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APPENDIX T

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DIFFERENTIAL NEUTRON ENERGY SPECTRA MEASURED ON SPACECRAFT IN LOW EARTH ORBIT

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Abstract—Two methods for measuring neutrons in the range from thermal energies to dozens of MeV were used. In the first method, α-particles emitted from the ^{6}Li(n,α)T reaction are detected with the help of plastic nuclear track detectors, yielding results on thermal and resonance neutrons. Also, fission foils are used to detect fast neutrons. In the second method, fast neutrons are recorded by nuclear photographic emulsions (NPE). The results of measurements on board various satellites are presented. The neutron flux density does not appear to correlate clearly with orbital parameters. Up to 50% of neutrons are due to albedo neutrons from the atmosphere while the fluxes inside the satellites are 15–20% higher than those on the outside. Estimates show that the neutron contribution to the total equivalent radiation dose reaches 20–30%.

INTRODUCTION

THE RADIATION environment in low Earth orbits is studied, as a rule, using thermoluminescent dosimeters and plastic nuclear track detectors (Benton *et al.*, 1977; Akatov *et al.*, 1981, 1984). Measurements of this type yield data on absorbed dose, but cannot give information on radiation quality or on dose component composition. Also, a serious underestimation may occur because neutrons are disregarded. A few investigations were previously carried out to study the neutron component. The experimental work of Dudkin *et al.* (1968), Merker *et al.* (1970), Jenkins *et al.* (1971), Bhaff (1976), and calculational efforts of Lingenfelter (1963), Armstrong *et al.* (1973) and Merker (1973) studied the neutron fluxes and energy spectra in near-Earth orbits. These previous efforts were, at best, sporadic, so that characteristics of the neutron component in the Earth's environment have not yet been systematically studied.

The aim of the present work was to experimentally study the energy spectra and fluences of neutrons in low Earth orbit as a function of flight parameters. Two methods were used, namely, the method of fission foils with shielding screens and the NPE method. The measured values of neutron fluxes were then used to estimate the neutron dose equivalent in different energy groups and its contribution to the total equivalent dose.

MEASUREMENT TECHNIQUES

The large cross-sections for capture of thermal and resonance neutrons by ^{6}Li nuclei makes detection possible through the ^{6}Li (n,α)T reaction. The fluences of α-particles emitted from ^{6}LiF film surfaces are recorded in plastic nuclear track detectors, for example, in a CR-39 detector. Thermal neutrons can be separated from resonance neutrons using Gd foils which shield a detector. In our experiment, 25 μm-thick foils were used. The difference between shielded and non-shielded detectors gives the value of thermal neutron flux, whereas the shielded detectors measure resonance neutron fluxes. The 4.5 mg cm^{-2} ^{6}LiF thickness defines the detector sensitivity to thermal neutrons which is 4.9×10^{-3} tracks/thermal neutron. The sensitivity to resonance neutrons (0.2 eV–1 MeV), where the dependence of the neutron spectrum was assumed to be ($1/E_n$), was calculated to be 2.56×10^{-4} tracks/resonance neutron. The fluence of high-energy neutrons ($\geqslant 1.0$ MeV) was roughly estimated using thorium foils. The foils recorded the track densities produced by Th fission fragments. The disintegrations were caused by fast neutrons and by protons. Therefore, to separate neutrons and protons it was necessary to assume the forms of their energy spectra and their relative intensities.

The differential fast-neutron spectrum was determined by the NPE method using the low-sensitivity 400 μm-thick BYa-type emulsion layers whose recording power corresponds to particles whose linear energy transfer (LET) exceeds the LET of protons with kinetic energy of about 50 MeV. The background from particles with lower LET values was reduced by this method.

The fast-neutron spectrum was recovered using the recoil proton energy spectrum generated as a result

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of the elastic (n,p)-scattering of neutrons from the hydrogen in the emulsion.

The recoil proton path in an exposed and developed emulsion was determined by measuring two orthogonal projections of a track whose ends were located within the volume of an NPE layer. Allowance was made for the fact that a fraction of the recoil protons will leave the emulsion layer and that the probability of such an event rises with increasing recoil proton energy and, hence, the energy of a neutron scattered by the recoil proton. The factor f, which depends upon proton energy and NPE layer thickness, was introduced into the recoil-proton path (energy) distribution to correct for the loss of tracks. To correctly construct the proton path (energy) distribution in NPE, the NPE shrinkage factor K_{sh} was also included.

