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APPENDIX P

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by

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NEUTRON FLUENCES AND ENERGY SPECTRA IN THE COSMOS-2044 BIOSATELLITE ORBIT

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Abstract—Joint Soviet–American measurements of the neutron component of space radiation (SR) were carried out during the flight of the Soviet biosatellite Cosmos-2044. Neutron flux densities and differential energy spectra were measured inside and on the external surface of the spacecraft. Three energy intervals were employed: thermal ($E_n \leq 0.2$ eV), resonance ($0.2 \text{ eV} < E_n < 1.0$ MeV) and fast ($E_n \geq 1.0$ MeV) neutrons. The first two groups were measured with U.S. ^{6}LiF detectors, while fast neutrons were recorded both by U.S. fission foils and Soviet nuclear emulsions. Estimations were made of the contributions to absorbed and equivalent doses from each neutron energy interval and a correlation was presented between fast neutron fluxes, measured outside the satellite, and the phase of solar activity (SA). Average dose equivalent rates of 0.018 and 0.14 mrem d^{-1} were measured for thermal and resonance neutrons, respectively, outside the spacecraft. The corresponding values for fast neutrons were 3.3 (U.S.) and 1.8 (U.S.S.R.) mrem d^{-1}. Inside the spacecraft, a value of 3.5 mrem d^{-1} was found.

INTRODUCTION

The present measurements are a continuation of previous investigations begun on board the biosatellite Cosmos-1887 which showed the necessity of further development within the S.U.–U.S. joint research program. The flight of Cosmos-2044 had two major features which distinguished it from other satellite flights. Firstly, its orbit was near to polar, and secondly, the experiment was carried out on the eve of the phase of maximal solar activity.

In our previous works (Akopova *et al.*, 1988; Dudkin *et al.*, 1990) we presented the results of neutron measurements in near-Earth orbits performed in recent years. Estimations of fast-neutron fluences at the end of the 1970s were made from nuclear emulsion data having insufficient statistical accuracy. Hence, the error in determination of fluence values reached ±50% and more. In recent years, the value of the statistical error in these investigations has been reduced to ±25%. Experimental data on fast neutrons have enabled us to evaluate the correlation of the neutron fluxes of $E_n \geq 1.0$ MeV with the SA-phase in order to verify the hypothesis that the neutrons recorded outside the spacecraft are mainly albedo neutrons and correlate with the fluxes of the GCR particles, i.e. with the SA-phase.

METHODS

The investigation of the SR neutron component was carried out both inside and on the external surface of the Cosmos-2044 biosatellite which had the following flight parameters: apogee = 294 km, perigee = 216 km, inclination ≃ 82°, flight time = 14 days (15–29 September 1989). The satellite was not oriented. Thermal and resonance neutrons were measured with the U.S. ^{6}LiF detectors through the $^6\text{Li}(n,\alpha)T$ reaction. The fluences of α particles emitted from ^{6}LiF film surfaces were recorded in plastic detectors (CR-39). Separation of thermal from resonance neutrons was made using Gd-foils which shielded the detectors. Rough estimation of fast neutrons was made with the help of the U.S. thorium (Th) foils, where the tracks of fission fragments produced by Th were recorded in mica detectors. Since disintegrations can be caused by both fast neutrons and protons, the estimation of neutron fluences by this method is complicated.

The differential fast-neutron energy spectra were measured using the recoil proton energy spectrum generated as a result of the elastic scattering of neutrons from unbounded hydrogen in the emulsion. Measurements were made only of proton tracks whose ends were located within the volume of the emulsion. Allowance should be made for the fact that, due to a significant visual error during

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Table 1. Experimental measurements of thermal neutrons on board Cosmos-2044

Detector	F_1	F_2	GC
Neutron fluence, neutr. cm^{-2}	$(2.56 \pm 0.16) \times 10^5$	$(2.23 \pm 0.16) \times 10^5$	$(0.15 \pm 0.05) \times 10^5$
Dose equiv. rate, mrem day^{-1}	0.019 ± 0.002	0.017 ± 0.002	—

Table 2. Experimental measurements of resonance neutrons on board Cosmos-2044

Detector	F_1	F_2	GC
Neutron fluence, neutr. cm^{-2}	$(0.99 \pm 1.16) \times 10^5$	$(6.8 \pm 1.3) \times 10^5$	$(4.29 \pm 0.46) \times 10^5$
Dose equiv. rate, mrem day^{-1}	0.036 ± 0.041	0.25 ± 0.04	0.15 ± 0.02

determination of the short path-length recoil protons ($E_p \leq 1.0$ MeV) and proton contamination from $^{14}N(n,p)$ reaction with emulsion nitrogen, neutron fluxes with $E_n < 1.0$ MeV were not measured in this experiment.

More detailed descriptions of measurements of neutron fluxes and spectra using fission foils and nuclear emulsion were given in Akopova *et al.* (1988) and Dudkin *et al.* (1990).

RESULTS AND DISCUSSION

Tables 1–3 present the results of measurements of thermal (Table 1), resonance (Table 2), and fast (Table 3) neutron fluxes in various locations on board Cosmos-2044. The data also include the equivalent dose estimations for each group of neutrons.

As is seen from Table 3, there is some disagreement between the U.S. and Soviet fluence values measured on the external surface of the spacecraft (about a factor of two). It may be accounted for by the fact that errors shown in the tables are exclusively statistical. The magnitude of the absolute error is significantly greater due to the ambiguity of the values of fast neutron and proton fluxes and their spectral forms and this must be borne in mind when TH fission foils are used. The estimated error is within a factor of 3.

