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Radiation Dosage in Flight through the Van Allen Belt

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ABOUT ten years ago, when aviation medicine developed a serious interest in the problem of cosmic ray hazards in flight at the top of and outside the atmosphere, it became common practice to express cosmic ray intensities in terms of tissue ionization dosages, that is, in roentgens equivalent physical (rep). This expedited the interpretation of the data of the physicists inasmuch as exposures quoted in rep or milli-rep immediately convey, to the radiobiologist, an idea about the effects on living matter to be expected. On the other hand, one should realize that dosages derived in this manner are not representative of the true exposure that would prevail if a human body were to replace the measuring device. Though cosmic ray intensities are often given in units of ion pairs per c.c. of standard air, thereby lending themselves easily to the indicated conversion, they usually have been measured with equipment which does not fulfill the requirements of "air equivalence" as set forth in the definition of the roentgen unit.

If tissue ionization dosages are to be indirectly determined by inference from data, which have been collected without any consideration of radiobiological implications, larger systematic errors are bound to enter the evaluation. The ionization in the gas of an ion chamber is representative for the tissue dosage only if a number of conditions are fulfilled. The filling gas and the walls have to be of the same mean atomic number as living matter. The thickness of the chamber walls must be large enough to equal the maximum range of secondary electrons and small enough not to attenuate the radiation to be measured. For a radiation of the utter inhomogeneity of the primary cosmic ray beam, the latter requirement leads to contradictory specifications of design. Another difficulty lies in the need for saturation voltage of the ion collecting field in the chamber. A sizable fraction of the total ionization of the primary cosmic ray beam is generated in absorption events of high local energy dissipation creating dense columns or giant clusters of

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ions. Considerable recombination loss is unavoidable for this fraction of the total ionization even if a high voltage is used for the ion collecting field. Finally, the cosmic ray apparatus of the physicist is usually designed to the most stringent specifications of compactness weighing a few pounds at the most. Accordingly, the dosage contribution from local scattering in casing, frame and equipment can be expected to be substantially smaller than for a human body in a large space capsule.

For all these reasons, the indicated evaluation of cosmic ray exposures in rep cannot claim accuracy. However, as long as the dosages involved remain small, not exceeding the 1 r level, this indeterminacy seems acceptable since on the biological level a similarly large margin of uncertainty exists with regard to the definition of the permissible dose. For the so-called quiescent cosmic ray beam beyond the atmosphere and with dose rates well below 0.1 rep per 24 hours, this specification seems well fulfilled. For space travel in general, however, a similar assurance no longer exists since Van Allen has shown that a field of intense radiation is girdling the earth beyond the 1,000 kilometer mark with dose rates exceeding the 10 rep per hour level. Despite these new aspects, it is nevertheless felt that in the present early phase of space exploration the use of the rep unit for dosage estimates, because of its better descriptiveness, should not be abandoned. If the aforementioned limitations are borne in mind, no misconceptions are likely to develop. When satellite techniques progress in the future and more detailed data on the radiation in the Van Allen belt are available, a more fruitful debate of how to carry out the determination of the true tissue ionization dosages in a manned space ship will be possible.

The discovery by Van Allen[2] that the earth is surrounded, in the equatorial region, by an intense radiation field extending from 1,000 to about 20,000 kilometers in altitude, has brought about a revolutionary change in the basic concepts of the radiation hazards in space flight. While present information is still too fragmentary to allow a precise determination of the tissue ionization dosages that will have to be accepted in flight through the Van Allen belt, the frequencies of ionizing particles have been accurately determined and some first clues as to the nature of these particles and their energies are available. This information indicates that exposure levels closely approaching or possibly fully entering the range of acute radiation damage prevail in the central zones of the Van Allen belt.