The kinematics of elastic scattering of a non-relativistic neutron of energy, E_n, has been described elsewhere (e.g. Nemetz and Gofman, 1975). The relationship of the differential neutron energy spectrum $\mathrm{d}N/\mathrm{d}E_n$ to the measured differential recoil proton spectrum $\mathrm{d}P/\mathrm{d}E$ is found by graphic differentiation and can be presented as

$$\frac{\mathrm{d}N}{\mathrm{d}E_n} = -\frac{\mathrm{d}}{\mathrm{d}E}\left(\frac{\mathrm{d}P}{\mathrm{d}E}\cdot\frac{1}{f(E)}\right)\frac{E_n}{n_0\cdot\sigma(E_n)\cdot V} \qquad (1)$$

where n_0 is the number of hydrogen nuclei in 1 cm^3 of NPE ($n_0 = 3.05 \times 10^{22}\,\mathrm{cm}^{-3}$ for the BYa-type emulsion; V is the volume of emulsion inspected (in cm^3); σ is the (n,p)-scattering cross-section (in cm^2).

To facilitate the graphic differentiation, we approximated the recoil proton spectrum including the correction factor f for the track extending beyond the NPE layer. The values of f as a function of proton energy, E_p, were calculated by the formulas presented in Perfilov *et al.* (1962), where the expression is of the type

$$y = \sum_i \alpha_i \cdot \exp(-\beta_i E)$$

where α_i and β_i are numerical factors.

The following three circumstances should be noted. Firstly, the measurements appear to be unreliable at neutron energies $E_n < 1.0$ MeV because of a large visual error when recording the short path-length protons (the 1 MeV proton path in NPE is $\sim 14\,\mu$m). Also, the measurements in the above-mentioned energy range are unreliable because the reactions of thermal and intermediate neutrons on nitrogen of the emulsion produce a 0.7 MeV neutron which cannot in practice be distinguished from a recoil proton in the (n,p) scattering. Secondly, the error of the given method increases at neutron energies above 10–15 MeV because the expression (1) has been obtained assuming an isotropic proton scattering in c.m.s. which is only possible at energies below 10–15 MeV. Thirdly, it should be borne in mind that, if the neutron spectrum is of a complicated non-monotone character, a differentiation error will distort the results substantially.

The reproducibility of this method in the neutron energy range above 1.0 MeV was verified by irradiating similar BYa-type emulsion packages with neutrons from sources whose spectra have been well documented in literature. For example, we irradiated the BYa-type emulsion packages with neutrons from ^{252}Cf and from Pu–Be sources, and obtained spectra which differed from published data by not more than ±20%.

RESULTS AND DISCUSSION

Flux densities and energy spectra of neutrons in different energy ranges were measured on board several U.S. and Soviet spacecraft. The measurements were made inside the satellites and on their external surfaces. The thickness of matter screening the detector inside a satellite was different in different satellites and varied from ~ 5 to $\sim 50\,\mathrm{g\,cm^{-2}}$. Unfortunately, the exact distribution of the mass of detector-surrounding matter was not known, thereby making the analysis of the measurement results difficult.

Table 1 presents some of the results of measuring neutron flux density on board various spacecraft with ^{6}LiF detectors and fission foils (Benton and Henke, 1983 and Benton, 1986). The table also presents the neutron doses calculated on the basis of these measurements.

The doses were calculated using the flux–dose conversion factors from NCRP Proceedings of 1971, while the quality factors were taken to be 2.0, 6.4, and 10.0 for thermal, resonance and fast neutrons, respectively.

The data on the forms of the neutron and proton spectra used in calculating the doses were taken from Merker (1973) and Hewitt *et al.* (1972), respectively, while the relation between the proton and neutron fluences was taken from Fishman (1974). It should be noted that, whereas the experimental data on proton spectra in similar flights generally can be found, the fast-neutron spectral data were not available. Obviously, this circumstance can give rise to probable errors in determining the doses which are difficult to estimate. Since, as seen from Table 1, the fast neutrons make the major contribution to the neutron dose, the method of using the fission foils needs further refinement.

Table 2 presents the results of measuring the flux density of fast ($E_n \geq 1$ MeV) neutrons on board various satellites of the Cosmos series by the NPE method. In each case, the differential neutron energy spectrum was measured and then used to find the neutron flux density by energy integration. The Table 2 results also show the dose equivalent rates obtained using the differential neutron spectra and the flux density–dose rate conversion factors taken from Vikhrov *et al.* (1978).

