19950119506

515-93

A 1.6039

N95- 25926

APPENDIX N

Linear Energy Transfer (LET) Spectra of Cosmic Radiation in Low Earth Orbit

by

A.B. Akopova, N.V. Magradze, V.E. Dudkin, E.E. Kovalev,
Yu.V. Potapov, E.V. Benton, A.L. Frank, E.R. Benton
T.A. Parnell and J.W. Watts, Jr.

Nucl. Tracks Radiat. Meas., Vol. 17, No. 2, pp. 93–97, 1990
Int. J. Radiat. Appl. Instrum., Part D
Printed in Great Britain

0735-245X/90 \$3.00 + .00
Pergamon Press plc

LINEAR ENERGY TRANSFER (LET) SPECTRA OF COSMIC RADIATION IN LOW EARTH ORBIT

A. B. AKOPOVA,* N. V. MAGRADZE,* V. E. DUDKIN,† E. E. KOVALEV,† YU. V. POTAPOV,† E. V. BENTON,‡ A. L. FRANK,‡ E. R. BENTON,‡ T. A. PARNELL|| and J. W. WATTS JR||

*Yerevan Institute of Physics, Yerevan, U.S.S.R.; †Institute of Biomedical Problems of the Ministry of Public Health of the U.S.S.R., Moscow 123007, U.S.S.R.; ‡University of San Francisco,§ CA 94117, U.S.A. and ||NASA Marshall Spaceflight Center, Huntsville, AL 35812, U.S.A.

(*Received* 30 *May* 1989)

Abstract—Integral linear energy transfer (LET) spectra of cosmic radiation (CR) particles were measured on five Cosmos series spacecraft in low Earth orbit (LEO). Particular emphasis is placed on results of the Cosmos 1887 biosatellite which carried a set of joint U.S.S.R.–U.S.A. radiation experiments involving passive detectors that included thermoluminescent detectors (TLDs), plastic nuclear track detectors (PNTDs), fission foils, nuclear photo-emulsions, etc. which were located both inside and outside the spacecraft. Measured LET spectra are compared with those theoretically calculated. Results show that there is some dependence of LET spectra on orbital parameters. The results are used to estimate the CR quality factor (QF) for the Cosmos 1887 mission.

INTRODUCTION

THE INTEGRAL linear energy transfer (LET) spectra are important for characterizing cosmic radiation (CR) because they can be used to estimate the absorbed and equivalent particle dose and to evaluate the respective quality factors. Earlier, the integral LET distributions were measured in the following works: Petrov *et al.* (1975), Benton (1983, 1986), and Akopova *et al.* (1985, 1986, 1987, 1988). As a rule, these investigations used passive detectors (plates, emulsions) which permitted measurements in a restricted LET interval. In some investigations (e.g. Akopova *et al.*, 1987, 1988; Heinrich, 1977; Heinrich and Baer, 1984), the LET distributions were calculated as a function of shielding. In all of these theoretical studies, only the galactic cosmic ray particles were regarded as sources of cosmic radiation.

This paper presents the results of a recent experimental and calculational study carried out by the authors. Particular attention was paid to comparing results obtained by various experimental techniques, and to finding the laws which govern the dependence of the forms of the integral LET distributions on orbital parameters. Measurements were taken in free space (behind very thin shielding), and inside the spacecraft where the mean thickness of the shielding of detectors reached tens of g cm^{-2}. The contribution of trapped protons and electrons is also taken into account in the theoretical calculations.

EXPERIMENTAL TECHNIQUES

The use of LET spectral data is necessary for appraising the radiation environment inside spacecraft. Previous measurements were made on board Cosmos 782, 936, and 1129 using an electron spectrometer, nuclear emulsions, and plastic detectors. These results have been presented by Benton (1986) together with dosimetric measurements and LET spectra obtained on board some of the U.S. Shuttle flights.

The current work presents the results obtained on board five Cosmos-type satellites using two types of detectors, namely, nuclear photo-emulsions (NPE) and solid state nuclear track detectors (SSNTDs). The NPE assemblies containing 200 μm thick BR- and BYa-type emulsions wrapped with light-tight paper and aluminized Lavsan were placed either in instrument modules outside the spacecraft or inside the spacecraft. After exposure and recovery, each layer of emulsion assembly was treated by the selective-development technique which makes it possible to control the NPE layer threshold sensitivity in a broad interval of LET (see Akopova *et al.*, 1983). The emulsion threshold sensitivity control is based on the introduction of Br^- ions into an exposed emulsion layer by diffusion. The Br^- ions emanated from BR-type layers (emitters) glued to either of the surfaces of the exposed layer that had been irradiated beforehand with blue–violet light. The Br^- ion generation and diffusion from the emitters to the exposed

