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COMPARATIVE EVALUATION OF THE RADIATION ENVIRONMENT IN THE BIOSPHERE AND IN SPACE

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SUMMARY PAGE

THE PROBLEM

Environmental ionizing radiation in space is, in quantity and quality, substantially different from that in the biosphere on Earth at sea level and at mountain altitudes. The fact that the biospheric radiation level varies over a comparatively wide range in different geologic territories, raises the question whether and to what extent living matter could maintain homeostasis over a still wider range that would reach up to radiation levels in space. Clarification of this issue would allow for a definition of a Maximum Permissible Dose for manned space operations which would approach the true critical threshold more closely than do the very conservative official Maximum Permissible Doses for terrestrial conditions involving large populations.

FINDINGS

The natural level of background radiation in the biosphere ranges from a lowest value of 6 microrem/hr over the ocean to values more than 300 times higher that are found in small inhabited areas in Brazil and India. These highest radiation levels in the biosphere overlap the lowest in space as long as only regions outside the radiation belt and conditions of a Quiet Sun are considered. Since shelters for solar proton storms on the moon or planets could be built utilizing indigenous rock, man's long-term survival in space appears to be assured as far as ionizing radiation is concerned.

The inconspicuous chronic damage, such as shortening of the life span, that would result from galactic radiation exposure in space is difficult to assess quantitatively. Extrapolating data on radiation-induced life shortening with gamma rays and neutrons for the mouse, one arrives at a figure of 25 per cent for the life-shortening effect of galactic radiation exposure in space in the sense that for 100 days spent in space, the residual life span of the astronaut would be shortened by 25 days.

As far as acute effects from trapped or flare-produced protons are concerned, by far the most acute problem operationally is the treatment and alleviation of discomfort from skin erythema, and possibly more severe skin damage, that would result from medium-high doses which would leave more deeply seated tissues and organs essentially intact because of the much lower depth doses of these peculiar radiations. This practical problem would seem to deserve much higher priority than the more sophisticated issues of synergistic effects of radiation combined with those of other stresses due to the cabin environment.

INTRODUCTION

The atmosphere of the Earth, representing a shielding layer that is equivalent to a steel shell of about 125-centimeter thickness, offers efficient protection from ionizing radiations of extraterrestrial origin to living matter on the planet's surface. The hard component of the galactic radiation penetrates to sea level with only about 0.6 per cent of its extraterrestrial intensity. Equally effective is the protection from the strong radiation surges accompanying solar flares, which would destroy all living structures on any unprotected planetary body within the solar system. Thus, a unique abode for the creation and evolution of life was created when the Earth built up its atmosphere.

If man sets out, in the space age, to leave the protective cover of the atmosphere and ultimately to spend sizeable fractions of his life span in space, he enters an environment wherein ionizing radiation prevails at levels to which life during evolution never had any chance to adjust. The very low level of natural background ionization in the biosphere on Earth below the protective shield of the atmosphere is rather constant with time, yet shows variations with geographic location. Aside from a small residual contribution from galactic radiation, the ionization is due exclusively to radioactive trace substances in the environment and the body tissues themselves. In the present context, the question arises as to what level this sea-level background could be increased without harmful effects on the genetic and somatic constitution of man. For many other parameters of the physical environment, such as temperature, air pressure, gravity, or magnetic field force, the human body can sustain and compensate substantial changes from the standard values without damage. Considering the fact that background radiation shows considerable natural variations at different locations, one would expect that ionizing radiation would be no exception to the just-mentioned rule and that living matter would show a similar tolerance margin beyond the width of natural variations.

Unfortunately, the biological significance of the natural background of ionizing radiation is not completely understood. Low level irradiation in general is a challenging and controversial topic in radiobiology, harboring a number of issues on which opinions and theories differ widely. The fact that even the highest forms of life, including man himself, have no sensory perception for ionizing radiation nor show adaptive responses to it could be invoked as evidence that background ionization represents a subthreshold type of environmental influence. Other lines of evidence support the opposite conclusion, suggesting that background ionization does exert subtle influences on living structures, possibly on both the genetic and somatic level.

It is obvious that the uncertainty concerning the biological significance of background ionization must hamper greatly the effort of judging the harmfulness of environmental radiation in space. To be sure, acute damage as it could develop from exposure to trapped protons and electrons in the radiation belt, or to a solar particle beam from a large flare, would not pose the main problem. Difficulties arise if it becomes a matter of assessing the inconspicuous effects of long-term exposure to the normal, i.e., galactic, background radiation in space. The latter problem assumes special importance when man's conquest of space is seen in its wider perspectives of astronauts spending substantial fractions of their life spans in the space radiation environment. Our present radiobiological understanding, especially of galactic radiation, falls far short of allowing precise determinations of maximum permissible dose (MPD) levels and shielding requirements under those circumstances. It seems, nevertheless, of interest to compare the various components of the radiation environment in space with the background prevailing in the biosphere on Earth. If nothing else, such a comparison promises at least to identify the areas where special efforts are needed to enhance our radiobiological understanding of the space radiation environment.

As mentioned before, the natural background of ionizing radiation on Earth varies with geographic, or better, geologic location. It is highest over igneous rock and lowest over the ocean. For man in particular, spending a substantial fraction of his time indoors, the type of dwelling introduces an additional variable (1) as radon and gamma radiation levels are substantially higher in brick, concrete, and stone houses as compared to wooden buildings. Table I shows a compilation of typical natural radiation levels (2, 3). Interest in the present context centers primarily on the variability range. Table I demonstrates that for normal conditions, the variability corresponds to a factor of 10, with dose rates ranging from 0.006 millirem/hour over the ocean to 0.06 in masonry buildings. If exceptional geologic conditions prevailing in certain limited regions are included, the variability factor becomes substantially larger, increasing to about 300.

