General Disclaimer

One or more of the Following Statements may affect this Document

- This document has been reproduced from the best copy furnished by the organizational source. It is being released in the interest of making available as much information as possible.

- This document may contain data, which exceeds the sheet parameters. It was furnished in this condition by the organizational source and is the best copy available.

- This document may contain tone-on-tone or color graphs, charts and/or pictures, which have been reproduced in black and white.

- This document is paginated as submitted by the original source.

- Portions of this document are not fully legible due to the historical nature of some of the material. However, it is the best reproduction available from the original submission.

Produced by the NASA Center for Aerospace Information (CASI)

PERSONNEL NEUTRON MONITORING IN SPACE

Hermann J. Schaefer

November 1978

FACULTY OF PHYSICS
THE UNIVERSITY OF WEST FLORIDA
PENSACOLA, FLORIDA 32504

SUMMARY

Although the primary galactic radiation in space does not contain neutrons, they are abundantly produced in nuclear interactions of high-energy primaries in the local hardware and the astronaut's body. Separate measurement of the dose contribution from neutron recoil protons in the presence of large fluxes of protons of different origin and other ionizing particles in general encounters considerable difficulties. Inferences from the build-up and transition of cosmic-ray produced neutrons in the Earth's atmosphere indicate that the neutron flux in a space vehicle in orbit will vary little with shielding and might contribute as much as 20 millirems per day to the astronaut's radiation exposure.

Since nuclear interactions are the main source of neutrons in space, the count of disintegration stars in emulsion offers itself as an indirect method for estimating the neutron flux. Supplemented with data on the prong number distribution, the star count even allows a general assessment of the fraction of stars originating in the tissue-equivalent gelatin matrix. At the same time, star and prong counts in emulsion furnish data on the dose contribution from protons and alpha particles released in nuclear interactions. Similarly to neutron recoil protons, the latter particles also require high Quality Factors for establishing dose equivalents in millirem.

Recent developments suggesting that officially recommended Quality Factors for neutrons might not be stringent enough for long-term low-dose exposures emphasize the importance of adequate neutron dosimetry in personnel radiation monitoring in space.

INTRODUCTION

Although the contribution of neutrons to the astronaut's radiation exposure in space has never been determined separately, strong indirect evidence indicates that it must be substantial. In the complex radiation environment in space, neutron recoil protons, trapped protons in the Anomaly, and secondary protons from local nuclear collisions produce a combined energy spectrum which can be resolved only with elaborate instrumentation. To be sure, such resolution would appear of no importance from a radiation safety viewpoint as long as the combined dose equivalent (DE) from all protons is accurately measured. Unfortunately, this requirement just cannot be fulfilled with plain and simple instrumentation because of the peculiar spectrum of neutron recoil protons. At the same time, that spectrum endows neutrons with a unique effectiveness for producing tissue damage, a fact which has led to the assignment of a Quality Factor (Q) of 10 to fast neutrons in official radiation protection guides.

In recent years, the adequacy of a Q of 10 for fast neutrons has been questioned in the light of experimental findings which indicate that the greater effectiveness of neutrons compared to x- or gamma rays still further increases for small and very small doses to the extent that a Q substantially larger than 10 is called for. In view of these developments, a separate assessment of the contribution of fast neutrons to the astronaut's radiation exposure appears all the more of importance. This report presents a brief review of available information on the galactic neutron spectrum and examines the difficulties encountered in the determination of the DE of neutron recoil protons in the presence of a substantially larger background of trapped and star-produced protons as well as other ionizing particles in space.

BASIC CONCEPTS OF NEUTRON DOSIMETRY

A peculiar physical mechanism of energy dissipation in tissue
or any other hydrogenous material distinguishes neutrons from
all other radiations with a high Linear Energy Transfer (LET).
For example, a proton of 6 Mev dissipates its energy in tissue
along a path of 950 microns with an LET varying from 7 kev/
micron tissue at 6 Mev to 90 kev/μT in the so-called Bragg Peak
at 0.08 Mev at the end of the track. Quite differently, a neut-
ron of 6 Mev transmits its energy in consecutive elastic colli-
sions to hydrgen nuclei imparting to them energies from near
zero in glancing blows to the full neutron energy in a direct
hit. As all these recoil protons pass through the Bragg Peak,
the energy dissipation centers heavily on high LET values.

The dynamics of elastic collision between neutrons and protons
with particular emphasis on dosimetric implications is well des-
cribed in Boag's classical study (1). The number of recoil pro-
tons receiving energies in the interval from E to E $+ \Delta$E is di-
rectly proportional to ΔE yet independent of E for the entire
interval from E = 0 to E = E_n where E_n stands for the energy of
the neutron before the collision. Dividing by E_n, we normalize
to unity and obtain the fraction of the total number of recoils
in the energy interval ΔE as $\Delta N = \Delta E/E_n$ or $dN = dE/E_n$. For any
interval E_1 to E_2, we find the fraction of recoils as
$N_{1,2} = \int_{E_1}^{E_2} dE/E_n = (E_2 - E_1)/E_n$. For $E_2 - E_1$ = 1 Mev, we obtain
the number of recoils per Mev as $1/E_n$. In other words, the first
collision spectrum of the recoil protons from mono-energetic
neutrons is a horizontal plateau. The transfer of any energy E
is equally probable. It is seen, then, that we can find, for
each collision transfering the energy E to the recoil proton
and leaving the neutron with the remaining E_n - E, a complemen-
tary collision transfering E_n - E to the proton and leaving the
neutron with E. This means that the first collision spectrum of
the recoil protons is at the same time the degraded spectrum of
the neutrons after the first collision. Either spectrum carries

half the total energy ac is also borne out by the fact that the mean energy transfer per collision is obtained as $\frac{1}{2}$ E_n.

