ABSORBED DOSE AND LET SPECTRA MEASUREMENTS ON LDEF*

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Summary

Total absorbed doses measured with TLDs, linear energy transfer (LET) spectra measured with plastic track detectors, and low energy neutrons measured on LDEF have been compared with model calculations. The total absorbed doses measured in TLDs were higher than predicted in the calculations of Armstrong *et al.* and differ from the calculations of Atwell *et al.*

LDEF LET spectra are dependent on detector orientation, shielding and experiment location. These factors need to be taken into account when modeling the LDEF LET spectra. LET spectra measured with plastic nuclear track detectors (PNTDs) also deviate significantly from calculations especially for high LET particles ($LET_\infty \cdot H_2O > 100 keV/\mu m$). Modeling efforts to date do not include the contribution of proton induced secondaries.

Analysis of polycarbonate PNTDs from the West-side of LDEF has revealed a very high fluence of tracks ($>1 \times 10^7$ tracks/cm^2 under 2 gm/cm^2 shielding). Fluence drops off rapidly as shielding depth increases. Tracks only form in the region of the detector closest to the surface, not in the bulk of the detector. To date no adequate explanation for this observation has been found.

We plan to measure range distribution of very high LET ($LET_\infty \cdot H_2O > 500 keV/\mu m$) secondary particles produced in silicon wafer by high energy primary cosmic ray particles. Refinements of experimental techniques and model calculations are also being carried out in order to understand existing discrepancies between experimental measurements and calculations.

INTRODUCTION

LDEF provided a unique opportunity to measure the space radiation environment in low Earth orbit. Since the spacecraft was gravity gradient stabilized, it was possible to measure total absorbed dose and LET spectra as functions of experiment location and orientation. The East/West trapped proton anisotropy in the South Atlantic Anomaly (SAA) was measured. An important result was the confirmation of the importance of contributions to LET spectra made by proton-induced elastic and inelastic secondaries.

A variety of passive radiation detectors were included in various LDEF experiments. Thermoluminescent Detectors (TLDs) were used to measure total absorbed dose. CR-39, polycarbonate and polyester Plastic Nuclear Track Detectors (PNTDs) were used to measure LET spectra and total track density. Fission foil/mica and ^{6}LiF/CR-39 detectors were used to measure the neutron environment. Figure 1 shows the location of experiments to measure ionizing radiation on LDEF and the orientation of LDEF relative to the East/West trapped proton anisotropy. Thin stacks of TLDs and PNTDs were included in the M0004 experiment located near the East (leading) edge and the P0004 experiment located near the West (trailing) edge of LDEF. Thick stacks of TLDs and PNTDs, interspersed with layers of Al degrader, were included in the A0015 and P0006 experiments located on the West side and the A0015 experiment located on the Earth-facing end of LDEF. Thermal and Resonance Neutron Detectors (TRNDs) were also included in the P0006 and A0015 experiments.

One of the primary objectives of the ionizing radiation measurements made on LDEF is the comparison of measurements with computer models of the space radiation environment. Comparisons of total absorbed dose measurements in TLDs have been compared with two sets of computer generated estimates. LET spectra has been measured at a variety of locations and shielding depths on LDEF. Comparison of measured LET spectra with pre-recovery estimates have highlighted the deficiencies in the calculations especially as they pertain to the contribution of proton-induced secondaries to the LET spectra above 100 keV/μm.

TOTAL ABSORBED DOSE: COMPARISON OF MEASUREMENTS AND CALCULATIONS

Total absorbed dose was measured using TLDs in several experiments flown on LDEF. The purpose of these measurements was to determine the dose exposure of LDEF as functions of experiment location and shielding depth. These measurements are being used in refining models of the ionizing radiation environment in low Earth orbit and in refining methods of calculating dose inside spacecraft. Total absorbed dose was measured in four experiment locations (Figure 1), M0004 East-facing leading edge, P0004 and P0006 West-facing trailing edge and A0015 Earth-facing end. The read out and analysis of TLD measurement data has been completed[1]. Comparisons have been made between these measurements and model calculations generated by Armstrong et al.[2] and Atwell et al.[3].

The original set of dose calculations were performed by Armstrong, Colborn and Watts[2]. They are based on the calculations of Watts[4] for the trapped proton exposure, a detailed three dimensional

