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CONTRIBUTION OF PROTON-INDUCED SHORT RANGE SECONDARIES TO THE LET SPECTRA ON LDEF*

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SUMMARY

The contribution to the LET spectrum from proton-induced short range secondaries was investigated by making measurements of total track density and LET spectra in CR-39 Plastic Nuclear Track Detectors (PNTDs) at varying shielding depths in the A0015 West-side stack. Proton-induced short range secondaries were found to make a significant contribution to the LET spectra, especially in the region above 100 keV/μm. At present, calculational models do not include this component.

Total track density was measured at five shielding depths and was seen to increase as a function of shielding. LET spectra were measured under two shielding depths (2.6 and 9.2 g/cm^2) and stayed fairly constant as a function of shielding. Prerecovery estimates of LET spectra dropped off rapidly in the 100-300 keV/μm region, while the measured LET spectra extended to higher LETs. Track density and LET spectra measurements of secondaries were made in a CR-39 PNTD stack exposed to 154 MeV accelerator protons. Similarities in LET spectra measured in the A0015 experiment and in the 154 MeV accelerator proton stack demonstrate that a useful first step in modeling the contribution to the LET spectra of secondaries induced by the spectrum of trapped protons would be to model a mono-energetic proton beam being transported through a one-dimensional geometry.

INTRODUCTION

Space radiation models for low Earth orbit are based in large part on the assumption that most of the total dose absorbed from the trapped proton environment is from primary particles and that the contribution of secondaries to the total absorbed dose is of lesser importance[1,2]. However, as the flux of primary trapped protons penetrates the shielding of a spacecraft, the cross section for the production of secondaries increases as the energy of the primary protons is attenuated. Thus, it is possible that the contribution of secondaries to the total dose is of greater importance than has been previously considered. Little work has been done in the past to either measure or model the contribution of secondaries to the

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LET spectrum. An attempt was made by Benton *et al.*[3] in connection with ionizing radiation measurements made aboard Biosatellite III. One reason why this component is usually neglected in computer-based models is the complexity of the problem. To accurately model the contribution of secondaries, one must propagate the entire proton energy spectrum incident upon the spacecraft in three dimensions through the known thickness and composition of shielding, taking into account the cross-sections of all possible interactions.

To investigate the contribution of secondaries to the LET spectrum, total track density and LET spectra were measured in CR-39 PNTDs as a function of shielding depth in the LDEF A0015 West-side stack. Due to restrictions imposed by detector processing and analysis, LET spectra could only be accurately measured for tracks from particles with ranges $>16\ \mu$m. Total track density measurements included all recognizable tracks, including those from particles with range $<16\ \mu$m, as is the case for many proton induced secondaries. LET spectrum and total track density measurements were carried out for a ground-based experiment in which a stack of CR-39 PNTDs similar to that of the A0015 experiment was exposed to a fluence of 154 MeV protons similar to that estimated for the West-side of LDEF. Since the LET of 154 MeV protons is below the threshold of track registration in CR-39, it was known that all tracks visible in the ground based experiment were the result of secondary particles. The ground based measurements compared favorably to those measurements made in the A0015 stack in terms of both LET spectra and total track density as functions of shielding depth.

EXPERIMENT

The A0015 West-side stack consisted of a variety of passive radiation detectors interspersed with layers of aluminum absorber. It was located in tray C2 on the West (trailing) side of LDEF. Figure 1 shows the position of the A0015 West-side stack on LDEF. Figure 2 illustrates the configuration of detectors in the A0015 West-side stack. Due to the fixed orientation of the LDEF relative to the Earth and the location of the A0015 experiment, the PNTD layers in the West-side stack were oriented normal to the beam of incoming trapped protons arriving from the West. The total shielding thickness of the A0015 stack was $\sim$11.9 g/cm^2. The stack was kept at $\sim$1 atm. pressure during the mission. The CR-39 layers were processed in a bath of 6.25 *N* NaOH at 50°C for 36 hr. A thickness of $\sim 8\ \mu$m was removed from each detector surface.

As a preliminary study to the measurement of LET spectra at different shielding depths in the A0015 stack, total track density (total number of particle tracks per unit area) was counted at five shielding depths. Track density was counted in single layers of CR-39 PNTD. Track selection criteria for counting included both conical and round (stopping) tracks. Spherical etch pits, which could have been produced by either particles or defects in the PNTD material, were not counted. All tracks from particles of range down to $\sim 1\ \mu$m were counted. The CR-39 detector layers were 7×7 cm^2 in area. Track density was counted in a 13×13 array. Each field of view was separated by 5 mm. The area of each field of view was 0.0018 cm^2.

