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# ABSORBED DOSE MEASUREMENTS AND PREDICTIONS ON LDEF*

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## SUMMARY

The overall radiation environment of the Long Duration Exposure Facility (LDEF) was determined in part through the use of thermoluminescent detectors (TLDs) which were included in several experiments. The results given here are from four experiments (A0015 Biostack, M0004 Fiber Optics Data Link, P0004 Seeds in Space, and P0006 Linear Energy Transfer Spectrum Measurement) and represent a large fraction of existing absorbed dose data. The TLDs were located on the leading and the trailing edges and the Earth end of the spacecraft under various shielding depths (0.48 to 15.4 g/cm$^2$). The measured absorbed doses were found to reflect both directional dependence of incident trapped protons and shielding.

At the leading edge, doses ranged from 2.10 to 2.58 Gy under shielding of 2.90 to 1.37 g/cm$^2$ Al equivalent (M0004). At the trailing edge, doses varied from 3.04 to 4.49 Gy under shielding of 11.7 to 3.85 g/cm$^2$ (A0015), doses varied from 2.91 to 6.64 Gy under shielding of 11.1 to 0.48 g/cm$^2$ (P0004), and a dose range of 2.66 to 6.48 Gy was measured under shielding of 15.4 to 0.48 g/cm$^2$ (P0006). At the Earth end of the spacecraft, doses from 2.41 to 3.93 Gy were found under shielding of 10.0 to 1.66 g/cm$^2$ (A0015). The effect of the trapped proton anisotropy was such that the western side of LDEF received more than 2 times the dose of the eastern side at shielding depths of ~1 g/cm$^2$. Calculations utilizing a directional model of trapped proton spectra predict smaller doses than those measured, being about 50% of measured values at the trailing edge and Earth end, and about 80% near the leading edge.

## INTRODUCTION

Passive detector assemblies were included in four separate experiments on the LDEF satellite. The detectors included plastic nuclear track detectors of various sensitivities for heavy particle LET spectra

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measurements, fission foil detectors and activation foils for neutron measurements and TLDs for total absorbed dose measurements. Only the TLD portion of the experiments is reported here.

The purpose of these measurements was to define the radiation environment, in some cases to determine the irradiation of experimental materials which accompanied the detectors, and in other cases to measure shielding and locational effects. All of the measurements are of use in the more general objectives of mapping the radiation environment and providing detailed measurements for intercomparison with calculations using modeling of the incident radiation and propagation through shielding. Preliminary calculations have been made using the Marshall Space Flight Center Proton Transport Code and detailed models of the experimental shielding materials.

## EXPERIMENTS

The TLDs located in the four LDEF experiments which are discussed here were surrounded by diverse shielding materials and thicknesses and were located on different parts of the LDEF vehicle.

In the P0006 experiment, 18 TLD-700 chips were spread evenly in each of five layers within a large detector stack. The stack was chiefly composed of layers of different plastic types and of aluminum. The overall stack was 10.8 cm square (with ~1.5 mm clipped from the corners) by 10 cm thick and was contained in an Al cylindrical canister with inner dimension of 15.2 cm diameter and 10 cm depth. It was located in Tray F2 near the trailing edge of the vehicle and positioned intermediately between four larger canisters of the P0004 experiment.

In the P0004 experiment, small plastic holders containing four TLD-700 chips were placed in six Al canisters carrying seeds (five canisters of tomato seeds, one canister with a variety of seeds). The canister interiors were 31 cm in diameter with average depths of about 12.5 cm, and they had rounded lids. They were arrayed, $3 \times 2$, in Tray F2. The TLDs were centered in the canisters, either at the top or bottom or at a position roughly centered within the seeds.

The M0004 experiment included two small Al canisters (interior dimensions of 4.8 cm diameter and 1.3 cm depth) containing two TLD plates each, which were separated by plastic stacks. Each plate contained either 3 or 4 TLD-700 chips. The canisters were mounted, canted 90° to each other, next to other flight components of the experiment in Tray F8 near the leading edge.