Selecting a burst of 600 mono-energetic neutrons of 6 Mev as a specific example, we see in Figure 1 the first collision spectrum as a plateau with a constant differential fluence of 100 protons/Mev. Proceeding to the second collision spectrum, we face a more complex situation. The 600 mono-energetic neutrons now have degraded into 600 neutrons with a heterogeneous spectrum covering the entire energy interval from $E = 0$ to $E = 6$ Mev with a constant differential fluence of 100 neutrons/Mev. Resorting to numerical integration, we break down the energy interval into small fractions and treat the neutrons in each fraction as mono-energetic. Each fraction, then, furnishes second collision recoil protons showing a plateau of different height and width and we obtain the complete second collision spectrum as the sum of all plateaus. Since for each plateau the equipartition of energy as well as the one-to-one correspondence of protons and neutrons hold, it follows that the second collision spectrum is again identical for both collision partners with either spectrum carrying one half of one half, i.e., one quarter of the total energy of the original 600 neutrons. The second collision spectrum is also shown in Figure 1 and so is the third one obtained by the analogous procedure. Looking at the process of spectral degradation in general, we see the 600 neutrons generate, in each consecutive collision, 600 new recoil protons with the n-th generation carrying $1/2^n$ of the original energy. At the same time, each consecutive spectrum centers more heavily on low energies as Figure 1 demonstrates for the first three collision spectra.

It is seen that the formalism describing the spectral degradation leads asymptotically to neutrons of zero energy after infinitely many collisions. Actually, this final stage is never reached because the neutrons are eliminated, at very low but finite energies, through capture reactions. As a neutron slows down to energies of a few e-volts and below, the probability

of being captured by the collision partner rather than elasti-
cally scattered increases continuously according to the well
known $1/v$ law where v denoted the speed of the neutron. In tis-
sue, the two most common capture reactions involve hydrogen and
nitrogen nuclei. The $_1H^1(n,gamma)_1H^2$ reaction leads to forma-
tion of a nucleus of heavy hydrogen and emission of a 2.2 Mev
gamma ray. The $_7N^{14}(n,p)_6C^{14}$ reaction leads to formation of a
carbon-14 nucleus and emission of a 0.58 Mev proton. Since cap-
ture reactions are essentially limited to neutrons of very low
energies which would generate, in elastic collisions, recoil
protons of equally low energies well under the Bragg Peak at
0.08 Mev, they do not alleviate the load of high-LET recoil
protons. In fact, the N reaction even adds to the load by cre-
ating an extra proton of high LET. However, for the particular
configuration of the neutron spectrum in space capture reac-
tions contribute only insignificantly to the total neutron DE.

The spectral degradation of a one-time burst of mono-energetic
neutrons represents a conceptual case. In actual exposures, a
sustained flux of neutrons prevails at any point of observa-
tion in tissue leading to a steady-state spectrum of recoil
protons. Similar to the degradation of a burst, the basic re-
lationship for the steady-state spectrum of a continuous flux
of mono-energetic neutrons reads dN = dE/E where E is now inde-
pendent variable and not a constant as in the earlier case.
Integration furnishes a log distribution for the recoil protons.
Per primary neutron, we obtain the number of recoils in the
energy interval E_1 to E_2 as $N_{1,2} = \int_{E_1}^{E_2} dE/E =$
log nat E_2 - log nat E_1 = log nat (E_2/E_1). Replacing the one-
time burst of 600 neutrons originally assumed in Figure 1 by
a sustained flux of 600 neutrons per unit time, we obtain the
steady-state recoil spectrum shown in Figure 1. For a hetero-
geneous neutron spectrum as it develops locally in a vehicle in
space, numerical integration is the best way of establishing
the recoil spectrum.

4

ENERGY SPECTRUM OF COSMIC-RAY PRODUCED NEUTRONS

Outside the nuclear bond, the neutron is an unstable particle
disintegrating into a proton-electron pair with a half life of
about 12 minutes. Therefore, the primary galactic radiation does
not contain any neutrons. However, at near-Earth orbital alti-
tudes, a small flux of so-called albedo neutrons prevails ori-
ginating in nuclear interactions of high-energy primary protons
or heavier nuclei with oxygen or nitrogen nuclei of the atmos-
phere and re-emitted into space. There is also a very small
flux of solar neutrons. Yet by far the most prolific source of
neutrons in a space vehicle is found in nuclear interactions
of high-energy galactic primaries in the local hardware and the
astronaut's body itself. Direct measurements of the energy
spectrum of these neutrons in a manned space vehicle have never
been conducted. Many investigators did study, experimentally
and theoretically, the spectrum of cosmic-ray produced neut-
rons in the Earth's atmosphere. As extensive as these efforts
may have been, they have clarified the problem only to a limit-
ed extent. While satisfactory agreement exists on the basic
shape of the energy spectrum, major discrepancies still prevail
with regard to absolute flux values.