§USF work partially supported by NASA–Ames Research Center Grant No. NCC2-521, NASA–MSFC Grant No. NAG8-071 and NASA–JSC Grant No. NAG9-235.

layers gives rise to a negative bromine barrier around the latent image centers, thereby increasing the induction periods of developing centers. The ability of the centers to be developed depends, then, upon the ratio of the height of the barrier restricting the arrival of electrons at the centers to the depth of the potential well in which the electrons are captured. Thus, controlling the NPE threshold sensitivity is based on different degrees of dispersion of the latent image centers produced by particles with different LET values. The threshold sensitivity of the exposed layer permits only those particle tracks to be developed for which the LET is at least equal to some threshold LET value. Therefore, the technique of finding the planar fluence of the particles with $LET \geq LET_{thresh}$ does not require the track parameters to be measured but is reduced to counting the number of the tracks traversing a particular section of an NPE surface. Calibration of the technique was achieved by exposing NPEs to particle beams of well-defined LETs.

We used BYa-type emulsion which permits the integral LET spectra to be measured within an interval from 12 to $\sim 10^4$ MeV cm^{-1} of biological tissue (water), with the lower limit (~ 12 MeV cm^{-1}) being defined by the effective sensitivity of the BYa-type emulsion. To obtain a complete LET distribution, we sometimes used the relativistic BR-type emulsion, thereby making it possible (to within a large microscope scanning error) to find the planar fluence of cosmic radiation particles at small LET values (the LET of relativistic protons in tissue is $\simeq 2.0$ MeV cm^{-1}. The error in counting these tracks at $LET_{thresh} \simeq 2.0$ MeV cm^{-1} increases (i) due to a high track exposure of the detectors (the satellite flights lasted, as a rule, for more than 10 days) and (ii) because the operator can easily overlook tracks of relativistic protons (low grain densities).

The second technique for finding the LET distributions is based on the use of SSNTDs of the CR-39, CN, and polycarbonate type, whose effective LET thresholds of track detection are 40, 1000, and 2250 MeV cm^{-1} in water, respectively. CN and Lexan were used in earlier measurements (the ASTP, Skylab, and Apollo 17 missions). During later flights, including the 24 initial flights of the U.S. Shuttle, use was made of SSNTDs of the CR-39, polycarbonate, and polystyrene types which were subjected after the flights to the standard NaOH etching with 6.25 N at 70°C. Preliminary scanning showed that the density of the tracks detected in polycarbonate and polystyrene was very low compared with that of CR-39. The method for using SSNTD to find the LET spectra is described in detail by Henke and Benton (1974).

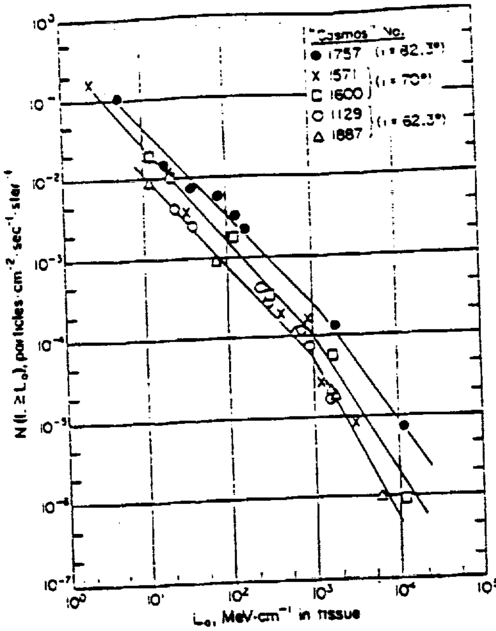

FIG. 1. The experimental LET spectra obtained from different satellites of the Cosmos series at $\delta \leqslant 1.0$ g cm^{-2} by the NPE method.

RESULTS AND DISCUSSION

In Fig. 1 are shown the results of LET spectra measurements by the NPE method. The NPE assemblies were placed in external instrument modules on spacecraft with different orbital parameters (see Table 1). For these external assemblies, the shielding thickness may be considered not to exceed ~ 1.0 g cm^{-1}. The shielding of the detectors by the satellite bodies and by the Earth and the geometry of the exposures were approximately the same for all of the flights.