In the A0015 experiment, detector stacks containing TLD plates were included in three different Biostack canisters. The canisters were of Al with acrylic plastic liners. Interior dimensions were 9.7 cm diameter and 8.5 cm depth and the detector stacks were 7 cm square (with ~1.5 mm clipped from the corners) and 8.5 cm thick. The stacks were mainly composed of layers of different plastic types and Al. Canister #1 was located at the Earth end of the vehicle and contained three TLD plates with 4 or 5 TLD-700 chips. Canister #2 was located in Tray C2 near the trailing edge and also contained three TLD plates with 4 or 5 TLD-700 chips. Canister #3 was also located in Tray C2 but was vented to space and only partially devoted to radiation detectors. It contained one TLD plate with 6 TLD-700 chips.

Table 1. P0006: LDEF Absorbed Dose Measurements With TLD-700

| TLD Plate No. | Tissue Absorbed Dose (Gy) | Dose Rate (mGy/d) | Al Equivalent Shielding ($g/cm^2$) |
|---|---|---|---|
| 1 | 6.48 ± 0.24 | 3.07 ± 0.11 | 0.48 |
| 2 | 3.92 ± 0.21 | 1.85 ± 0.10 | 4.10 |
| 3 | 3.16 ± 0.15 | 1.49 ± 0.07 | 8.34 |
| 4 | 2.76 ± 0.13 | 1.31 ± 0.06 | 12.2 |
| 5 | 2.66 ± 0.12 | 1.26 ± 0.06 | 15.4 |

The doses were approximately uniform over Plates 1 and 2 and were non-uniform over Plates 3, 4, and 5 (due to lesser shielding through the sides than through the top of the detector assembly for the deeper TLD plates). The minimum shielding to the side (for only the detector assembly) of the individual TLDs was 1.96 to 6.66 $g/cm^2$ Al equivalent. All shielding was converted to Al equivalent on the basis of the relative ranges of 100 MeV protons in the materials.

## MEASUREMENTS

The TLD measurements from the four experiments are given in Tables 1-4. The highest doses are seen to be near the trailing edge under thin shielding. Doses are lower by more than a factor of two near the leading edge, taking shielding into account, and doses at the Earth end are intermediate between the leading and trailing edges. This distribution of doses is due to trapped proton anisotropy combined with the shielding from the LDEF vehicle, which together yield a dose maximum at the western side of the vehicle.

The distribution of doses within a given flight canister is also complex, as demonstrated from the P0006 measurements in Fig. 1. As vertical shielding thickness of the TLD plates increases, average dose decreases and the spread in doses across a plate increases. The spread is due to radiation entering through the sides of the canister. The solid line represents the distribution of smallest doses from the TLD plates, near the plate centers, where the effect of radiation entering through the sides of the canister is minimized. A comparable study of dose distribution cannot be done for the other three experiments where there were only a few TLDs per plate.

The doses measured in the A0015 Biostack canisters can be compared with other canister measurements reported by Reitz.[1] Table 5 shows an approximate agreement of measured doses at the trailing edge and at the Earth end, as functions of vertical shielding thickness. Only approximate agreement can be expected since the measurements are from different canisters with different contents, internal geometries and horizontal distributions of TLDs.

Table 2. P0004: LDEF Absorbed Dose Measurements with TLD-700.

| Detector No. | Canister No. | Tissue Absorbed Dose (Gy) | Dose Rate (mGy/d) | Al Equivalent Shielding (g/cm$^2$) |
|---|---|---|---|---|
| 1 | 6 | 6.64 ± 0.29 | 3.14 ± 0.14 | 0.48 |
| 2 | 6 | 2.91 ± 0.07 | 1.38 ± 0.03 | 11.1 |
| 3 | 6 | 3.88 ± 0.22 | 1.83 ± 0.10 | ~5 |
| 4 | 4 | 3.12 ± 0.08 | 1.48 ± 0.04 | 6.11 |
| 5 | 2 | 3.05 ± 0.08 | 1.44 ± 0.04 | 6.10 |
| 6 | 5 | 3.09 ± 0.08 | 1.46 ± 0.04 | 6.10 |
| 7 | 7 | 2.93 ± 0.10 | 1.39 ± 0.05 | 6.10 |
| 8 | 3 | 3.15 ± 0.08 | 1.49 ± 0.05 | 6.10 |
| GC1 | | $3.2 \pm 0.2 \times 10^{-3}$ | $1.3 \times 10^{-3}$* | |
| GC2 | | $3.2 \pm 0.2 \times 10^{-3}$ | $1.3 \times 10^{-3}$* | |