A ground-based experiment consisting of a thick stack of CR-39 PNTDs interspersed with layers of

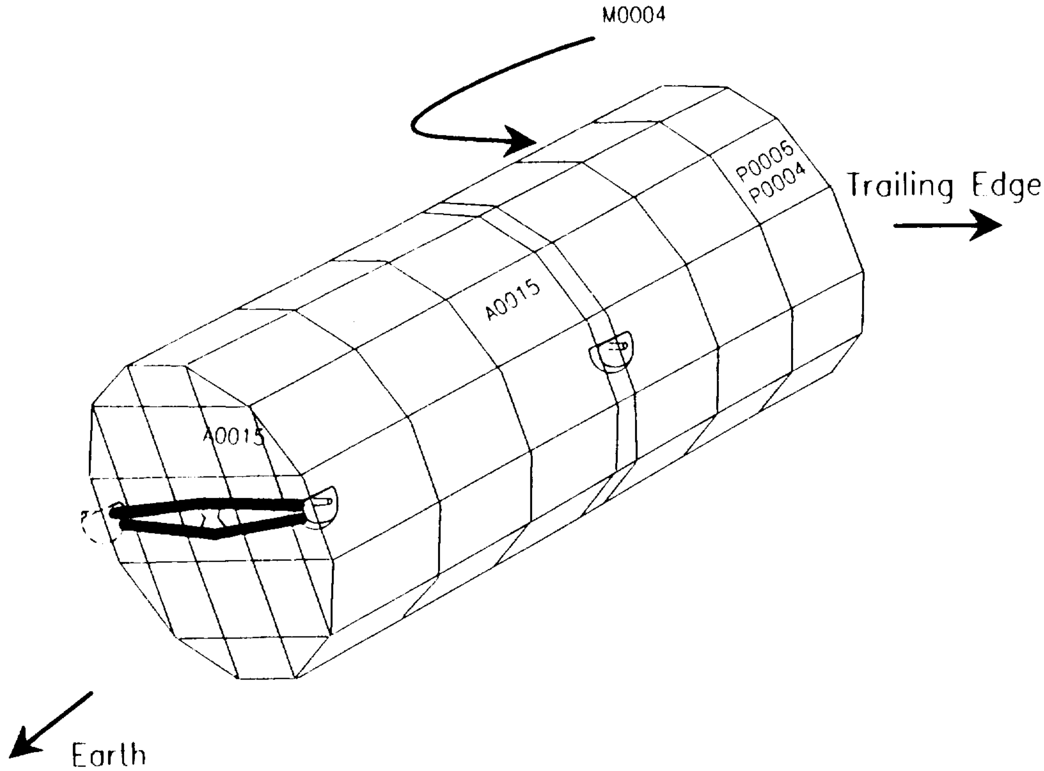

Figure 1: Location of the A0015 West-side stack on LDEF.

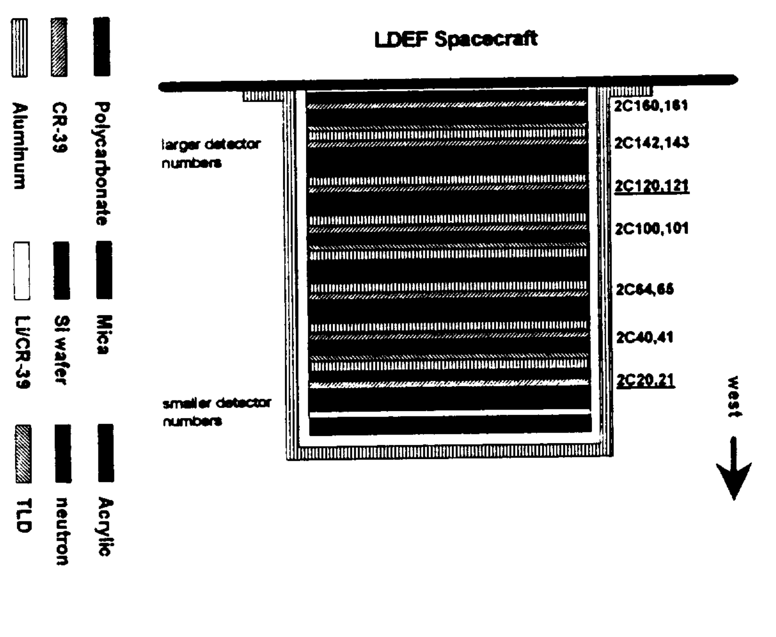

Figure 2: Configuration of detectors inside the A0015 West-side stack.

Al absorber was exposed to 154 MeV protons at the Harvard Cyclotron. Protons of this energy are close to the peak energy of the trapped proton energy spectrum[2]. The stack was exposed to ~10 rads or $\sim 10^8$ protons/cm^2. The stack was oriented normal to the incident proton beam. The range of 154 MeV protons in Al is ~21 g/cm^2. Under the lesser shielding depth in which the track densities were counted in the A0015 stack, 154 MeV protons cannot form visible tracks since their LET is below the threshold for track registration. Hence all tracks seen under this shielding are the result of secondary particles. These tracks are from elastic and inelastic collisions between the primary protons and hydrogen, carbon and oxygen nuclei of the stopping material. After ~18 g/cm^2 of shielding, the proton energy has attenuated sufficiently to allow formation of tracks from the primary protons. However, 18 g/cm^2 is well in excess of the 11.9 g/cm^2 shielding of the A0015 West-side stack. The CR-39 PNTDs from the 154 MeV proton experiment were processed and readout in the same manner as those from the LDEF experiment.

