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APPENDIX Q

Experimental and Calculated LET Distributions in the Cosmos-2044 Biosatellite Orbit

by

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EXPERIMENTAL AND CALCULATED LET DISTRIBUTIONS IN THE COSMOS-2044 BIOSATELLITE ORBIT

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Abstract—During the flight of the Cosmos-2044 biosatellite, joint U.S.S.R.–U.S.A. investigations of different characteristics of cosmic radiation (CR) in the near-Earth environment were carried out. The U.S. dielectric track detectors CR-39 and Soviet BYa- and BR-type nuclear photo-emulsions were used as detectors. The present work shows some results of experimental measurements of linear energy transfer (LET) spectra of CR particles obtained with the use of these detectors, which were placed both inside and outside the satellite. The LET spectra measurement with plastic detectors is composed of two parts: the measurement of galactic cosmic rays (GCR) particles, and of short-range particles. The contributions of these components to the total LET distribution at various thicknesses of the shielding were analyzed and the results of these studies are presented. Calculated LET spectra in the Cosmos-2044 orbit were compared with experimental data. On the basis of experimental and calculated values of the LET spectra, absorbed and equivalent CR doses were calculated. In the shielding range of 1–1.5 g cm^{-2}, outside the spacecraft, the photo-emulsions yielded 10.3 mrad d^{-1} and 27.5 mrem d^{-1} (LET $\geq$2 MeV cm^{-1}) while the CR-39 yielded averages of 1.43 mrad d^{-1} and 13.4 mrem d^{-1} (LET $\geq$40 MeV cm^{-1}). Inside the spacecraft ($\geq$10 g cm^{-2}) the photo-emulsions yielded 8.9 mrad d^{-1} and 14.5 mrem d^{-1}.

INTRODUCTION

THE EXPERIMENTAL studies which were begun on board Cosmos-1887 (Akopova *et al.*, 1990) showed the necessity of extending investigations of the near-Earth space environment using passive detectors. The present experiments had two characteristic properties: the orbit of Cosmos-2044 was near to polar (inclination $i \simeq 82°$), and the flight period almost coincided with the maximum of solar activity (SA).

In our previous work (Akopova *et al.*, 1990) we analyzed the experimental LET distributions which were available at that time and showed some orbital dependence. It was noted that some orbits were not amply studied. Also, it was necessary to verify the conclusion that absolute values of LET distributions, and, consequently, absorbed and equivalent doses, are more strongly dependent on orbit inclination (i) than on altitude, for H = 200–400 km above the Earth, in the case of highly inclined ($i \geq 60°$) orbits.

As is apparent from the above, the main purpose of the present investigation was to obtain experimental data about LET distributions of the CR particles in a nearly polar orbit of the satellite in close to maximum SA-phase, using various passive detectors. Comparisons of experimental data for LET distributions at different shielding thicknesses are also discussed.

EXPERIMENTAL TECHNIQUE

The flight parameters of the satellite were as follows: inclination (i) $\simeq 82°$, apogee altitude = 294 km, perigee = 216 km, duration = 14 days from 15 to 29 September 1989; i.e. the flight was in the period close to the solar maximum.

The assemblies of passive detectors (plastic detectors CR-39 and BYa and BR-type nuclear photo-emulsions) were placed on the lid and the bottom of a special container with scientific equipment (outside assemblies), and inside the satellite (nuclear photo-emulsions).

After exposure and recovery, the layers of nuclear emulsions were treated by the selective-development technique (Akopova *et al.*, 1983) to ensure quenching of the accompanying background and threshold sensitivity control in a broad interval of LET. It is then possible to develop only those particle tracks for which the LET is not below threshold.

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In the experiment, BYa-type photo-emulsions were used to measure LET spectra within an interval from 12 to 3.5×10^3 MeV cm^{-1} in biological tissue with the lower limit being defined by the effective sensitivity of BYa-type emulsions. In several cases in this experiment we have succeeded in obtaining the planar fluence of the particles with LET $\simeq 2.0$ MeV cm^{-1} in tissue, using the relativistic BR-type emulsion, thereby making it possible to evaluate the doses from CR particles practically within the whole LET interval.