The integral LET spectra shown in Fig. 1 have been obtained mainly with the BYa-type emulsions, so the distribution ranged from 12 to 1.5×10^4 MeV cm^{-1} of tissue. From Fig. 1 it is seen that the values of the integral spectrum at the lower LET values were

Table 1. The flight parameters of the satellites on which the NPE assemblies were exposed

Cosmos series satellite	Exposure time	Apogee/ perigee (km)	Orbital inclination	Solar activity period
1129	Sep. 25–Oct. 10, 1979	406/226	62.8°	max
1571	Jun. 11–Jun. 26, 1984	420/355	70°	min
1600	Sep. 27–Oct. 10, 1984	420/354	70°	min
1757	Jun. 11–Jun. 19, 1986	252/189	92.3°	min
1887	Sep. 29–Oct. 12, 1987	406/224	62.8°	min

obtained using the relativistic BR-type emulsion on board Cosmos 1571 and 1757 only. In order to make the presentation of data clear, the experimental points have been unified by a solid line of the approximate form $\alpha \cdot L^{-\beta}$, where L is LET in tissue: α and β are constants.

The following preliminary conclusions may be drawn from the curves presented in Fig. 1:

(1) experimental values of the integral LET distributions are very close to each other for the satellites with similar orbital parameters (Cosmos 1129 and 1887, Cosmos 1571 and 1600);

(2) effects of solar activity are insignificant (the values of the spectra obtained from Cosmos 1129 and 1887 are alike);

(3) slopes of the integral spectra obtained from satellites differing in orbit inclination, i, are similar to each other (the spectral index β of all three spectra for the LET ranging from 10 to 10^3 MeV cm^{-1} of tissue is the same within deviations of $\pm 15\%$);

(4) values of the LET spectra seem to rise with increasing orbit inclination at $i \geq 60°$;

(5) the integral LET spectrum obtained from Cosmos 1757 is higher than all the other spectra despite the fact that the particular orbit was 1.5 times lower in altitude than the other orbits.

A preliminary conclusion may be drawn from comparing these results with the results of Benton (1983): in the case of highly inclined orbits ($i > 60°$) the absolute flux values of the LET spectra and, hence, of the absorbed and equivalent doses, depend more strongly on the orbit inclination (i) than on altitude (h), whereas in the case of low inclination orbits ($i < 60°$) their flux values depend more strongly on altitude than on orbit inclination. Further measurements in high inclination orbits are needed for verification.

The observation can be understood by considering how the various contributions to LET vary with orbital altitude and inclination. Above 60° inclination at low altitudes galactic cosmic rays dominate the LET. The GCR is not strongly modulated by altitude at the altitudes considered, but is modulated by the rigidity cut-off, which is a function of geomagnetic latitude. For lower inclination orbits, trapped particles are more important. Trapped particles are strongly modulated with altitude, but not so strongly modulated with inclination.

Figures 2 and 3 present the integral LET spectra obtained from Cosmos 1887 by the NPE and SSNTD methods. The respective values for the external assemblies are shown in Fig. 2, while the data obtained inside the satellite are presented in Fig. 3. The two figures also show the calculated results obtained by the method described in Akopova *et al.* (1987) behind shielding thickness $\delta = 1.0$ g cm^{-2} (Fig. 2) and $\delta = 1.0$, 10.0, and 20.0 g cm^{-2} (Fig. 3). The calculations were made for the Cosmos 1887 orbit parameters. The number of histories is 10^4.

A method for calculating the integral LET spectrum of galactic cosmic ray particles is described in Akopova *et al.* (1987). Our work is the first to include both the galactic cosmic ray particles and the radiation belt protons in the region of the South Atlantic Anomaly (SAA). The LET distributions from the protons were determined from the energy spectra of radiation belt protons calculated using the Sawyer

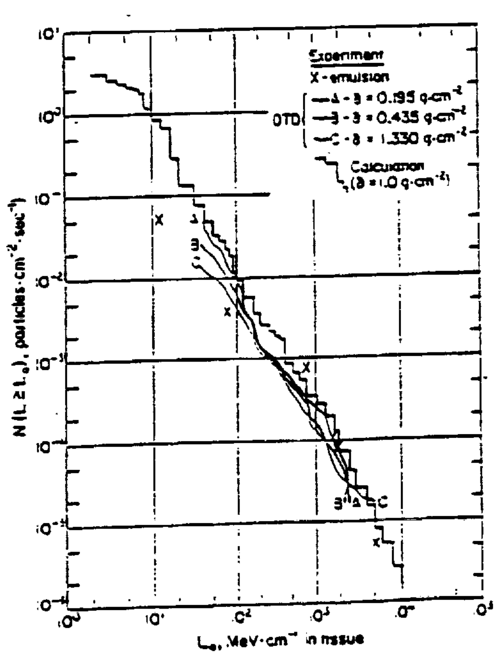

FIG. 2. The experimental and calculated integral LET spectra obtained from Cosmos 1887 (outside the satellite).