LET spectra were measured under two shielding depths of the A0015 West-side stack, 2.6 and 9.2 g/cm^2, and under three shielding depths in the 154 MeV proton stack, 2.9, 8.5 and 14.4 g/cm^2. Tracks were selected for measurement using the coincident pair method; two adjacent layers of CR-39 were processed and then reassembled into the experiment configuration. Particle events were selected for measurement if a pair of companion tracks were found on the middle adjacent surfaces and only conical tracks were measured. This insured that all the particle events had been formed during the period encompassing the experiment. Since the amount of material removed from each surface (bulk etch) was ~8 μm, all measured events, both primary and secondary, are from particles of range >16 μm.

The standard method used by this laboratory to reduce particle track data into LET spectra involves the assumption that the flux of particles is isotropic. For both the A0015 and the 154 MeV proton experiments, this was not the case. The beam of protons was incident normal to the surface of the CR-39 PNTDs for the ground-based exposure while there was a preferred direction of arrival from the West, nearly normal to the detector surface, for the A0015 West-side stack. While it might be argued that isotropy is still valid in the case of inelastic collisions, there is a directional dependence, based on the directionality of the primary protons, for elastic collisions. Instead of generating integral LET spectrum based on the assumption of isotropy, the track data was reduced in such a way as to yield the average differential LET spectra for a given solid angle. A solid angle of 20° normal to the detector surface was chosen. This angle was a compromise between a small angle, which is better from the point of view of detector efficiency, and an angle large enough to measure enough tracks for good statistics. Measured tracks that did not fall within this acceptance angle were rejected.

LET spectrum data was collected by measuring the major and minor axes of 300 track pairs in each detector. These track parameters, along with the bulk etch, were then transformed into LET values by a calibration function. For the detectors on the A0015 West-side stack, an additional 50 long range events were measured. Long range events are from particles which left tracks on each of the four surfaces of the reassembled detector pair. These events are considered to be from relativistic Fe and were used as part of an internal calibration. They were not included in the LET spectra.

RESULTS

The track density measurements for the A0015 experiment were plotted as a function of x-y coordinates to produce track density profiles. Figure 3 shows the profiles for each of the five layers counted. Shielding depth of each counted layer is to the left of the corresponding profile. While there appears to be little discernible structure in the total track density as a function of x-y position on the detector surface, total track density is seen to increase as a function of shielding. The track density on the frontside of the CR-39 detector under 2.6 g/cm^2 shielding was 1.08×10^5 tracks/cm^2. This increased to 1.62×10^5 tracks/cm^2 under 11.9 g/cm^2. Total track density measurements were also made on the backside surface of each detector. The backside of the 2.6 g/cm^2 detector had a track density of 1.09×10^5 tracks/cm^2. Under 11.9 g/cm^2, the total track density was 1.38×10^5 tracks/cm^2 on the backside. Figure 4 shows track density as a function of shielding for the A0015 West-side stack CR-39 PNTDs.

Figure 4 also shows track density as a function of shielding as measured in the CR-39/Al stack exposed to 154 MeV protons. Track density was normalized to the A0015 2.6 g/cm^2 track density. Track density is also seen to increase as a function of shielding until the stopping point for 154 MeV protons at ~21 g/cm^2. Between ~18 and ~22 g/cm^2 shielding, the CR-39 detectors were saturated with tracks making it impossible to accurately count the total track density in this region. However, in the region below 11.9 g/cm^2, the total shielding thickness of the A0015 West-side stack, the LET of the protons is below that for the registration of latent tracks. All tracks seen in this region are the result of secondaries produced by interactions with the 154 MeV primary protons. Total track density increases from an absolute value of 6.69×10^5 and a normalized value of 1.07×10^5 tracks/cm^2 under 2.9 g/cm^2 to an absolute track density of 8.26×10^5 and a normalized track density of 1.32×10^5 tracks/cm^2 under 11.41 g/cm^2. The curve showing the increase in total track density for the 154 MeV proton exposure is similar to those from the A0015 experiment, especially on the back surfaces of the A0015 detectors, for shielding below 11.9 g/cm^2. Since it is known that the tracks in the 154 MeV proton detectors are from secondaries, the similarity between the 154 MeV proton and LDEF curves confirms that a significant fraction of the tracks being counted in the LDEF detectors are the result of secondaries.

Figure 5 is a comparison of the total track density measurements and measured doses from TLDs as functions of shielding depth in the A0015 West-side stack. The TLD dose is seen to decrease with depth, reflecting the attenuation of lower LET particles as a function of shielding. These lower LET particles do not register as tracks in CR-39 PNTDs. Track density increases as a function of shielding due to the contribution of higher LET secondaries.

