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LET SPECTRA MEASUREMENTS OF CHARGED PARTICLES IN THE P0006 EXPERIMENT ON LDEF*

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SUMMARY

Measurements are under way of the charged particle radiation environment of the LDEF satellite using stacks of plastic nuclear track detectors (PNTDs) placed in different locations of the satellite. In the initial work the charge, energy and linear energy transfer (LET) spectra of charged particles were measured with CR-39 double layer PNTDs located on the west side of the satellite (Experiment P0006). Primary and secondary stopping heavy ions were measured separately from the more energetic particles. Both trapped and galactic cosmic ray (GCR) particles are included, with the latter component being dominated by relativistic iron particles.

The results from the P0006 experiment will be compared with similar measurements in other locations on LDEF with different orientation and shielding conditions.

The remarkably detailed investigation of the charged particle radiation environment of the LDEF satellite will lead to a better understanding of the radiation environment of the Space Station Freedom. It will enable more accurate prediction of single event upsets (SEUs) in microelectronics and, especially, more accurate assessment of the risk — contributed by different components of the radiation field (GCRs, trapped protons, secondaries and heavy recoils, etc.) — to the health and safety of crew members.

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INTRODUCTION

Cosmic ray and trapped charged particles contribute to the health risk of crew members of manned space flight and produce single event upsets (SEUs) in microelectronics in space. Risk estimations are usually based on measurements of the charged particle radiation environment external to the spacecraft in space and using transport codes to calculate the radiation environment internal to the spacecraft. Measurements of the spacecraft radiation environment are also essential to validate transport codes based on three-dimensional mass models, and in some cases to provide direct data for risk estimation. Plastic nuclear track detectors (PNTDs) have been widely used to measure both external (charge and energy spectra of GCRs and trapped particles) and internal (LET spectra, charge and energy spectra of secondary particles) charged particle radiation environments.

PNTDs exposed as part of the LDEF P0006 experiment "Linear Energy Transfer Spectrum Measurement" are being analyzed in order to measure the charged particle radiation environment of the LDEF. Measurements are being made of the charge, energy and linear energy transfer (LET) spectra as functions of shielding and detector location and orientation on the LDEF. LET spectra measured from the P0006 experiment and from other LDEF experiments designed to measure the charged particle radiation environment of LDEF constitute a unique set of measurements not likely to be duplicated in the foreseeable future. Results from P0006 will be compared to other measurements made aboard the LDEF satellite and with model calculations.[1,2]

EXPERIMENTS

The P0006 experiment was located in the F2 tray near the trailing edge of the LDEF satellite. Tray F2 also contained the P0004 "Seeds" experiment. The P0006 consisted of nine modular stacks of passive ionizing radiation detectors assembled into a stack with detector layers oriented parallel to the plane of the experiment tray. Four side stack modules were placed on the sides of the main stack. The configuration of the P0006 is shown in Figure 1. Each detector module contained a variety of passive ionizing radiation detectors and a layer of aluminum separator. The P0006 stack was 4.5" by 4.5" square and 4.0" high. It was sealed in an aluminum canister and bolted to the F2 tray. Air pressure was maintained within the canister over the duration of the mission.

Measurements of the LET spectrum as a function of shielding and detector orientation are under way. In addition, detailed measurements of the high LET tail region of the LET spectra are being made. Preliminary results of these measurements are presented below.