LDEF in the South Atlantic Anomaly

West-side
Trapped Protons

M0004

P0004/
P0006

Direction of Travel

East-side
Trapped Protons
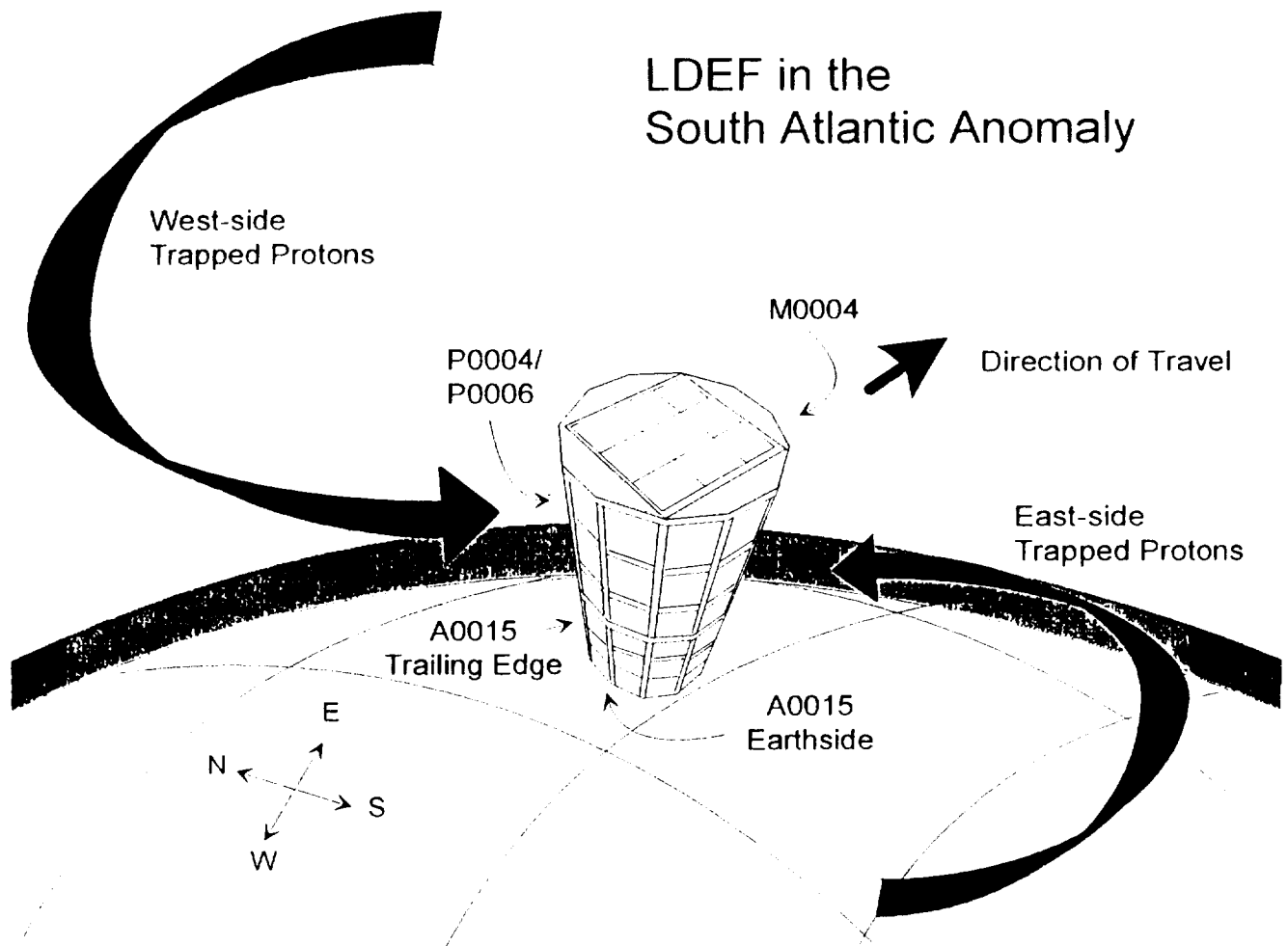
A0015
Trailing Edge

A0015
Earthside

E

N

S

W

Figure 1: Location of experiments containing radiation detectors on LDEF, relative to the East/West proton anisotropy in the South Atlantic Anomaly.
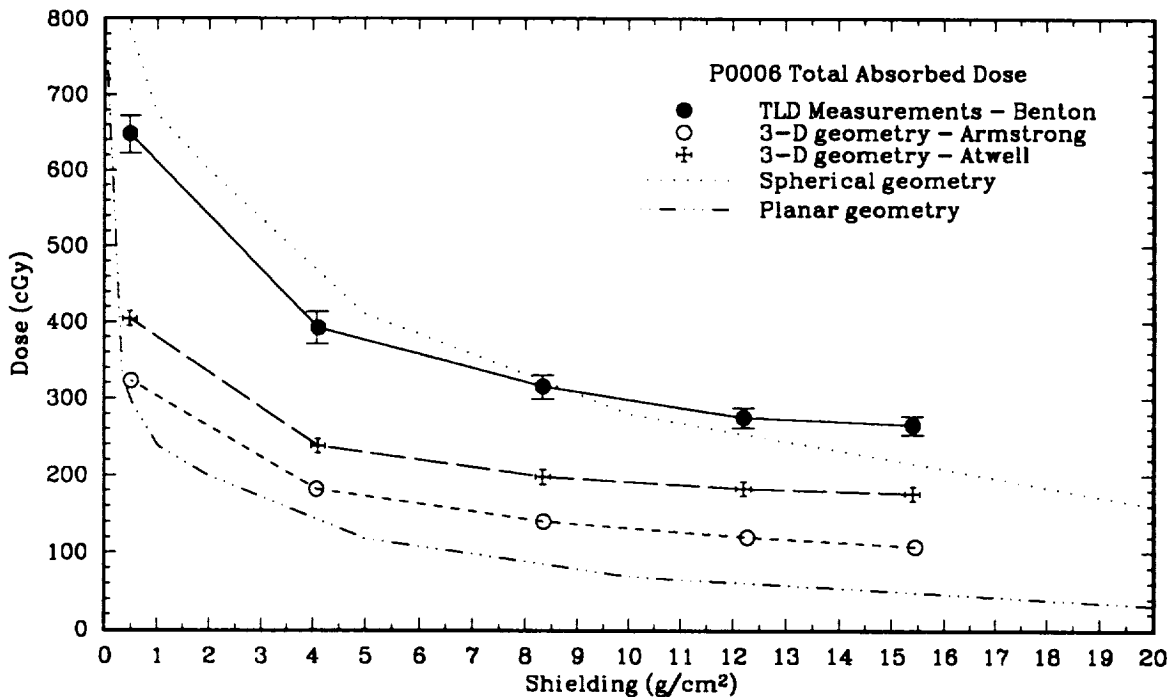
Figure 2: P0006 Total Absorbed Dose: comparison of measurements and calculations.

geometry/mass model developed by Colborn and Armstrong[5] and the transport code of Burrell[6]. The proton exposure model is based on the AP8 omnidirectional proton flux model[7]. Atmospheric height, solar cycle information and a model of the trapped proton anisotropy were included in the calculations.