Frequently referred to is the energy spectrum reported by Pat-
terson, Hess, Moyer, and Wallace (2, 3). Using a whole arsenal
of dosimeters consisting of a bismuth fission ion chamber, a
recoil proton proportional counter, and a moderated and a bare
borontrifluoride counter, the authors measured the entire
spectrum from thermal to relativistic energies at mountain al-
titudes and in a B-36 aircraft covering   the region from
10,000 to 40,000 feet. The variety of sensors ensures that at
least the basic configuration of the spectrum is reliably es-
tablished. With regard to absolute fluxes, error margins are
not indicated accurately enough to ensure satisfactory assess-
ment of DE's through out the spectrum. More recent measure-
ments have been conducted by Klumpar, Lockwood, Onge, and Fri-
ling (4). Especially instructive in the latter reference is a

synoptic graph comparing the reported findings with those of other investigators. A drawback is that the data cover only the spectral region from 3 to 20 Mev. That means the spectrum is left undefined in the important section at and closely below 1 Mev where the maximum of the differential flux has been reported by Patterson and is to be expected for theoretical reasons as Hess, Canfield, and Lingenfelter (5) have shown. Similar shortcomings hold for the data of a number of other investigators. Some even report only the integral flux summarily for specified energy intervals such as 2 to 10 Mev or still more vaguely using the general term "fast neutrons".

Selecting the data of Patterson for further evaluation, we have to point out that they cover the energy interval from 10^{-9} to 10^3 Mev. However, in the present context only the section from 0.01 to 100 Mev shown in Figure 2 is of significance. The spectrum holds for a pressure altitude of 190 g/cm^2 or 40,000 feet and for conditions of solar minimum when the interplanetary magnetic field is weak and galactic radiation at its maximum. An easy assessment indicates that the section below 0.1 Mev contributes less than 1 per cent to the total DE whereas the section from 0.1 to 10 Mev accounts for 80 per cent and the remaining very high energies for the balance. The interval from 0.1 to 10 Mev is at the same time the main source for recoil protons. Above 10 Mev, energy dissipation shifts increasingly from elastic collisions to nuclear interactions which in turn are an abundant secondary source of neutrons most of them with energies well below 10 Mev. It is seen, then, that the dosimetric characteristics are predominantly determined by the spectral section from 0.1 to 10 Mev.

The upper graph in Figure 3 shows once more the just identified spectral section as a semi-log plot for better resolution. Dividing the spectrum into small sections and numerically integrating the log nat(E_2/E_1)-terms explained above, we obtain the energy spectrum of the recoil protons shown in the lower graph of Figure 3. The two graphs demonstrate again the basic problem

of neutron dosimetry in space. While the spectrum of the neutrons themselves covers a wide range with a broad maximum at 0.5 Mev, the actual energy dissipation in tissue does not take place at these energies because the neutrons merely carry the energy to hydrogen nuclei which are the actual ionizing agents. As each neutron passes the energy on to several or many protons in elastic collisions, an entirely different spectrum develops.

Illustrating the task of recording recoil protons with nuclear emulsion, we convert the energy spectrum in the lower graph of Figure 3 into the corresponding range spectrum for emulsion shown in Figure 4. It is seen that the track population centers heavily on lengths of a few microns and less. Identifying such short tracks in the maze of other tracks of all lengths and grain densities which accumulate in an emulsion exposed to radiation in space is all but impossible.

With regard to the dosimetry of neutron recoil protons in general, it should be pointed out that the range distribution in Figure 4 actually could be recorded only with a very thin emulsion embedded in tissue. The geometry of a film badge on the astronaut's body is more correctly modeled with an emulsion layer on a semi-infinite slab of tissue. For the latter system, the energy spectrum of the recoils emerging from the slab is somewhat different from the one prevailing within. Kronenberg and Murphy (6) have conducted an erudite study and derived formulae for the emerging recoil spectrum at the tissue/air interface for any continuous neutron spectrum. However, the changes involved do not significantly alter the basic configuration of the recoil spectrum. They would have to be considered only in actual numerical evaluations of dosimeter readings.

For a correct assessment of the importance of neutron dosimetry in operational radiation monitoring, we need specific information on DE's and DE rates. Following official recommendations, we apply to the neutron spectrum in Figure 3 the flux/DE rate conversion factors set forth in Report 38 of the National Committee on Radiation Protection and Measurements (NCRP) (7).

Applying numerical integration by dividing the spectrum into small intervals, we find a total DE rate of 470 microrem/hour. This radiation level holds for an atmospheric depth of 190 g/cm^2. For extrapolation to smaller thicknesses we refer to measurements of the complete altitude profile of the fast neutron flux reported by Korff, Mendell, Merker, and Sandie (8). Figure 5 is based on the altitude profile of the authors. It has been obtained by equating the flux at 190 g/cm^2 to the DE rate as it follows from Patterson's data for the same pressure altitude. We read from Figure 5 a maximum DE rate of 790 microrem/hour prevailing at 35 g/cm^2. The latter depth is not typical for the range of shield thicknesses of space vehicles. For the Apollo Command Module, for instance, the shield distribution over the anterior hemisphere about the Command Pilot ranged from 1.8 to 28 g/cm^2. The posterior hemisphere with most of it covered by the heavy Service Module offered substantially larger shield thicknesses. Quite generally, it is seen from Figure 5 that the neutron radiation level is a rather weak function of shielding up to thicknesses of about 100 g/cm^2. Therefore, shielding is not a critical factor in establishing estimates of the neutron DE for specific mission parameters.

