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CRITERIA FOR PERSONAL DOSIMETRY IN MIXED RADIATION FIELDS IN SPACE

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Prepared for:

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As manned space missions are becoming routine operations, the complex arsenal of instruments for personal radiation monitoring ought to be simplified. The necessary compromises concerning accuracy and completeness of record should be carefully evaluated. The report analyzes the dosimetrically relevant parameters of the three main contributions to the astronaut's radiation exposure in space: trapped protons, tissue disintegration stars, and neutrons. It is shown that interference and superposition effects from different components impose certain principal limitations on resolution. Possible ways and means for a system of restricted dosimetry which would record only certain parameters and establish the total dose equivalent from known characteristics of the radiation field are discussed.

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SUMMARY PAGE

THE PROBLEM

As manned space missions are about to become routine operations, the complex arsenal of direct reading and passive dosimeters used on past missions for radiation monitoring should be simplified. This task inevitably entails compromises sacrificing accuracy and completeness of the record for more expedient procedures. Striking the right balance in such compromises requires a detailed determination of the various components of the radiation exposure in space in terms of dosimetrically relevant quantities. This report furnishes such an analysis for the three most important components: trapped protons, tissue disintegration stars and neutrons.

THE FINDINGS

For a complete determination of radiation exposure, absorbed doses have to be converted to dose equivalents. This in turn requires analysis of the LET spectra involved in order to define the Quality Factor (QF) for the conversion. Using track and grain count data in nuclear emulsions from the first lunar landing mission Apollo XI and the Skylab mission 1/2, the report presents the LET spectra for the proton exposures on the two missions and compares them to the corresponding spectra for standard x-rays and recoil protons of U-235 fission. The comparison reveals a close similarity of the spectrum for trapped protons with standard x-rays and a profound dissimilarity with fission recoil protons. This finding is reflected in the mean QF of 1.6 for trapped protons as compared to 10 for fission recoils.

No adequate dosimetric methods exist for LET analysis of tissue disintegration stars. Indirect methods using star data from nuclear emulsions indicate that the preponderance of low energy protons and alpha particles in the prong spectrum of stars leads to a mean QF far above 1.0. The LET spectra for the proton and alpha component of a typical evaporation star are established separately and then combined yielding a grand total mean QF of 6.

The complete energy spectrum of neutrons has not been reported on any manned mission. Only limited data on thermal neutrons recorded with activation foils and on a small section of the fast neutron spectrum are available. Recourse to more abundant information on the transition of the galactic neutron fluence in the Earth's atmosphere allows a quantitative estimate of the local neutron dose in a vehicle in orbit. The complete LET spectrum of that dose is established and compared to the spectrum for fission recoils. While both spectra peak closely below 1 Mev, the galactic spectrum declines toward higher energies much more slowly than the fission spectrum. Accordingly a slightly lower mean QF than the official value of 10 for fission neutrons might be indicated for the galactic neutron dose in space.

INTRODUCTION

On manned space missions of the past, the astronauts' radiation expsoure has been measured with a variety of different instruments, some allowing direct inflight reading of instantaneous radiation levels, others furnishing only a postflight record of accumulated doses. On the Apollo and Skylab missions in particular, four different kinds of dosimeters were used. A Personal Radiation Dosimeter for readout by the crew displayed integrated doses up to 1000 rad in 10 millirad increments. A Radiation Survey Meter also for readout by the crew, displayed instantaneous radiation levels in four ranges from zero to 0.1 or 1 or 10 or 100 rad/hr. A Van Allen Belt Dosimeter with two identical ion chambers for skin and depth, the latter carrying an aluminum shield simulating 5 cm tissue, was equipped with an onboard data recorder and a telemetry link to the ground. It had logarithmic output providing an operating range from 1 millirad/hr to 1000 rad/hr. Finally, Passive Dosimeters carried by the crew on the body contained foil detectors, film badge and nuclear emulsions, neutron activation foils and LiF thermoluminescent detectors for postflight analysis.

The provision of such a large arsenal of dosimetric instrumentation was not only prompted by the newness of the task, but also and very much so reflected the complex nature of the radiation environment in space which one could not possibly expect to measure adequately with just one instrument. On the other hand, it is obvious that radiation monitoring should be limited to minimum requirements as we approach the point where manned operations become routine. Such limitation inevitably entails compromises that will have to be accepted with regard to the completeness of the exposure record. The question then arises what criteria we would want to establish for a dosimetry which would sample only selected parameters of the total exposure and establish the total mission dose to some measure indirectly from known spectral characteristics of the various ionizing agents involved. To what extent this proposition is feasible can be decided only on the basis of a critical analysis of the radiation environment in space.

TABLE I

RADIATION FIELDS IN SPACE

I. Trapped Protons

II. Trapped Electrons

III. Galactic Radiation

- A. Nucleon Cascades
  1. Tissue Disintegration Stars
  2. Neutrons
- B. Photon Electron Cascades
- C. HZE Particles

IV. Solar Particle Beams

Table I lists the main types of radiation fields encountered in space. It is seen that of the seven components only two, trapped electrons and photon electron cascades, represent low-LET radiation that can be measured adequately in terms of absorbed dose. The five others require, for conversion of absorbed doses to dose equivalents, determination of the LET spectrum. Under ordinary circumstances, three of these five components contribute most prominently to the mission dose. They are trapped protons, tissue disintegration stars, and neutrons. The following analysis is essentially limited to these three dose contributions.