In Table 2 there is a large difference between resonance neutron measurements from the two outside detectors (F_1 and F_2). The ground control detector (GC) gave a fluence value which was a significant fraction of that from F_2 and larger than that from F_1. The reason for the variation is not known but it is larger than statistical uncertainties would account for.

Figure 1 presents experimental differential neutron spectra measured in the flight of Cosmos-2044 with nuclear photoemulsions. These spectra are in the range from 1.0 to 10–15 MeV with a maximum, as a rule, in the 2–5 MeV neutron energy range. Neutron fluxes inside the satellite are approximately twice as high as on the external surface, i.e. somewhat greater than the values obtained in our previous investigations (Dudkin *et al.*, 1990).

According to the current concepts, the neutrons detected in near-Earth orbits originate mainly from two sources: the albedo neutrons produced in the interaction of galactic cosmic rays (GCR) with the Earth's atmosphere, and the secondary neutrons produced in the spacecraft hull and structure (local neutrons). The form of the local neutron spectra is similar to the form of the spectra produced in nuclear reactions.

The analysis of Dudkin *et al.* (1990) did not reveal any definite dependence of the neutron flux density on altitude or orbital inclination to the plane of the equator. In the present work we made the first attempt to analyse dependence of the fast neutron flux density on the phase of solar activity. If the albedo neutrons do originate mainly from the GCR particles, then neutron fluxes, especially those measured outside the satellite where the contribution of local neutrons is small, must correlate with the phase of solar activity; i.e. in the period of minimum SA, they must be more numerous than in the period of maximum solar activity, in proportion to the ratios of the GCR particle fluxes in a given orbit. Figure 2 illustrates this assumption, showing values of the fast neutron flux densities (the experimental points) measured on flights of various satellites within the

Table 3. Experimental measurements of fast neutrons on board Cosmos-2044

Detector	Outside F_1 (U.S.A.)	Outside F_2 (U.S.A.)	Outside Avg. for assemblies Nos 1, 3, 5 (U.S.S.R.)	Inside Avg. for assemblies Nos 2, 4 (U.S.S.R.)
Neutron fluence, neutr. cm^{-2}	$(8.1 \pm 1.1) \times 10^5$	$(7.0 \pm 1.1) \times 10^5$	4.0×10^5	7.74×10^5
Dose equiv. rate, mrem day^{-1}	3.5 ± 0.5	3.0 ± 0.5	1.80	3.50

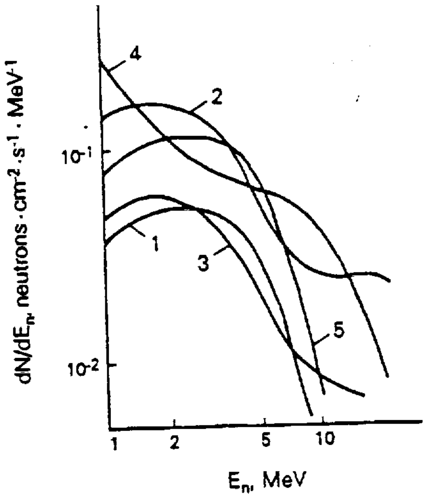

FIG. 1. Differential neutron energy spectra measured outside and inside the Soviet biosatellite Cosmos-2044. (1) Assembly No. 1 (outside); (2) assembly No. 2 (inside); (3) assembly No. 3 (outside); (4) assembly No. 4 (inside); (5) assembly No. 5 (outside).

past five years with inclination $i = 70–90°$ and $h = 200–400$ km. Curve 1 is a calculated dependence curve (Lingenfelter, 1963) of the albedo neutron flux on the SA-phase for the same orbits. Curve 2 shows a relative time dependence of the GCR particle flux. This curve is constructed on the basis of our calculations of the GCR particle fluxes in high-latitude orbits, taking into account the geomagnetic cutoff. As is seen in this figure, our assumption about correlation of the albedo neutrons with measured neutron fluxes and with the dependence of these values on SA-phase (in correlation with the GCR particle fluxes) found strong confirmation.

It appears that in future studies special attention should be given to neutron energy regions where measurements have not yet been made, or have been made with rough accuracy—less than 1.0 MeV and higher than 15 MeV.

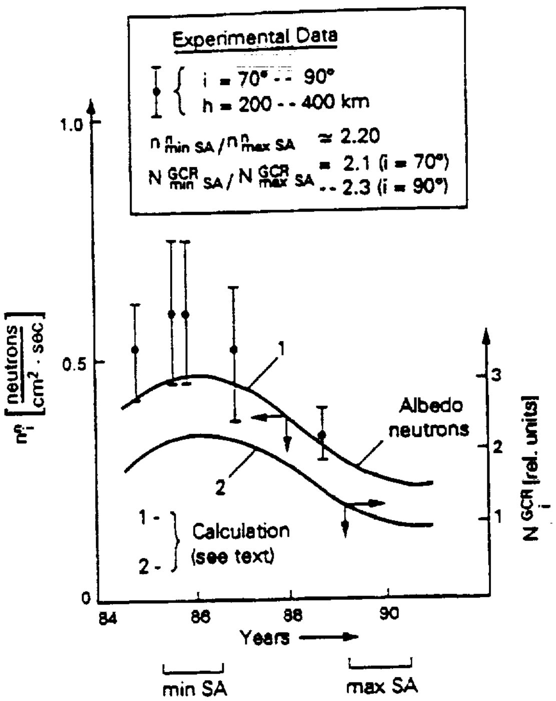

FIG. 2. The correlation of fast-neutron fluxes with solar activity (SA) phase in near-Earth orbits. Curve 1: calculated dependence of albedo neutron flux on SA cycle (Lingenfelter, 1963). Curve 2: calculated relative time dependence of GCR particle flux (this paper).

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