REVISED QUALITY FACTOR FOR SMALL DOSES

Recent experimental evidence indicates that the Q of 10 for fast neutrons, which is based on animal data for acute exposures, underrates the true DE for small doses. As dose decreases, the effectiveness of fast neutrons for producing tissue damage grows continuously as compared to x- or gamma rays and Q can reach values well above 100 for very small doses. The special significance of this finding for the rather small exposures to fast neutrons in space is obvious.

The reasons for the increased effectiveness at small dose levels are to be sought in the basically different microdosimetric patterns of energy dissipation for low and high-LET radiations. Combining the results of a detailed theoretical analysis

with experimental data for low dose levels, Rossi (9) has derived a mathematical equation linking Q to LET and proposes it as a replacement for the well known Q/LET table set forth by the International Commission on Radiological Protection (ICRP). Substituting for LET the corresponding energy for protons, we arrive at the Q/E function shown in the upper graph of Figure 6. For a direct comparison, the corresponding function as it follows from the official Q/LET table of the ICRP is plotted in the lower graph of the same figure.

For assessing the impact of the proposed revision on the galactic neutron DE, it is helpful to define a magnification factor $M = Q_p/Q_o$ denoting the ratio of the proposed to the official Q value. Reading corresponding Q pairs from the graphs in Figure 6, we discover that M is not at all constant but increases steeply and continuously with decreasing energy, i.e., with increasing LET. We obtain, for instance, for 6 and 1 and 0.6 Mev M-factors of 10 and 22 and 27 respectively. Projecting this strong trend of M upon the energy spectrum of recoil protons in the lower graph of Figure 3, we realize that a computation of mean Q values in the usual way would lead to strongly varying results for minor changes in the configuration of the recoil spectrum. Tests of typical proton recoil spectra as they are encountered in neutron radiation fields about reactors and accelerators suggest that a mean Q of 100 represents a well balanced choice for general use. The galactic neutron spectrum resembles the just named terrestrial spectra as far as the location of the maximum at 0.5 Mev is concerned. It differs somewhat inasmuch as the galactic flux decreases more slowly toward higher energies. The latter circumstance should depress the mean Q in comparison to terrestrial conditions. A mean Q of 100 for galactic neutrons thus would seem a conservatively high value IF one wants to apply the revision in question to radiation exposure in space. The Q of 100 would increase the galactic neutron DE rate from o.79 millirem/hour to 7.9 "millirem"/hour. This represents indeed a large increase.

If instituted officially, the revision would create a much more serious problem for radiation exposures in space than for exposures in terrestrial installations. Statistical data on the dose distribution among radiation workers show that the overwhelming majority of workers receives only small fractions of the official Maximum Permissible Dose (MPD). Quite differently, radiation exposures in space approach the MPD much more closely. In fact, more liberal MPD values for manned space operations have been requested by NASA authorities and tentatively approved by the Space Science Board (10) already long before the issue of a revision of existing Q values for fast neutrons had been raised. So far, however, neither the NCRP nor the ICRP has made any official pronouncement concerning radiation protection guides in space.

CONCLUSIONS AND RECOMMENDATIONS

We have seen that the galactic neutron radiation level in space, established on available information and on the basis of existing official recommendations, possibly is as high as 20 millirem/24 hours. The bulk of this exposure is produced by recoil protons of very short range, a fact which calls for complex instrumentation if LET is to be resolved satisfactorily for accurate assessment of the DE. While a number of investigators have measured the various physical parameters of cosmic-ray produced neutrons, the corresponding DE as it would build up on a manned space mission is by far not known to a degree of accuracy which would be considered mandatory for terrestrial installations. A comparatively large effort is required to fill the gap.

It is recommended that measurements be conducted with a space-borne system adequately simulating the conditions of personnel exposure. The system should consists of a sufficiently large tissue phantom as moderator and an LET spectrometer with high resolution for pulses of low-energy protons near the Bragg Peak. The instrument should be sensitive enough to respond to

a flux of a few neutrons per cm^2 per sec, yet stable enough not to jam in the Anomaly. Once reliable data on the neutron DE rate for a human target in space have been established, compromise solutions applying sampling dosimetry with passive sensors can be developed more specifically.

Even if the proposed major effort is instituted promptly, results will not be available soon. Therefore, interim procedures have to be worked out for obtaining reasonable estimates of the neutron DE on manned missions. We propose the star count method in emulsion for this purpose. We do so on the basis of the following rationale. Nuclear collisions in local matter are the main source of neutrons in a vehicle in space. The frequency of such collisions in emulsion manifesting themselves as stars represents at least a semi-quantitative measure of the neutron fluence. While the plain star count furnishes only a rough estimate, the prong count allows a separation of the stars in the tissue-equivalent gelatin matrix from those in the silverhalide. Admittedly, star and prong counting with the microscope is a laborious task. However, before condemning the method as unacceptable for operational use, one should realize that an emulsion represents a permanent record of exposure which can be read and re-read as often as desired and at any level of effort and corresponding accuracy.