Table 1. Radiation characteristics of neutrons in near-Earth orbits (measurements performed with solid-state detectors and fission foils)

	Satellite	Cosmos 936	Cosmos 1129	STS-3	STS-4	STS-5	STS-6
Flight parameters	Launch date	August 1977	September 1979	March 1982	June 1982	November 1982	April 1983
	Flight time (days)	18.5	18.56	8.13	7.04	5.08	5.00
	Inclination (degree)	62.8	62.8	38	28.5	28.5	28.5
	Apogee/perigee or circular orbit (km)	419/224	394/226	280	297	284	293
Thermal neutrons	Flux density (cm^{-2} day^{-1})	(1.9 ± 0.4) × 10^4	(2.7 ± 0.5) × 10^4	(4.1 ± 1.0) × 10^3	(6.1 ± 1.1) × 10^3	(6.1 ± 1.8) × 10^3	(6.0 ± 1.6) × 10^3
	Equivalent dose rate (mrem day^{-1})	0.020 ± 0.004	0.028 ± 0.006	0.004 ± 0.001	0.006 ± 0.001	0.006 ± 0.002	0.006 ± 0.002
Resonance neutrons	Flux density (cm^{-2} day^{-1})	(6.5 ± 3.2) × 10^4	(7.5 ± 3.8) × 10^4	(4.6 ± 2.2) × 10^4	(4.7 ± 2.3) × 10^4	(3.0 ± 1.8) × 10^4	(7.6 ± 3.8) × 10^4
	Equivalent dose rate (mrem day^{-1})	0.32 ± 0.16	0.40 ± 0.20	0.25 ± 0.12	0.23 ± 0.11	0.14 ± 0.08	0.38 ± 0.19
High-energy neutrons	Flux density (cm^{-2} day^{-1})	(1.1 ± ?) × 10^5	(1.1 ± ?) × 10^5	(1.6 ± ?) × 10^4	(3.4 ± ?) × 10^4	(3.5 ± ?) × 10^4	(2.2 ± ?) × 10^4
	Equivalent dose rate (mrem day^{-1})	6.8 ± ?	6.8 ± ?	0.95 ± ?	2.0 ± ?	2.2 ± ?	1.3 ± ?
Neutrons in total	Flux density (cm^{-2} day^{-1})	1.94 × 10^5	2.1 × 10^5	6.6 × 10^4	8.7 × 10^4	7.1 × 10^4	1.0 × 10^5
	Equivalent dose rate (mrem day^{-1})	7.1	7.2	1.2	2.2	2.3	1.7

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Table 2. Radiation characteristics of fast neutrons in near-Earth orbits (measurements by the NPE method)

A Cosmos series satellite (number)	Flight parameters						
	Launching data	Time of flight (days)	Inclination (degrees)	Apogee/perigee (km)	NPE placed	Neutron flux density ($cm^{-2}\ day^{-1}$)	Equivalent dose rate ($mrem\ day^{-1}$)
936	3 August 1977	18.5	62.8	419/224	inside	$(1.1 \pm 0.5)\ 10^5$	4.5 ± 2.2
1129	25 September 1979	18.56	62.8	394/226	inside	$(1.1 \pm 0.4)\ 10^5$	4.5 ± 1.4
1129	25 September 1979	18.56	62.8	394/226	outside	$(8.6 \pm 2.6)\ 10^4$	3.5 ± 1.0
1514	14 December 1983	4.92	82.3	288/226	inside	$(7.4 \pm 2.2)\ 10^4$	3.0 ± 0.9
1514	14 December 1983	4.92	82.3	288/226	outside	$(6.2 \pm 1.7)\ 10^4$	2.5 ± 0.7
1571	11 June 1984	15.3	70	420/355	outside	$(6.9 \pm 1.7)\ 10^4$	2.8 ± 0.7
1600	27 September 1984	13.2	70	420/355	outside	$(7.8 \pm 2.6)\ 10^4$	3.1 ± 1.0
1667*	10 July 1985	7.0	82.7	297/222	outside I	$(6.7 \pm 1.7)\ 10^4$	2.7 ± 0.7
1667*	10 July 1985	7.0	82.7	297/222	outside II	$(5.6 \pm 1.7)\ 10^4$	2.2 ± 0.7
1757	11 June 1986	14.0	82.3	252/189	outside	$(5.2 \pm 1.7)\ 10^4$	2.1 ± 0.7
1781	17 September 1986	14.0	70.4	405/217	outside	$(5.2 \pm 1.7)\ 10^4$	2.1 ± 0.7
1887	29 September 1987	12.6	62.8	394/226	inside	$(5.2 \pm 1.7)\ 10^4$	2.1 ± 0.7
1887	29 September 1987	12.6	62.8	394/226	outside	$(4.5 \pm 1.7)\ 10^4$	1.8 ± 0.7

*External assembly I oriented towards the Sun; assembly II oriented towards the Earth.

