maximum concentrations occurring in the plane of the magnetic equator; the peak intensity in each zone occurs roughly at 3500 and 18,000 kilometers from the surface of the earth (Fig. 1). They are usually referred to as the Van Allen radiation belts, after their discoverer.

Present theories of these radiation belts postulate that the particles are trapped by the earth's magnetic field and may remain there for considerable periods of time. As an electron or proton travels toward the earth from the sun, it encounters the earth's magnetic field, which deflects the particle toward either the north or south polar regions in such a way that it spirals around a line of force. As the particle approaches the earth, the converging magnetic lines of force cause it to be reflected back along the same line toward the opposite pole, where the process is repeated. Thus, the particles may continue their back-and-forth motion for days or perhaps months, even though a single traverse may take only a few seconds or less.

Although the origin of charged particles in the radiation belts has not been fully established, it appears that most, if not all, are of solar origin. One hypothesis (*2*) assumes that the particles of the two belts have different origins. According to this hypothesis, those of the outer belt originate in the sun, perhaps as a result of a solar eruption, and after being trapped in the geomagnetic field are lost slowly by collision with the very sparse atmosphere. They are then replenished at the next time of solar activity. In times of violent solar activity the particles "spill over" in large numbers in the upper atmosphere in the polar regions, thus accounting for the aurorae.

According to this theory, many of the particles of the inner belt have a different origin. Primary cosmic ray particles, traveling at too high a velocity to be trapped by the earth's magnetic field, are stopped in the high atmosphere partly by nuclear collisions which lead to nuclear disintegrations, producing neutrons which radiate in all directions. As neutrons are unstable and decay spontaneously into electrons and protons, those neutrons which travel away from the earth can provide a source of charged particles which are then trapped in the magnetic field and produce the inner Van Allen belt.

This theory is very attractive and thus far is supported by satellite and space probe observations. It is known that the radiation in the belts varies greatly with solar activity, and the position of the belts probably varies considerably as a function of time.

Thus, outside the earth's atmosphere there is a radiation field which continually waxes and wanes and shifts about very considerably. Some average values have been estimated by Van Allen (*3*), and these are given in Table 1; they can be taken at the present time only as rough approximations.

So far these radiation belts have not been found at an altitude of less than 600 kilometers; it seems reasonable to assume that this represents an approximate lower limit for the inner belt and that no great hazard to man will be encountered below this altitude.

Assuming the values of Table 1 to be correct, one can compute the biological dose under any desired condition. First, if one assumes a condition of no shielding it is possible to predict a dose of radiation of millions of rads per hour at the peak intensity of both radiation belts. (A rad represents a dose of radiation received when 100 ergs of energy per gram of matter has been absorbed.) It should be noted that a dose of 500 rads is probably fatal to man; 100 rads would cause serious later effects; and 10 rads would cause

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only minor effects. These figures mean that it would be impossible for man to exist in the radiation belts unshielded, even for very short periods of time.

The slight protection offered by a space suit would cause some change in the situation, but the dose rates would still be thousands of rads per hour. This means that if man is required to operate in space at an altitude of, say, 10,000 miles in the neighborhood of the equator, he would receive a fatal dose of radiation in a few moments. If he were in a space vehicle with shielding thick enough to provide a mass of 1.0 gram per square centimeter of surface area (a reasonable shell for a space ship), the situation would change considerably. The dose rate would be about 10 rads per hour in the inner zone and 50 rads per hour in the outer zone; thus a traverse, lasting some minutes, of one or both of these belts in such a ship would be admissible, but repeated exposures could not be tolerated.

It should be emphasized that Van Allen's values may be in error by an order of magnitude. For example, Schaefer (*5*), computing from some data of Freden and White (*6*), concludes that the maximum dose rate in the inner belt behind shielding of 2 grams per square centimeter would be about 120 rads per hour, as opposed to 10 rads per hour behind shielding of 1.0 gram per square centimeter, as estimated from Van Allen's data. Nevertheless, it seems reasonable to assume that shielding of 10 grams per square centimeter would be required to shield against virtually all the radiation of the outer belt. This would be a heavy but perhaps not impossible load. In the inner belt there is a strong component of very energetic protons, and a much heavier shield would be required. However, the flux of these particles is not great, so a brief stay in this zone with a moderately heavy shield would probably not be serious.