Star and prong number counts have been an integral part of radiation monitoring on all manned missions. Details have been described in a number of reports and publications (11, 12). For the Apollo-Soyuz mission, very extensive star counts have been conducted as reported in the second of the just quoted references. Using upper-limit values for all error margins of the Apollo-Soyuz counts, one arrives at a neutron DE for the mission of 64 millirems. It is reassuring that this value amounts to only one third of the general estimate of 180 millirems that follows from the dose rate of 20 millirem/24 hours established above from Patterson's data for a mission duration of 216 hours or 9 days. On the other hand, even the smaller

11

assessment of 64 millirems demonstrates that neutrons contributed indeed a substantial fraction of the total mission DE on Apollo-Soyuz.

Reviewing the capabilities of emulsion as LET discriminator in general, one should remember that the star count furnishes an estimate not only of the neutron DE but also of the additional dose from protons and alpha particles originating in nuclear interactions. Although less heavily concentrated on low energies, the particles in question account for another component carrying a high Q value. A passive dosimeter such as a TLD badge merely recording absorbed doses will not adequately monitor the contributions from neutrons and tissue disintegration stars. Adding emulsion to such a badge is an expeditious way of providing clues on LET and Q for assessing the mission dose equivalent.

REFERENCES

1. Boag, J. W., The distribution of Linear Energy Transfer or "Ion Density" for fast neutrons in water.
    Rad. Res. 1, 323 - 341, 1954.

2. Hess, W. N., Patterson, H. W., and Wallace, R. W., Cosmic-ray neutron energy spectrum.
    Phys. Rev. 116, 445 - 457, 1959.

3. Patterson, H. W., Hess, W. N., Moyer, B. J., and Wallace, R. W., The flux and spectrum of cosmic-ray produced neutrons as a function of altitude.
    Health Phys. 2, 69 - 72, 1959.

4. Klumpar, D. M., Lockwood, J. A., Onge, R. N., and Friling, N. A., Energy spectrum and flux of 3- to 20-Mev neutrons and 1- to 10-Mev gamma rays in the atmosphere.
    J. Geophys. Res. 78, 7959 - 7985, 1973.

5. Hess, W. N., Canfield, E. H., and Lingenfelter, R. E., Cosmic-ray neutron demography.
    J. Geophys. Res. 66, 665 - 677, 1961.

6. Kronenberg, S. and Murphy jr, H. M., Energy spectrum of protons emitted from a fast-neutron irradiated hydrogenous material.
    Rad. Res. 12, 728 - 735, 1960.

7. NCRP Report No. 38: Protection against neutron irradiation. Recommendations of the National Council on Radiation Protection and Measurements. Washington, D. C., 1971.

8. Korff, S. A., Mendell, R. B., Merker, M., and Sandie, W., Cosmic-ray fast-neutron flux measurements in the atmosphere at various latitudes.
    Canad. J. Phys. 46, S 1024 - S 1026, 1967.

9. Rossi, H. H., A proposal for revision of the Quality Factor.
    Rad. and Environm. Biophys. 14, 275 - 283, 1977.

10. Space Science Board: Radiation Protection Guides and Constraints for Space-Mission and Vehicle-Design Studies Involving Nuclear Systems.
    National Academy of Sciences, Washington, D. C., 1970.

11. Schaefer, H. J., Benton, E. V., Henke, R. P., and Sullivan, J. J., Nuclear track recordings of the astronauts' radiation exposure on the first lunar landing mission Apollo XI.
    Rad. Res. 49, 245 - 271, 1972.

12. Schaefer, H. J. and Sullivan, J. J., Nuclear emulsion measurements of the astronauts' radiation exposure on the Apollo-Soyuz mission.
    NAMRL 1228. Naval Aerospace Med. Res. Lab., Pensacola, Florida, 1976.
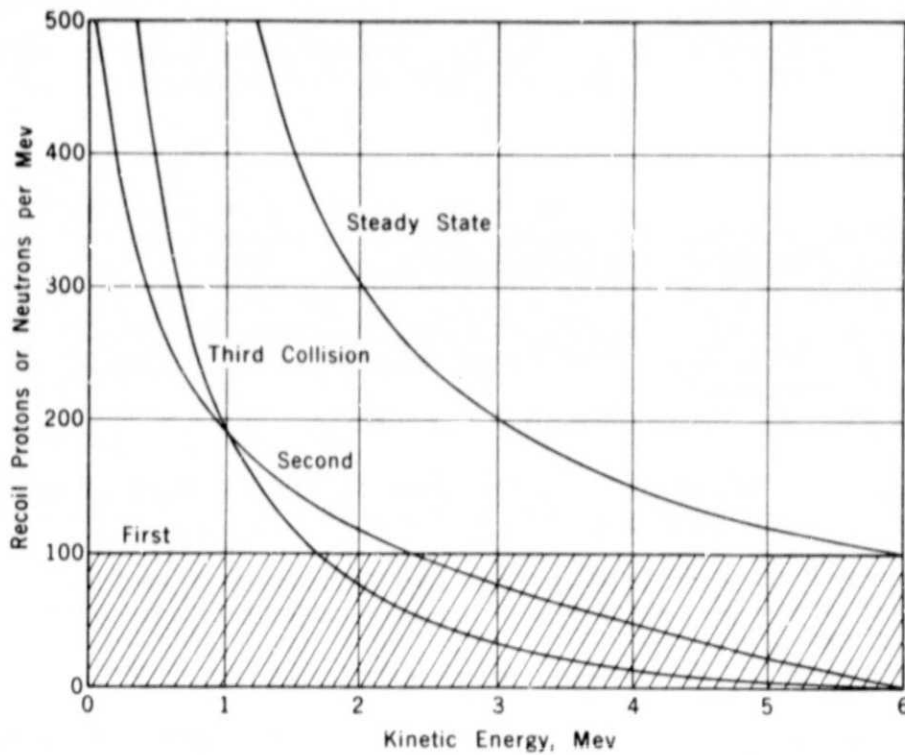
* * * * * * * * * *