*For a total detector assembly time of 2418 days. The flight detectors are averaged over the LDEF orbital duration of 2115 days.
The minimum shielding to the side (for only the detector assembly) of the individual TLDs was ~12.4 g/cm$^2$ Al equivalent. All shielding was converted to Al equivalent on the basis of the relative ranges of 100 MeV protons in the materials. The proton range in the seed was assumed to be equal (in units of g/cm$^2$) to that of polycarbonate plastic.

Table 3. M0004: LDEF Absorbed Dose Measurements with TLD-700.

| Detector No. | TLD Plate No. | Tissue Absorbed Dose (Gy) | Dose Rate (mGy/d) | Al Equivalent Shielding (g/cm$^2$) |
|---|---|---|---|---|
| 1 | 1 | 2.10 ± 0.13 | 0.99 ± 0.06 | 2.90 |
| | 2 | 2.37 ± 0.10 | 1.12 ± 0.05 | 1.37 |
| 2 | 1 | 2.19 ± 0.12 | 1.04 ± 0.06 | 2.90 |
| | 2 | 2.58 ± 0.09 | 1.22 ± 0.04 | 1.37 |
| 3(GC) | 1 | $2.9 \pm 0.2 \times 10^{-3}$ | $1.3 \pm 0.1 \times 10^{-3}$* | |
| | 2 | $3.2 \pm 0.2 \times 10^{-3}$ | $1.4 \pm 0.1 \times 10^{-3}$* | |
| 4(GC) | 1 | $2.9 \pm 0.2 \times 10^{-3}$ | $1.3 \pm 0.1 \times 10^{-3}$* | |
| | 2 | $2.9 \pm 0.2 \times 10^{-3}$ | $1.3 \pm 0.1 \times 10^{-3}$* | |

*For a total detector assembly time of 2271 days. The flight detectors are averaged over the LDEF orbital duration of 2115 days.
All shielding materials were converted to Al equivalent on the basis of the relative ranges of 100 MeV protons in the materials.

Table 4. A0015: LDEF Absorbed Dose Measurements with TLD-700.

| Canister No.* | TLD Plate No. | Tissue Absorbed Dose (Gy) | Dose Rate (mGy/d) | Al Equivalent Shielding (g/cm$^2$) |
|---|---|---|---|---|
| 1 | 1 | 3.93 ± 0.08 | 1.86 ± 0.04 | 1.66 |
| | 2 | 2.74 ± 0.23 | 1.30 ± 0.11 | 6.23 |
| | 3 | 2.41 ± 0.18 | 1.14 ± 0.09 | 10.0 |
| 2 | 1 | 4.49 ± 0.11 | 2.12 ± 0.05 | 3.85 |
| | 2 | 3.29 ± 0.22 | 1.56 ± 0.10 | 7.83 |
| | 3 | 3.04 ± 0.32 | 1.44 ± 0.15 | 11.7 |
| 3 | 1 | 3.47 ± 0.22 | 1.64 ± 0.10 | — |

*Canister #1 was to Earthside.
*Canister #2 was at the trailing edge.
*Canister #3 was vented to space and at the trailing edge.
Minimum shielding to the side (for only the detector assembly) of the individual TLDs was 2.52 to 5.31 g/cm$^2$ Al equivalent.
All shielding materials were converted to Al equivalent on the basis of the relative ranges of 100 MeV protons in the materials.