TRAPPED PROTONS

By far the largest share of the astronauts' radiation exposure on near-Earth orbital as well as lunar missions is produced by trapped protons in the radiation belt. On Earth-orbital missions, the dose accrues in repeated passes through the South Atlantic Anomaly. On lunar missions, two complete traversals of the radiation belt on trans-lunar and trans-Earth injection furnish the total dose. For an appraisal of the true radiation load, we have to establish the dose equivalent which, in turn, requires analysis of the LET distribution. Figure 1* shows the integral LET spectrum for the Skylab 1/2 and the first lunar landing mission Apollo XI reported earlier (1). For the latter mission total proton fluence happened to be very nearly 10 times smaller than for Skylab 1/2. In the graph, the Apollo data are scaled up by a factor of 10 for normalization to the Skylab spectrum. It is seen that the Skylab scores obtained by grain count analysis of the population of proton tracks in G.5 emulsion level off toward low LET values. This is not a real feature of the spectrum but an artifact due to a deficiency of the scanning process in oversaturated emulsions. As LET and grain density decrease in such emulsions, an increasing number of track segments are missed by the scanner. However, the grain count data do connect well to data of a solid state particle detector in the region of 80 to 100 Mev/cm T indicating that at that LET counting efficiency reaches 100 percent. We therefore have adopted the upper section of the curve marked "Fluence," which reflects the scores of the solid state detector, as the basis for evaluating absorbed dose and dose equivalent.

A striking feature is the extreme heterogeneity of the spectrum with a mission fluence of 1000 protons/cm^2 in the highest LET class, 9000 more in the next lower, 90,000 more in the third lower and so on until an integral fluence of 13,000,000 protons/cm^2 is reached at minimum LET. For dosimetric evaluation, LET resolution of fluence is needed only in the interval from 35 Mev/cm T to maximum LET since the Quality Factor (QF) is constant and equal to 1.0 for all lower values. A full account of how the various LET regions contribute to absorbed dose and dose equivalent is given in Figure I by the two curves marked "Absorbed Dose" and "Dose Equivalent." Special attention is directed to the linear ordinate scale for these curves as opposed to the logarithmic scale of fluence. Absolute values of the total mission dose are 1140 millirads

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* In order not to break the continuity of the text, all illustrations appear at the end.

and 1760 millirems, respectively. Both values are normalized to unity in Figure 1. They furnish a mean QF of 1.54 for the mission dose from protons.

Reading the fluence and the corresponding fractional dose for the LET of 35 MEV/cm T, one sees that 57 percent of the total dose equivalent is produced by 3.5 percent of the total particle fluence. Since this is at the same time the fraction to which QF values > 1.0 are limited, it is seen that LET discrimination can be dispensed with for the remaining 96.5 percent of the total particle fluence. All that is needed for those 96.5 percent is measurement of the total ionization. For the interval from 35 to 850 Mev/cm T, however, high resolution of LET is required since QF shows a strong dependence on LET growing from 1 0 for 35 Mev/cm T to 13 for the Bragg peak of 850 Mev/cm T.

The fact that a large part of the proton dose is produced at low LET is well demonstrated by comparing the LET distribution to the one for standard x-rays as it has been reported by Cormack and Johns (2). Figure 2 shows the latter distribution in the uppermost graph aligned with the distribution for the proton dose in the center. The bottom graph shows the distribution for neutron recoil protons from thermal fission of U-235 as reported by Kronenberg and Murphy (3) for which a mean QF of 10 applies. Comparing the three LET distributions one will readily agree that protons in space hardly can be called high-LET radiation since their LET spectrum extends beyond the x-ray spectrum only with a rather small fraction. Quantitatively, this similarity of trapped protons to standard x-rays is expressed in the mean QF of 1.56 which is so much closer to 1.0 than to 10.

The foregoing discussion has shown that measuring the total dose equivalent of the proton spectrum of Figure 1 can be reduced to essentially two subtasks: measurement of the total ionization in bulk for the region from minimum to 35 Mev/cm T and measurement of the LET distribution of the total ionization for the remainder from 35 to 850 Mev/cm T. Since the latter subtask requires rather elaborate instrumentation, it is of considerable interest to point out that it can be simplified substantially by utilizing the count of so-called enders, i.e., of protons reaching the end of their ionization ranges in tissue. In scanning nuclear emulsions for proton tracks, enders stand out conspicuously as "black" tracks ending abruptly. At the same time their frequency per field is substantially smaller than the one for through-tracks from protons of medium and low LET because of the aforementioned steep negative slope of the LET spectrum of fluence. Therefore, a statistically significant count of enders can be accumulated with a much smaller scanning effort than would be required for a count of the total population of proton tracks.

Since the LET along a proton track as a function of residual range in emulsion is well established, the ender count furnishes directly the LET distribution at the upper end of the LET scale without any particular device for resolving LET. How far down below the Bragg peak this method furnishes valid results depends on the configuration of the LET spectrum. An LET of 35 Mev/cm T corresponds, for protons, to an energy of 14 Mev and a residual range of 2.5 mm tissue. In an absorbing layer of that thickness,

a unidirectional beam with a spectral configuration shown in Figure 1 will undergo an attenuation of the local ender frequency of about 8 percent. In other words, calculating the fluence at 35 Mev/cm T from the ender count, i.e., from the fluence at 850 Mev/cm T, underrates the former by 8 percent. This loss of accuracy would seem an acceptable price to pay for the substantial simplification of the measuring procedure.

Actually, in establishing the spectrum of Figure 1, the ender count was used only down to an LET of 71 Mev/cm T corresponding to an energy of 5.9 Mev and a residual range of 540 microns tissue. For that thickness, the local ender count should only decrease by slightly less than 2 percent and so should the calculated fluence for 71 Mev/cm T. The latter fluence is indicated in Figure 1 by a cross. It connects well to the fluence data as they follow from the grain count analysis in G.5 emulsion indicated in Figure 1 by circled dots.