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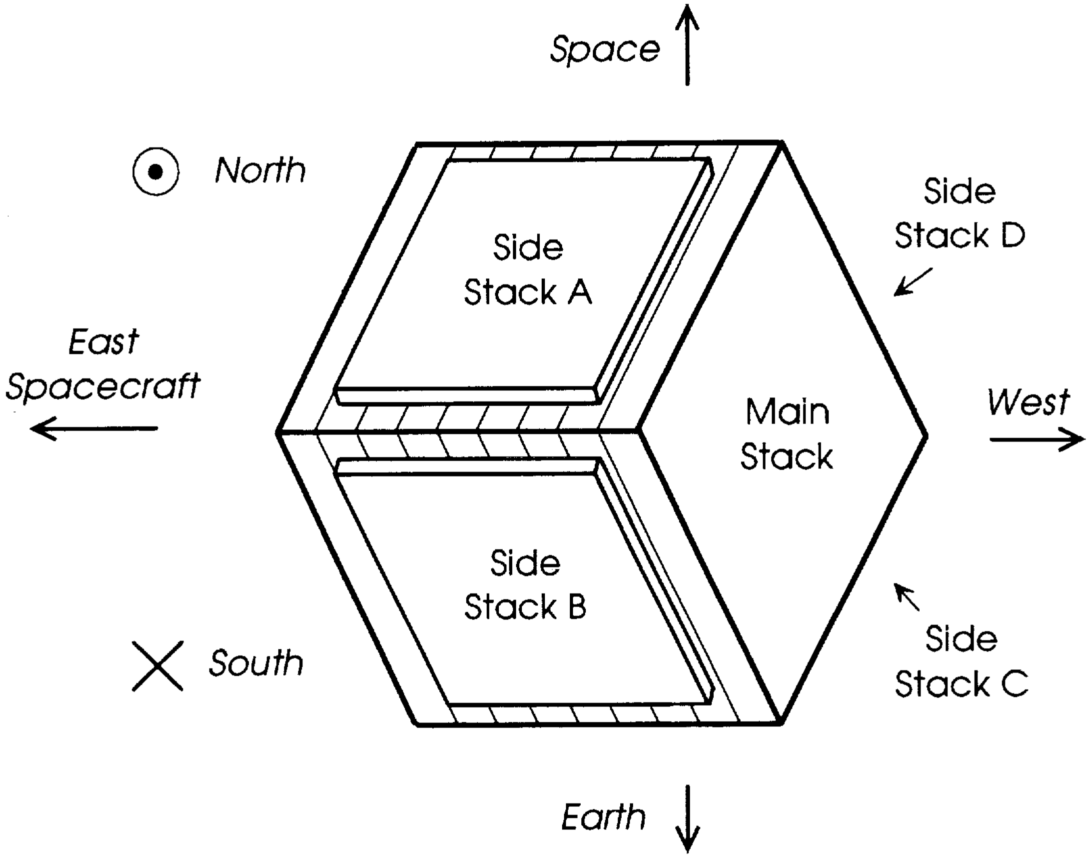

Figure 1: Configuration of LDEF P0006.

RESULTS

Dependence of LET Spectra on Shielding

LET spectra were measured in the main stack in CR-39 made with 1% DOP plasticizer under 6.5 and 9.5 g/cm^2 Al equivalent shielding. The CR-39/DOP detectors were at the center of the main stack and measurements were made in the same region of each detector. CR-39 with DOP is somewhat less sensitive than pure CR-39, but has a clearer surface making track location and measurement easier. The detectors were processed for 36 hours in 6.25 N NaOH at 50°C. Measurements were made using a double layer Track Coincidence Method. Two adjacent layers of CR-39 were etched and then reassembled into their flight configuration relative to one another on the microscope stage. Particle events were selected for measurement when two tracks produced by the same particle were found, one on each adjacent surface. Major and minor axes of the track were measured using a video micrometer. LET was calculated using a detector response function based on data from accelerator-exposed calibration samples. A further internal calibration was carried out by adjusting the spectrum with respect to the relativistic iron peak.

Figure 2 is the integral LET flux spectra for the two shielding configurations. Curve ○ was measured under 6.5 g/cm^2 and curve □ was measured under 9.5 g/cm^2. At low LET ($<$100 keV/μm) curve ○ lies a factor of 2 above curve □. This shows the attenuation of low LET particles, most likely trapped protons, as a function of shielding. There is good agreement between the two curves at high LET ($>$100 keV/μm). For the LDEF orbit (28.5° inclination) the major contribution to the high LET portion of the spectrum is from short range recoils. The good agreement between the two curves in the high LET region shows that the density of recoil tracks is not a steep function of shielding at these shielding depths. The shortest recoil track measured in this plot has a range of $\sim$16 μm. Hence the shorter range recoil events are excluded from these LET flux spectra.

Dependence of LET Spectra on Detector Orientation

Four PNTD stacks were attached to the sides of the main stack. The exact orientation of the P0006 was based on comparison of experimental results with expected directional dependent effects and is represented in Figure 1. Side stack A was oriented toward the north and toward the space end of the satellite. Side stacks B and C were oriented toward the Earth end of the satellite. B was oriented toward the north while C was oriented toward the south. Measurements were made in CR-39/DOP. The self shielding of the P0006 experiment was 1.3 g/cm^2 in the locations where the side stack LET spectra were measured. The effect of the additional shielding from the P0004 experiment and from the LDEF satellite is not known at this time. The detectors were processed for 36 hours in 6.25 N NaOH at 50°C.