A second set of calculations were made by Atwell, Badhwar, Hardy and Weyland[3] at JSC. These are considered to be preliminary calculations. The proton flux is based on the AP8 omnidirectional proton flux model[7] and a vector flux model of Kern[8]. Atmospheric scale height and solar cycle were modeled, but the trapped proton anisotropy was not included in the calculations. A simple mass model of the LDEF was used to model the distribution of shielding.

Figure 2 is a comparison of TLD measurements and calculations of absorbed dose in the P0006 experiment. Both sets of model calculations lie below measured values. The largest discrepancy is for the least shielded point ($\sim$0.5 g/cm^2) where the calculations fall below measurements by nearly a factor of two. Also plotted in Figure 2 are the pre-recovery estimates of total absorbed dose using planar and spherical geometry models. The spherical geometry model provides the closest agreement with measured values. Figure 3 compares measured absorbed doses from TLDs with calculations for the P0004 experiment as a function of shielding depth. Like Figure 2, both sets of calculations fall below the measured values and the biggest difference is for the least shielded point.

Figure 4 shows a comparison of dose measured in TLDs with calculations as a function of shielding for the M0004 experiment on the leading (East) edge of LDEF. The smaller measured and calculated
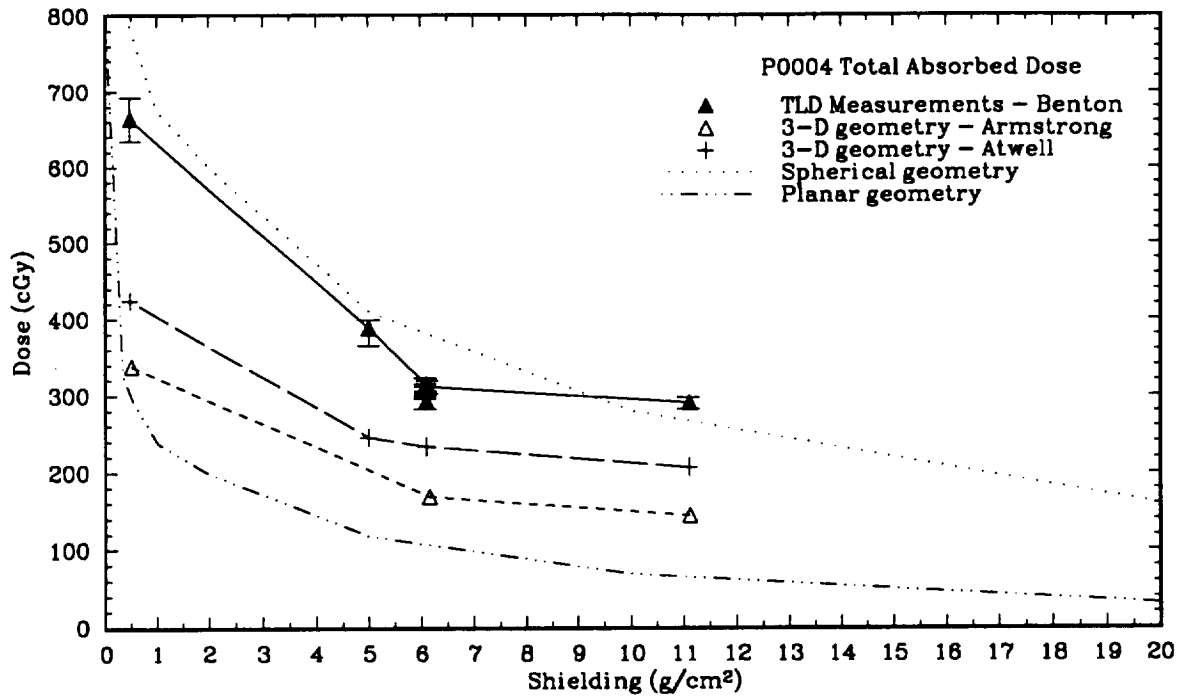
Figure 3: P0004 Total Absorbed Dose: comparison of measurements and calculations.

doses of M0004 as compared with P0006 and P0004 show the effect of the East/West trapped proton anisotropy. The largest difference can be seen for the low shielding point (0.5–1.0 g/cm^2) where the dose on the West side exceeds that of the East side by about a factor of three. The calculations of Armstrong show a ~1.5 times greater dose on the West side as compared to the East side under ~1.5 g/cm^2. Atwell's calculations show little difference between doses (300 cGy Earth-side, 350 cGy West side) between East and West due to the fact that the East/West proton anisotropy was not accounted for in the calculations. Figure 5 is a comparison of total absorbed dose measurements in TLDs from this laboratory (USF) and DLR and with the calculations of Armstrong and Atwell. There is close agreement between the two sets of measurements. The Atwell calculations lie quite close to the DLR measurements, but fall below the USF measurements while Armstrong's calculations fall below both sets of measurements.