The impact of this sensational turn of events is so strong that some might be inclined to forget the vast region between 200 and 1000 kilometers in altitude in which long-lived stable orbits can be established and the radiation hazard seems entirely acceptable. It is this very region, upon which the sound, practical development of human space flight in the near future will center. Global passenger transportation with ballistic vehicles and permanently orbiting observation and relay platforms will both operate in this altitude range. In fact, both types of operation are likely to heavily favor the lower third of the altitude range in question. Nevertheless, the challenge of manned flight beyond the 1000 kilometer mark will always be there, and calls for a tentative assessment of the radiation hazards in these regions.

THE VAN ALLEN BELT

Graphs and pictures of the general isointensity contours of the Van Allen belt, as they follow from the recordings of the *Explorer* satellites and *Pioneer* probes, have been published repeatedly.[1] They are all based on Van Allen's original graph in his report on the *Pioneer III* data.[3] The basic structural feature of the belt is the division in two zones showing maximum radiation intensity at about 3000 and about 15,000 kilometers in altitude above sea level. Inasmuch as the probing vehicles carried diverse detectors, some first clues on the composition of the radiation in the two zones are also available. The most penetrating component in the inner zone seems to consist of protons in the 100 million e-volt energy range. This component produces, even behind 1 gram per cm^2 absorbing material, a dose rate of more than 10 rep per hour and is little attenuated by an additional shield of 3 millimeters of lead. Without the indicated absorbers, the maximum intensity in the inner zone is tremendous, yet the bulk of the beam consists of particles of low energy corresponding to a penetrating power of less than 140 milligrams per cm^2. The remaining intensity of higher penetration than 140 mg per cm^2 exhibits a less steep decline towards higher energies. This means that a man freely exposed in a space suit of minimum design for pressurization and heat insulation (about 0.2 g per cm^2) will receive an entrance dose to his skin of substantially more than 10 r per hour and the depth dose of this radiation will not show a very steep decline.

The outer zone seems to consist exclusively of electrons, which show a similarly steep energy spectrum falling off rapidly toward higher energies (i.e., penetrating powers). While protection from the electrons themselves would pose no serious weight problem because of their low penetrating power, the actual exposure conditions are seriously aggravated by the circumstance that electrons in the process of being stopped produce x-rays in the so-called *bremsstrahlung* processes, and these x-rays have about a thousand times higher penetration than the electrons generating them. This local x-ray production in the outer surface of the vehicle represents the main, if not exclusive exposure threat in the outer zone of the Van Allen belt.

The best weight economy in the design of shielding from the radiation in the outer zone would be afforded by laminated walls assigning the task of stopping the beta rays to a material of low atomic number Z, thereby minimizing the production of x-rays, and the task of attenuating the x-rays to an element of high Z which offers greater absorption on the same weight basis than a lighter material.

INTEGRAL EXPOSURE IN DIFFERENT ORBITS

Another possibility of reducing the radiation exposure in flight through the radiation belt lies in speeding up the traversal of the regions of highest intensity. The following example serves best to explain the basic issue. Nearest at hand is the case of the lunar transfer, i.e., the trip to the moon.

For reasons of fuel economy, the proper trajectory for this trip is the so-called transfer ellipse. It means that the vehicle is put into an elliptical orbit around the earth with the apogee of the ellipse in the vicinity of the moon. Such a transfer ellipse is drawn to scale in the upper graph of Figure 1. Also indicated in that sketch is another possible trajectory, the radial shot. The relative navigational merits of the two possible trajectories shall be discussed later. The point of interest here is the relative radiation dosages. Since dosage equals dose rate times exposure time, it depends, for a given radiation field in space, directly on the speed of the vehicle. For the circular symmetry of the Van Allen belt in particular, the radial speed component of a given trajectory is the determining factor. For the two trajectories under discussion, this component is shown in the lower graph of Figure 1. It is seen that a vehicle on a transfer ellipse enters the first belt at less than half the radial speed as compared to the radial shot. For the second belt, the corresponding difference is much smaller, yet still sizable. In view of the fact that the shielding problem in the first belt is more difficult because of the high energy proton component, the advantage of the radial shot over the transfer ellipse actually is much greater than the mere kinematic difference would seem to indicate.