Figure 3 shows the integral LET flux spectra for side stacks A, B, and C. In the low LET region, there is good agreement between the measurements from B and C, while A rises above the other two by about a

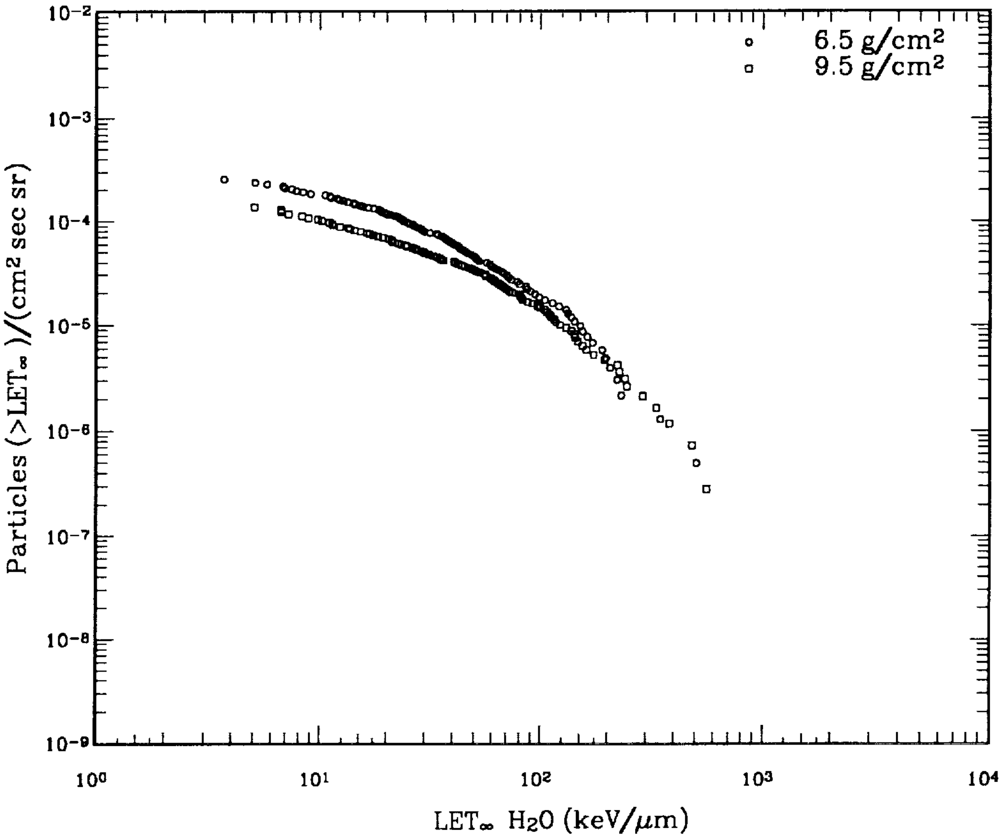

Figure 2: LET Spectra measured in the main stack beneath two shielding depths. Curve ○ was under 6.5 g/cm^2 and Curve □ was under 9.5 g/cm^2. Both spectra were measured in CR-39/DOP using the track coincidence method.

factor of two. Under the assumption that our interpretation of the experiment orientation is correct, this shows a higher flux of low LET particles from the space side of the satellite than from the Earth side. These low LET particles, most probably trapped protons, approach the experiment from the space/west side of the spacecraft. At higher LET, the reasons for the good agreement between A and B and their poor agreement with C are still not known.

High LET Tail

Sheffield Polycarbonate Measurements

Sheffield polycarbonate (PC) is a much less sensitive PNTD than CR-39, but has some advantages in measuring the high LET tail. Without ultraviolet (UV) sensitization, its LET threshold is about 300 keV/μm which means it cannot detect protons or alpha particles. Hence, the track densities in LDEF PC samples are much lower than in CR-39 samples and the overlapping of tracks is negligible. In the higher LET portion, PC has higher LET resolution than CR-39.

In a preliminary study, PC pairs were etched to remove about 10 μm from each surface. Overetched, bubble-like tracks were found on both surfaces which were identified as tracks from short range heavy recoil particles. To be able to use the track coincidence method, an even shorter etching time (12 hours in 6.25 N NaOH at 50°C) was used which removed about 3–4 μm from the layer surfaces. The range of the short range particles which can be identified as pairs using the track coincidence method is on the order of twice the thickness of the removed layer and was about 6-8 μm in this case.

The etch rate ratio was determined from the measured minor and major axes of the tracks using a constant etch ratio assumption. This approximation is very good if the residual range of the particle is significantly greater than the removed layer. In our case, the residual range of the majority of particles was on the order of the removed layer which means that some systematic error is present in the etch rate ratio estimation. This error depends on the range and on the dip angle of the particle and in most cases it was estimated to be within about 50%.

The LET of the particles was calculated from the etch rate ratios using an external calibration curve. The calibration curve was generated using tracks of stopping Ar ions obtained from the Bevalac (Berkeley). It also contains some known uncertainties which, together with the constant etch rate ratio approximation, makes the LET determination not better than about a factor of 2.