Table 5. Comparison of LDEF A0015 Absorbed Doses from TLD-700.

| Location | Laboratory | Tissue Absorbed Dose (Gy) | Vertical Shielding (g/cm$^2$) |
|---|---|---|---|
| Earthside | USF* | 3.93 ± 0.08 | 1.66 |
| | DLR** | 3.79 ± 0.17 | 0.7 |
| | | 3.89 ± 0.19 | 0.7 |
| | USF | 2.41 ± 0.18 | 10. |
| | DLR | 2.22 ± 0.30 | 12. |
| | | 1.99 ± 0.25 | 14. |
| Trailing Edge | USF | 4.49 ± 0.11 | 3.85 |
| | DLR | 4.73 ± 0.26 | 0.7 |
| | | 3.88 ± 0.64 | 2. |
| | USF | 3.04 ± 0.32 | 12. |
| | DLR | 2.38 ± 0.22 | 12. |
| | | 2.46 ± 0.26 | 12. |

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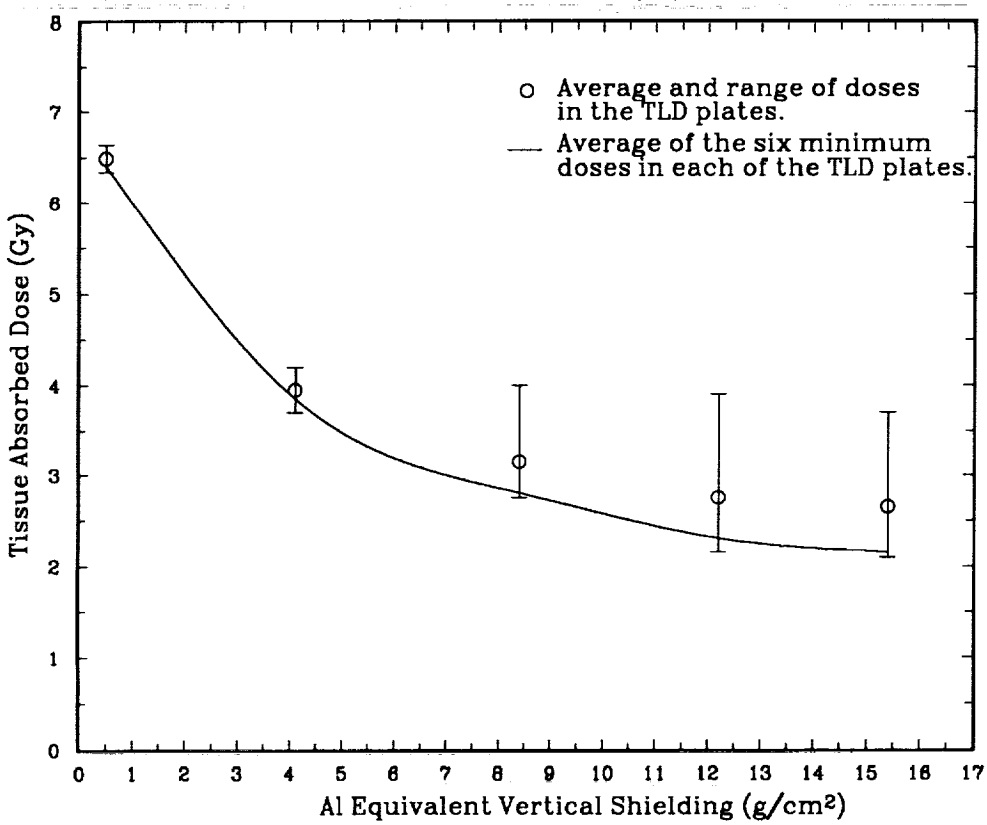


Figure 1: TLD-700 doses in the LDEF P0006 experiment.

## COMPARISON OF MEASURED AND CALCULATED DOSES

The Marshall Space Flight Center Proton Transport Code, which utilizes directionally-dependent trapped proton spectra[2], has been used to calculate doses for comparison with measured values. The flight canister physical configurations were modeled for the calculations.[3] Comparisons with measurements are shown in Table 6. The ratio of calculated to measured doses is approximately 50% near the trailing edge and at the Earth end, and approximately 80% near the leading edge. The GCR contribution to dose is not included in the calculations but at the LDEF orbit this represents a small fraction of total dose.[4,5] The differences seen are representative of the present state of trapped proton models and calculational codes. The different dose ratios near the leading edge, as compared with other locations, are not presently understood.