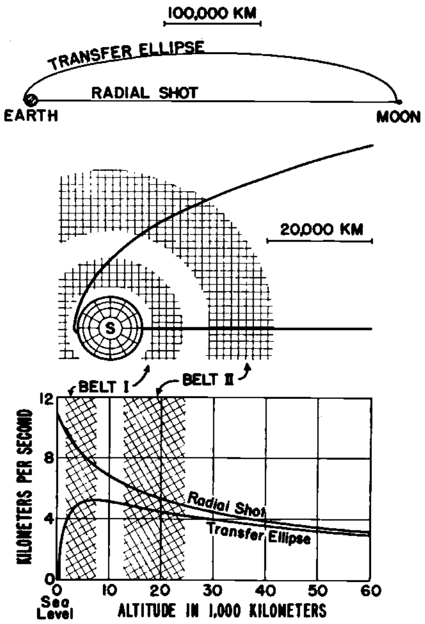

Fig. 1. Traversal of Van Allen belt on lunar trip. Top and center graph are drawn to scale. Bottom graph shows radial speed component for both trajectories. Note large difference in first radiation zone.

With regard to the integral dose on traversal, it must be remembered that its accurate value in rep cannot be assessed at present since only particle intensities, but not actual ionization intensities have been recorded so far. The dose rate profile in the top graph of Figure 2, therefore, is tentative and based only on the component of highest penetration. One should realize that due to the extreme heterogeneity of the radiation involved, the dose rate quite basically depends on filtration. Even if at some future time the ionization intensities will be exactly known, the special conditions of the individual case, such as material and thickness of the vehicle wall and the pilot's clothing, will strongly influence the entrance dose on the body surface and the depth dose pattern within the body. For a discussion of the relative merits of the different trajectories, these relationships obviously are irrelevant as long as the radial structure of the radiation intensity is correctly known in relative terms.

Routine mathematical procedures lead from the altitude profile of the speed (bottom, Fig. 1) to the altitude profile of the time, which in turn can be combined with the altitude profile of the dose rate (top, Fig. 2) furnishing finally the altitude profile of the integral dose (bottom, Fig. 2). Of special interest also is the time profile of the dose rate for the two trajectories in question, since it conveys direct information on the critical time intervals during which high radiation intensities prevail. These time profiles are shown in Figure 3. The areas under the curves are directly integral doses.

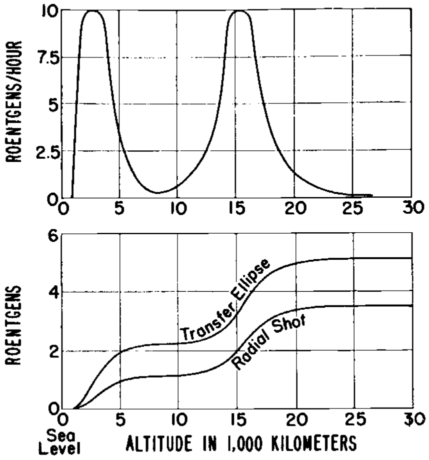

Fig. 2. Radiation dosage in Van Allen belt. Dose rate as a function of altitude above sea level over equator (above). Accumulated dose as a function of altitude for the two trajectories of Figure 1 (below).

It is interesting to notice that, for the radial shot, the critical time intervals within which the bulk of the full dose is administered equal 7 minutes for the first, and about 15 minutes for the second belt. It seems conceivable that a space pilot during such relatively short periods could accept some discomfort in order to ensure better protection as shown in Figure 4. Rolling up to a fetal position the man could cram himself into a lead lined capsule which provides only minimum space for movement. It is obvious that the total surface and therefore also the weight of such a capsule is considerably smaller than that of one designed for a man in a more comfortable position. At the same time, a man in a rolled-up position receives a smaller total body dose in a given radiation field than in a standing or sitting position, because the body offers a smaller total entrance cross section to the radiation beam with a correspondingly greater equivalent target thickness. In view of the large fraction of particles of low penetration in the incoming radiation, this will result in a substantial lowering of the kilogram roentgen total body radiation burden.