The foregoing discussion has been conducted in greater detail in order to demonstrate how criteria for adequate personal dosimetry for the proton exposure in space differ basically from those for adequate analysis of the physical characteristics of the proton component of the radiation environment in space. For the former purpose, i.e., for determination of absorbed dose and dose equivalent, measuring the total ionization and the ender frequency is entirely sufficient. For the latter purpose, much more elaborate provisions would be required.

It is beyond the scope of this report to examine possible approaches to the design of instruments which would meet the indicated dosimetric specifications and could replace the cumbersome and tedious emulsion technique preferably with solid state or pulse ion chamber type devices. It should be pointed out though from the very beginning that actual operational conditions in space are such that other radiation fields are superimposed upon the proton field. With regard to instrumentation, this raises the question of interference as well as the possibility of integrated response to all components involved. As we proceed to examine the other radiation fields in space one by one, the complexity of the task of personal dosimetry in space will become apparent.

TISSUE DISINTEGRATION STARS

A sizeable fraction of the mission dose is produced by nuclear interactions of high-energy primaries, particularly protons, with the component atoms of tissue. From the characteristic appearance of their traces under the microscope, these disintegrations are called stars. In terms of absorbed dose, the contribution of the star phenomenon to the total exposure is comparatively small. However, since a large number of the secondaries released in stars consist of protons and alpha particles of low energies, a high QF applies to the absorbed dose which raises their share of the dose equivalent substantially. On the first lunar landing mission Apollo XI, for instance, on which the dose contribution from trapped protons was comparatively small, the star phenomenon accounted for almost 25 percent of the total mission dose equivalent.

A large volume of information is available in the literature on disintegration stars released by galactic protons as well as accelerator particles. However, since most of these data have been obtained with nuclear emulsions, establishing the tissue dosage of the star phenomenon runs into an impasse because nuclear emulsion is not a tissue equivalent material. It is for this reason that existing dosimetric methods for quantitative determination of the dose equivalent from tissue disintegration stars are entirely inadequate. As mentioned before, stars result from nuclear collisions of high-energy galactic primaries with nuclei of the constituent elements of the body of the astronaut. The most common type, evaporation stars, is produced by projectile nuclei in the energy region from fractions of a Gev to about 30 to 50 Gev. Less frequent are so-called knock-on stars released by primary particles of extremely high energies.

Radiobiologically, the special significance of the star dose rests in the fact that the bulk of the energy dissipation in tissue is produced by secondary protons und alpha particles in the energy band from a few tc some 30 or 50 Mev, i.e., with particles of high LET and correspondingly high QF values. Another unique feature of the star dose is the extremely non-uniform microdosimetric pattern of energy dissipation, which almost places this part of the space radiation exposure in the same class with HZE particles. The secondaries produced in an evaporation-type nuclear collision are mainly neutrons, protons, and alpha particles with heavier fragments occuring quite seldom because tissue contains only low-Z constituents. Figure 3 shows the energy spectra for the disintegration products of evaporation stars. The spectra center on low energies. Accordingly, the LET distributions for star-produced protons and alpha particles shown in Figure 4 center heavily on high and very high QF values, quite differently from the LET distribution for trapped protons.

Assessment of the tissue dose from star data in emulsion requires an indirect approach. Two methods have been described by Birnbaum and co-workers (4). The first one utilizes the change in slope which the integral prong spectrum of a star population in emulsion shows in the vicinity of Atomic Number Z=8. The second method uses the theoretical interaction cross sections for the gelatin matrix and the silver bromide for assessing the fractional star populations originating in the two components. Both methods have been described briefly in an earlier publication (1). At the same place more detailed references to the literature are given.

For operational dosimetry in space the influence of shielding on the residual star dose within the vehicle is of special interest. Direct data on this influence cannot be retrieved from recordings on manned missions because of the complex shield distributions involved. Very detailed information is available on the transition of the star phenomenon in the Earth's atmosphere. Resorting to these data we present in Figure 5 the altitude profile of the star phenomenon in the atmosphere. It is seen that in the build-up maximum stars account for a dose equivalent rate of 250 microrems/hr or 6 millirems/day. Our star counts on Skylab 1/2 lead to a contribution of 10 millirems/day. This finding seems to indicate that inferences from the atmospheric profile lead to comparatively low estimates.

The makeup of the star dose described in Figures 3 to 5 indicates quite clearly that accurate determination of the true dose equivalent would require full resolution of the prong spectra of the fractional star population released in the gelatin of the emulsion. It should be obvious that the indirect methods on which we are relying at present can furnish only semi-quantitative information. If we try to visualize a detector with tissue equivalent response which would resolve the LET distributions involved, we come to realize the specific problem for such instrumentation. What is to be resolved is an instantaneous burst of several protons and alpha particles, all with different initial energies emitted "simultaneously," i.e., at such short time intervals that the resulting ion columns develop and disappear simultaneously. A further pursuit of these thoughts is beyond the scope of this report.

NEUTRONS

Disintegration stars not only produce protons and alpha particles but also neutrons. They do so with about the same abundance as for protons. Because neutrons have a completely different attenuation mechanism and also because they do not produce visible prongs in nuclear emulsion, they are usually treated as a separate entity apart from the other disintegration products of stars. Although their energy spectrum of emission closely resembles that of protons, neutrons diffuse out to much greater distances from the star center until they finally terminate, after several or many elastic collisions, in a capture reaction. In this slowing-down process the local energy spectrum undergoes continuous changes toward greater depth in the attenuating material until finally an equilibrium spectrum is established. For neutrons of galactic radiation, the equilibrium spectrum is a wide continuum extending from thermal to relativistic energies. However, the bulk of the dose equivalent is produced by neutrons in a comparatively narrow band extending from about 0.1 to some 30 to 50 Mev. These fast neutrons dissipate their energy in tissue mainly through recoil protons and to a lesser degree through heavier recoils. Although the energy spectrum of galactic neutrons at the body of the astronaut or any other location within a large vehicle in space, has never been measured, a first approximation can again be established from data on the transition of the galactic neutron spectrum in the Earth's atmosphere. Figure 6 shows the equilibrium spectrum for the energy interval from 0.1 to 1000 Mev. To be sure, the spectrum actually reaches all the way down to thermal neutrons. However, 95 percent of the tissue dose equivalent is produced in the energy interval shown in Figure 6.