## CONCLUSIONS

TLD measurements in four LDEF experiments have yielded absorbed dose as a function of shielding thickness near the leading and trailing edges and at the Earth side of the LDEF vehicle. A consistent set of dose values is produced which defines much of the LDEF radiation environment and provides comparisons for dose calculations using advanced trapped proton predictions and transport codes. Dose rates up to 3.14 mGy/d (0.48 g/cm$^2$ shielding) and down to 1.26 mGy/d (15.4 g/cm$^2$ shielding) were found near the trailing edge. The dose rate range near the leading edge was 0.99-1.22 mGy/d (2.90-1.37 g/cm$^2$ shielding) and at the Earth end it was 1.14-1.86 mGy/d (10.0-1.66 g/cm$^2$ shielding). Calculations using directionally dependent trapped proton spectra produced doses less than those measured with ratios of about 50% for locations near the trailing edge and at the Earth end, and about 80% near the leading edge. Further refinement is needed in the trapped proton modeling. This goal may be advanced by results from other radiation detectors flown in the LDEF experiments which are still under analysis.

## REFERENCES


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Table 6. LDEF Absorbed Dose Calculations: Comparison with TLD Measurements.

| | Detector | Location | Shielding Min. Al. Equiv. ($g/cm^2$) | Absorbed Dose in Tissue (cGy) Measured | Calculated | Ratio: Calculated/ Measured |
|---|---|---|---|---|---|---|
| Exp. P0004 | #1 | Can. #6 | 0.48 | 664 ± 29 | 338 | 0.51 |
| | #3 | Can. #6 | ~5 | 388 ± 22 | 170(a) | 0.44 |
| | #4 | Can. #4 | 6.1 | 312 ± 8 | 172 | 0.55 |
| Tray F2 | #5 | Can. #2 | 6.1 | 305 ± 8 | 170 | 0.56 |
| Near Trailing | #6 | Can. #5 | 6.1 | 309 ± 8 | 172 | 0.56 |
| Edge | #7 | Can. #7 | 6.1 | 293 ± 10 | 167 | 0.57 |
| | #8 | Can. #3 | 6.1 | 315 ± 8 | 172 | 0.55 |
| | #2 | Can. #6 | 11.1 | 291 ± 7 | 141 | 0.48 |
| Exp. P0006 | TLD Plate #1 | | 0.48 | 630(b) | 327 | 0.52 |
| | TLD Plate #2 | | 4.1 | 367 | 182 | 0.50 |
| Tray F2 | TLD Plate #3 | | 8.3 | 275 | 138 | 0.50 |
| Near Trailing | TLD Plate #4 | | 12.2 | 218 | 118 | 0.54 |
| Edge | TLD Plate #5 | | 15.4 | 208 | 110 | 0.53 |
| Exp. M0004 | #1 | Plate #2 | 1.37 | 237 ± 10 | 198 | 0.84 |
| Tray F8 | #1 | Plate #1 | 2.90 | 210 ± 13 | 168 | 0.80 |
| Near Leading | #2 | Plate #2 | 1.37 | 258 ± 9 | 207 | 0.80 |
| Edge | #2 | Plate #1 | 2.90 | 219 ± 12 | 180 | 0.82 |
| Exp. A0015 | TLD Plate #1 | | 1.66 | 393 ± 8 | 205(c) | 0.52 |
| Tray G2 | TLD Plate #2 | | 6.23 | 274 ± 23 | 127 | 0.46 |
| Earth End | TLD Plate #3 | | 10 | 241 ± 18 | 113 | 0.47 |

(a) Calculated at 6.1 $g/cm^2$ depth.
(b) Measured values at middle TLD plate (i.e. minimum TLD value in plate), corresponding to location used in calculations.
(c) Detailed geometry description of Tray G2 not included in calculations.