Differential LET fluence spectra were measured under two shielding depths, 2.6 and 9.2 g/cm^2, of the A0015 West-side stack, and under three shielding depths, 2.9, 8.5, and 14.4 g/cm^2, in the 154 MeV proton stack. Figure 6 is the differential LET fluence spectra measured in the A0015 West-side stack under 2.6 g/cm^2 and is plotted with error bars. Similar errors were calculated for the other four spectra. Note that the y-axis is a logarithmic scale, so while the error appears to decrease with increasing fluence, it is actually increasing. Figure 7 shows the differential LET spectra measured in the A0015 West-side stack under 2.6 and 9.2 g/cm^2. There is close agreement between the two A0015 LDEF curves within the

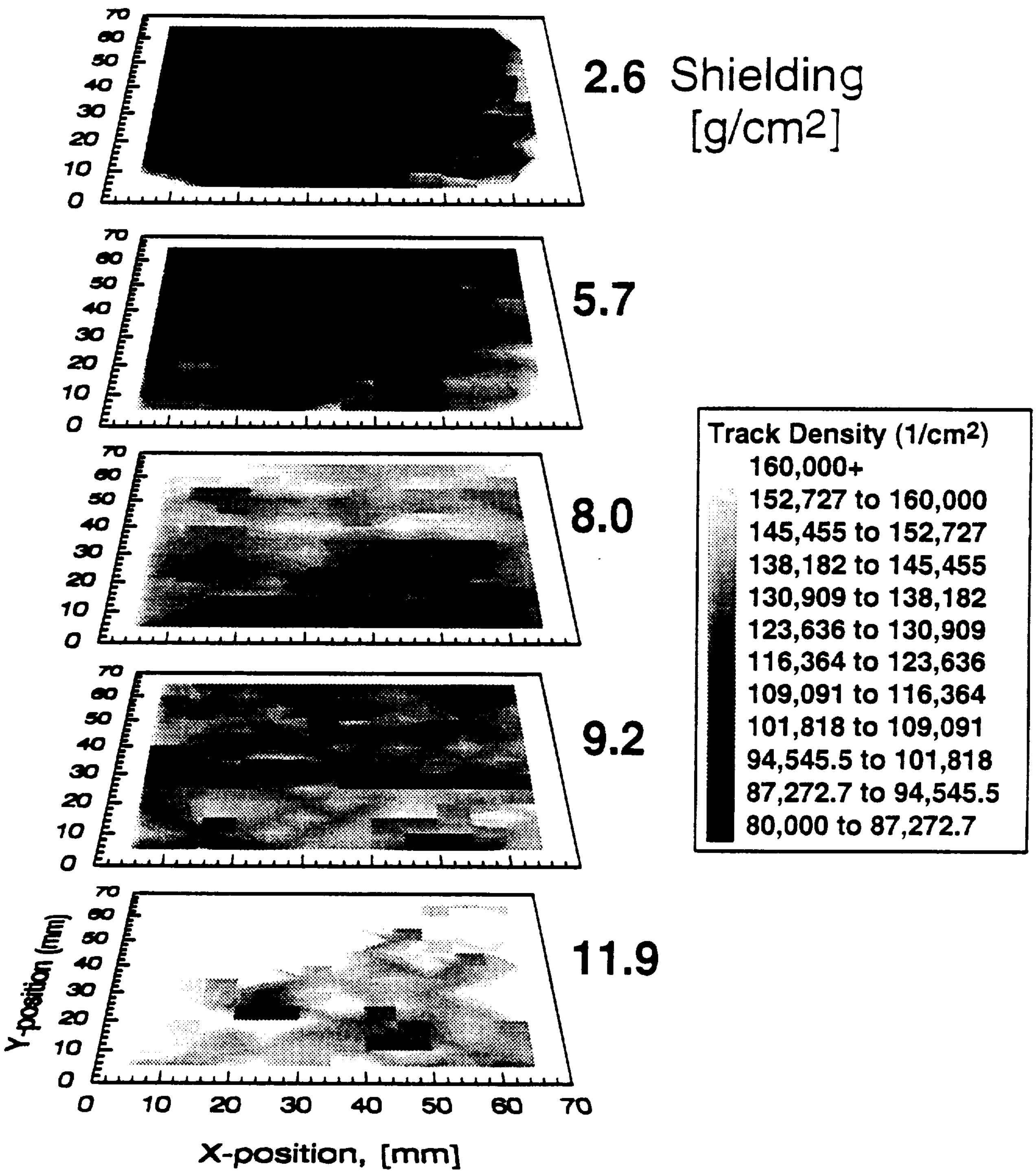

Figure 3: Total track density plots under five shielding depths for the A0015 West-side stack. Track density is seen to increase with greater shielding.