The calculations of Armstrong are consistently lower than measurement of dose by approximately a factor of two. This would seem to indicate that there is a systematic omission in the model. The calculations of Atwell fall on both sides of the measurements. There is close agreement with measured doses on the Earth side. Atwell's calculations exceed the measurements of the East side and fall below measurements made on the West side. One difference between the two sets of calculations is the vector flux model used. The Armstrong calculations are based on a vector flux model of Watts[4] and a comparatively high atmospheric scale height. The Atwell calculations are based on a newer vector flux model being developed by Kern[8] at JSC which uses a lower atmospheric scale height. Discrepancy between measurements and Armstrong's calculations might also be due to inadequacies in the trapped proton anisotropy model. While a ratio of 1.5 was calculated between doses on the West and East sides and agreed well with the measured ratio, the measured ratio only included the shielding of the experiment
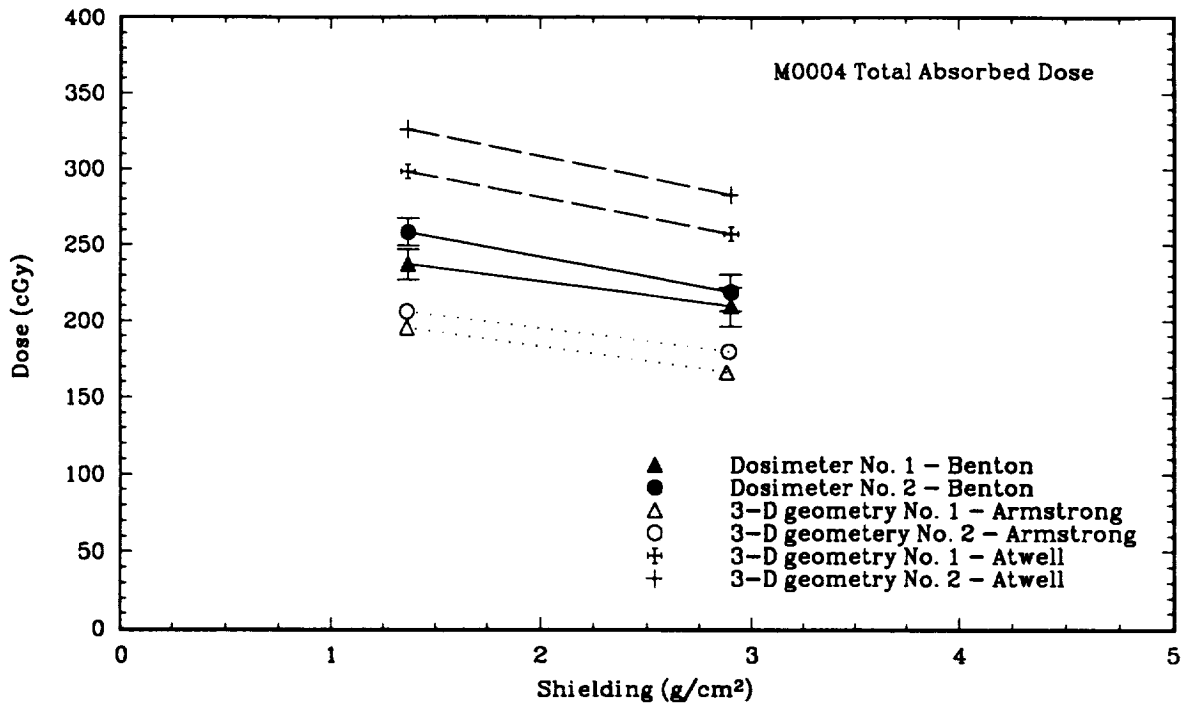
Figure 4: M0004 Total Absorbed Dose: comparison of measurements and calculations.
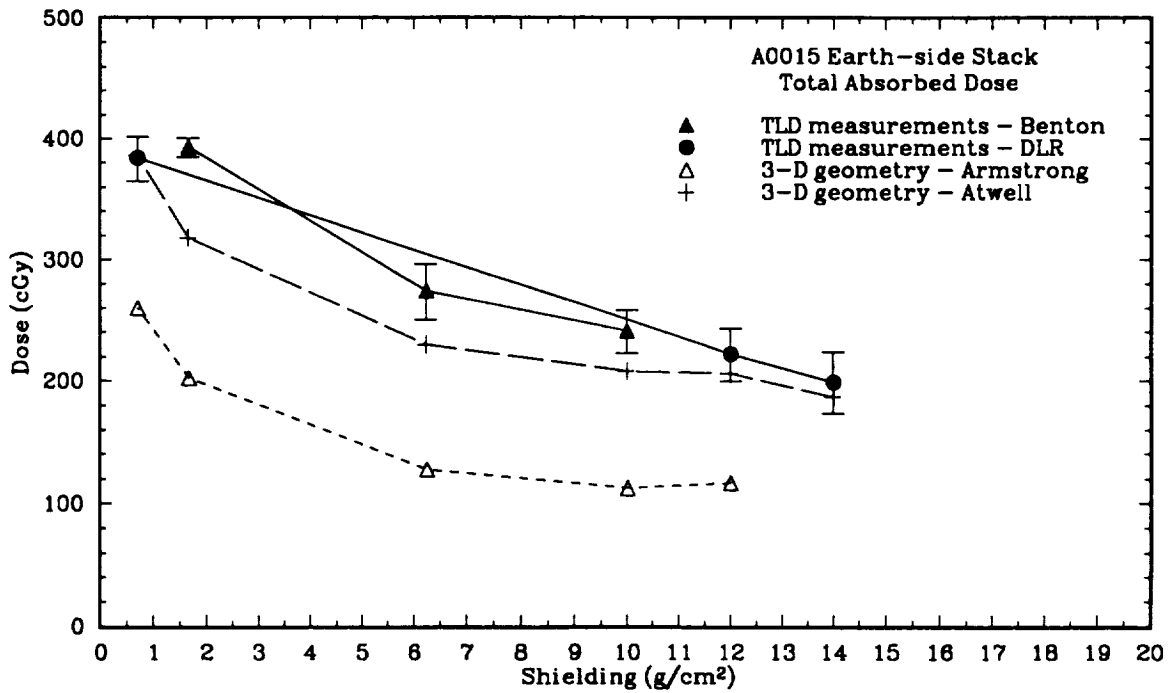

Figure 5: A0015 Total Absorbed Dose: comparison of measurements and calculations.

itself and not the shielding of the entire spacecraft, making the validity of this comparison questionable. The ratio of measurements of induced radioactivity on the West and East sides of the spacecraft is closer to a factor of three. Refinements are expected to be made to both models and new sets of calculations will soon be published.