From these estimates it can be seen that a satellite having an orbit which passed through even the fringes of the radiation belts would be habitable for only an hour or two. For a rocket which leaves the earth, the escape velocity is such that, with reasonably heavy shielding, a man would receive a dose of the order of 10 rads. The "escape hatch" at the poles could be used, but this route is much more difficult technically.

In the foregoing discussion, it is assumed that all radiations have the same biological effect. This is not strictly true. The relative biological effectiveness of protons of about 1 Mev energy is about 2.3 as compared with gamma rays, but when the energy increases to about 20 Mev, the relative biological effectiveness approaches unity. The radiations which would be encountered inside a space ship passing through the Van Allen radiation belts would have all the slow components filtered out by the walls of the ship; only fast electrons, fast protons, and some x-rays would be left. These all have roughly the same relative biological effectiveness, and thus the correction required by this factor would seem to be minor.

X-rays will be generated when the electrons of the radiation belts are stopped in the walls of the space ship (bremsstrahlung). The magnitude of these x-rays will depend not only on the weight of the shield but also on its composition and design. The correct design of a shield for a complex radiation spectrum such as exists in the radiation belts is a difficult mathematical problem. However, with careful shield design such x-radiation can probably be kept to reasonably low values and, for any situation likely to be encountered in a space ship, will probably always be well below the radiation doses received from particles which penetrate the shield.

Recent measurements (*4*) have shown the presence of x-rays of energies up to 90 kev as a normal component of solar radiation, but these do not, of course, penetrate the earth's atmosphere very far. These measurements have shown that most of this radiation is in the very soft x-ray region below 10 kev, and penetration through a shield satisfactory for protection from other radiations would be so slight as to be negligible. In the harder x-ray region (30 to 90 kev), the flux is so low that it can be ignored as a biological hazard.

Thus, it would seem that the Van Allen radiation belts present a challenging problem to those interested in putting a man in space. There is every

Table 1. Energy spectrum of radiations in the radiation bands. [From Van Allen and Frank (*3*)]

Particles	Energy	Intensity
	Inner band	
Electrons	> 20 kev, unidirectional	2×10^9/cm² sec sterad
Electrons	> 600 kev, unidirectional	1×10^7/cm² sec sterad
Protons	> 40 Mev, omnidirectional	2×10^4/cm² sec
	Outer band	
Electrons	> 20 kev, omnidirectional	10^{11}/cm² sec
Electrons	> 200 kev, omnidirectional	10^8/cm² sec
Protons	> 60 Mev, omnidirectional	10^2/cm² sec