FIGURE 1

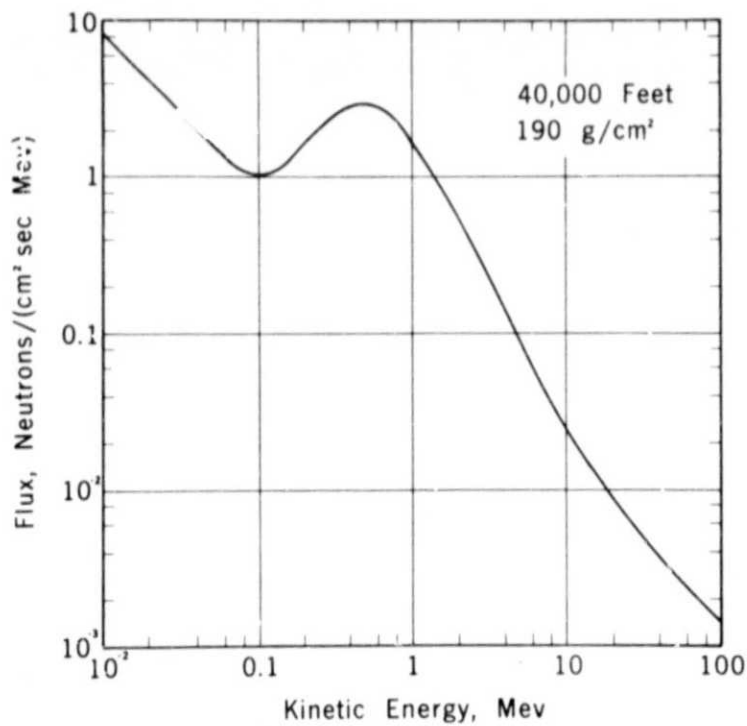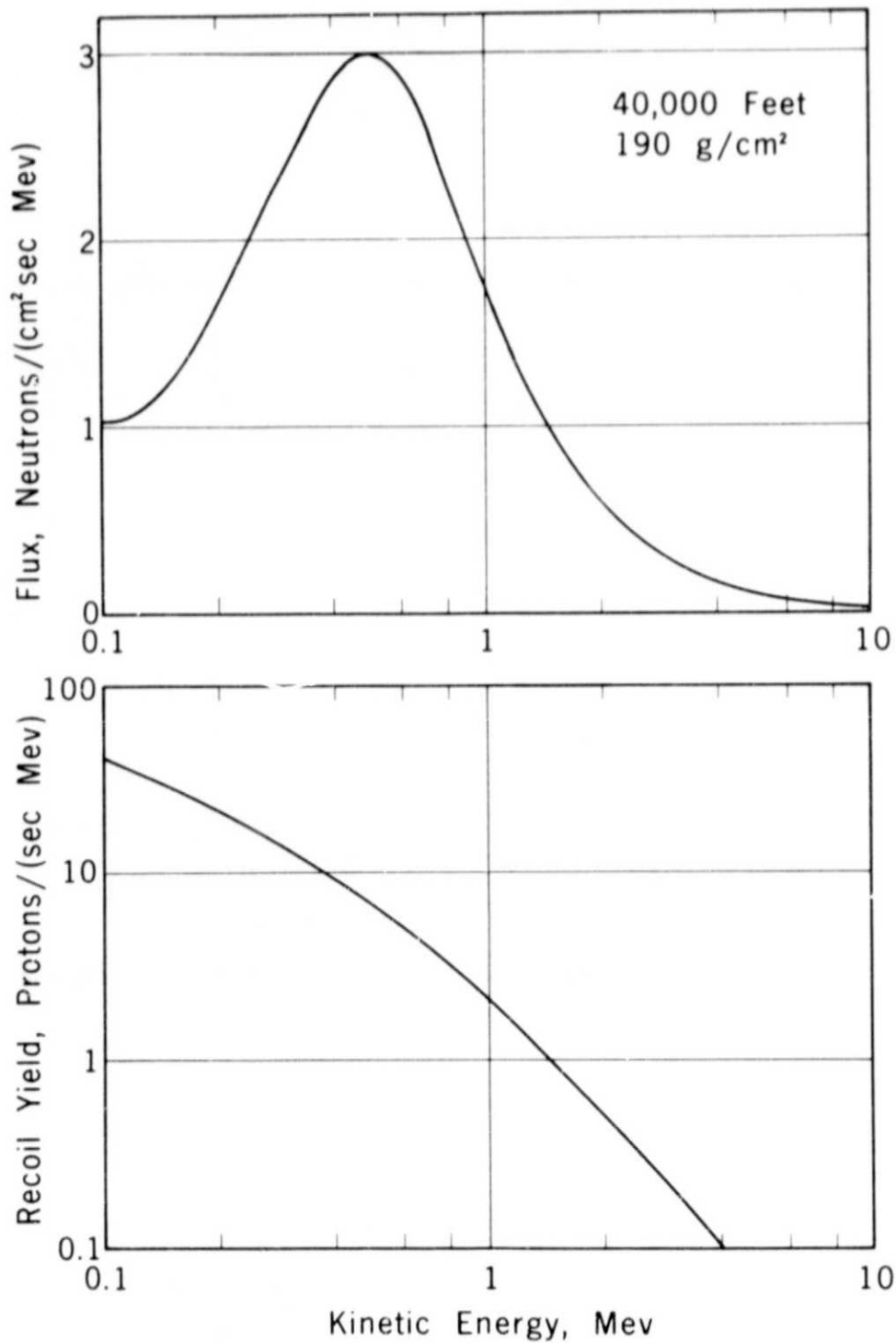