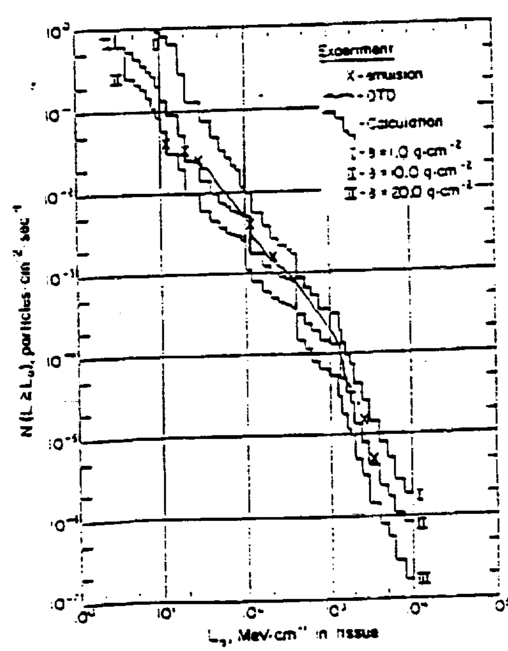

FIG. 3. The experimental and calculated integral LET spectra obtained from Cosmos 1887 (inside the satellite).

and Vette (1976) AP8MIN trapped proton environment. Figures 2 and 3 present the total calculated LET distributions (the histograms).

The following preliminary conclusions may be drawn from analyzing the curves presented in Figs 2 and 3.

(1) the experimental results obtained by the NPE and SSNTD methods are similar in the region where the LET spectra overlap, thereby indicating that both methods may be used in studies of this type. The best agreement between the experiments was obtained from measurements made inside the spacecraft (Fig. 3);

(2) the experimental and calculated data are also in satisfactory agreement with each other. The fact that the experimental and calculated curves shown in Fig. 3 are about the same at $\delta = 10.0\ \mathrm{g\ cm^{-2}}$ seems to imply that the mean thickness of the shielding of the detectors was close to $\sim 10.0\ \mathrm{g\ cm^{-2}}$;

(3) it should be noted that the calculated and experimental data disagree at small shielding thicknesses ($\delta \leqslant 1.0\ \mathrm{g\ cm^{-2}}$) especially for the lower LET values (Fig. 2). As shown by a relevant analysis, 85–95% of the spectrum at the LET values from ~ 10 to 100 MeV $\mathrm{cm^{-1}}$ of tissue is due to the radiation belt protons (on assumption of the isotropic proton distribution in the SAA). The trapped proton calculations therefore seem to be less consistent with the experiment than the GCR calculations. However, the experimental points are scanty in the given LET range, a fact that should be taken into account in further studies;

(4) the results of calculating the integral LET spectra from galactic cosmic ray particles behind shielding from 0 to 50 $\mathrm{g\ cm^{-2}}$ were previously done by Heinrich (1977) and Heinrich and Baer (1984), where the following two main conclusions were reached, namely, (i) the spectral slopes change at $\sim 10^3\ \mathrm{MeV\ cm^{-1}}$ for all shielding thicknesses and (ii) the spectral slope angle is independent of shielding thickness for LET $> 10^3\ \mathrm{MeV\ cm^{-1}}$ and depends upon the latter (increases with thickness) for LET $\leqslant 10^3\ \mathrm{MeV\ cm^{-1}}$. Our studies have confirmed the first conclusion completely. Our calculations have shown that the slope angles of the LET spectra are alike in the range of LET $\geq 10^3\ \mathrm{MeV\ cm^{-1}}$ where the value of the spectrum is defined solely by the galactic cosmic ray particles (mainly, by Fe nuclei). The contribution of radiation belt protons to the total integral LET distribution decreases with increasing shielding thickness. The opposing dependencies lead to the near-independence of the slope angle of the total GCR and proton distributions on shielding for shielding thicknesses up to at least 20 $\mathrm{g\ cm^{-2}}$, for LET $\leq 10^3\ \mathrm{MeV\ cm^{-1}}$.