LET SPECTRA AND FLUENCE MEASUREMENTS WITH CR-39 PNTDS

Measurements of nuclear particle tracks in CR-39 PNTDs provide fluence, flux, dose and dose equivalent LET spectra for different LDEF experiments. LET spectra are useful in refinement of models of both trapped proton and GCR environments in LEO and in development of calculational methods of determining LET spectra. LET spectra, as measured on LDEF, are dependent on detector orientation, shielding, and experiment location. These three factors must be taken into account in any effort to model LDEF LET spectra. The importance of the contribution of proton-induced short range elastic and inelastic secondaries to the LET spectrum has been confirmed. This is seen as an increase in the fluence of high LET (>100 keV/μm) particles and is presently not included in the calculational models.

Due to both the directional sensitivity of the CR-39 detectors and the fixed orientation of LDEF relative to the Earth, track density and LET spectra are dependent on detector orientation. This fact, together with experiment location can be used to measure particular features of the trapped proton environment, such as East/West trapped proton anisotropy. A0015 and P0006 stacks were on the West-side oriented perpendicular to the direction of maximum proton flux, while the M0004 experiment was located on the East-side. Directional sensitivity and the dependence on orientation of the detectors can be illustrated by looking at LET spectra measured in the four side-stacks of the P0006 experiment. Figure 6 shows the orientation of the P0006 stack relative to the Earth. Perpendicular to the main stack were four side stacks labeled A through D. Figure 7 shows total track density plots for the four side stacks. Higher track density is seen near the West end of the detectors than near the East end. Side stack D which faced North and toward space, shows the greatest track density.

Spacecraft shielding affects the LET spectra in two ways: it attenuates the flux of incoming primary protons and galactic cosmic rays and it increases the cross section for the production of secondaries. The contribution to the LET spectra from proton-induced short range elastic and inelastic secondaries was first measured by this laboratory over 20 years ago as part of the investigation into radiation exposure of Biosatellite III[9]. Additional measurements of secondary tracks have not been carried out until LDEF and the contribution of secondaries to the LET spectra has not been sufficiently taken into account in any of the current calculational models. LET spectra were measured under two shielding depths in the A0015 West-side stack[10]. Similar measurements were made in a stack exposed to 154 MeV protons. The LET of 154 MeV protons is below that for track registration, indicating that all the tracks seen in these proton exposures were the result of inelastic and elastic collisions. The similarity in slopes of the differential LET spectra suggests that a significant fraction of tracks measured in the LDEF CR-39 PNTD layers were the result of secondaries. The details of these measurements and plots of the resulting LET spectra may be found in reference 10.
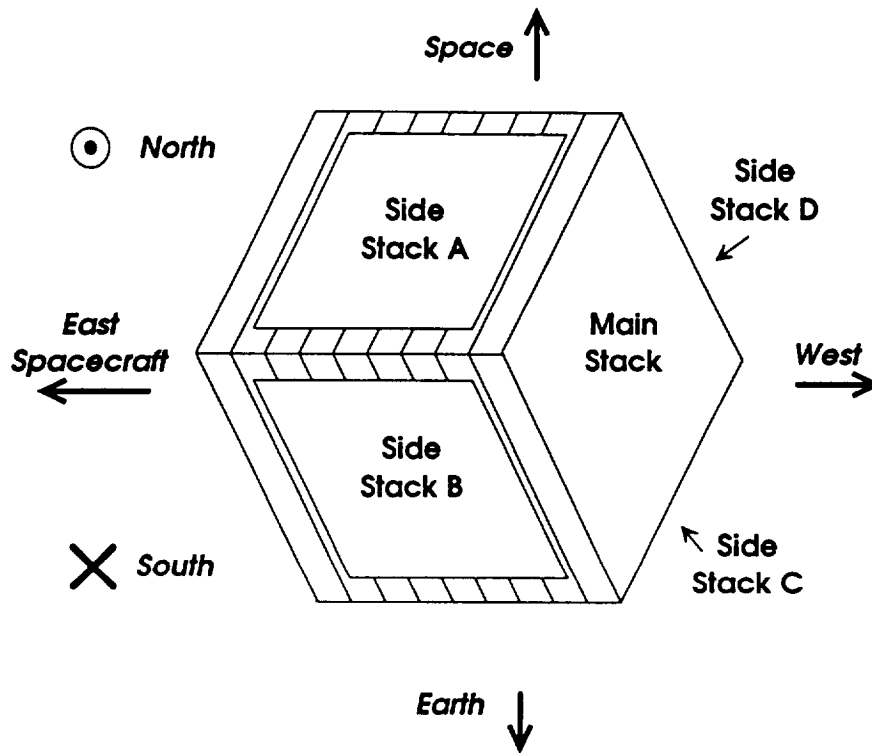
Figure 6: Orientation of side stacks in LDEF P0006 experiment relative to the spacecraft.
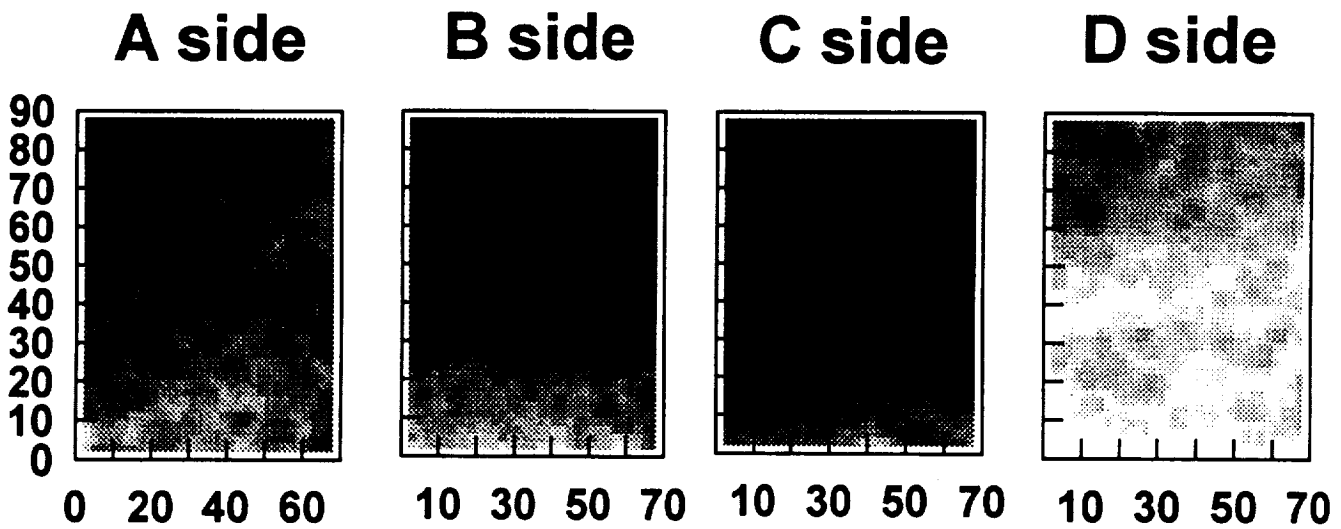