Table I

Typical Radiation Levels on Earth

Location	Radiation Level microrem/hr	Radiation Level millirem/yr
Mid-Atlantic	6	55
New York City	8-15	70-130
Stockholm,		
Outdoors	14-17	120-150
Houses	17-59	150-520
Travancore, India	900	8,000
Guarapari, Brazil,		
Houses	103	900
Beach, average	140	1,200
Beach, hot spot	2,000	17,500

In Figure 1, the just-mentioned radiation levels in the biosphere are shown in a horizontal histogram on a logarithmic scale of dose rate and compared with the three basic components of the radiation environment in space. Also shown, in the second bar in Figure 1, are the two basic MPD values recommended by the International Commission on Radiation Protection (ICRP) (4). The lower value, 57 microrem/hour = 0.5 rem/year, represents the MPD for "Members of the Public," and the ten-times larger upper limit is the MPD for radiation workers. It is interesting to note that the full interval delineated by these two MPD's is contained within the variability range of natural radiation levels in the biosphere.

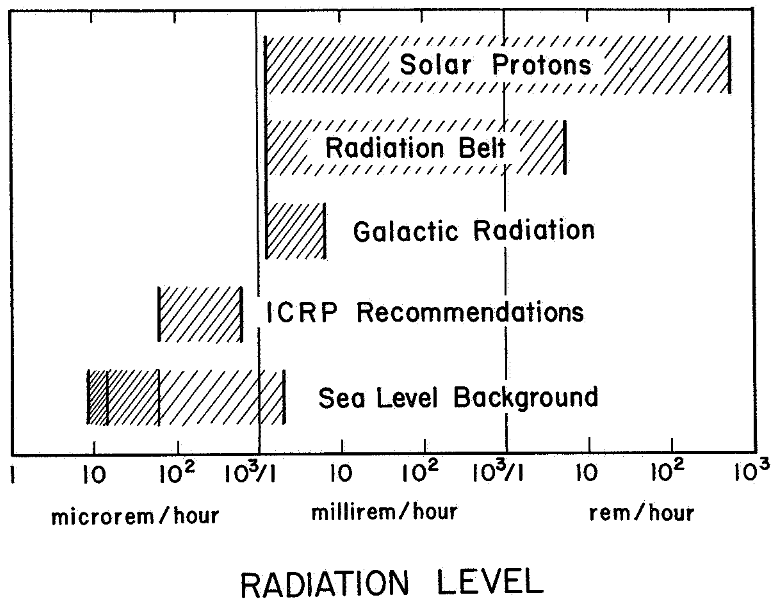

Figure 1

Variability Ranges of Environmental Radiation Levels in the Biosphere on Earth and in Space

Proceeding to the radiation environment in space, one sees from Figure 1 that, with a small overlap, the lowest level connects to the highest level in the biosphere. To be sure, this statement is correct only as long as the comparison is carried out in terms of conventional dosimetric units. For the heavy nuclei of galactic radiation, this is a rather inadequate way of describing the exposure, because the "microbeam" effectiveness of heavy nuclei in the cellular structure of tissue cannot be measured with a dose unit defined for macroscopic tissue volumes. As no satisfactory alternate dosimetric unit for microbeam irradiation has been proposed so far, the heavy nuclei portion of the galactic dose must at present remain unresolved as far as its biological effectiveness is concerned. Only the physical parameters of the energy dissipation of heavy nuclei in tissue can be analyzed.

THE GALACTIC RADIATION ENVIRONMENT IN SPACE

A peculiar characteristic of galactic radiation as compared to the background radiation at sea level is the pronounced periodic variation in anticorrelation to the 11-year solar cycle. As will be shown in detail later, this variation not only pertains to the radiation level as such, expressed in terms of absorbed tissue dosages, but also to the configuration of the energy spectra of the various components of the galactic flux. This slow periodic variation of galactic radiation has no counterpart in the terrestrial environment and poses a special problem if long-term effects are to be assessed.

In examining the basic physical characteristics of galactic radiation in more detail, we must realize that measurements in deep space so far have been carried out only with instrumentation on which, for obvious reasons, severe weight limitations were imposed. Available data, therefore, are incomplete. Nevertheless, the composition of the primary radiation is fairly well known. A larger margin of uncertainty has to be accepted if the transition of the primary radiation in a large scatterer such as a manned ship is to be assessed in its influence on the local dose. Additional uncertainties are involved if absorbed doses are to be converted to dose equivalents. This is due to the fact that a substantial fraction of the galactic dose is produced by heavy nuclei showing Linear Energy Transfer (LET) values greatly exceeding those of conventional high LET radiation from terrestrial sources. Furthermore, if we proceed to the analysis of the dose from secondaries, it must be mentioned that a larger fraction of this dose is produced by neutrons which requires a Quality Factor (QF) of 10 for the conversion from absorbed dose to the dose equivalent. The aforementioned lack of accurate data on the production of secondaries in local scattering material, therefore, magnifies the error in the assessment of the dose equivalent from secondary neutrons.

Figure 2 shows the energy spectrum of the primary alpha component at solar maximum and solar minimum based on data by Waddington (5) and Balasubrahmanyan (6). Also plotted in the graph is the LET over the same abscissa scale. It is seen that the variation with the solar cycle affects a substantial part of the spectrum, yet is most pronounced for lower energies. How this variation is reflected in the LET distribution of the galactic exposure at different phases of the solar cycle is a rather complex proposition. While a complete account is beyond the scope of this treatise, it should be pointed out that the build-up phenomenon, which is responsible for the dose contribution from secondaries, originates to a large degree from primaries of very high energies, i.e., from a section of the spectrum where flux variations with the solar cycle are moderate or small. The pronounced changes of the primary spectrum in dependence on the solar cycle, therefore, are reflected in the total energy dissipation to a substantially smaller degree. Similarly complex is the analysis of the mean QF values of the various Z components for solar maximum and minimum. The situation is further complicated by the fact that the low energy section of the spectrum, upon which the LET variation centers, is also more sensitive to shielding. A full quantitative analysis of the variation in question, therefore, cannot be carried out in general terms, but requires specification of the shielding system involved. In a heavily shielded lunar base, for instance, the mean QF of the galactic exposure at solar minimum can be expected to be markedly different from that in a lightly shielded surface vehicle or, all the more, for an astronaut walking on the lunar surface protected merely by his space suit.