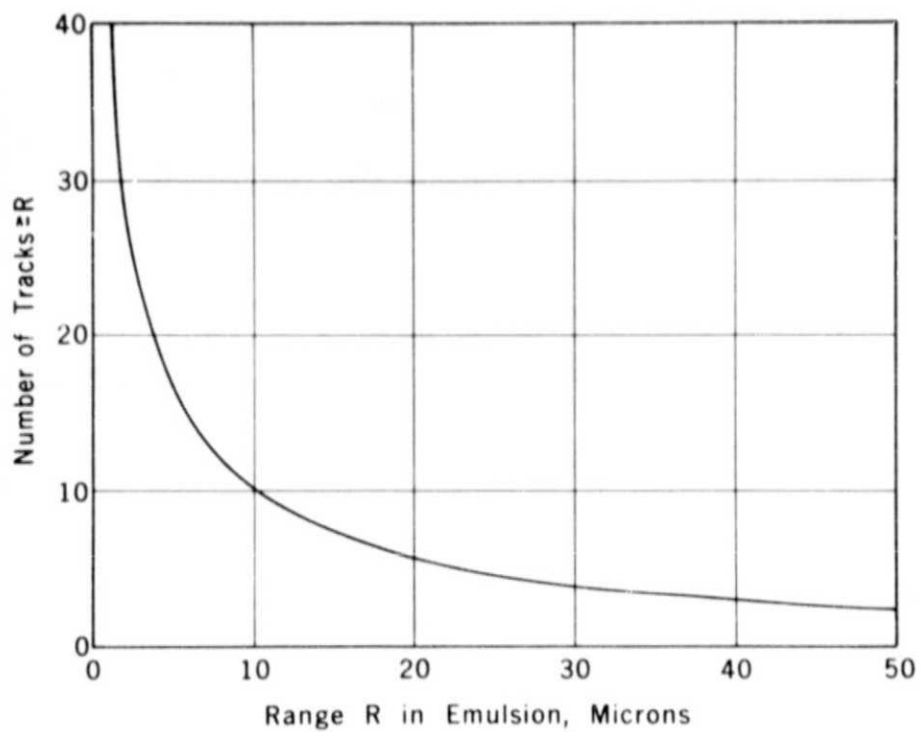**SPECTRAL DEGRADATION OF 600 MONOENERGETIC NEUTRONS OF 6 MEV IN TISSUE**