In sorting available data on galactic neutrons one has to distinguish two quantities: spectral configuration and absolute fluences. While the former appears fairly reliably established, major discrepancies still exist between the results of a number of experimental and theoretical studies with regard to fluences. The spectrum shown in Figure 6 is based on a study by Hess and co-workers (5) published in 1961. Several more recent studies indicate that Hess' fluences are too small, possibly by a factor exceeding 10. However, Hess' data seem to render the details of spectral configuration correctly. Scaling up fluences for a balanced compromise and applying a QF of 10, we arrive at the altitude profile for the galactic neutron dose equivalent rate in the atmosphere shown in Figure 7. It is seen that a radiation level of about 500 microrems/hr is reached

in the build-up maximum. The curve holds for solar minimum and high latitudes. That means it represents an upper-limit estimate of the galactic neutron dose as it would be encountered in deep space outside the magnetosphere and for minimum solar modulation.

Figure 8 shows the LET distribution of the absorbed dose for the neutron equilibrium spectrum. The broken line indicates the contour of the LET spectrum for fission recoil neutrons. It is seen that galactic recoils dissipate a sizeable portion of energy at LET values well below those of fission recoils. This difference should be considered by assigning a lower mean QF to the galactic as compared to the fission spectrum. In other words, the straightforward use of a QF of 10 for the fast neutron dose of galactic radiation overrates the dose equivalent. Applying the QF/LET relationship of the ICRP to the LET spectrum in Figure 8 leads to a mean QF of about 6. This would scale down the maximum of 500 microrems/hr for the neutron dose to 60 percent and set the galactic neutron dose equivalent at 7 millirems per day as a more reasonable value.

As mentioned before, the value of 7 millirem/day for the galactic neutron dose holds for deep space outside the magnetosphere and solar minimum. For a near-Earth orbit the radiation level is substantially smaller. The mean orbital radiation level for Skylab is estimated at less than half the free-space value. It is seen, then, that the percentage contribution of galactic neutrons to the total mission dose equivalent varies greatly with the type of mission. For a deep-space mission with peripheral crossings of the radiation belt and a correspondingly small dose from trapped protons, galactic neutrons can account for as much as 25 percent of the total mission dose equivalent. On the Skylab missions with their numerous crossings of the South Atlantic Anomaly on the one hand and substantial geomagnetic protection on the other, galactic neutrons have not contributed more than 3 percent to the mission dose equivalent.

These complex relationships make it difficult to establish general guide lines for dosimetry of the galactic neutron component. A continuous exposure ranging from about 3 to 7 millirem/day does not constitute an alarming radiation load for the astronaut. On the other hand, it is a quantity which one certainly would want to determine accurately and carry in the long-term exposure record. It should also be pointed out in this connection that a conventional LET analyzer with tissue-equivalent response for trapped protons cannot discriminate particle origin and therefore will record neutron recoil protons as well. As long as it does that correctly, a distinction as to the origin of the recorded particles is entirely irrelevant as far as the astronaut's radiation load is concerned. The sophisticated instrumentation that the physicist would ask for if the neutron component is to be identified as such certainly could be dispensed with without impairment of the radiation safety record.

Furthermore, it should be remembered that the galactic neutron exposure is quite stable varying systematically and predictably with geomagnetic location and solar modulation. Fortunately, it is also rather insensitive to variations in shielding. Conceivably, then, the dose equivalent from neutrons could be established from orbital parameters and solar data and entered into the record without actual measurement.

CONCLUSIONS

As we proceed to draw the conclusions from the foregoing analysis concerning possibilities of simplifying personal radiation monitoring in space, we realize that we do not simply face a number of free choices where we could record certain components only incompletely. The truth rather is that for certain components adequate dosimetric instrumentation is just not available. This is especially true for the dose contribution from tissue disintegration stars. To a lesser degree problems also exist for the neutron component although they are not of a principal nature but concern interference effects that are limited to comparatively short time intervals in crossings of the anomaly or the proton belt itself.

In view of the just described situation it seems unrealistic to discuss a system of restricted dosimetry in space which would sample only certain parameters of the radiation field because such a system is likely to require instrument capabilities that cannot be met with existing devices. What is needed first is that the instrument designer addresses himself to the problem how the shortcomings of the various types of existing LET spectrometer in regard to the peculiar requirements of space radiation dosimetry can be overcome. To point out those requirements in specific detail was the main purpose of this report.

As a final remark, we should like to mention briefly the HZE particle problem. Although this component of the space radiation environment certainly is most unique in both its dosimetric and radiobiological aspects, a discussion of minimum requirements for operational dosimetry is not possible for the principal reason that present understanding of the mode of action of HZE particles on living matter is still very fragmentary. While local damage from single hits has been demonstrated, nothing is known about long-term damage from total body irradiation. In the wide continuum of the LET scale of galactic heavy primaries extending from conventional values up to some 40,000 Mev/cm tissue, a point of demarcation or a transition region presumably exists separating the HZE particles in the restricted sense of the term from heavy nuclei in general. For the latter ones, normal dosimetric quantities and units are applicable whereas for HZE particles proper new dosimetric concepts and units have to be defined. Where this threshold is located in the LET scale is at present entirely problematic. Therefore, operational dosimetry must resign itself for the time being to recording event sizes and frequencies using an arbitrary classification. Standard detectors for the purpose are nuclear emulsion, plastic foil and the silver chloride monocrystal. Whether these sensors can eventually be replaced with solid state or pulse analyzing devices remains again a mute question as long as the radiobiologically relevant parameters remain undefined.