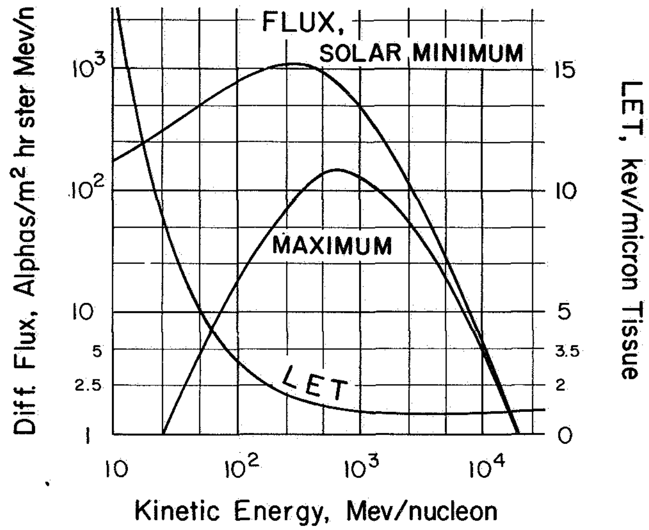

Figure 2

Differential Flux and Linear Energy Transfer of Galactic Alpha Particles as Functions of Kinetic Energy at Solar Maximum and Minimum

As the energy spectra in Figure 2 implicitly indicate, the LET distribution for galactic alpha particles differs from that for radium or thorium alpha particles to such a degree that radiobiologically the two types represent completely different radiations. Figure 3 shows the LET distributions for the two types of alpha radiations aligned with the QF/LET relationship recommended by the ICRP (l.c., 4). It is seen at once that the bulk of the galactic alpha dose is produced at LET values below the threshold of 3.5 kev/micron tissue at which the QF begins to rise above 1.0. Quite differently, Polonium alpha particles produce their entire ionization dosage in the vicinity of the Bragg peak covering the QF interval from 12 to 20.

While this basic difference in the LET distributions of galactic and terrestrial alpha particles constitutes a very substantial alleviation of the radiation hazard from the former as compared to the latter, it must be pointed out that the components of the galactic flux with higher Z numbers not only reach up fully to the LET values of natural alpha particles, but also even substantially surpass them. This is demonstrated in Figure 4 which shows the LET distribution of four selected components of the primary flux reaching from Z = 1 (protons) to Z = 26 (Fe nuclei). The upper graph of Figure 4 shows, over the same abscissa scale, the LET distribution for 200 kv x-rays, and again shows the QF relationship as recommended by the ICRP which was presented in Figure 3.

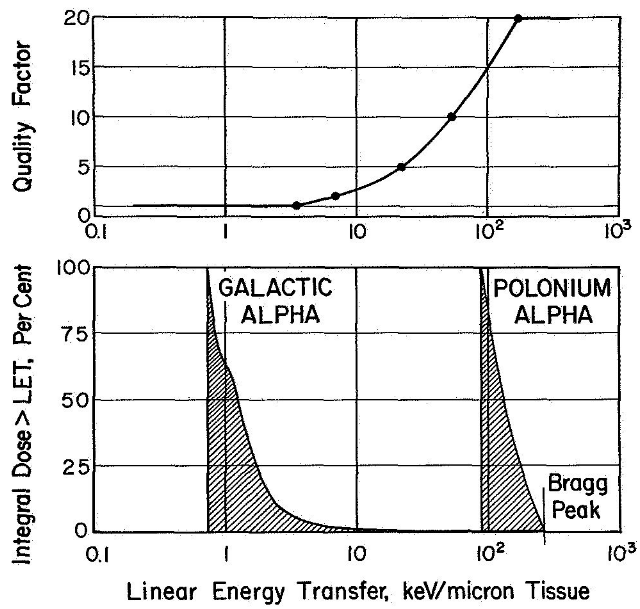

Figure 3

Upper: QF/LET Relationship Recommended by the International Commission for Radiation Protection

Lower: LET Distributions of Galactic and Polonium Alpha Particles

Note great difference in QF for the two radiations.

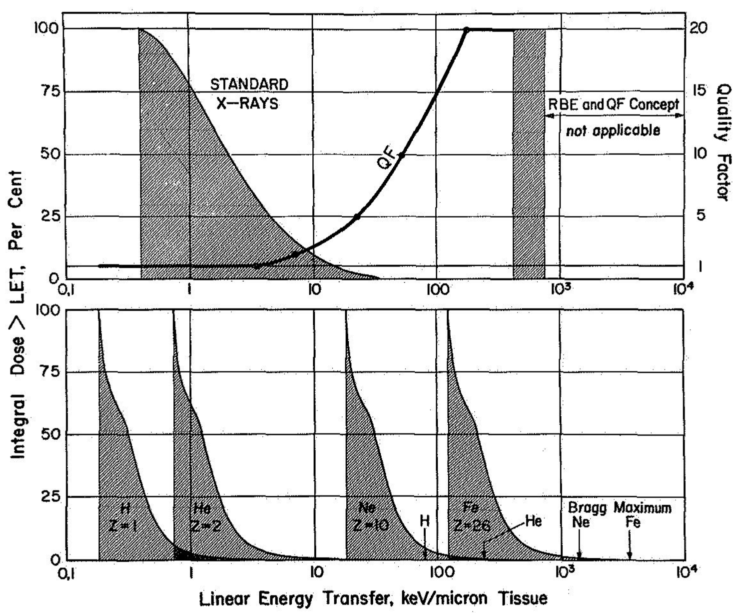

Figure 4

Upper: QF/LET Relationship of ICRP and LET Distribution of Standard X-Rays

Lower: LET Distributions of Four Representative Components of Primary Galactic Radiation

Combining the LET distributions as shown in Figure 4 with the corresponding fluxes of the various components of the primary radiation, one can easily compute the absorbed doses and QF dose equivalents. On the basis of the best available data on the composition of the primary radiation (5, 7), the just-named doses and dose equivalents are presented in Table II. Again, 2-pi incidence is assumed, i.e., conditions as they would hold, for instance, for the surface of the Moon where the lunar body shields one hemisphere of the sky completely. For free-space conditions in a vehicle far away from any planetary body, the dosage values would be twice as large. It should be emphasized once more that the dosages listed in Table II pertain to the primary particles only and without consideration of the dose contribution from secondaries. In other words, they hold for the fictitious case of an infinitesimally small tissue sample freely floating in deep space without any scattering material in its vicinity.