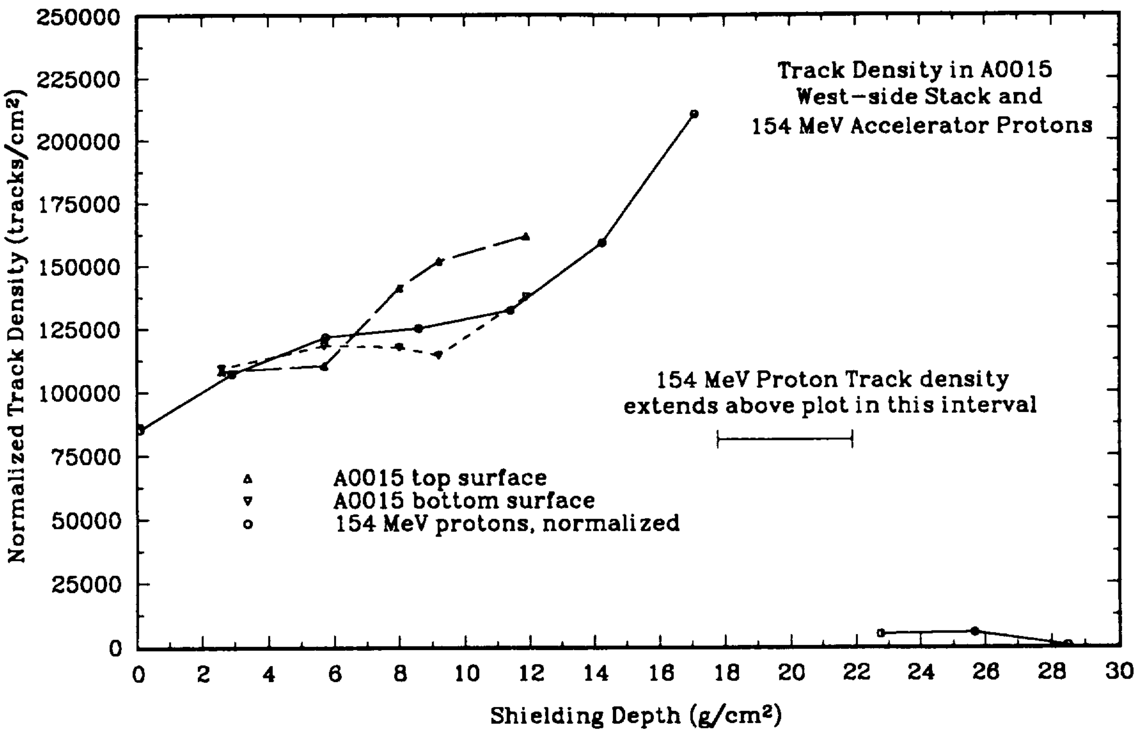

Figure 4: Total track density as a function of shielding depth for the front and back surfaces of the A0015 West-side stack detectors and the front surfaces of the 154 MeV proton detectors. The track density counted in the 154 MeV proton detectors is normalized to the A0015 results under 2.6 g/cm^2.

limits of error. At lower LETs (below 100 keV/μm) much of the spectra is made up of secondaries from elastic proton-proton collisions. Tracks from elastic and inelastic collisions between primary trapped protons and carbon and oxygen nuclei of the stopping material have higher LETs and contribute only to the right-most portion of the spectrum.

Figure 8 shows the differential LET spectra measured under 2.9, 8.5 and 14.4 g/cm^2 in the 154 MeV proton stack. The slopes of the 154 MeV proton curves are similar to those measured in the LDEF detectors, showing that a significant number of the tracks counted in the LDEF detectors are the result of secondaries. Although the three curves lie close together, the fluence increases with shielding depth, presumably because of the increase in cross-section with decreasing primary proton energy. The two sets of curves, A0015 West-side detectors and 154 MeV proton detectors, at similar shielding depths lie close together. The slopes are similar, especially for $LET_{\infty} \cdot H_2O < 100$ keV/μm, the region dominated by elastic recoils. At higher LET, there appears to be a larger number of inelastic secondaries in the LDEF detectors. This result might be due to the fact that LDEF was exposed to the full spectrum of trapped proton energies and not to just one mono-energetic proton beam.