In conclusion a word of caution seems in place. Personal radiation dosimetry in space certainly should be consolidated and simplified to a level more commensurate with the comparatively small risk involved. However, whatever compromises and minimum standards one might be willing to accept for a system of restricted dosimetry, quite some sophisticated subminiaturization of circuitry would be required for a pocket-size instrument that would maintain at least a semblance of a quantitative record.

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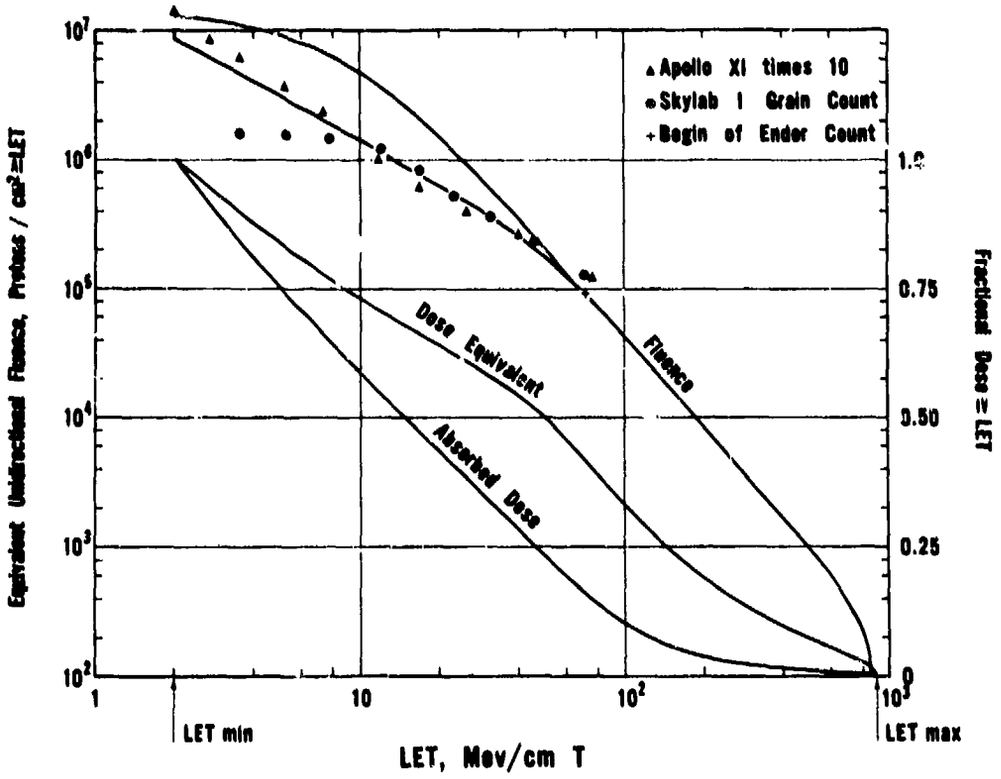
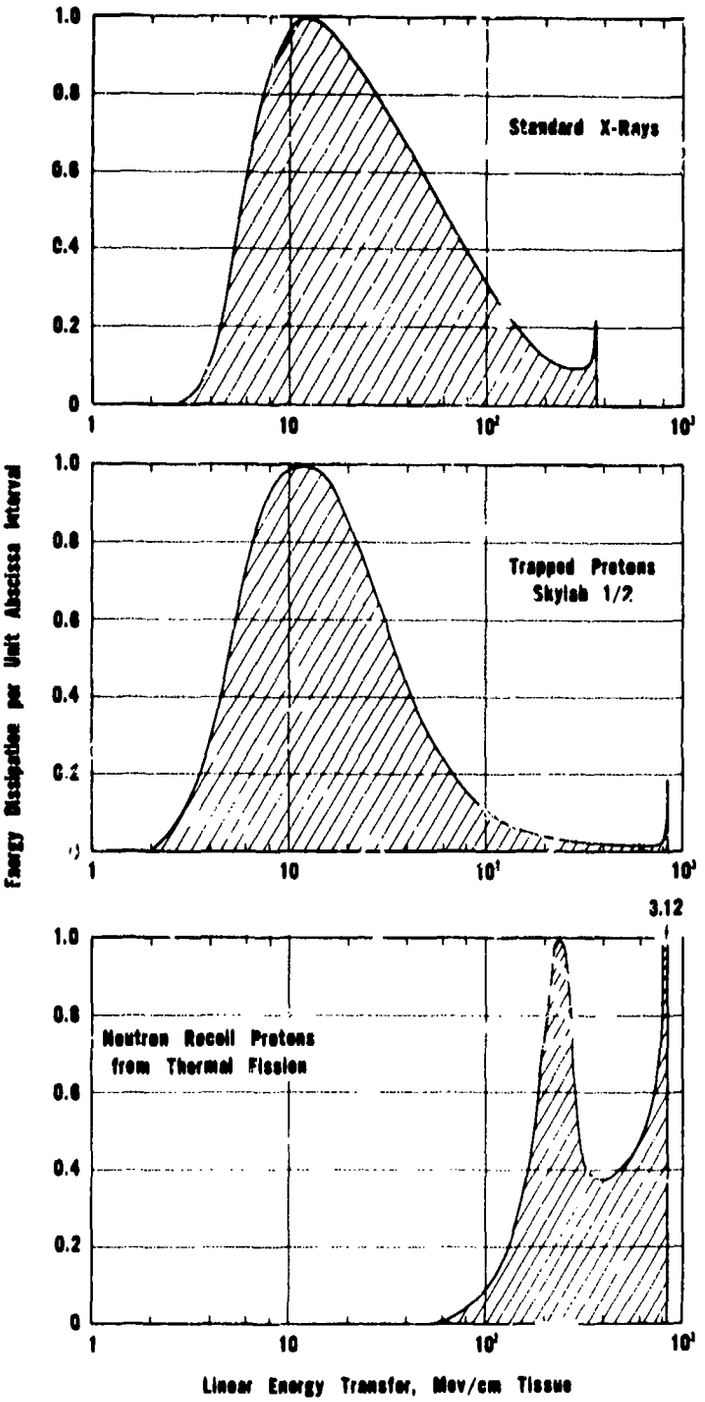