The CR-39 detectors have higher effective LET thresholds of track detection (~ 40 MeV cm^{-1} in tissue). In the present experiment, their assemblies were located, as a rule, next to nuclear emulsions to provide more accurate comparison of measurements made with the two types of detectors, with due account taken of the difference in LET intervals of the particles which are registered by these detectors.

Two integral LET spectra were measured in each location of the CR-39—the spectrum generated by the GCR particles which are not stopped in the detector, and the spectrum formed by short-range particles. Since the CR-39 registers particles with LET ≥ 40 MeV cm^{-1} in tissue (corresponding to the protons with energy less than ~ 12 MeV, alpha particles with energy less than ~ 65 MeV nucleon^{-1}, and particles heavier than carbon with any energy) and the satellite had an almost polar orbit, a great number of low-energy particles were stopped and registered in the detectors.

Besides the above-mentioned detectors, other investigators measured the LET spectra on board Cosmos-2044 using plastic track detectors (Beaujean *et al.*, 1990) and detectors based on AgCl (Baican *et al.*, 1990).

In this work, together with experimental studies, LET spectra for the Cosmos-2044 orbit were calculated according to two different programs developed in the U.S.S.R. and the U.S.A. The U.S. program takes into consideration the contribution to the total LET distribution of the GCR particles (protons and alpha particles only), protons of the internal radiation belt of the Earth, and the contribution from the anomalous component with the charge $Z = 1$. The program takes into account the close-to-maximum SA phase during which the flight took place, geomagnetic cut-off, and screening of particles by the Earth. However, it disregards geomagnetic disturbances. A similar program was developed in the U.S.S.R., but it included only the contribution of GCR particles from hydrogen to nickel.

To compare experimental data with calculations, LET distributions from the GCR particles with $Z > 3$ were calculated following the U.S.S.R. code, and added to the corresponding LET distributions resulting from the U.S. program. All experimental and calculated LET distributions were normalized for 2π geometry.

Table 1. Fluxes of CR particles with LET >40 MeV cm^{-1} in tissue behind small shieldings ($\delta < 2.0$ g cm^{-2}) on board the biosatellite Cosmos-2044

Particles cm^2 s sr $\times 10^{-4}$			δ
N_{ST}	N_{GCR}	N_Σ	g cm^{-2}
10.23	5.60	15.83	0.0935
25.18	2.11	27.29	0.164
12.83	2.02	14.85	0.239
10.92	1.82	12.74	0.250
5.58	1.72	7.30	0.397
2.27	2.20	4.47	1.49
1.53	1.52	3.05	1.95

N_Σ = total flux; N_{GCR} = flux of GCR particles; N_{ST} = flux of particles producing short-length tracks.

RESULTS AND DISCUSSION

Experimental data concerning the integral LET distributions on the external surface of Cosmos-2044 were obtained with two assemblies of detectors: the U.S. detectors F-1 and F-2, behind shielding thicknesses $\delta = 0.164$, 0.239, 0.397, 1.47 and 1.95 g cm^{-2} (assembly F-1) and $\delta = 0.0935$, 0.250, 1.49 and 1.97 g cm^{-2} (assembly F-2), and the Soviet detectors, $\delta = 1.2$ and 1.9 g cm^{-2}. Inside the satellite, LET spectra were measured with the Soviet detectors.