Shown as an example in Fig. 1 are the neutron energy spectra measured inside and outside the Cosmos 1514 and 1887 satellites. For comparison, Fig. 1 presents also the results of a calculated albedo neutron spectra obtained in Lingenfelter (1963) for solar minimum at different orbital inclinations to the plane of the equator ($i = 40°$ and $90°$).

Analyzing the experimental data has shown that most of the fast-neutron energy spectra are of the characteristic 'evaporation' form with a maximum in the 1.5–4.0 MeV neutron energy range. In any case, the form of neutron spectra presented here is realized in all the spectra measured inside the spacecraft. The external neutron spectrum is, as a rule, softer.

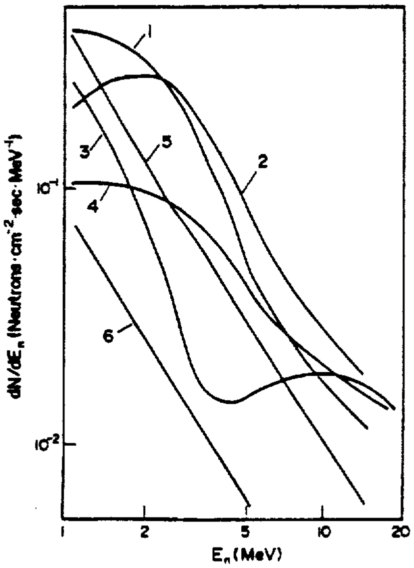

FIG. 1. Differential neutron energy spectra measured in spacecraft in low Earth orbit. Curves 1 and 2 are the Cosmos 1514 data obtained outside (1) and inside (2) the satellite. Curves 3 and 4 are the Cosmos 1887 data obtained outside (3) and inside (4) the satellite. Curves 5 and 6 are the albedo neutron spectra calculated in Lingenfelter (1963) at angle $i = 90°$ (5) and at $i = 40°$ (6) during solar minimum.

According to the present-day concepts, the detected neutrons originate from two sources, namely, the albedo neutrons produced in interactions of galactic cosmic rays with the Earth's atmosphere and the secondary neutrons produced in the spacecraft structure (the local neutrons). The form of the local neutron spectra is similar to the form of the spectra generated in inelastic proton–nuclear interactions. The local neutron spectra are obviously more rigid compared with the spectra of the albedo neutrons which undergo multiple scatterings and attenuation in the atmosphere.

The data of Table 2 show that the neutron fluences inside the spacecraft are 15–20% higher than on the outside, thereby indicating that local neutrons are accumulated in the instruments simultaneously with attenuation of albedo neutrons. This trend is observed in the neutron dose rates measured both inside and outside the satellites.

Comparing the data of Tables 1 and 2 it is seen that the fast neutron flux densities measured by the two different methods are in approximate agreement. A difference in the dose rates shown is probably due to different values of the flux–dose coefficients used.

Analyzing the measurement results has shown that the neutron flux density does not exhibit any unambiguous dependence on altitude, orbital inclination, and phase of the solar cycle. According to Jenkins *et al.* (1971), the flux density of the albedo neutrons with $E_n \geqslant 1$ MeV increases by a factor of ~10 as a satellite moves from the equator to the poles and is $0.03\ n\ cm^{-2}\ s^{-1}$ at the equator and 0.2–$0.5\ n\ cm^{-2}\ s^{-1}$ at the poles. This is confirmed by our experiments (see Table 1) where the fast-neutron dose decreases by a factor of ~3 as the orbit inclination angle varies from 60 to 30°.

Analyzing the measurement results has also shown that the albedo neutron contribution to the total neutron flux may reach ~50%, which is in good agreement with the estimate obtained by Yushkov

(1988) where the albedo neutron contribution to the total counting rate of the neutron detector flown on Salyut-6 was found to be 2/3.

It is of interest to estimate the neutron contribution to the total dose in low Earth orbit. This is possible since thermoluminescent detectors were used in all of the flight experiments. The rates of absorbed neutron doses are approximately a few per cent of the total absorbed dose, whereas the neutron contribution to the dose equivalent reaches 20–30% (because of a high quality factor).