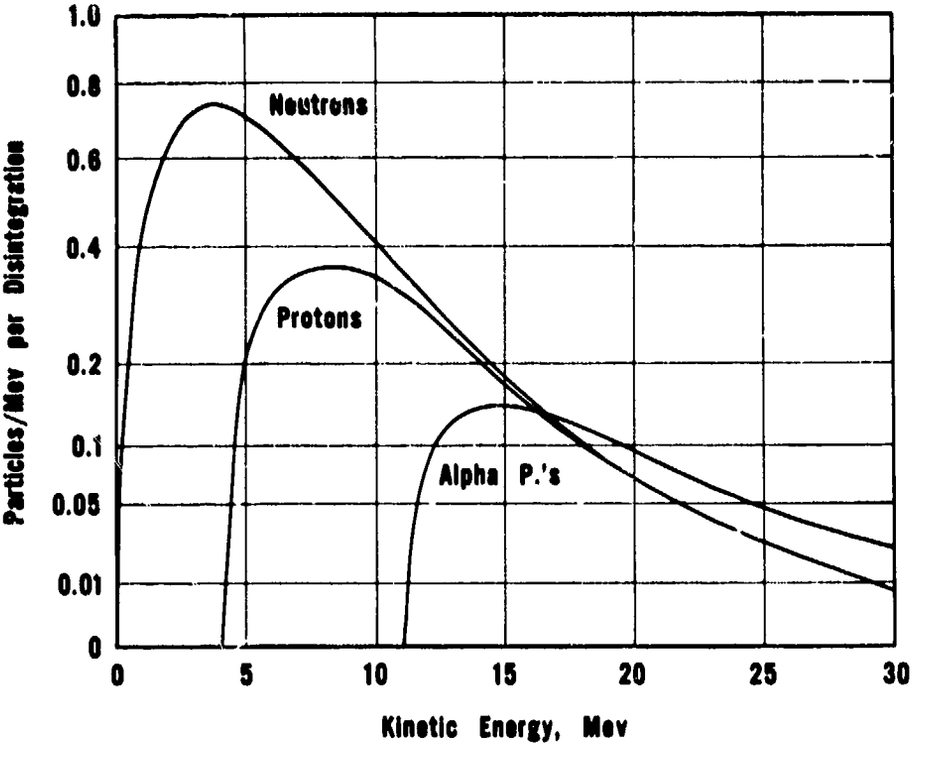
INTEGRAL LET SPECTRA AND DOSE DISTRIBUTIONS FOR PROTON EXPOSURES ON APOLLO 11 AND SKYLAB 1/2

FIGURE 1



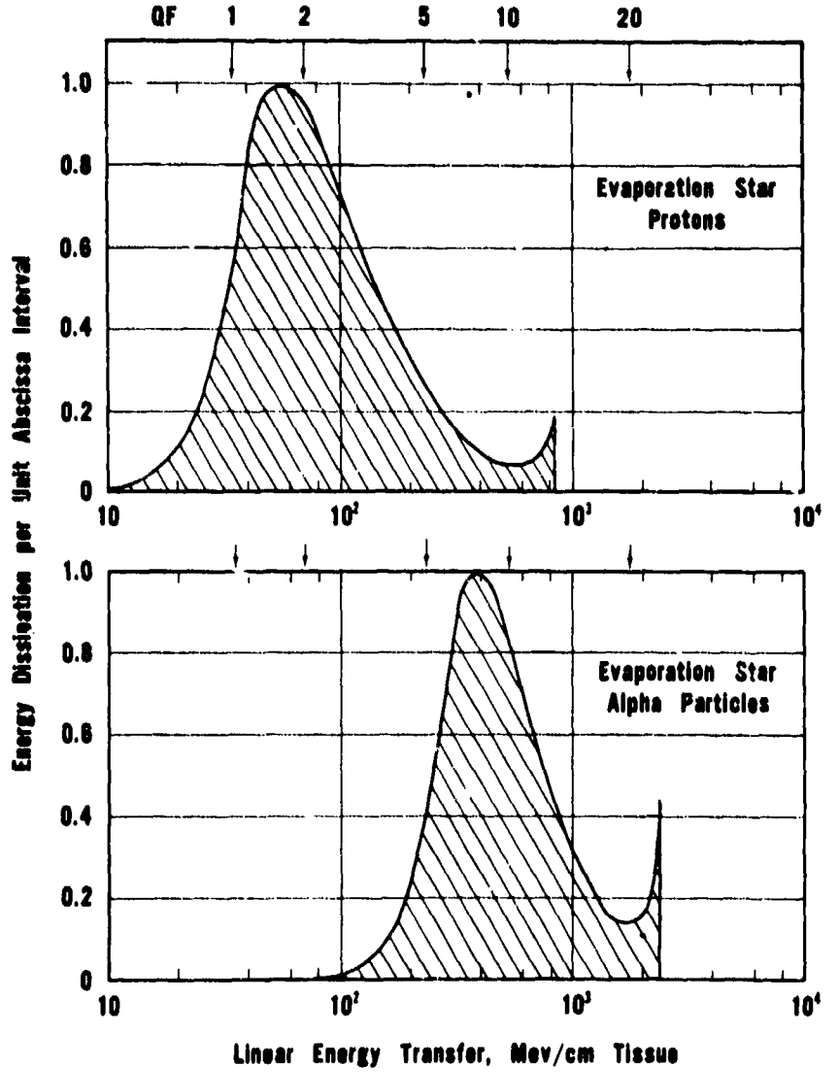
LET DISTRIBUTIONS OF ENERGY DISSIPATION FOR STANDARD X-RAYS (TOP), TRAPPED PROTONS (CENTER), AND FISSION NEUTRON RECOIL PROTONS (BOTTOM)