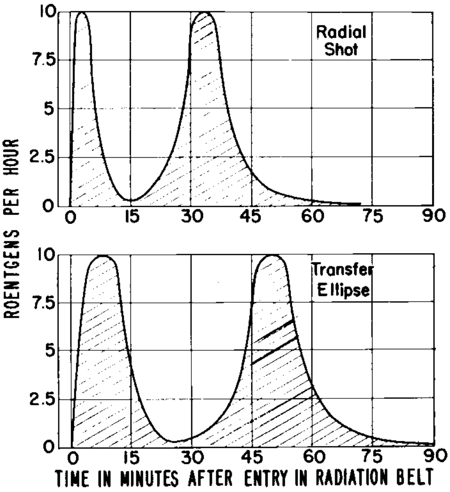

Fig. 3. Time profile of dose rate in Van Allen belt for the two trajectories of Figure 1. Note shorter time intervals at high dose rates for radial shot, especially in the first zone.

Another question which should be discussed in this connection concerns the directional properties of the radiation. There are some lines of evidence that a large part of the electrons and protons in the Van Allen belt travel at right angle to the magnetic lines of force of the earth's field. In terms of the local conditions in a space ship this would mean that the primary radiation shows cylinder-symmetrical incidence. It has been suggested that this circumstance could be utilized for further weight savings with the design of a ring- or barrel-shaped shield leaving top and bottom open (right, Fig. 4). However, it seems questionable whether substantial gains can be accomplished along these lines since a large part of the tissue dose within the ship will be contributed by secondaries produced locally in the structural material and equipment of the vehicle. This scattered radiation is likely to show largely omni-directional symmetry of incidence.

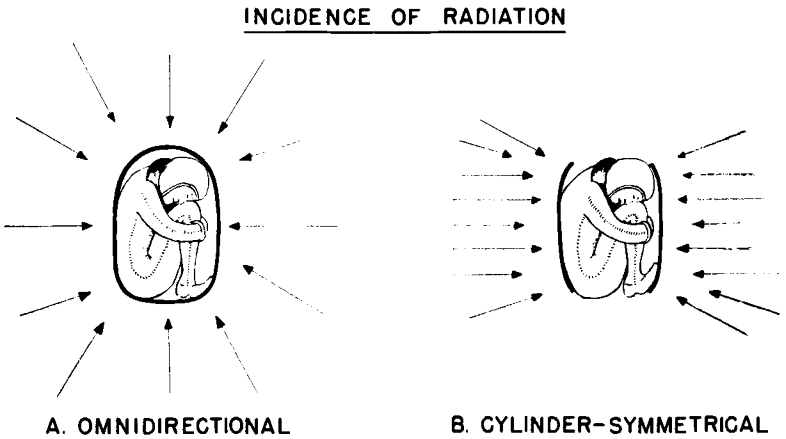

Fig. 4. Fetal position of pilot for minimizing exposure in short duration traversal of intense radiation fields. Two advantages: (1) total surface, i.e., weight of shield is minimal, (2) volume dose in kilogram roentgens is minimal because of greater mean depth of target which means smaller depth doses.

A third question pertains to submersion in water. We know that a considerable alleviation of accelerative stresses can be achieved by total body submersion in water. Combining the two principles of water submersion and radiation shielding, one could conceive of a water-filled barrel with lead-lined walls. This would open the possibility of allowing somewhat more space and positional freedom inasmuch as the water would partly take over the task of creating a compact ball-like target volume for the radiation, minimizing thereby the depth dose and the integral volume dose for the man in it. As mentioned before, better data on the actual roentgen dosages involved are needed before it can be decided to what extent these potential ways and means of protection will have to be used. There is no question that they are all rather costly in terms of weight. What makes it especially frustrating is that they would be needed for only a rather small fraction of the total traveling time.