Figure 7: Track Density plots for P0006 side stacks. The darkest region corresponds to a track density $<5 \times 10^5$ tracks/cm^2, while the lightest region corresponds to a density $>9 \times 10^5$ tracks/cm^2.
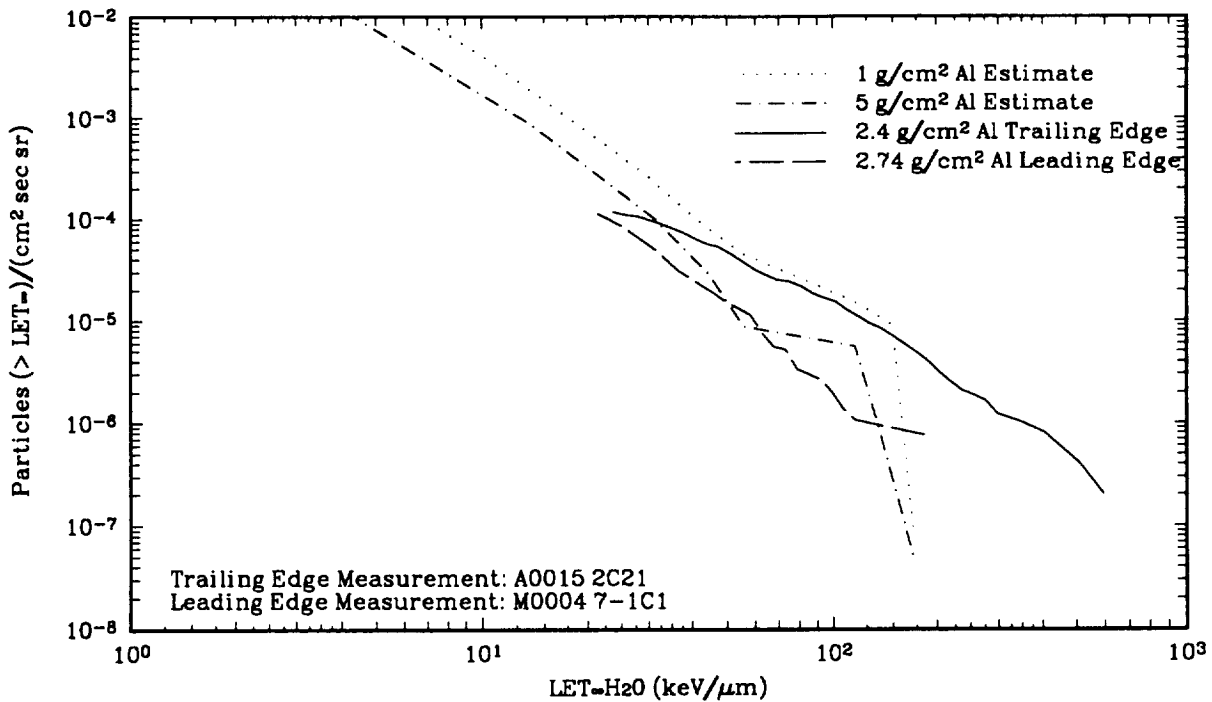
Figure 8: LET Spectra measured on East and West sides of LDEF and LDEF pre-recovery estimate LET spectra for 1 and 5 g/cm².

The dependence on detector location of the LET spectra may be seen in a comparison of LET spectra measured on the East and West sides of LDEF. Figure 8 shows LET spectra measured in the M0004 experiment on the East (leading) edge of LDEF and in the A0015 experiment on the West (trailing) edge under similar shielding between 2.4 and 2.6 g/cm². The two curves converge at lower LETs (~20 keV/μm), indicating perhaps that the difference in proton fluences of about 1.5 MeV in energy at the two locations is less than the difference in the higher LET secondary particle fluences. For higher LETs, the West-side curve lies above the curve measured on the East-side, illustrating the effect of the trapped proton anisotropy in the South Atlantic Anomaly. Most of the flux between 20 and 100 keV/μm is the result of trapped primary protons and elastic proton secondaries. Above 100 keV/μm, inelastic collisions between incident trapped protons and carbon and oxygen nuclei of the stopping material make a contribution.