FIGURE 2



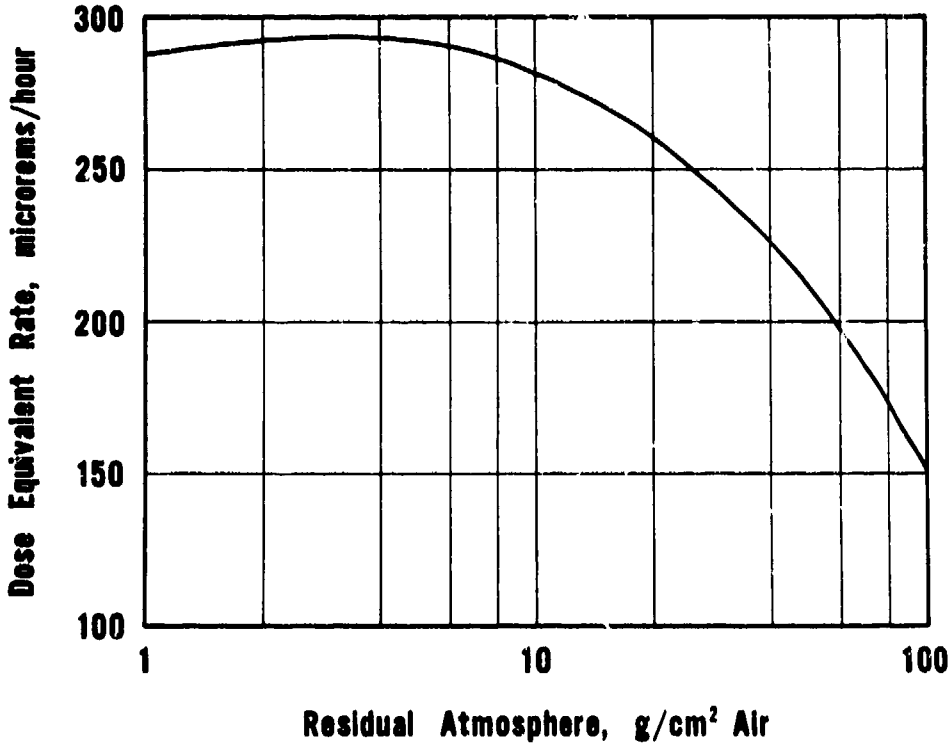
DIFFERENTIAL ENERGY SPECTRA OF SECONDARIES
FROM EVAPORATION STARS

FIGURE 3



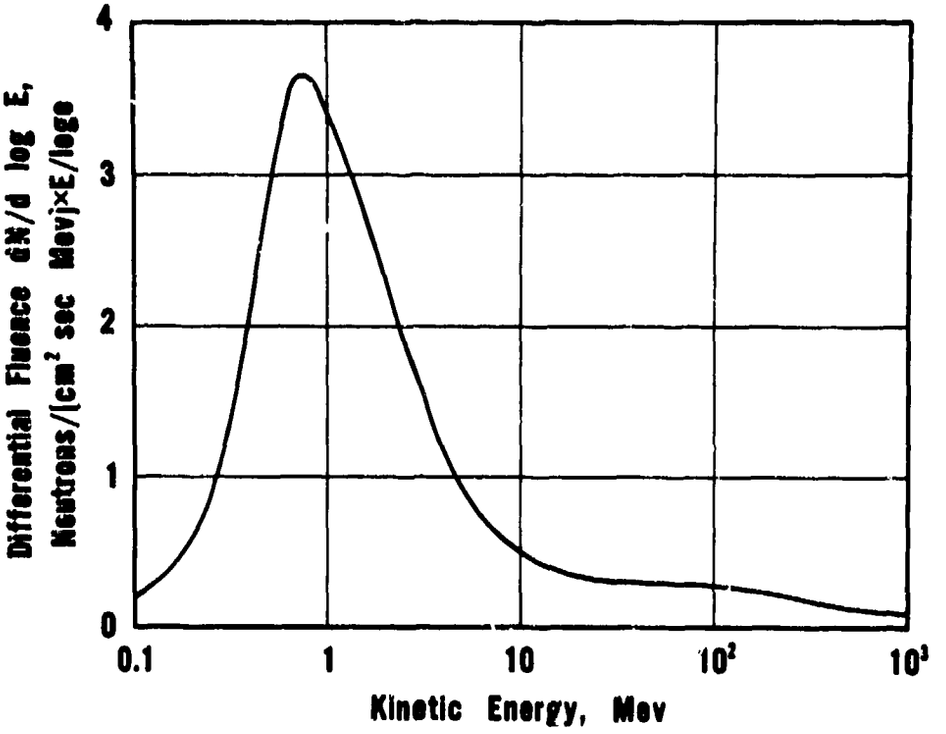
LET DISTRIBUTIONS OF ENERGY DISSIPATION FOR EVAPORATION STAR PROTONS AND ALPHA PARTICLES