Since the orbit of the satellite was near to polar, it was assumed that the number of low-energy particles with various charges was great and this would cause a difference in fluxes of particles registered on the external surface of the satellite even behind shieldings slightly differing in thickness. This premise can be confirmed by the data in Table 1 which exhibit the values of fluxes of particles measured with the U.S. detectors behind small shielding with $\delta < 2$ g cm^{-2} at LET >40 MeV cm^{-1} in tissue on board Cosmos 2044. Shielding with thickness under 1.5 g cm^{-2} is made of plastic; at $\delta > 1.5$ g cm^{-2} shielding is composed of 0.59 g cm^{-2} stainless steel, 0.120 g cm^{-2} is

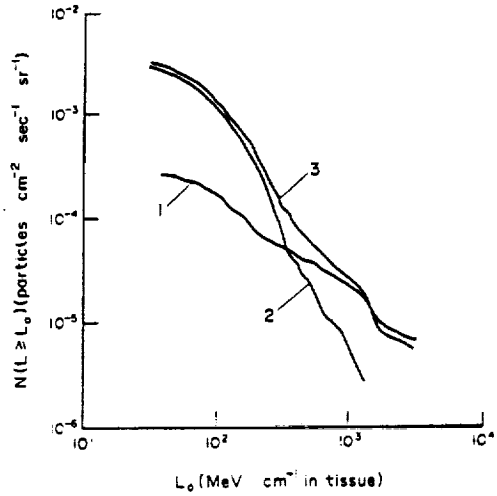

FIG. 1. Integral LET spectrum measured on board Cosmos-2044 with CR-39 track detectors behind $\delta = 0.164$ g cm^{-2}.

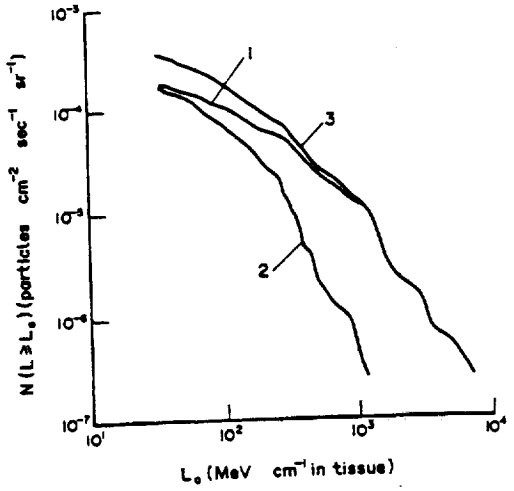

FIG. 2. Integral LET spectrum measured on board Cosmos-2044 with CR-39 track detectors behind $\delta = 1.95$ g cm^{-2}.

nuclear emulsion and the rest is plastic. Flux values corresponding to the smallest thicknesses in the F-1 and F-2 containers (0.164 and 0.0935 g cm^{-2}) show that there was a significant difference in orientation or external shielding between the two.

Moreover, this hypothesis is clearly verified by the data presented in Figs 1 and 2. Figure 1 shows LET distributions measured with CR-39 on the external surface of the satellite behind shielding with $\delta = 0.164$ g cm^{-2}; Fig. 2 shows the analogous distributions at $\delta = 1.95$ g cm^{-2}. In these figures, curves 1 denote LET spectra formed by the GCR particles; curves 2, the LET spectra of low-energy, short-range particles; and curves 3, their total. Comparing the curves from Figs 1 and 2 and analyzing similar LET distributions measured in this experiment behind other shieldings and at $L_0 > 40$ MeV cm^{-1}, it becomes evident that at $\delta < 1.0$ g cm^{-2} the main contributors

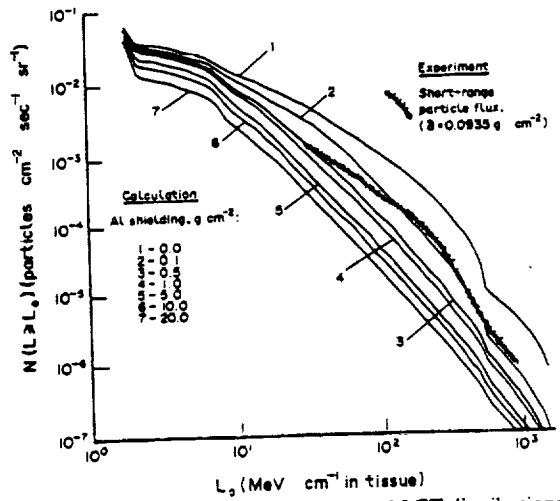

FIG. 3. Comparison of calculated integral LET distributions from trapped protons and GCRs of $Z < 3$ (curves 1–7) with the experimental LET spectrum produced by short-range particles in the flight of Cosmos-2044.