With regard to the energy spectra of the primary components heavier than He, it should be pointed out that they can be generated from the alpha spectra in Figure 2 with the aid of the flux constants listed in Column 4 of Table II.

Much less precise than the data on the primary flux components are those on the dose contributions from secondaries. Accepting a wide margin of error, one could establish an estimate from the altitude profile of the total ionization of galactic radiation in the Earth's atmosphere (8). Since materials of higher Atomic Numbers than those represented in the atmosphere are likely to be present in compact space systems such as a vehicle or a lunar base, a somewhat larger build-up factor than the one observed in the atmosphere should be used in order to keep the estimate on the safe side. Furthermore, because of the smaller relative share of low energy particles in the primary flux, the build-up factor at solar maximum can be expected to be higher than at solar minimum. Making liberal allowances for the indicated effects, one arrives at an estimated total galactic exposure of 12 millirad/24 hr or 30 millirem/24 hr at solar maximum and of 50 millirad/24 hr or 150 millirem/24 hr at solar minimum, corresponding to QF values of 2.5 and 3.0, respectively. Again, these radiation levels hold for 2-pi incidence. For assessment of the corresponding dose rates for 4-pi incidence in free space specific information of the amount of matter in the vehicle and its spatial distribution about the body of the astronaut would be required. As will be shown in more detail below, the development of the full build-up requires quite heavy moderating layers of material for which even a very large ship would not provide.

RADIOBIOLOGICAL INTERPRETATION OF GALACTIC RADIATION EXPOSURE IN SPACE

If we proceed now from the dosimetric analysis of the galactic radiation exposure in space to its radiobiological interpretation, we have to identify the radiation injury to human beings living under continuous irradiation at a dose rate of 150 millirem/day. As the comparatively low dose rate makes this exposure a typical case of low level irradiation, the early classical work of Egon Lorenz (9) and his group in the Manhattan Project comes to mind; this established a continuous irradiation at the dose rate of 0.11 r/day as the lowest radiation level for which a significant increase in the incidence of malignancy in mice could be obtained. To be sure, this early reference is not quoted

Table II

The Primary Galactic Radiation at Solar Maximum and Minimum

Atomic Number, Z	Chemical Element	Group Representative, Z	Flux Constant	Solar Maximum Absorbed Dose, millirad/ 24 hr	Solar Maximum Dose Equivalent, millirem/ 24 hr	Quality Factor	Solar Minimum Absorbed Dose, millirad/ 24 hr	Solar Minimum Dose Equivalent millirem/ 24 hr	Quality Factor
1	H	1	7000	1.73	1.73	1.00	8.32	8.32	1.00
2	He	2	1000	0.99	0.99	1.00	4.75	5.27	1.11
3-5	Li-B	4	22.5	0.09	0.10	1.14	0.43	0.85	2.00
6-9	C-F	6	24.3	0.66	1.57	2.37	3.18	12.16	3.83
10-12	Ne-Mg	10	27.0	0.285	1.47	5.16	1.37	10.64	7.75
13-21	Al-Sc	18	4.4	0.35	4.45	12.6	1.69	25.65	15.1
22-28	Ti-Ni	26	4.0	0.67	12.41	18.5	3.22	62.08	19.3
		Total:		4.8	22.7		23.0	125.0	
		Mean:				4.73			5.43

here to induce a state of panic in regard to long-term space missions. The sensitivity of the mouse for radiation-induced malignancies is very much higher than that of man. On the other hand, it should be realized that a sizeable fraction of the galactic dose is produced by high LET radiation which is known to show a substantially smaller recovery factor than the gamma rays used by Lorenz's group, especially in exposures of low dose rates.

Unfortunately, progress in the 20 years since Lorenz's study was not very impressive in regard to the most important issue in radiation carcinogenesis, namely, the so-called linear hypothesis. That is the hypothesis that dose/effect relationships experimentally established for high and medium doses can be linearly extrapolated to low and very low doses for which animal experimentation, because of the smallness of the effects to be established, becomes statistically unmanageable. Selecting radiation-induced leukemia as a frequently investigated end point in radiobiological experimentation as well as in the evaluation of human data, we find at the present state of knowledge that the experts are divided into opposing groups with apparently equally strong arguments for (10) and against (11) the linear hypothesis. Assuming the linear dose/response relationship as correct, which if wrong would overestimate the risk involved, we would have to work from the figure of two to four leukemia deaths per one million rem per year (12). It is seen immediately that the risk involved for galactic radiation exposure in space is extremely small. For instance, a crew of 24 men on duty for one year in a lunar base and receiving 0.15 rem/day would accumulate an exposure of about 1300 man rems, corresponding to a probability of 0.0035 to 0.005 of inducing one case of leukemia. This constitutes indeed an almost infinitesimally small risk.

Less reassuring are the prospects for another long-term effect of ionizing radiation, life shortening. Again, the uncertainty concerning the linear hypothesis holds essentially also for this reaction. If we do assume linear regression down to very low doses as valid and assume furthermore that the sensitivity for radiation-induced life shortening is the same for man and mouse if the natural life spans of the two species are normalized, we arrive at a life-shortening effect of 2.5 days/rad for low LET radiation such as x- or gamma rays and of 20 days/rad for high LET radiation (l.c., 12). These data hold for chronic irradiation at dose rates below 1 rad/day. That means they are directly applicable to the case of galactic radiation exposure. Although it is irrelevant in the present context, it might be mentioned for completeness sake that the QF value of 8, which the just-mentioned efficiency factors imply, drops substantially as dose rate increases and ends up at a value of 2 for acute instantaneous exposure.