Finally, the LET spectra were generated using an assumed isotropic directional distribution of recoil particles. This assumption is also very questionable because of the known strong anisotropy of the high energy trapped proton environment by which these recoils were produced. In a calibration experiment with 200 MeV protons, we found that the directional distribution of heavy recoils reflects the directionality of the primary beam.[3]

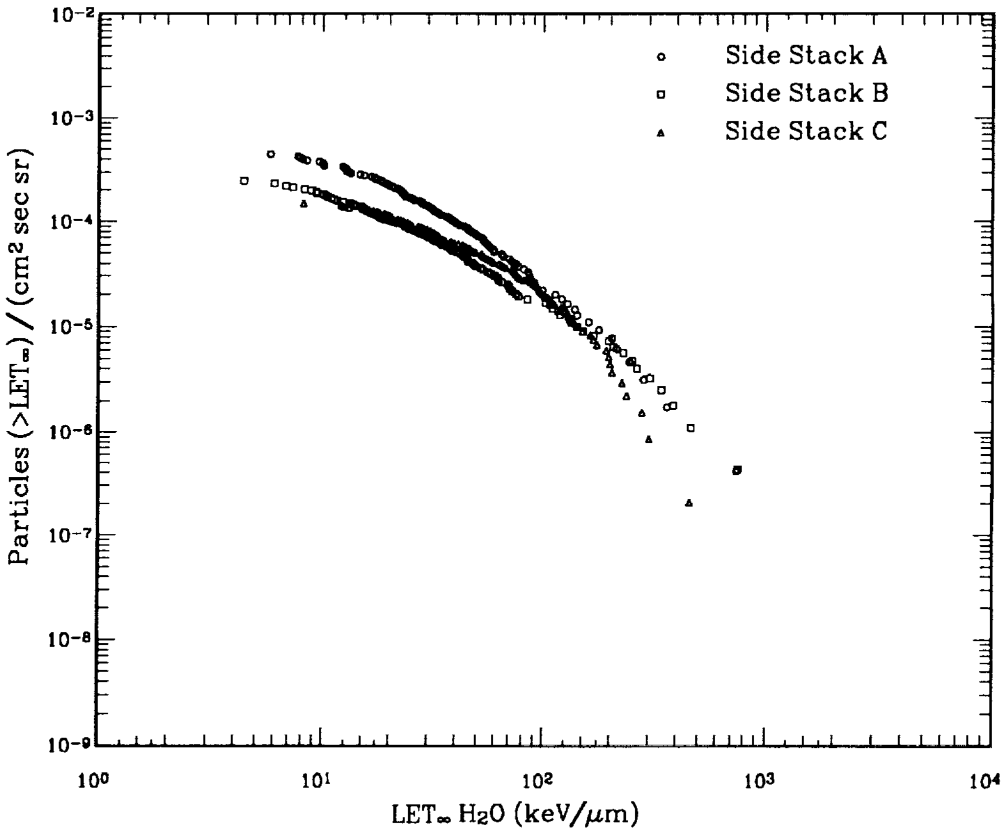

Figure 3: LET Spectra in side stacks showing effect of orientation of detectors. Curve o is from side stack A and faced toward space/north. Curve □ is from side stack B and faced Earth/north. Curve △ is from side stack C and faced Earth/south. All three spectra were measured in CR-39/DOP under a shielding of 1.3 g/cm^2.

CR-39 Measurements

The high LET tail was measured in CR-39(DOP) using a multiple-etch technique. After a short etching time only tracks of high LET particles are present. Tracks of low LET particles are not present because of the low etch rate ratio and a possible etch induction layer. High LET particles in CR-39 are mainly heavy recoils, but include stopping alpha particles, too. After longer etching times, the tracks of short-range recoils become overetched and they can no longer be recognized as pairs. At the same time, pairs of lower LET particles appear and become measurable. With this technique, a large portion of the high LET tail can be covered. Shortest range particles included in the spectra are determined by the shortest etching time, which is limited by the resolution of the microscope used to measure the track dimensions.