In order to understand better the nature of the cosmic ray neutron component in low Earth orbit and in order to make the absolute dose measurements more accurate, it is necessary to carry out further experiments on board oriented spacecraft in different orbits and during varying phases of the solar cycle. The distribution of shielding mass about the detectors must also be taken into account. Lastly, further refinement of the measurement techniques is still necessary.

REFERENCES

Akatov Yu. A., Arkhangelsky V. V., Aleksandrov A. P., Fehér I., Deme S., Szabó B., Vagvölgyi J., Szabó P. P., Csöke A., Ránky M. and Farkas B. (1984) Thermoluminescent dose measurements on board Salyut-type orbital stations. *Adv. Space Res.* 4(10), 77.

Akatov Yu. A., Vikhrov A. I., Dudkin V. E., Marenny A. M., Nefedov N. A., Potapov Yu. V., Spurný F., Turek K. and Hashegan D. (1981) Study of cosmic radiation attenuation on board Cosmos-1129. *Third All-Union Conf. Prot. Against Ionizing Radiat. Nucl. Tech. Installation.* Tbilisi.

Armstrong T. W., Chandler K. C. and Barish J. (1973) Calculations on neutron flux spectra induced in the Earth's atmosphere by galactic cosmic rays. *J. geophys. Res.* 78, 2715.

Benton E. V. (1986) Summary of radiation dosimetry results on U.S. and Soviet manned spacecraft. XXVI COSPAR Meeting, Toulouse, 1986. COSPAR Paper No. VII. p. 7.

Benton E. V. and Henke R. P. (1983) Radiation exposures during space flight and their measurements. *Adv. Space Res.* 3(8), 171.

Benton E. V., Henke R. P. and Peterson D. D. (1977) Plastic nuclear track detector measurements of high-LET particle radiation on Apollo, Skylab and ASTP space missions. *Nucl. Track Detection* 1, 27.

Bhatt V. L. (1976). Neutron high-energy spectra at 5 mbar near the geomagnetic equator. *J. geophys. Res.* 81, 4603.

Dudkin V. E., Kovalev E. E., Novikova N. R., Ostroumov V. I., Potapov Yu. V., Skvorsov S. S. and Smirenny L. N. (1968) Measuring the proton and neutron spectra and fluxes on board satellites of the Cosmos series. *Kosm. Issled.* VI, 887.

Fishman G. J. (1974) Neutron and proton activation measurements from Skylab. AIAA Paper No. 74-1227. *AIAA/AGD Conf. scient. Experiments Skylab.* October 1974, Huntsville, Alabama.

Hewitt J. E., Schaefer H. J. and Sullivan J. J. (1972) Radiation exposure during the biosatellite III primate flight. *Hlth Phys.* 23, 461.

Jenkins R. W., Ifedili S. O., Lockwood J. A. and Razdan H. (1971) The energy dependence of cosmic-ray neutron leakage flux in the range of 0.01–10 MeV. *J. geophys. Res.* 76, 7470.

Lingenfelter R. E. (1963) Cosmic ray neutron leakage flux. *J. geophys. Res.* 68, 5633.

Merker M. B. (1973) The contribution of galactic cosmic rays to the atmospheric neutron maximum dose equivalent as a function of neutron energy and altitude. *Hlth Phys.* 25, 524.

Merker M. B., Light E. S., Mendell R. B. and Korff S. A. (1970) The flux of fast neutrons in the atmosphere. *Acta physiol. hung.* 29 (Suppl. 2), 739.

Nemetz O. F. and Gofman Yu. V. (1975) *Handbook on Nuclear Physics*, p. 386. Naukova Dumka, Kiev.

Perfilov N. A., Loszkin O. V. and Ostroumov V. I. (1962) *Nuclear Reactions Induced by High-energy Particles.* Acad. Sci. U.S.S.R. Editorial Board. Moscow.

Vikhrov A. I., Dudkin V. E., Kovalev E. E., Komochkov M. M., Lebedev V. N., Litvinova E. G., Mitricas V. G., Potapov Yu. V., Potemkin E. L., Sichov B. S. and Frolov V. V. (1978) *Atlas of Dose Characteristics of External Ionizing Radiation* (Edited by Kovalev E. E.). Atomizdat, Moscow.

Yushkov B. Yu. (1988) Measuring neutron fluxes on board Salyut-6 orbital station. *Kosm. Issled.* 5, 793.

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