When the limit between low and high LET radiation at the LET of 3.5 kev/micron tissue is set in accordance with official recommendations of the International Commission on Radiological Protection (l.c., 4), the galactic exposure with a total dose rate of 50 millirad/24 hr breaks down into a low LET fraction of 40 and a high LET fraction of 10 millirad/24 hr. An easy computation shows that this leads to a total life-shortening effect of about 25 per cent in the sense that for 100 days in space at the full galactic radiation level during solar minimum, a life-shortening effect of 25 days has to be accepted. In forming an opinion as to whether this is a high or a reasonable price to pay, one should take into consideration the other serious risks to life that inevitably are incurred if man ventures out of the safe haven of his native territory, the biosphere at the bottom of the air ocean surrounding the Earth.

A radiobiological appraisal of the galactic radiation exposure in space would be incomplete if the dose contribution from heavy nuclei would be assessed merely in conventional dosimetric units of absorbed doses and dose equivalents. As is well known, the LET spectrum of the dose from heavy primaries extends upwards to values that greatly exceed the maximum LET of terrestrial backgound radiation. The radiobiological significance of this phenomenon is best described with the term "microbeam," indicating that a single traversal of a heavy nucleus with a sufficiently high LET produces an energy dissipation in the microstructure of tissue that can be likened to a beam of narrow cross-section. The unique effectiveness of such individual traversals of nuclei with very high LET values has been demonstrated for monocellular specimens by Eugster (13), for the maize embryo by Curtis (14), and for the pigment cells in the hair follicle of the black mouse by Chase (15). Unfortunately, the just-quoted findings, striking as they are, can be considered only as pilot experiments inasmuch as an actual dosimetric identification of the individual nuclei producing the damage has not been carried out, except in the classical experiment of Eugster. Therefore, precise information is not available on the threshold LET value at which a single nuclear traversal can be considered a microbeam for a given type of cellular damage. Establishing quantitative data on the subtle effects that would develop from accumulated total body exposures to heavy nuclei microbeams at low dose rates appears to be a still more difficult problem. So far, the experts seem to agree only on the blank proposition that microbeam exposure cannot be adequately quantitated in terms of any of the common dosimetric concepts or units. This tenet is stated officially and quite clearly by the RBE Committee of the ICRP (16).

Within the LET range accessible to laboratory experimentation, it is well established that QF values for high LET radiations, as a rule, are substantially larger for long-term exposures at low dose rates as compared to instantaneous exposure. For the life-shortening effect, for instance, this is well demonstrated by the data quoted above. That this phenomenon is accompanied by different threshold doses for the two types of radiations is suggested, but not yet conclusively proven by the experimental data available. It seems a distinct possibility that for microbeams, no safe subthreshold dose or hit frequency exists in the sense that even one hit, i.e., one traversal by a heavy nucleus, produces subtle, yet nonrecuperable tissue damage, constituting a permanent addition to the exposure status.

In some quarters, special interest has been directed recently to the so-called superheavy nuclei. These are nuclei heavier than iron (Fe). Such nuclei have been reported, as individual events, in the older literature repeatedly. Fowler (17) has reported recently on nuclear emulsion recordings with a balloon-borne experimental arrangement specifically designed to identify superheavy nuclei. Fowler's data allow, for the first time, at least some estimates on abundances. For instance, two uranium nuclei were found for 200,000 iron nuclei. There is no doubt that the experimental data are of considerable interest for cosmological theory in general and the origin of cosmic rays in particular. However, as far as the radiobiological significance of the heavy nuclei phenomenon is concerned, the finding of superheavy nuclei would not seem to open any new avenues. As a tool for biological experimentation, as well as a hazard for astronauts, the extremely low frequency of superheavy nuclei renders them useless and harmless.

THE SHIELDING PROBLEM FOR GALACTIC RADIATION

Although the comparatively small galactic radiation levels, which prevail in space even under worst conditions, suggest that they could be accepted as they are without any countermeasures, it seems of interest, if only for completeness sake, to examine briefly the shielding aspects. As shown in detail in the preceding sections, the galactic radiation is characterized by a build-up effect of unusual proportion in the sense that multiple production of secondaries outweighs attenuation down to considerable depths in any absorbing material. Accurate quantitative information (l.c., 8) is available only for the transition effect of galactic radiation in the Earth's atmosphere. The two curves marked "Galactic" in Figure 5 are based on these data. They show skin dose rates in a human target as functions of shield thickness. It is seen that a very strong transition effect exists which in turn depends on the phase of the solar cycle. At solar maximum, any shielding effort providing less than 110 g/cm^2 is not only useless, but positively detrimental by pushing the radiation level behind the shield above the level of the incident beam. For solar minimum the situation is less extreme, yet reduction of the exposure level to half its value for the incident beam still requires a shield thickness of more than 100 g/cm^2. It is quite obvious that under these conditions, protection from galactic exposure by shielding is not feasible because of the enormous weight penalties involved. The shielding weights involved would be prohibitive even for terrestrial installations.

It should be realized that in the transition region in which the radiation level behind the shield initially increases and then drops to its original value, continuous profound changes in the composition of the radiation occur. In other words, the absorbed dose for zero shield thickness is produced by a radiation quality very different from that producing the same dose behind a shield of 110 g/cm^2 at solar maximum. As far as these changes pertain to the breaking up of heavy nuclei into smaller nuclei or the production of neutrons as secondaries, they constitute changes in QF values of the local energy dissipation that would have to be taken into consideration for a complete dosimetric assessment.