Returning again to the computational procedure of evaluating the integral radiation dose, it is interesting to note that a very descriptive method of graphical plotting of radiation fields is obtained by dividing the local dose rate at a certain distance from the earth by the local vertical speed component of the vehicle. The result of this division is a quantity, which has the dimension of dose divided by distance. It is, in other words, the dose which the vehicle accumulates in traveling over unit distance. Figure 5 shows the corresponding graph with the 1,000 kilometer dose plotted on the ordinate. The characteristic difference of the two trajectories now shows up most clearly. At the same time, the plot is an altitude profile and not a time profile. This is a definite advantage since it restores the connection to the altitude profile of the dose rate and permits direct mapping of the radiation field in conventional terms of altitude and latitude.

The main reason for the usefulness of the 1000 kilometer dose rests in the fact that for most interplanetary operations, such as transfer to the moon or to Mars, or Venus, by far the largest part of the propulsion work is performed in getting the vehicle out of the gravitational reach of the earth. Since this work is the same for any mission, the required launching speed of the vehicle will be largely the same. As is well known, to each distance from the earth within its gravitational reach a corresponding characteristic escape velocity can be assigned. If the dose rate of ionizing radiation at that distance is also known one can immediately determine the corresponding 1000 kilometer dose for that particular point as the quotient of the local dose rate and the local escape velocity. This 1000 kilometer dose is a much more realistic term than the dose rate itself, since it directly defines the local exposure hazard. For instance, the same dose rate of 10 r per hour encountered at an altitude of 6,000 kilometers is equivalent to 0.35 r per 1000 kilometers, encountered at 60,000 kilometers altitude it is equivalent to twice as much, namely, 0.7 r per 1000 kilometers.

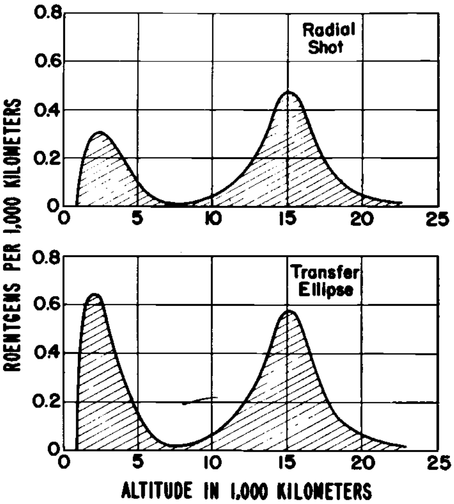

Fig. 5. Altitude profile of 1,000 kilometer dose for the two trajectories of Figure 1.

It is too early to decide to what extent such elaborate mapping of radiation fields in space will be necessary. It is not even known yet whether these fields are constant enough to make such a general analysis worthwhile and realistic. A radically different way of solving the radiation issue is bypassing the Van Allen belt entirely by choosing the so-called polar escape route. Figure 6, drawn strictly to scale, shows the initial section of such a lunar transfer ellipse. It is interesting to notice that the vehicle could be launched into this orbit from a location as far down as the geomagnetic equator and still would clear the radiation belt by a large distance. It would be erroneuos, however, to assume that the possibility of using a transfer ellipse for this orbit would restore the navigational advantages of this type of trajectory over the radial shot. The conventional lunar transfer ellipse, which has been exclusively used so far for all moon probes, the *Pioneers* as well as *Mechta*, is coplanar with the moon's orbit. This ensures a greater chance of still reaching the moon despite navigational launching inaccuracies. Expressed in the jargon of the astronaut, the moon is a larger target for a coplanar ellipse. Furthermore, the coplanar orbit allows utilizing the rotation of the earth as an additional "push" in launching saving fuel. Both advantages do not exist for the non-coplanar ellipse. Since the plane of this orbit forms an angle close to 90 degrees with the plane of the moon's orbit, the moon is a target not significantly larger than for the radial shot. That the rotation of the earth cannot be utilized either, is obvious.