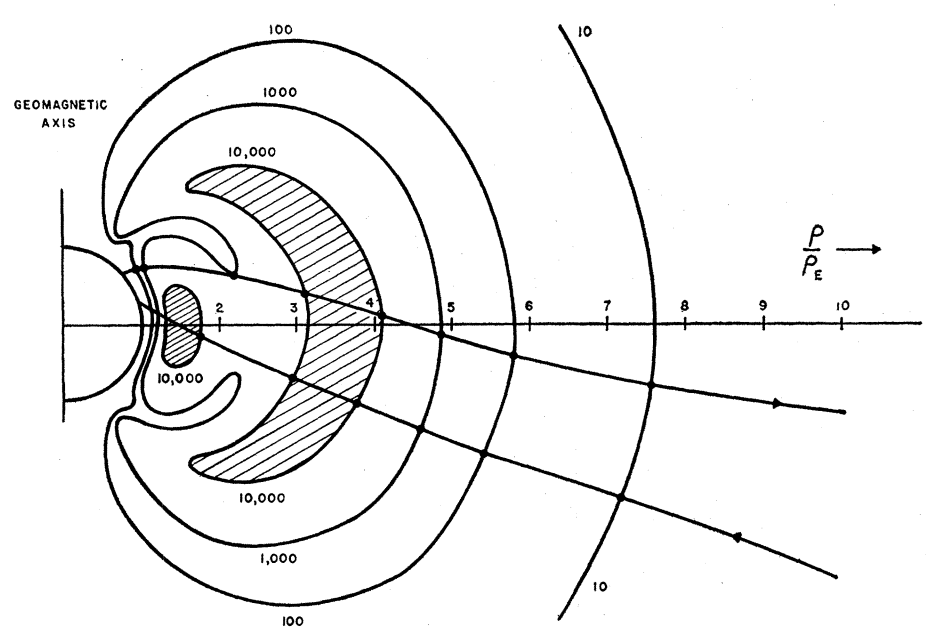

Fig. 1. A plot in a geomagnetic meridian plane of the intensity of the radiation belts around the earth. The contour numbers represent the counting rates recorded from a Geiger-Muller tube in Pioneer III or in satellite 1958E. The cross-hatched areas represent regions where the counting rate may be much higher than 10,000. [From Van Allen and Frank (*3*)]

indication at the present time that with careful planning these problems can be solved, so that radiation hazard will be no greater than the many other hazards associated with space flight.

Effects of Cosmic Rays

Primary cosmic rays consist of charged atomic nuclei, stripped of their planetary electrons; atomic nuclei of all the elements in the periodic chart up to iron have been observed in these radiations, although not all in equal numbers. They apparently originate outside the solar system and pervade the galaxy. The earth's magnetic field imposes an energy cutoff condition such that the cosmic ray flux is greater near the magnetic poles and at a minimum in the plane of the magnetic equator. The nuclei interact with the earth's atmosphere, and the heavy particles do not penetrate below an altitude of about 16 kilometers, terminating in nuclear reactions in the upper atmosphere.

These radiations can be divided into two parts—the lighter group, consisting of protons and helium, on the one hand, and all the heavier elements on the other. The former group has a much higher flux; it has been estimated that there are about 50,000 particles in this group per square centimeter per day striking the earth's atmosphere, as compared to about 500 of the heavy group (Fig. 2). The heavy group contributes more ionization in the high atmosphere per particle, but the lighter particles contribute most (perhaps ten times as much) to the total ionization produced. From these figures one can estimate that a man in an unshielded situation at an altitude of 100,000 feet or more would receive a total radiation dose of the order of 15 millirads per day. Since such a dose is due almost entirely to protons, of which the biological effects are well known, one would be inclined to neglect it as being too small to be of any importance in human space travel. However, there has been some recent evidence indicating that the heavy particles, even though producing a relatively negligible amount of ionization (dose), may produce special biological effects of considerable importance. It thus becomes necessary to examine these effects critically.