Since the changes in question are extremely complex, a quantitative analysis is beyond the scope of this treatise. We shall examine here merely one feature of the attenuation of the heavy components which is of special interest from a radiobiological viewpoint. It has been pointed out above that heavy nuclei with a sufficiently high LET act on living tissue essentially as do microbeams. Although the threshold LET at which microbeam effectiveness develops is not yet exactly defined, the experimental evidence quoted above clearly demonstrates microbeam effectiveness as such. Since this particular quality centers upon very high LET values, it must be most pronounced for nuclei of lowest energy and particularly for those reaching the end of their ionization ranges in tissue. In analyzing the transition of a beam of heavy nuclei in shielding material or in the human body, then, the flux of those nuclei that come to rest in tissue, the so-called "enders," should be carried as a separate entry.

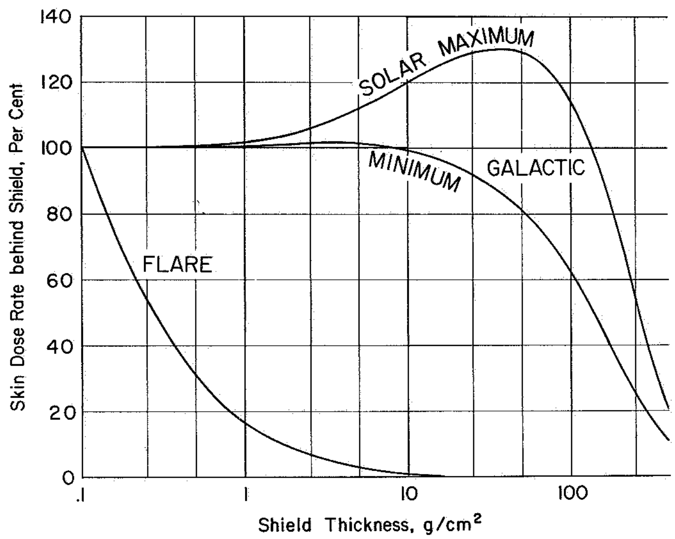

Figure 5

Normalized Skin Dose Rates as Functions of Shield Thickness for a Typical Flare Beam and Galactic Radiation at Solar Maximum and Minimum

Figure 6 shows the results of an analysis distinguishing total flux and enders for the Fe components of the primary radiation. It is interesting to see that the enders frequency shows what could be called a "pseudo build-up" inasmuch as it passes through a maximum at a certain finite depth in the shielding material or tissue. To be sure, this phenomenon is not due to a local production of additional enders, but is merely an outcome of the configuration of the energy spectrum that shows a maximum flux for a certain finite energy, i.e., for a certain finite depth.

As can be seen from Figure 6, the enders frequency is smaller than the total flux by about a factor of 100. This introduces great difficulties for any experimental design which would attempt to identify the special effects produced by enders in a biologic test specimen. The problem is further complicated by the circumstance that, especially in the case of nuclei of a very high Z such as the Fe component shown in Figure 4, a certain unknown fraction of the "through shots," i.e., of the total flux, can be expected to contribute to microbeam effects.

The foregoing brief discussion of the shielding aspects for galactic radiation indicates that two basically different attenuation functions must be distinguished, one for the total ionization dosage, and one for the heavy flux where the latter function would split up again into two separate relationships, one for the total flux and one for enders. Whereas shield thicknesses that would markedly reduce the total ionization

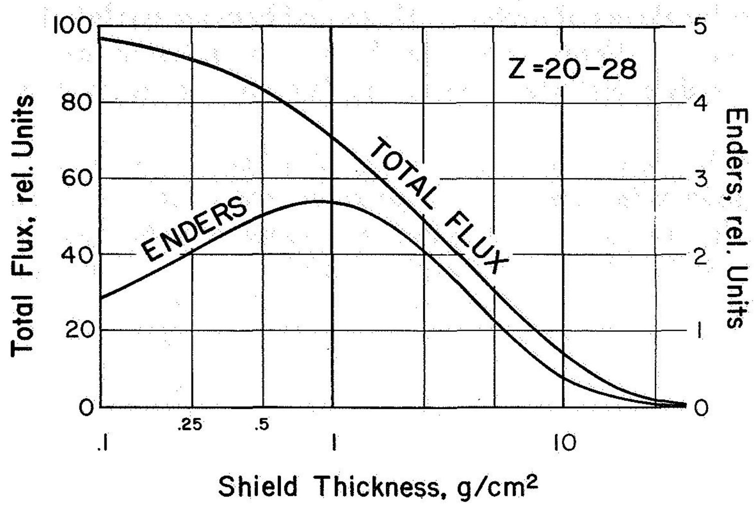

Figure 6

Normalized Total Flux and Enders for Z = 20 - 28 Component of Primary Galactic Radiation as Functions of Shield Thickness

(Both curves normalized to total flux = 100 at zero shield. Total flux expressed as "Through Shots" and enders as "Thindowns" per unit volume.)

dosage are prohibitively large, attenuation of the heavy flux is already substantial for a shield of a few g/cm^2. To what extent the two kinds of shielding actually will be needed for space missions of long duration would seem to hinge primarily on the as yet unexplored "microbeam" effects of heavy nuclei. Therefore, any specific estimates of shielding requirements, or alternately of maximum permissible exposure times, cannot be established at the present time. Since both parts of the galactic radiation exposure, the ordinary total dose equivalent as well as the heavy nuclei hit frequency, are typical low dose rate exposures that would cause concern only for late effects, even prolonged missions extending over many months are not likely to be endangered by any manifest effects on the astronauts that would impair their performance. As mentioned repeatedly before, galactic radiation as a typical low dose rate exposure causes concern only for chronic damage that would manifest itself only on a statistical basis in a population of astronauts completing long careers in active space exploration.

RADIATION HAZARDS FROM TRAPPED RADIATION AND SOLAR PARTICLE BEAMS

Besides galactic radiation, two other kinds of radiation fields contribute to the radiation hazard in space. Contrary to the former, these kinds involve acute exposures at levels from a few to several 100 rad/hr. One of these fields is limited to a sharply defined region in the magnetosphere of the Earth called radiation belt. It is made up of trapped particles, mainly protons and electrons, forced into closed trajectories by the geomagnetic field. The second kind is the solar particle beams, again mainly consisting of protons with smaller fluxes of alpha particles and heavier nuclei ejected into interplanetary space from solar flares. Because of the high radiation levels involved, both types of radiation fields constitute a severe problem for manned space missions.