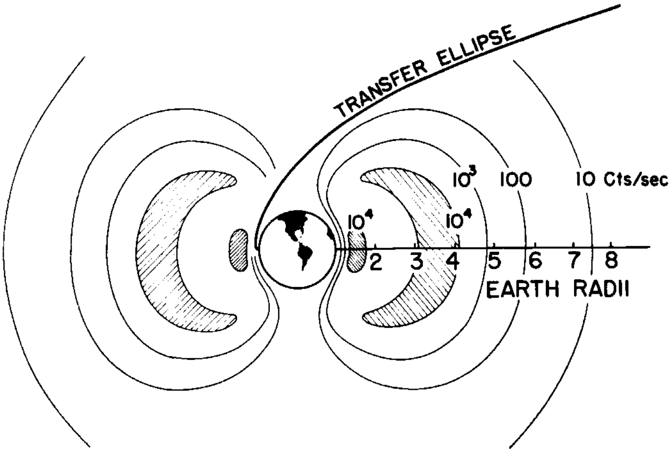

Fig. 6. So-called polar escape route for lunar trip bypassing Van Allen belt. Note that actual launching and injection into orbit can take place at any latitude including equator.

At the present state of the art, both advantages of the coplanar transfer ellipse, the saving of propulsion work and the safer nagivation, seem to weigh rather heavily as rocket experts assert. Since the time for man's flight to the moon has not quite come yet, it seems that the final decision which solution appears to be the best choice can safely be postponed until better data on the various parameters, which have to be weighed in this decision, are available.

SUMMARY

The Van Allen belt is a field of intense radiation girdling the earth in the equatorial plane between about 1,000 and 18,000 kilometers altitude. The radiation intensity shows two maxima about 3,000 and 15,000 kilometers. The first zone seems to consist of protons exhibiting a very broad energy spectrum with a tremendous particle flux of low penetrating power. The intensity declines, first steeply, and then more gradually toward spectral sections of higher penetration. The hardest component, tentatively assumed to consist of protons in the 100 million e-volt range, produces behind 1 gram per cm.^{2} absorber thickness about 10 rep per hour and is little attenuated by an additional 3 millimeters of lead. The second zone seems to consist of electrons. Though they are completely absorbed in any wall of minimum structural stability, the shielding problem is complicated by the production of secondary X-rays in the stopping process of electrons. Laminated shields offer, for this dual protection, better weight economy than plain ones. Generally, shielding in the outer zone imposes a much smaller weight penalty. The integral dose on a lunar trip is investigated for two different trajectories, the transfer ellipse and the radial shot. It is shown that a vehicle on the latter enters the first radiation zone at twice the radial speed than the former thereby receiving a distinctly smaller integral dose.

The most radical solution of the radiation issue is the complete avoidance of the Van Allen belt by choosing a polar escape route. It is shown that a vehicle can be launched on this route from any latitude including the equator and still clear both radiation zones by a large distance. The navigational disadvantages of the radial shot and the polar transfer ellipse consist in higher fuel requirements because the rotation of the earth cannot be utilized for propulsion and in smaller aiming accuracy because the moon is a smaller target for these trajectories.

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"This is Your Captain Speaking"

What the airline pilot cares to do in the way of comforting or cosseting the passengers—giving them flight news over the public-address system, or making chitchat on visits up and down the aisle—is left pretty much up to him. No particular credit or discredit is attached to his conduct in this respect so long as he's civil, and brings his plane in approximately on time. The captain pilot is invested with command authority: if in his judgment the plane shouldn't be taken aloft, it doesn't go, and in flight he is responsible for more than $1 million of company property and the safety of several score lives. But after he climbs out of the cockpit nobody asks for his opinion about anything much.—Robert Sheehan: What's Eating the Airline Pilots? *Fortune*, April, 1959.