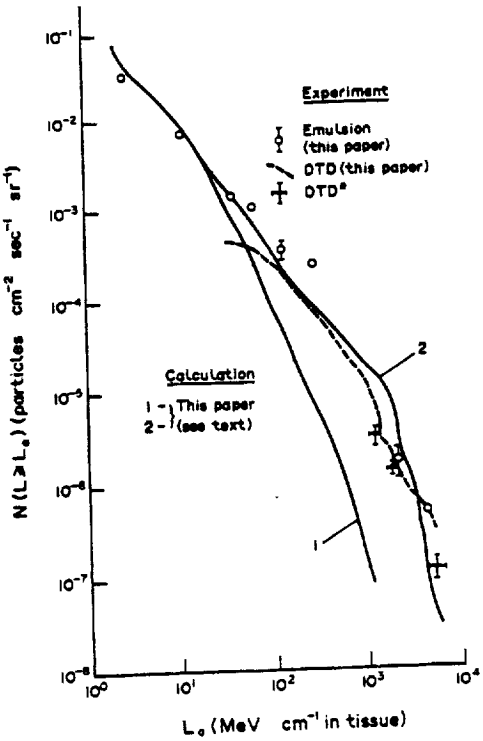

FIG. 4. Comparison of calculated and experimental LET distributions in investigations on board Cosmos-2044 behind small shielding ($\delta = 1.0$–1.5 g cm^{-2})—external assemblies. [*(DTD): Beaujean *et al.*, 1990.]

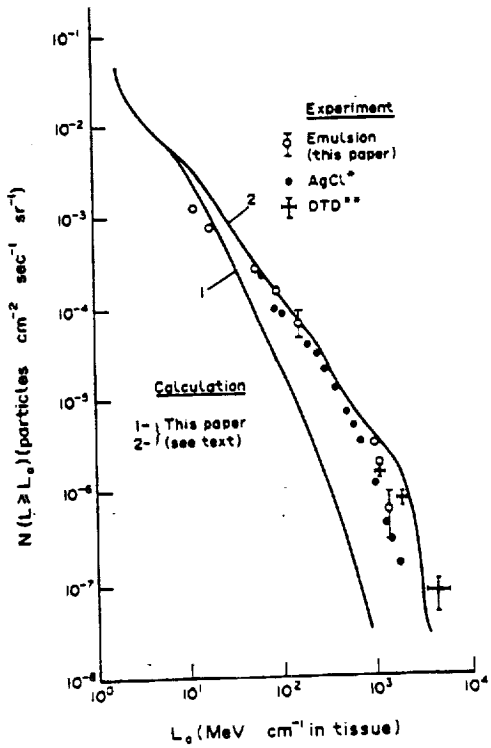

FIG. 5. Comparison of calculated and experimental LET distributions in investigations on board Cosmos-2044 (behind shielding of $\delta > 10$ g cm^{-2})—internal assemblies. [*(AgCl): Baican *et al.*, 1990; **(DTD): Beaujean *et al.*, 1990.]

to the LET spectra are the short-range particles (under $L_0 = 200$–300 MeV cm^{-1}), and with an increase of L_0 this role passes to the GCR particles. At $\delta > 1.0$ g cm^{-2}, in practically the whole LET range of particles registered with CR-39, the bulk of the contribution belongs to the GCR particles.