Figure 4 shows the LET spectra from the Sheffield polycarbonate under 7.5 g/cm^2 and the LET tail measured in CR-39(DOP) under 0.65 g/cm^2. The LET spectra in CR-39(DOP) under 6.5 g/cm^2 shielding measured by the track coincidence method are included for reference. The standard track coincidence method neglects short-range recoils as can be seen in the high LET portion of the spectrum as compared with the other measurements in this figure. The LET spectrum tail measured in polycarbonate lies to the left of the CR-39(DOP) multiple-etch spectrum. The minimum range of particles measured in the polycarbonate was 6—8 μm. While this is a significant improvement over the minimum range of measurements in the multiple-etch spectrum ($\sim$16 μm), it still excludes even shorter range recoils. The high LET tail measured by the multiple-etch technique in CR-39(DOP) under 0.65 g/cm^2 lies above and to the right of that for polycarbonate. The shortest range tracks measured are 2—3 μm in length. There is good agreement between the two polycarbonate measurements demonstrating that density of recoils in the high LET tail is not highly dependent on shielding. The high LET tail measured in CR-39(DOP) is considered to be more accurate than that in polycarbonate due to the shorter range particles included in the spectra, the more accurate determination of LET from measured track parameters in the CR-39 and to the inherent uncertainties in the polycarbonate measurements for the calibration and determination of LET. The multiple-etch LET measurement may also show an effect from the very low shielding (0.65 g/cm^2) of this CR-39 layer.

CONCLUSIONS

LET spectra have been measured for a number of detector layers in the P0006 main stack and side stacks. The dependence of the low LET region of the spectrum on shielding and detector orientation has been established. The major contribution to the high LET tail has been determined to be from short-range recoils. The density of short-range recoils, and hence the high LET tail, was found to be relatively independent of shielding up to several g/cm^2 for the LDEF orbit.

The high LET tail is being measured using the multiple-etch technique at different shielding depths in the main stack. These measurements will determine any dependence of the shorter range recoils on shielding. In addition, further etching and measurement of the CR-39 layer already measured will provide charge and energy spectra of the high LET tail and an internal calibration based on stopping protons and possibly stopping alpha particles. The internal calibration will improve the accuracy of the high LET tail measurement.

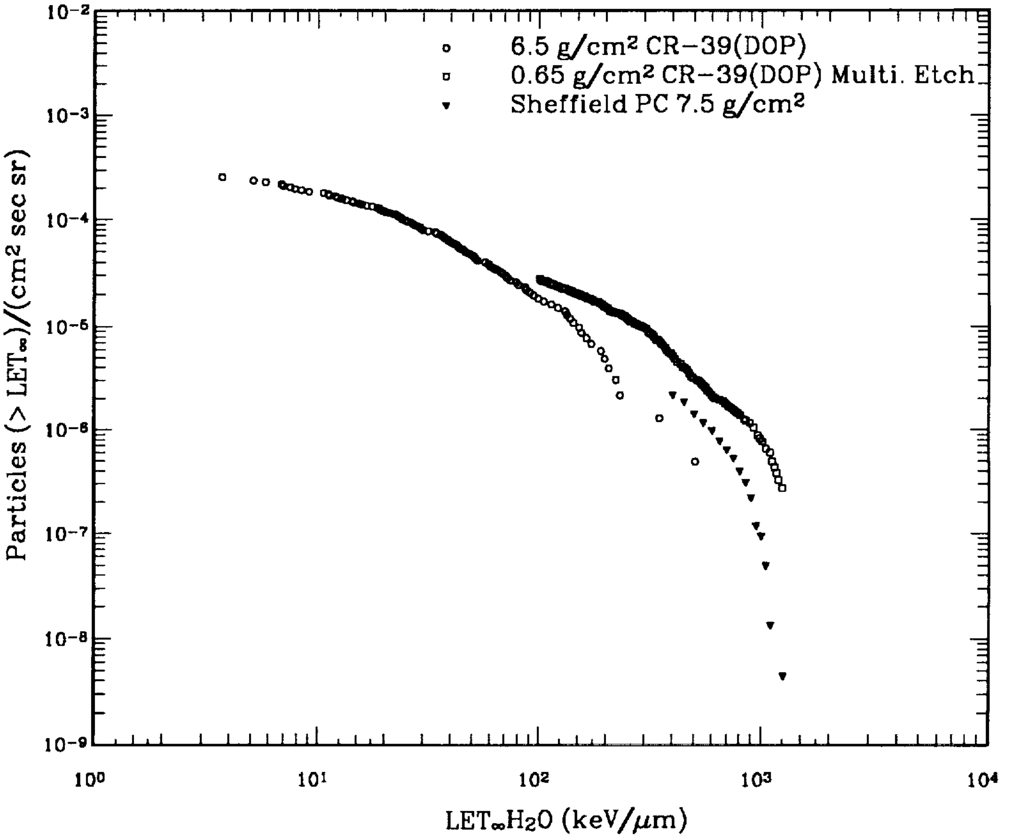

Figure 4: Measurements of the high LET tail in PC and CR-39(DOP).

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