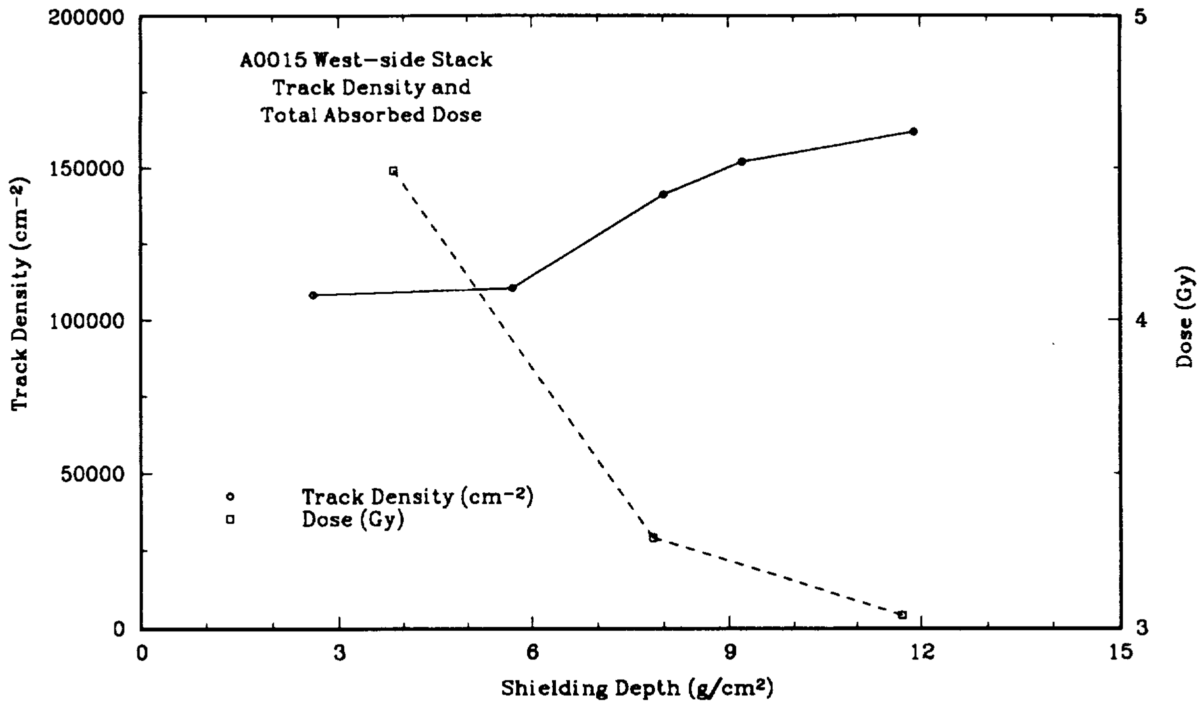

Figure 5: Comparison of total track density measurements with total absorbed dose measurements as a function of shielding for the A0015 West-side stack.

DISCUSSION AND CONCLUSIONS

As had been suggested in earlier work[3], proton-induced, short range secondaries were found to make a significant contribution to the LET spectra. The similarity in slopes between the differential LET spectra measured in the LDEF A0015 West-side detectors and the CR-39 PNTD stack exposed to 154 MeV accelerator protons normally incident to the detector surface supports the conclusion that a substantial fraction of the tracks seen in the LDEF detectors are the result of secondaries. An increase in track density as a function of shielding depth was measured and can be explained by an increase in the cross section for the production of secondaries as the primary proton energy is attenuated. A pronounced increase in fluence as a function of shielding depth was not seen in the differential LET spectra. This is due to the difference in track selection criteria between the two types of measurements. The total track density measurements included all tracks from particles with a range greater than ~ 1 μm while the differential LET spectra measurements consisted of all tracks from particles with range >16 μm. This indicates that the number of short range secondaries increased more rapidly than the number of longer range secondaries as a function of shielding.

Figure 9 is a comparison between the LET flux spectrum measured under 2.6 g/cm^2 in the A0015 West-side stack and model LET spectra under 1.0 and 5.0 g/cm^2 calculated by the CREME code for galactic cosmic rays (GCRs) at the LDEF orbit[1]. In this orbit the particle fluxes are dominated by trapped protons, but a small contribution by GCRs is present. The measured spectrum has been reduced

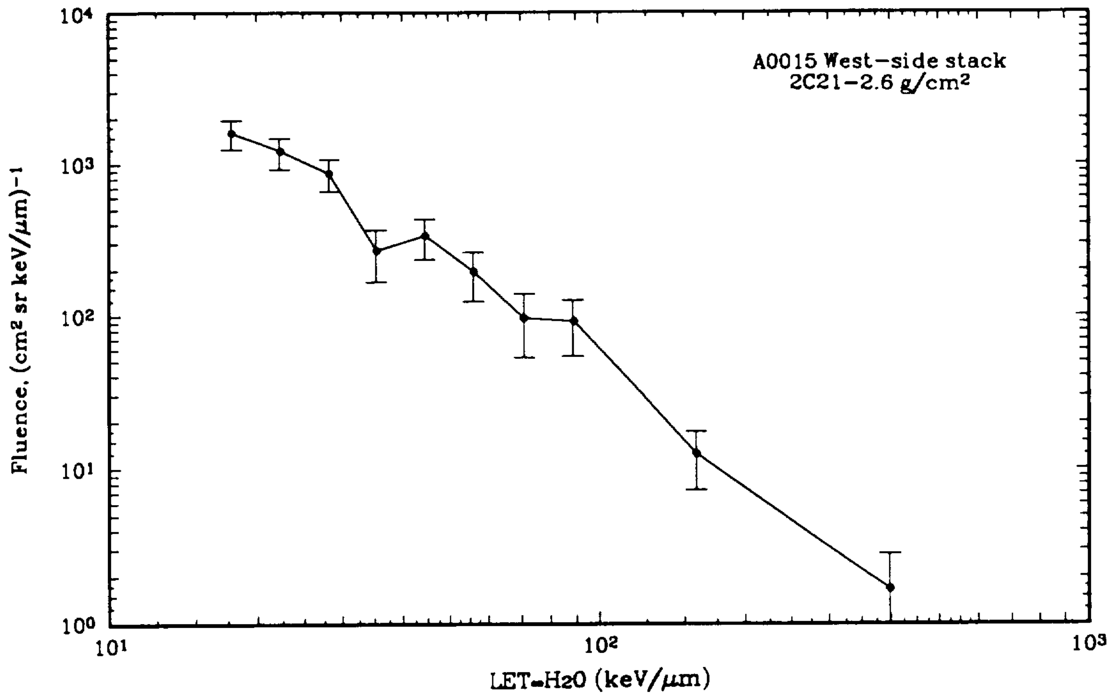

Figure 6: Differential LET fluence spectrum, including error bars, measured in CR-39 under 2.6 g/cm^2 in the A0015 West-side stack.