Figures 3–5 demonstrate results of comparison of the experimental and calculated data. Comparison of LET distributions, calculated according to the U.S. code (without accounting for the contribution of the GCR particles with $Z > 3$) and the experimental LET spectrum, produced by low-energy particles with a residual path $< 1200\ \mu$m in CR-39 plastic (Fig. 3) with shielding $\delta \simeq 0.1$ g cm^{-2}, revealed a satisfactory agreement in the range of L_0 from 100 to 1000 MeV cm^{-1}. At $L_0 < 100$ MeV cm^{-1} the calculated curve surpasses the experimental one by approximately a factor of two, which may possibly be explained by the contribution to the total distribution from fast particles which have a residual path $> 1200\ \mu$m in the plastic detector.

Figures 4 and 5 show the comparison of experimental and calculated data with respect to LET distributions on the external surface of the satellite ($\delta \simeq 1.0$–1.5 g cm^{-2}) (Fig. 4) and inside it ($\delta > 10.0$ g cm^{-2}) (Fig. 5). The figures also include, for comparison, data obtained by other investigators during the flight of the satellite. Calculated curves in Figs 4 and 5 were constructed following the above-mentioned techniques (curve 1: the U.S. code, curve 2: the sum of curve 1 and the LET distribution contributed by GCR particles with $Z > 3$, calculated by the Soviet program). Explanations of the experimental data are given in the corresponding figures. Results of experimental measurements made with different detectors (nuclear emulsions, plastic detectors, AgCl detectors) should be noted as to their satisfactory conformity with total calculated integral LET distributions. Differences in calculated and experimental data values at $L_0 \gtrsim 10^3$ MeV cm^{-1}, apart from experimental errors, can also be explained by rather great statistical errors in calculations by the Monte Carlo method.

LET spectra from the present experiment were compared with results of our previous investigations of LET spectra (Akopova *et al.*, 1990) for various inclinations of the orbit (i) from 60 to 83°. The Soviet satellite Cosmos-1757, as well as Cosmos-2044, had an inclination $i = 82°$. However, in the first case, the magnitude of the values of LET spectra flux was two- to three-fold higher compared with the present data. In our opinion, there are three factors which may be involved in this phenomenon. Firstly, Cosmos-1757 was in orbit in the period of deep SA-minimum when fluxes of the GCR particles in these orbits increase 1.5–2.0 times compared with the SA-maximum, when Cosmos-2044 was launched. Secondly, the shielding of detectors used for LET distribution measurements presented in Fig. 4 ($\delta = 1.0$–1.5 g cm^{-2}) was almost an order of magnitude greater than in the experiment on board Cosmos-1757 ($\delta = 0.1$–0.2 g cm^{-2}). This conclusion is also confirmed by measurements which were made in this experiment with plastic detectors behind various shieldings (Table 1). Indeed, the difference in fluxes behind $\delta = 0.164$ g cm^{-2} and $\delta = 1.95$ g cm^{-2} is almost equal to an order of magnitude. This difference is observed over the whole interval of LET which was registered by the plastic detectors. And, thirdly, in our work (Akopova *et al.*, 1990) we took into account the fact that Cosmos-1757 was oriented and detectors were located on the external surface of the satellite in the spot where, to quote Akopova *et al.* (1989), the normalizing geometric factor, allowing for the spatial angle at which a CR particle penetrates a detector, was 4.1 against 6.28 in the flight of Cosmos-2044. Each of these three factors affected an increase of the fluence of particles in the experiment on board Cosmos-1757 compared with Cosmos-2044.

The data contained in the integral LET spectra were used to estimate the radiation environment inside and outside the biological satellite. Values of absorbed and equivalent doses were calculated using

Table 2. Values of absorbed and equivalent doses obtained from experimental data and calculated values of LET spectra on board Cosmos-2044