In view of their operational importance, attention has been focused almost exclusively on trapped radiation and solar particle beams, and a large literature has accumulated on both their basic physics and the dosimetry with special emphasis on the shielding problem. A detailed review of this easily accessible information is not intended here. The pertinent radiation levels are indicated in the two uppermost bars of Figure 1. The reader is once more reminded that the response to shielding is quite different in these two radiation exposures especially as compared to galactic radiation. Since both trapped and solar proton beams contain large fractions of particles of low penetration, the exposure level in a vehicle strongly depends on the inherent shielding of vehicle frame and equipment and the astronauts' bodies themselves. A general estimate of the radiation levels involved, therefore, can be established only for a given shield thickness. The data in Figure 1 are derived for a shield equivalent of 2 g/cm^2. The basically different response of trapped and flare-produced proton radiations on the one hand and galactic radiation on the other to increasing shield thickness is demonstrated strikingly in Figure 5. It is seen that no transition effect exists for flare-produced protons and that a substantial reduction of dose rate can be accomplished by light shielding.

As far as the type of space mission is concerned, one could say that trapped particles in the radiation belts pose a serious problem for manned satellites in near-Earth orbits. The so-called South Atlantic Anomaly especially will impose severe limitations upon maximum permissible duty times in orbit for missions such as the Manned Orbital Laboratory. Quite differently, the radiation belts do not constitute a serious hazard for deep space ventures such as the lunar mission. A lunar trajectory involves only two quick passages through the radiation belts on the outbound and inbound legs of the trip. Therefore, the accumulated exposure remains on a much lower level than for a near-Earth satellite mission of the same duration. Measurements on Apollo VI, the unmanned test flight of the Apollo vehicle in April 1968, have established the radiation exposure for a large spaceship directly traversing the core of the inner radiation belt at speeds corresponding to those on a lunar transfer ellipse. The maximum exposure of 2.5 rads found on this flight is surprisingly small and indicative of the substantial protection afforded by the inherent shielding of the Apollo vehicle.

Turning to solar particle beams, we face exposure levels that are substantially larger than those in the radiation belts. However, contrary to trapped particles in the radiation belts, flare-produced particle beams occur only as brief excursions and comparatively seldom. Because weight is at an enormous premium in space, the flare hazard could not be coped with as it would be in a terrestrial installation simply by providing shielding for the worst possible conditions. Heavy dead weight shielding for a flare that might never come penalizes the entire design of the vehicle by curtailing the weight allowance for safety reserves.

For terrestrial conditions, unexpected sudden excursions of the radiation level, for instance, in an atomic energy installation occur as accidents. As such, they can be reduced in frequency by safety provisions, warning devices, and caution in the operation. In contradistinction, flare-produced radiation excursions in space occur at random and are utterly beyond any human influence. The statistics on past events allows a quantitative assessment of the risk function, showing the probability of receiving a specified radiation exposure on a mission of specified length. Such probability plots for the maximum of solar cycle 19 (1954-1965) have been presented repeatedly. Figure 7, based on data by Webber (18), is an attempt to explain the basic configuration of such plots without entering into details. It is seen that for a mission of exactly defined duration launched at random, no exactly defined radiation exposure can be predicted. Merely the probability of not tresspassing any MPD that one might want to specify can be determined. Figure 8, based on the same material as Figure 7, shows tissue dose as a function of mission duration. It is seen that a wide corridor spans a large range of possible radiation exposures for any given mission duration and depends on good or bad luck in selecting the launch date.

The plots of Figures 7 and 8 demonstrate that assuring radiation safety on a space mission in compliance with a fixed MPD is impossible in principle. Since the probability of a flare-produced "accidental" radiation excursion leading to an exposure in excess of conventional MPD's is generally high, operational planning should consider a flare-produced radiation excursion as a routine occurrence and should provide beforehand detailed instructions for evasive or corrective action, depending on the severity of the excursion and the objective of the mission. An essential prerequisite for such planning is precise instantaneous information on the accumulated exposure of the astronauts so that the safety margin to the critical point at which impairment of performance would begin is known at all times. Combining this factual dosimetric information with the astrophysicist's forecast of the most likely time profile of the radiation level for the remainder of the mission, those in charge would have to decide whether an early re-entry and retreat behind the protective shield of the atmosphere are indicated.

Completely different from the situation of a vehicle in orbit is that of a crew operating a manned lunar or planetary base. On such an installation, the provision of heavy shielding is not subjected to the severe weight restrictions imposed on a vehicle in orbit. For a base on the Moon in particular, lunar rock could be utilized for the construction of a heavily shielded proton storm shelter. The time of stay in the shelter would be limited to some 10 hours or less at a time in most cases, yet might exceed a full day at rare occasions. Since such shelters would not have to be used more than about once a month, even during the maximum of solar activity, the living space could be rather limited as long as all vital supplies and facilities were provided.