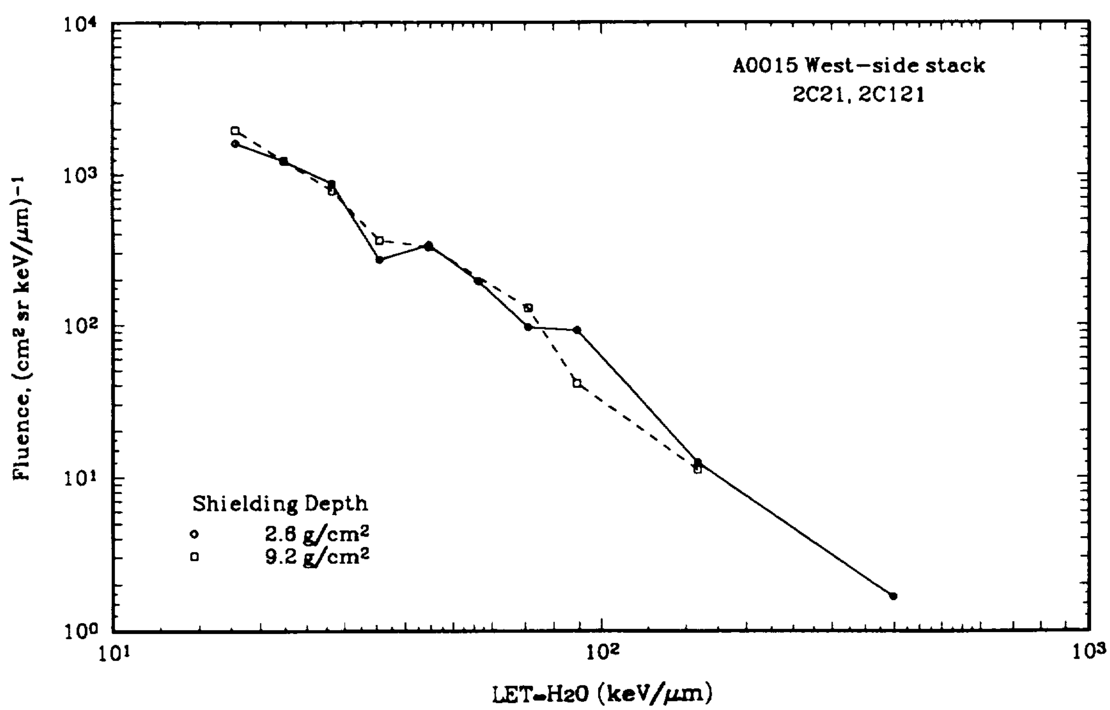

Figure 7: Differential LET fluence spectrum measured in CR-39 under 2.6 and 9.2 g/cm^2 in the A0015 West-side stack.