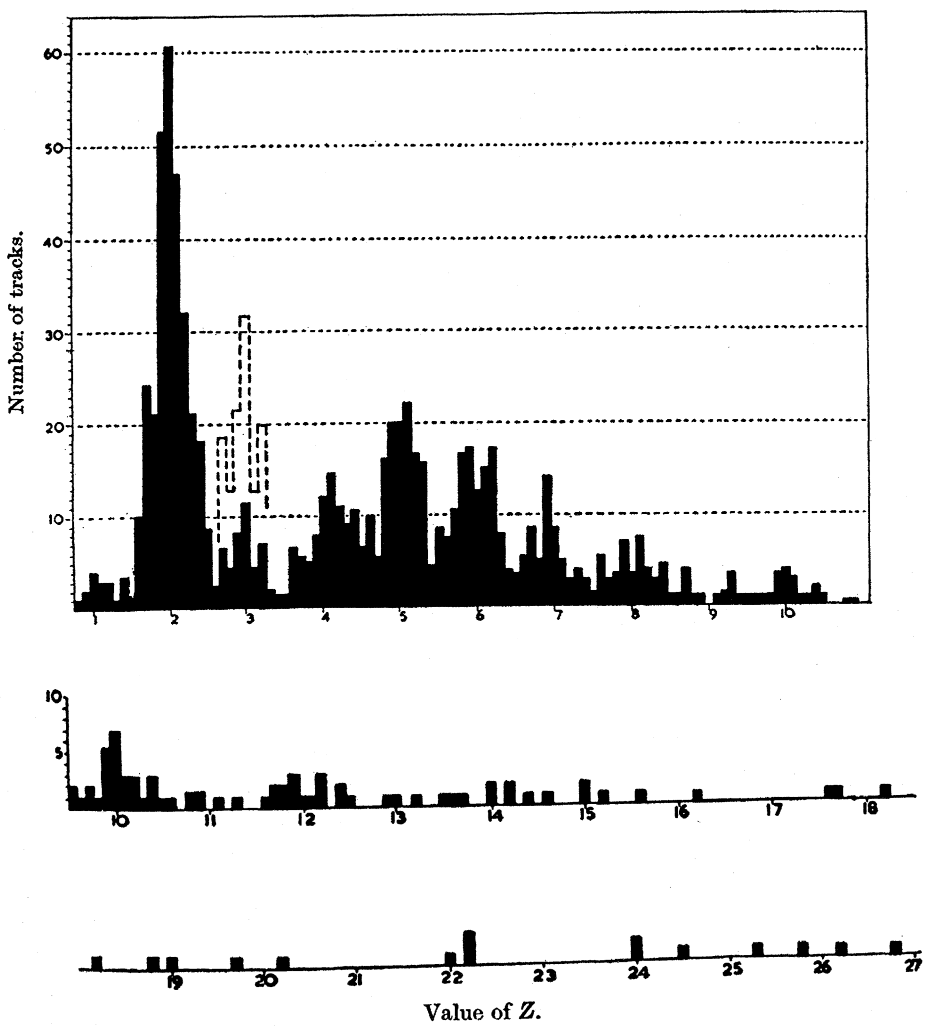

Fig. 2. Distribution of primary cosmic ray particles as a function of atomic number. The tracks from very heavy particles are quite rare events. [From Dainton *et al.* (11)]

The primary cosmic rays may have energies as high as 10^7 Bev per nucleon, but particles with such high energies are extremely rare, and most of the particles have energies of a few billion electron volts per nucleon. When they enter tissue one of two things may happen. First, they can interact with the atomic nuclei in the tissue to form stars. In this process the particle makes a head-on collision with an atomic nucleus of the tissue, resulting in nuclear disintegration from which a number of small high energy particles and some gamma rays are emitted. Since these secondary radiations are very penetrating, the energy of the primary radiation is dissipated over a large volume of tissue and is of relatively small radiobiological importance.

The second possibility is that the primary particle may gradually lose its energy by collisions with the electrons of the tissue. Not only does this process cause ionization of the atom of the electron in question but the electron itself is ejected at an angle to the track of the primary particle and causes additional ionization close to this track. This dual process causes intense ionization along the particle track. As the primary particle slows down, its rate of energy loss becomes larger and larger, so that toward the end of the particle path the track of ionization becomes quite wide and intense (Fig. 3). Schaefer (7) has calculated the energy distribution in these tracks under a variety of conditions. Briefly, he computes that the area of intense ionization occurs only at the end of the track and is only about 1 millimeter long, even though the particle may penetrate many centimeters of tissue. This intense effect is known as a "thin-down," which can be as wide as 25 microns. In the center, the ionization density is equivalent to doses of the order of 10,000 rads, with the dose decreasing radially from the center. Thus, a thin-down would produce a small cylindrical volume of intense ionization about 1 millimeter long and up to 25 microns in diameter. A maximum of 15,000