FIGURE 2

**ENERGY SPECTRUM OF COSMIC-RAY PRODUCED
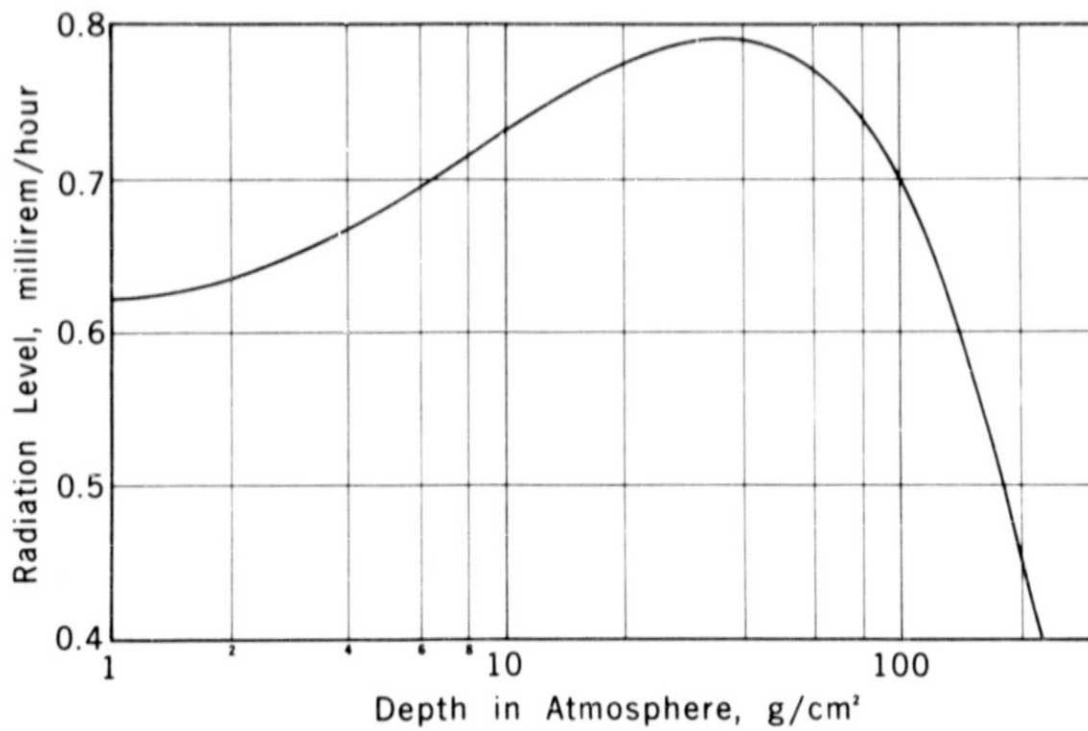NEUTRONS IN EARTH'S ATMOSPHERE**

14

**SPECTRA OF COSMIC-RAY PRODUCED NEUTRONS
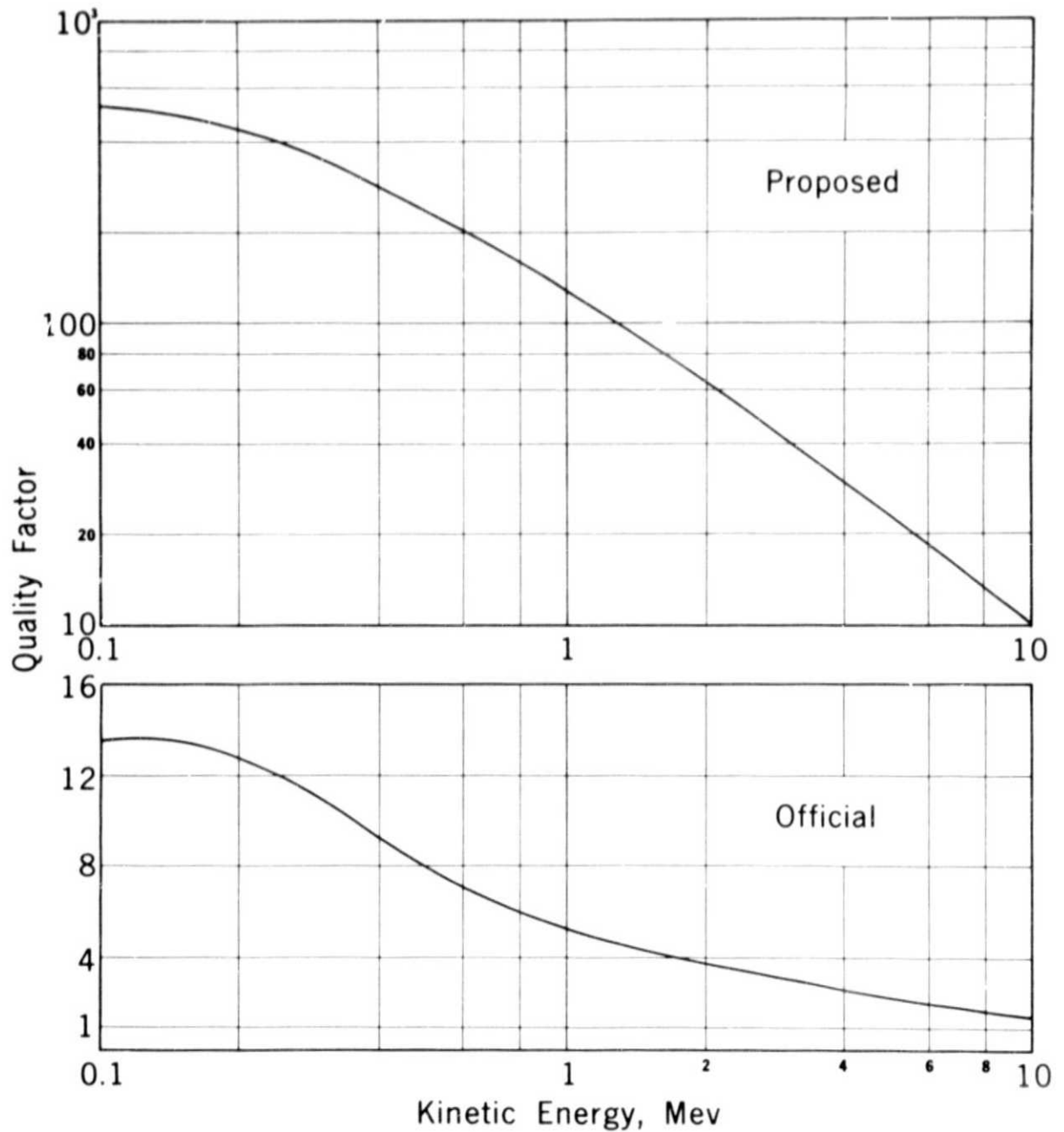AND RECOIL PROTONS IN TISSUE**

FIGURE 3

15

INTEGRAL RANGE DISTRIBUTION OF RECOIL PROTON TRACKS IN EMULSION

FIGURE 4

16

TRANSITION OF GALACTIC NEUTRON RADIATION LEVEL IN ATMOSPHERE

FIGURE 5

17

OFFICIAL AND PROPOSED QUALITY FACTORS AS FUNCTIONS OF PROTON ENERGY

FIGURE 6

18