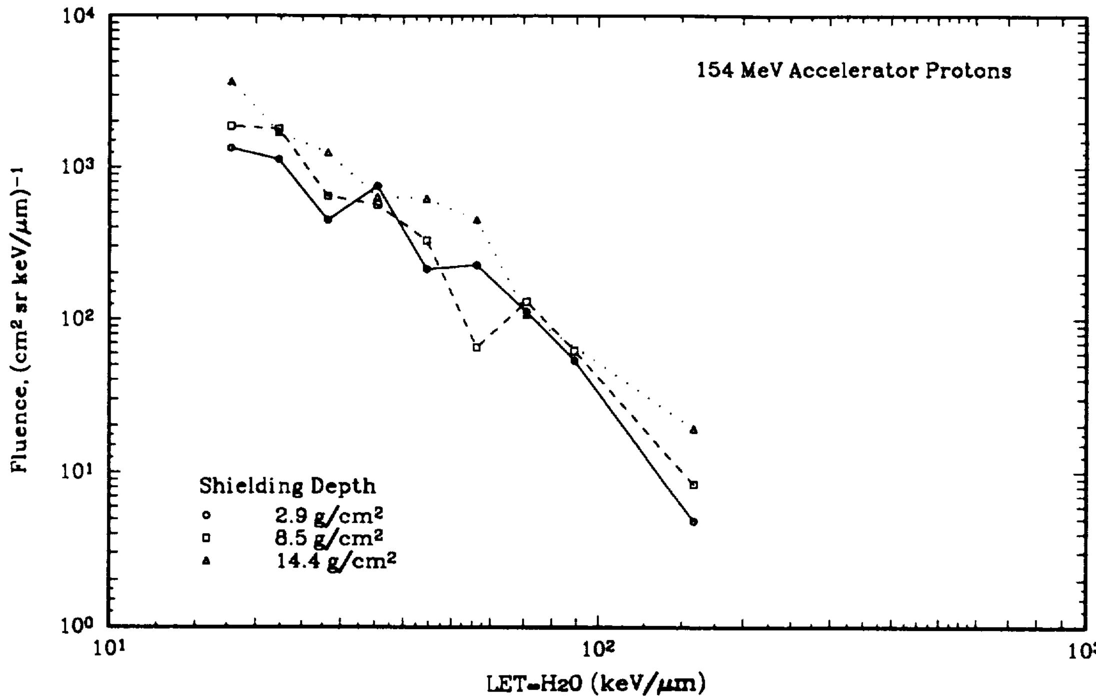

Figure 8: Differential LET fluence spectrum in CR-39 PNTDs under 2.9, 8.5, and 14.4 g/cm^2 for a 154 MeV proton exposure.

by a factor of 4π for a comparison of slopes with the CREME calculations. Both calculated curves drop off between 100 and 300 keV/μm due to the geomagnetic cut-off of Fe. The measured LET spectra extend beyond this drop, illustrating the contribution of high LET short-range secondaries to the LET spectrum.

Previous modeling efforts have not included the contribution of secondaries to the LET spectrum[1]. To accurately model the LET spectra of LDEF, the spectrum of trapped proton energies must be transported through the geometry of the spacecraft shielding while the probability of producing elastic and inelastic secondaries is calculated. The similarities in LET spectra measured in LDEF detectors and those measured for a mono-energetic proton beam and the greater simplicity of modeling such a proton beam through a one-dimensional geometry suggest that measurements and modeling of secondaries from mono-energetic proton beams are potentially useful in incorporating the proton-induced secondary component into LET spectra calculations.

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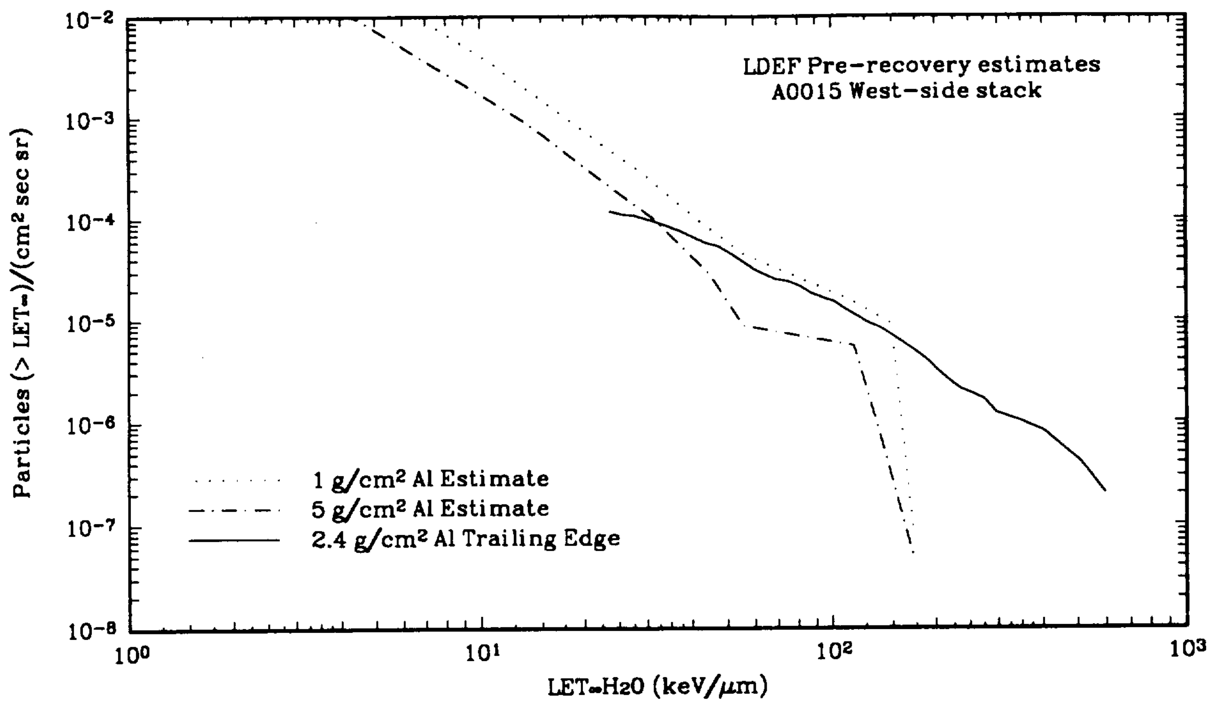

Figure 9: Comparison of measured and calculated LET flux spectra. The measured spectra has been reduced using the assumption of isotropic flux.

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