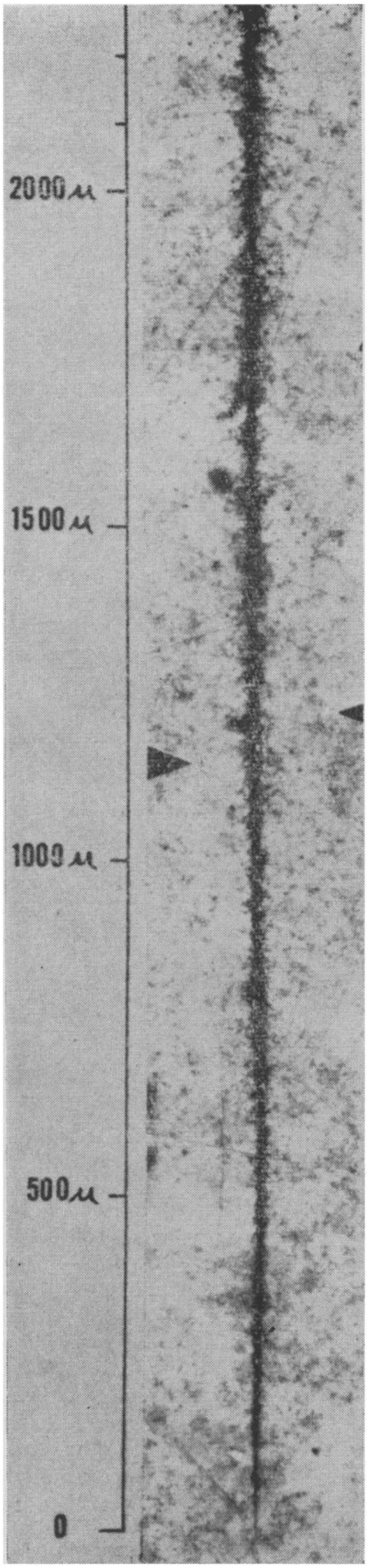

Fig. 3. Track of a heavy cosmic ray primary of atomic number about $Z = 20$ in a photographic emulsion. The emulsion has a density of about 3, so the spread of the track would be much wider in tissue. [Modified from Schaefer]

mammalian cells would be involved in such a volume. Schaefer has further estimated that a man weighing 70 kilograms would receive about 100 such hits per hour in interstellar space. Since most of the cells involved would receive only a relatively small dose and would therefore be unaffected, thin-downs would seem to constitute only a minor hazard except for certain organs where the loss of a relatively few cells would be very serious. The organs most likely to be affected would be the hypothalamus of the brain or the lens of the eye. In the former case, small brain nuclei are responsible for such functions as temperature regulation and, in the latter, a small defect may grow to form a cataract.

These thin-downs represent quite a different type of radiobiological action, on which there has been little laboratory experimentation. The energies of these particles are greater than 1 Bev per nucleon, while the best of the heavy ion accelerators, the HILAC at Berkeley, can accelerate ions to only 10 Mev per nucleon. Single cell organisms such as yeast are being studied with the HILAC, but the lower energies involved may not produce significant changes in terms of tissue damage.

An attempt has been made by Chase (*8*) to measure directly the biological effect of these thin-downs by sending black mice in balloons to the top of the atmosphere at altitudes up to 120,000 feet. It was observed that some of these black mice grew some gray hairs. Hairs turn gray when the melanin-producing cells of the individual hair follicle are destroyed; these cells are known to be very sensitive to radiation. Thus, when a hair turns gray in a young mouse, it is presumptive evidence that the follicle has been hit by radiation. In one series of studies in 1954, involving three balloon flights, there was a significantly greater number of gray hairs on the experimental animals than on the control animals, but in another series a year later no such difference was found. These experiments are thus quite inconclusive.

In these thin-downs practically all the damage would be caused by secondary radiation, and the only unique feature would be its high concentration along discrete paths. Thus, a very small beam of radiation, 25 microns in diameter or less, should produce the same effect in tissue as a single primary particle. Such a microbeam has been developed, and experiments have been undertaken by Zeman, Curtis, Gebhard, and Haymaker (*9*) in which they used the brain of a mouse as the experimental tissue. The microbeam consists of deuterons from the 60-inch Brookhaven cyclotron collimated in a beam whose diameter can be varied from 25 microns to 1 millimeter. It is found that with the large-beam diameter a dose of 14,000 rads will cause almost complete destruction of cells of the cerebral cortex along the beam path, as judged by histological examination. This result is to be expected from experience with x-ray. However, as the beam diameter is decreased, an increasingly large dose in the beam is required to cause cell destruction, until at a beam diameter of 25 microns, more than 400,000 rads is required (Fig. 4). This is a very striking phenomenon.