		Outside ($\delta = 1.0$–1.5 g cm^{-2})		Inside ($\delta \geq 10$ g cm^{2})	
	Doses / Data	D, mrad day^{-1}	H, mrem day^{-1}	D, mrad day^{-1}	H, mrem day^{-1}
1	2	3	4	5	6
LET ≥ 2.0 [MeV cm^{-1}]	Calculation	9.30 ($\delta = 1.0$)	23.6 ($\delta = 1.0$)	4.40 ($\delta = 20.0$)	9.14 ($\delta = 20.0$)
	Experiment (NPE)*	10.30 ($\delta = 1.2$)	27.5 ($\delta = 1.2$)	8.9 ($\delta = 10.0$)	14.5 ($\delta = 10.0$)
LET ≥ 40.0 [MeV cm^{-1}]	Calculation	1.38 ($\delta = 1.0$)	16.8 ($\delta = 1.0$)	—	—
	Experiment (CR-39)	1.32 ($\delta = 1.47$)	12.8 ($\delta = 1.47$)	—	—
		1.53 ($\delta = 1.49$)	13.9 ($\delta = 1.49$)	—	—

*NPE: nuclear photo-emulsion method.

Table 3. Calculated components of total absorbed dose (mrad day^{-1}) in the orbit of Cosmos-2044

No.	Sources	h, km	(δ, g cm^{-2}) 1.0	1.5	2.0	10	20
1.	Electrons of RBE*	200	52.6	10.7	1.25	0.12	—
		300	72.0	20.0	1.73	0.17	—
2.	Protons of RBE*	200	0.06	0.05	0.04	—	—
		300	3.71	3.20	2.94	1.11	0.52
3.	GCR	200	6.64	6.58	6.52	5.28	4.19
		300	6.71	6.65	6.58	5.34	4.29
4.	2 + 3	200	6.70	6.63	6.62	5.30	4.20
		300	10.4	9.8	9.4	6.45	4.8
5.	1 + 4	200	59.6	17.3	7.8	5.4	4.2
		300	82.4	30.0	11.2	6.6	4.8

*RBE: radiation belts of Earth.

total flux curves (curves 3) in Figs 4 and 5 (Table 2, line 1). The table lists the values of doses obtained from the experimental data (nuclear emulsions) covering the whole interval of LET (Table 2, line 2), as compared with the plastic detector interval of $L_0 \geq 40$ MeV cm^{-1} in tissue (Table 2, calculation: line 3; experiment: line 4).

The dose values in Table 2 do not include the contribution of electrons which, as it was shown in Akatov *et al.* (1990), at small shieldings can reach 70–90% of a total dose. In view of this, the dose values for maximal SA would be: $D(\delta = 1.0) = 69.3$ mrad day^{-1} and $H(\delta = 1.0) = 83.6$ mrem day^{-1} and $D(\delta = 1.2) = 27.8$ mrad day^{-1} and $H(\delta = 1.2) = 48.0$ mrem day^{-1}. Contribution of electrons at $\delta > 10$ g cm^{-2} is negligibly small. The dose values calculated for positions inside the satellite are approximate due to the absence of information about mass distribution in the shielding which screened these detectors.

The techniques described in Akatov *et al.* (1990), were used to calculate dose values for the orbit of Cosmos-2044. Results of these calculations, presented in Table 3, are in satisfactory agreement with the experimental data in Table 2.

CONCLUSIONS

(1) In orbits with a large angle of inclination, a strong dependence of the CR particle fluence on the shielding thickness is observed in a range from 0.1 to 2.0 g cm^{-2}. This has been confirmed by previous investigations.

(2) For similar satellite orbits, the magnitude of total fluence is a function of the measurement period, i.e. on SA-phase.

(3) The LET spectra measured by different methods (nuclear emulsions, plastic detectors, AgCl detectors) are in satisfactory agreement within overlapping intervals of registration.

(4) Calculated estimations in an undisturbed magnetic field allow a satisfactory prediction of the results of experiments.

Future investigations should be aimed at quantification of total fluence of all particles including relativistic protons.

It is also necessary to give more detailed study to LET spectra with a sufficiently high experimental statistical accuracy in the area of very low (< 10 MeV cm^{-1}) and very high ($> 5 \times 10^3$ MeV cm^{-1}) LET values.

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