It is seen, then, that the real problem area concerns manned vehicles in orbit. As was mentioned, most important in this case is precise information on the accumulated exposure and the margin left for safe operations. For this information, the medical radiologists would have to provide a detailed scale of exposure levels and corresponding

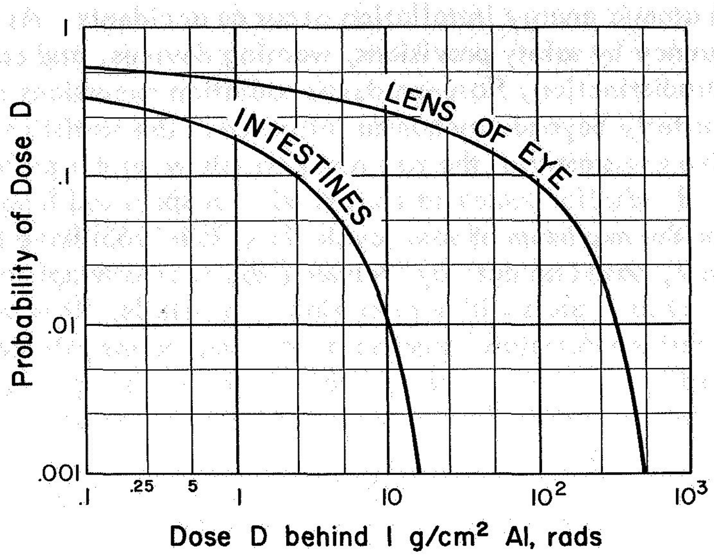

Figure 7

Probability of Encountering a Total Flare Dose of D or Greater on a 30-Day Mission During Maximum of Solar Cycle 19 (1954-1965)

Based on data of reference 18.

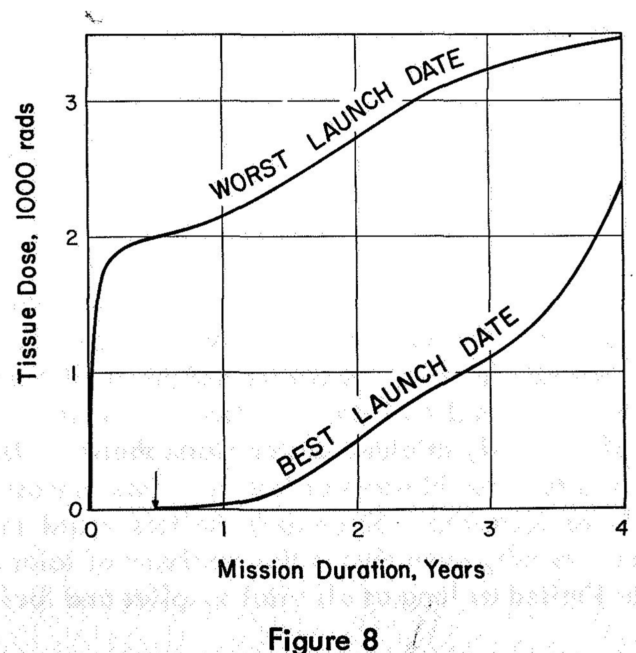

Figure 8

Total Flare Dose in Body Surface Behind 1 g/cm² Aluminum as a Function of Mission Duration for Solar Cycle 19

Based on data of reference 18.

total body and local effects. At this point, the lack of reliable data for man, and, for that matter, also for test animals, on damage levels for the bizarre depth dose patterns that would develop under irradiation with flare-produced particles in space makes itself acutely felt. Referring once more to Figure 7, we see that critical exposure levels in the body surface would develop much earlier than in deeper regions. Because of this basic characteristic of flare-produced radiation, the most likely form of a moderately severe overexposure would produce painful skin burns, yet would leave bone marrow and intestines essentially intact. This means that the astronaut might have to perform his duties in a state of otherwise comparatively good health, yet with the more or less severe discomfort of a skin erythema or even wet desquamation, while wearing at the same time a space suit loaded with radiation sensors and carrying all sorts of biosensors fastened to the skin. This distinct possibility certainly would seem the most pressing problem from an operational standpoint and deserves the attention of the radiologist much more than sophisticated speculations on the possible effects of radiation combined with other stresses in manned space operations.

CONCLUSIONS

In summary, it is seen that the radiation environment in space as compared to sea-level background on the Earth is not just of a different magnitude, but of a basically different nature. It is made up of quite heterogeneous components, some of them at present only incompletely understood in their mode of action on living matter. A prognosis as to the long-term effects on a Tellurian population dedicated to the conquest of space and the colonization of other planetary bodies would have to remain largely conjectural at this early phase of space exploration. It shall not be undertaken here. As space technology progresses, pertinent areas of radiobiology and radiology can be expected to score similar advances. Hopefully, then, these disciplines will catch up eventually to the point where they will be capable of accurately assessing the level of damage from exposure to the space radiation environment. It is still wishful thinking at the present time that a discipline may emerge that could be called preventive radiology and that would establish techniques of desensitizing tissue to radiation or allaying by other novel ways and means radiation effects in the body.

For the time being, the radiation hazard in space just has to be accepted as a calculated risk. As it is impossible to shield from galactic radiation and to predict flare exposures, conventional radiation safety procedures in terrestrial installations based on enforcement of rigidly established MPD's have to be abandoned. As the Federal Radiation Council has stated expressly (19), ". . . there can be no single permissible or acceptable level of exposure without regard to the reasons for permitting the exposure . . . and . . . there can, of course, be quite different numerical values for the Radiation Protection Guide depending upon the circumstances." Although those who formulated this principle did not visualize, at the time, the space radiation issue, the general logic of the statement is obvious. Enunciated as it is in an official code of regulations, it constitutes the basis on which, at least for the space program of the United States, more specific recommendations for implementation will have to be issued as our knowledge of the space radiation environment and its effects on man increases.

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13. ABSTRACT

Natural radiation levels in the biosphere on Earth vary from 6 microrem/hr over the ocean to values 300 times larger in certain geologic territories. The upper end of this scale overlaps the lowest galactic radiation levels in space. Except for acute radiation exposure in the radiation belt or from solar protons, the radiation environment in space would not seem to constitute a basic obstacle to man's survival in space. Since proton storm shelters on the Moon or planets could be built with with indigenous rock, only galactic exposure has to be dealt with in long-term missions. This exposure can be expected to result in inconspicuous chronic damage, such as life shortening which can be estimated to amount to 25 per cent of the time spent in space. As far as acute effects from trapped or solar particles are concerned, these comparatively soft radiations will mainly affect the skin, possibly producing erythema or more severe skin damage, with bone marrow and intestines remaining essentially intact. Operationally, this problem would require the main attention to be focused on in-flight medical care.

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