These results can most easily be explained by assuming that with a wide

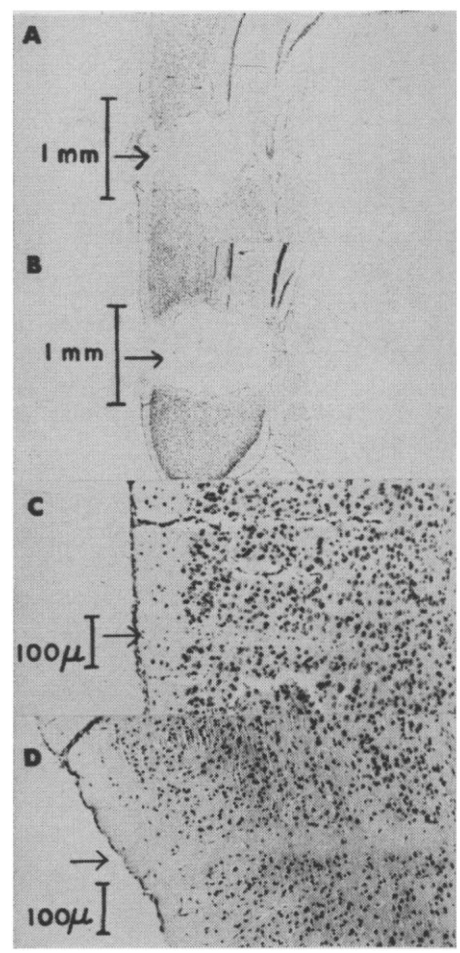

Fig. 4. Frontal sections of cerebral cortex of mice irradiated with deuteron beams: (*A*) 1-mm beam, 50,000 rad, 24-day survival; (*B*) 1-mm beam, 60,000 rad, 24-day survival; (*C*) 0.025-mm beam, 1.1×10^6 rad, 6-day survival; (*D*) 0.025-mm beam, 1.1×10^6 rad, 48-day survival. [From Zeman *et al.* (*9*)]

radiation beam most of the effect seen in the brain is secondary to vascular damage. As the beam becomes very narrow it has an excellent chance of going through the tissue without hitting even one capillary, since the average distance between capillaries in the brain is 65 microns. Even if the beam did hit and destroy a single capillary, it seems certain that other, neighboring capillaries could carry out its function, since there must be that much of a factor of safety for the capillary circulation. It seems almost incredible that individual nerve cells in the brain can sustain a direct hit with a dose of 400,000 rads before being destroyed, but such is the case. It should be pointed out that these cells never undergo cell division, and this undoubtedly accounts for their radioresistance. In these experiments the histological appearance of the cells was taken as the sole criterion of effect. However, if a cell appears cytologically perfect 48 days after irradiation, it seems highly likely that it is functional.

Since the smallest of the beams used is large as compared to the diameter of a thin-down, and since the dose required to cause cell destruction is many times higher than that in the most intense part of a thin-down, it can be concluded that these thin-downs will probably not prove destructive to the brain. Experiments are now under way with the microbeam to test other tissues, principally the lens of the eye and the hair follicles.

Since primary cosmic radiations which will be encountered in space are so energetic, shielding against them would be very difficult and would require about 100 grams of aluminum per square centimeter of surface area to decrease their intensity significantly. Less shielding than this might make the situation worse, since it would only slow down the particles and insure that the thin-down occurred in the body.

It is worth noting that a few rockets for which recovery was planned carried biological test objects. The principal radiobiological objective was the test of the foregoing conclusions, to make sure that nothing had been overlooked. Three different types of objects have been flown: mammals, including two monkeys and some mice; microorganisms (in an attempt to observe some abnormal types of mutations); and seeds (the plant embryo constitutes a sensitive radiobiological indicator, since a change in even one cell may show up as an abnormal plant when grown). None of these experiments demonstrated any radiobiological damage—a finding which is not surprising in view of the relatively low altitude and short duration of the flight. Some biopacks have been included in satellites designed for recovery, but none has been recovered yet.

Thus it seems that at the present time the heavy cosmic ray primaries do not constitute as serious a hazard as was once feared. The actual radiation dose delivered by them is negligible, and apparently the damage to the brain would not be appreciable. The effect on the eye is not known yet, but it does not seem likely that it will prove to be a serious problem. It should be pointed out that the results of Chase on the graying of hair at a very high altitude have never been either explained or confirmed, and until this matter is settled one cannot speak with full assurance.

Summary

These conclusions (*10*) may be summarized as follows:

1) Flight below the Van Allen belts seems reasonably safe without radiation shielding.

2) It is probably impractical to shield a rocket sufficiently to permit a man to remain in the inner Van Allen belt for more than about an hour, but it should be possible for him to go through it without serious harm.

3) Shielding for the outer Van Allen belt is possible but would have to be quite heavy if a stay of more than a few hours were contemplated.

4) The primary cosmic radiation is not intense enough to deliver a serious radiation dose, even for exposures of a few weeks, and the heavy cosmic ray primaries do not seem to present an unusual hazard.

References and Notes

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