Figure 8 also shows two LET spectra calculated using the CREME code from the LDEF pre-recovery estimates[11] under 1 and 5 g/cm². These calculated spectra do not take the contribution of secondaries produced by collisions with high energy trapped primary protons into account. At ~150 keV/μm, the two calculated curves quickly drop off in the region of relativistic Fe due to the geomagnetic cutoff. The measured curves continue to high LETs and fall off much more gradually, illustrating the need to integrate the contribution of secondaries into the calculational models. Calibrations of CR-39 PNTDs are still in progress and future LET spectra curves may show an increase in integral fluence and flux. However this change would have little effect on the dose or dose equivalent derived from the spectra.
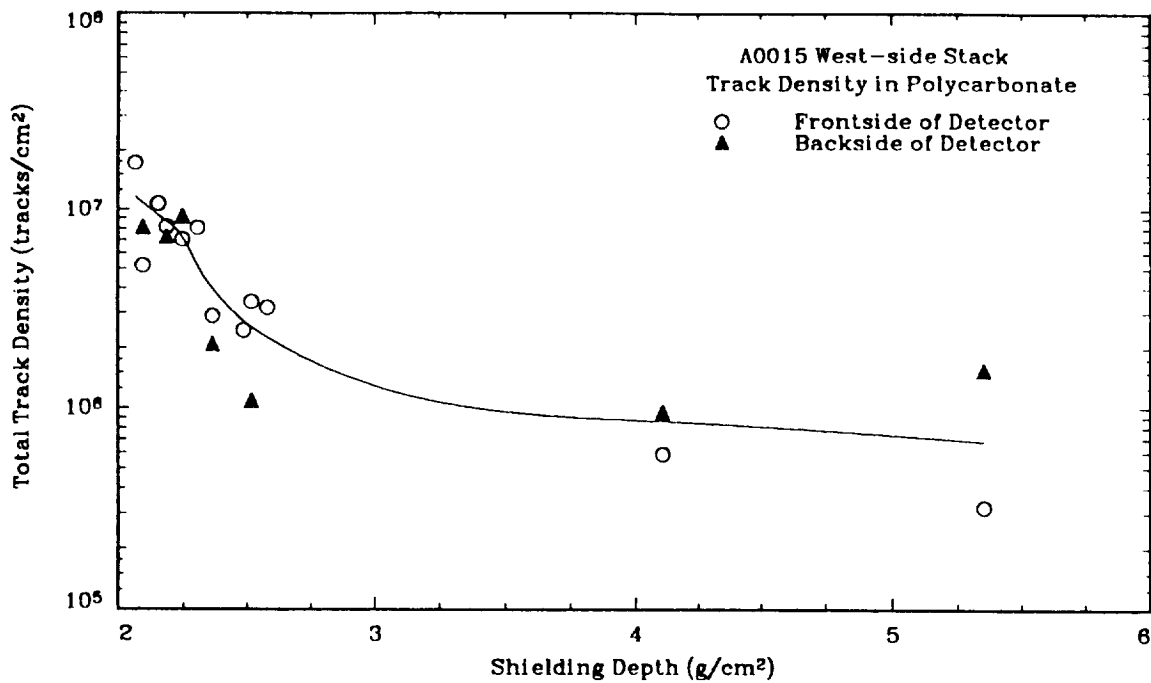
143

Figure 9: Track densities measured in A0015 West-side polycarbonate PNTDs as a function of shielding depth.

HIGH TRACK DENSITIES IN A0015 POLYCARBONATE PNTDS

Analysis of Sheffield and Tuffak polycarbonate (PC) PNTD layers from the A0015 West-side stack has revealed a much higher than expected track density. A track density of $> 10^7$ tracks/cm^2 was counted on the least shielded PC layer (2.0 g/cm^2). This is far higher than expected considering that the threshold for track registration in PC is usually accepted to be $\sim$250 keV/μm. By comparison, the track density measured in the CR-39 layer closest in the A0015 West-side stack (2.6 g/cm^2) was $\sim$1.1 $\times$ 10^5 tracks/cm^2. Track densities were counted on the front and back surfaces of each PC layer. Figure 9 shows track density in PC as a function of shielding depth. The track density can be seen to decrease with increasing shielding.

The Sheffield and Tuffak PC layers involved in this analysis were processed for only a short time and a layer of $\sim$2.5 μm thickness was removed from each surface. Figures 10 and 11 are photomicrographs of two of the PC layers showing the high densities of tracks. Most of the tracks are small and over-etched, indicating that the ranges of the particles which made them are less than 2.5 μm. Because the removed layer was so small, the resulting tracks were too small to accurately measure and only track densities were measured. Additional chemical processing enlarged the tracks, but did not uncover any new tracks, indicating that the latent tracks are present only in the few microns beneath the pre-etch surface.

To date, the origin of these tracks is unknown, but several possible causes have been eliminated. One possibility was that the material was irradiated at the time of manufacture. This can be discounted because high track densities are seen in both Tuffak and Sheffield PNTDs, polycarbonates made by
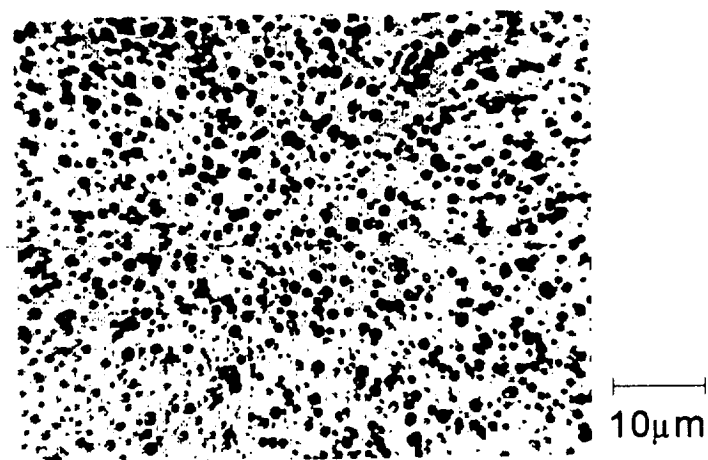
Figure 10: Photomicrograph of PC layer under 2.063 g/cm^2 from the AOO15 West-side stack. The track density is ~1.72 × 10^7 tracks/cm^2.
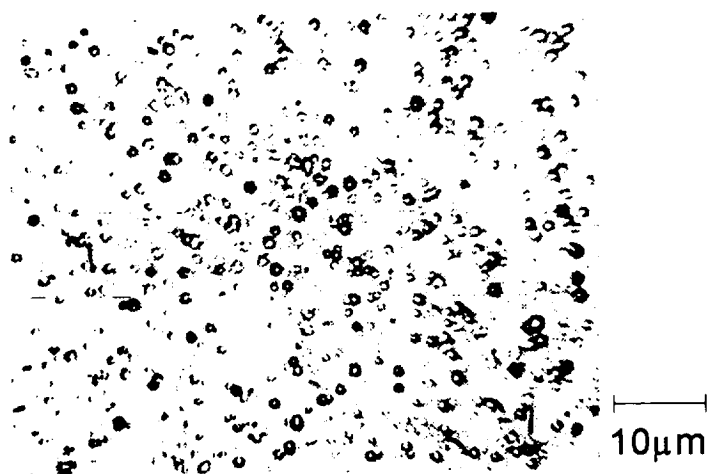