We have used our experimental and calculated LET distribution data to estimate the mean quality factor (QF) in the Cosmos 1887 orbit behind shieldings of 1.0 and 10 $\mathrm{g\ cm^{-2}}$. This applies to particles having LET in tissue from 2.0 to $10^4\ \mathrm{MeV\ cm^{-1}}$. We used the AE8MIN environment (Teague and Vette, 1972) to calculate the doses from the radiation belt electrons in the Cosmos 1887 orbit behind a 1.0 $\mathrm{g\ cm^{-2}}$ shielding. In the case of a 10.0 $\mathrm{g\ cm^{-2}}$ shielding, the electrons were neglected because of their small contribution to the total dose. We have found their QF to be 1.3 ± 0.2 and 1.7 ± 0.2 at 1.0 and 10.0 $\mathrm{g\ cm^{-2}}$, respectively. These values are in good agreement with the calculated and experimental data published elsewhere (Kovalev *et al.*, 1979; Curtis *et al.*, 1986).

In future studies, particular attention should be paid to detection of spectra at small LET values. In addition, knowing the distribution of the spacecraft shielding is extremely important, as this information will allow a more correct comparison between the calculated and experimental data.

REFERENCES

Akopova A. B., Dudkin V. E., Karpov O. N., Melkumyan L. V., Potapov Yu. V. and Rshtuni Sh. B. (1986) Determination of cosmic radiation characteristics aboard Salyut-7 orbital station. *Nucl. Tracks Radiat. Meas.* 12, 489–491.

Akopova A. B., Dudkin V. E., Karpov O. N., Melkumyan L. V., Potapov Yu. V. and Rshtuni Sh. B. (1988) Determination of cosmic radiation characteristics on board Salyut-7 orbital station. *Kosm. Issled.* XXVI, 162–165.

Akopova A. B., Dudkin V. E., Kovalev E. E., Magradze N. V. and Potapov Yu. V. (1987) Linear energy transfer spectra of cosmic radiation aboard Cosmos-1129 artificial satellite. *Radiat. Prot. Dosim.* 18, 153–156.

Akopova A. B., Magradze N. V., Moiseenko A. A., Muradyan S. H. and Ovnanyan K. M. (1983) Method of selective development of thick-layer nuclear emulsions. Preprint EFI-671 (61)-83 of the Yerevan Physical Institute, Yerevan, U.S.S.R.

Akopova A. B., Vikhrov A. I., Dudkin V. E., Magradze N. V., Moiseenko A. A., Muradyan A. H., Ovnanyan K. M. and Potapov Yu. V. (1985) Measuring the linear energy transfer spectra of cosmic radiation aboard the Cosmos-1129 satellite. *Kosm. Issled.* XXIII, 479–481.

Benton E. V. (1983) Dosimetric radiation measurements in space. *Nucl. Tracks Radiat. Meas.* 7, 1.

Benton E. V. (1986) Summary of radiation dosimetry results on U.S. and Soviet manned spacecraft. XXVI COSPAR Meeting, Toulouse. June/July. 1986. COSPAR Paper VII, p. 7.

Curtis S. P., Atwell W., Beever R. and Hardy A. (1986) Radiation environments and absorbed dose estimations on manned space missions. *Adv. Space Res.* 6, 269–274.

Heinrich W. (1977) Calculation of LET-spectra of heavy cosmic ray nuclei at various absorbed depths. *Radiat. Effects* 33, 143–148.

Heinrich W. and Baer J. (1984) The radiation situation in space and its modification by geomagnetic field and shieldings. *Adv. Space Res.* 4, 133–142.

Henke R. P. and Benton E. V. (1974) Heavy cosmic ray measurement on Apollo 16 and 17 missions. Results of the HZE Dosimeter Experiment. University of San Francisco, CA 94117. Technical Report No. 34.

186

Kovalev E. E., Bryskin V. N., Vinogradov Yu. A., Dudkin V. E., Kozlova S. B., Marenny A. M., Markelov V. V., Nefedov N. A., Potapov Yu. V., Redko V. I. and Hovanskaya A. I. (1979) Measuring the linear energy transfer spectra of cosmic radiation on board Cosmos-782 satellite. *Kosm. Issled.* XVII, 634–636.

Petrov V. M., Akatov Yu. A., Kozlova S. B., Markelov V. V., Redko V. I., Smirenny L. N., Khorsev A. V. and Chernych I. V. (1975) The study of the radiation environment in near-Earth space. *Space Res.* 13, 129.

Sawyer D. M. and Vette J. T. (1976) AP-8 trapped proton environment for solar maximum and solar minimum. NSSDS/WDS-A-R and S-76-06. National Space Science Data Center, NASA/Goddard Space Center, Greenbelt, MD.

Teague M. J. and Vette J. T. (1972) The inner ion electron model AE-5. NSSDS 72-10. National Space Science Data Center, NASA/Goddard Space Center, Greenbelt, MD, September 1972.