FIGURE 4



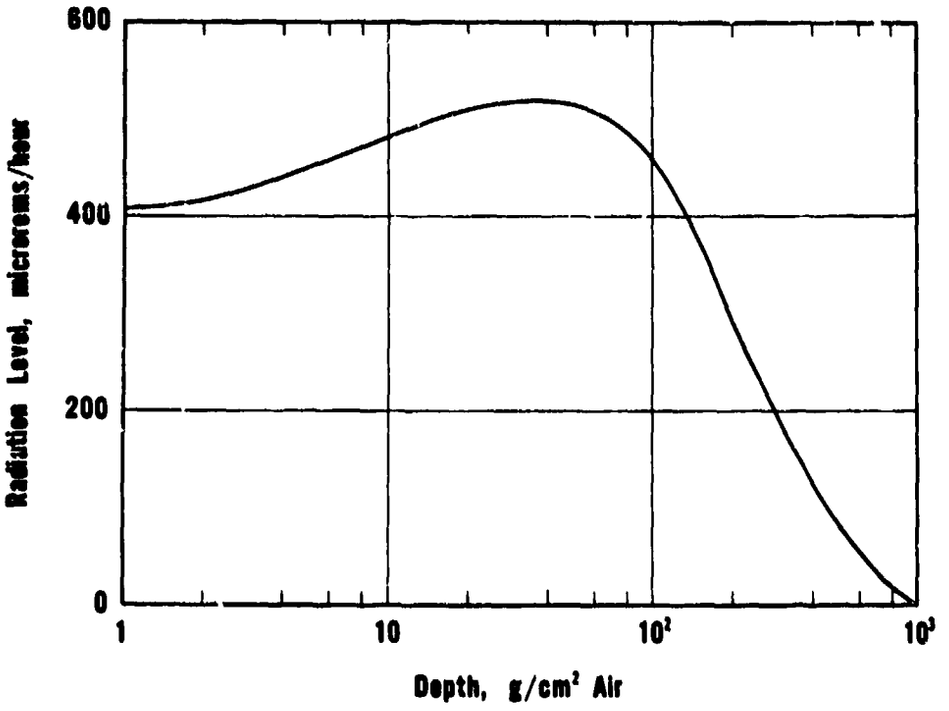
ALTITUDE PROFILE OF TISSUE STAR DOSE OF
GALACTIC RADIATION IN EARTH'S ATMOSPHERE

FIGURE 5



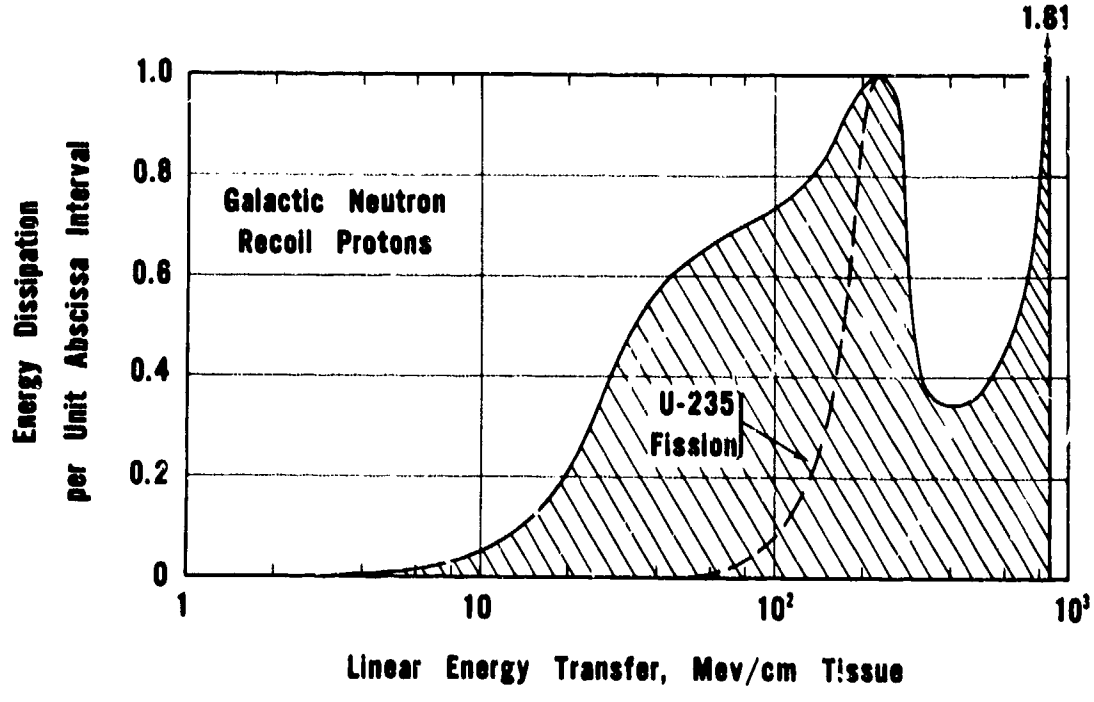
EQUILIBRIUM SPECTRUM OF GALACTIC NEUTRONS
IN EARTH'S ATMOSPHERE AT 200g/cm^2 (39,000 FEET)

FIGURE 6



ALTITUDE PROFILE OF GALACTIC NEUTRON DOSE IN EARTH'S ATMOSPHERE FOR SOLAR MINIMUM AND HIGH LATITUDE

FIGURE 7



LET DISTRIBUTION OF ENERGY DISSIPATION FOR
GALACTIC NEUTRON RECOIL PROTONS

FIGURE 8