Figure 11: Photomicrograph of PC layer under 2.485 g/cm^2 from the AOO15 West-side stack. The track density is ~8.13 × 10^6 tracks/cm^2.

different manufacturers. Since track density is seen to attenuate as a function of shielding depth in the stack, exposure must have taken place while the experiment was assembled. Another possibility is that what is being seen are not tracks, but an effect caused by detector handling or chemical processing. This possibility has also been ruled out since these high track densities were counted in detectors which were processed separately. In addition, this effect was not seen in unexposed control detectors processed under the same conditions.

Since the detectors were near the fission foil/mica and ^{6}LiF/CR-39 neutron detectors, it was suggested that the track must be from α-particles from these sources. This possibility has been eliminated due to the fact that the range of α-particles from these sources is too short to form tracks in all the PC layers. This high track density was not seen near the activation foils contained in the P0006 and A0015 Earth-side stacks. If the tracks were from ^{6}Li α-particles, a pattern of track density would be seen due to the placement of the ^{6}LiF chips in the experiment. No such pattern was seen.

It is possible that the tracks are from proton-induced secondaries. To test this hypothesis, a stack of Sheffield and Tuffak PC PNTDs was exposed to a beam of 154 MeV protons at the Harvard Cyclotron. While a small number of recoil tracks were detected, the density was far lower than the density of secondaries counted in the CR-39 PNTDs and could not account for the high track densities seen in the A0015 PC layers. In addition, if these tracks were from proton induced secondaries, a similar high track density should have been counted in the more sensitive CR-39 layers in the A0015 West-side stack. A similar argument can be used to dismiss the possibility that the tracks were from stopping protons or from low energy (trapped or anomalous) α-particles.

One conclusion that can be drawn from the analysis of the A0015 West-side PC layers is that the sensitivity of the material is not constant, but varies as a function of detector thickness. Since high track densities can be counted through many layers of PC on both the front and back surfaces of the detector and since these tracks only appear in the $\sim$3 μm region directly beneath the pre-etch surface and no deeper, it can be concluded that this outer-most region of the PC layer is more sensitive than the rest of the layer. This opens up a number of possibilities including the possibility that this region of the detector is even more sensitive than CR-39 and that the tracks being seen are from primary protons of energy greater than 16 MeV, the highest proton energy detectable in CR-39, but lower than the 154 MeV of the Harvard Cyclotron proton exposures. Similar analysis of Tuffak, Sheffield and Lexan PC is being carried out for other experiments containing PC on LDEF. Ground based experiments are also underway to try and reproduce the results seen in the A0015 West-side polycarbonate PNTDs.

DISCUSSION AND CONCLUSIONS

The LDEF mission provided an unprecedented opportunity to measure the ionizing radiation environment in low Earth orbit due to a number of unique aspects including the fixed orientation of the spacecraft with respect to the Earth and the 5.8 year duration. Measurements of the ionizing radiation exposure of LDEF made with CR-39 and PC PNTDs and with TLDs are useful in refining methods of calculating radiation transport and exposure in spacecraft. These measurements can also be used to

further develop models of the space radiation environment. Integrated doses and linear energy transfer (LET) spectra were measured as functions of spacecraft shielding, orientation and location in TLDs and PNTDs. Total absorbed doses in TLDs have been measured as a function of shielding depth and detector location for several LDEF experiments and comparisons have been made with two preliminary sets of calculated doses. The trapped proton anisotropy in the South Atlantic Anomaly was measured with both TLDs and PNTDs and a ratio of ~1.5 was found between measured doses on the spacecraft's West and East sides under similar experiment shielding. The contribution of proton-induced short range secondaries to the LET spectra, especially at higher LETs (>100 keV/μm), was measured. Unusually high track densities in excess of 10^7 tracks/cm^2 have been counted in polycarbonate PNTD layers from the West-side of the spacecraft. No explanation for these high track densities has yet been found.

Future work on the analysis of LDEF radiation detectors will include investigation of the high track densities measured in polycarbonate, and accelerator exposures to protons and α-particles will be carried out in order to reproduce these track densities. LET spectra will be measured in polycarbonate PNTDs in order to accurately measure the high LET region (>250 keV/μm). Comparisons will be made between the high LET measurements in polycarbonate and those previously measured in CR-39 PNTDs. A new method to measure very short range particles that stop within the removed bulk etch layer is being developed. This technique will measure the contribution of short range particles (2-10 μm) to the LET spectra. Measurements will be made of high LET (LET$_\infty$·H$_2$O>500 keV/μm) secondary particles produced in silicon wafers by high energy primary cosmic rays in the P0006 experiment. Dose and LET spectra measurements will be compared with model calculations. A comparison of measured LET spectra with model calculations that include the contribution of secondaries is of special interest.

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