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A MEASUREMENT OF THE RADIATION DOSE TO LDEF BY PASSIVE DOSIMETRY

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SUMMARY

The results from a pair of thermoluminescent dosimeter experiments flown aboard LDEF show an integrated dose several times smaller than that predicted by the NASA environmental models for shielding thicknesses much greater than 0.10 gm/cm^2 of aluminum. For thicknesses between 0.01 and 0.1 gm/cm^2, the measured dose was in agreement with predictions.

INTRODUCTION

The Space and Environment Technology Center of The Aerospace Corporation fielded two related experiments on LDEF to measure the energetic radiation dose by means of passive dosimetry. The sensors were LiF thermoluminescent dosimeters mounted behind various thicknesses of shielding. In this report, the details of the experiment are described first, followed by the results of the observations. A comparison is made with the predictions based upon the NASA environmental models and the actual mission profile flown by LDEF; conclusions follow.

EXPERIMENTS

The TLDs used in these two experiments were Harshaw TLD-100 LiF ribbon thermoluminescent dosimeters. Their size is 1/8" x 1/8" x .035". They were packaged at Harshaw on 10 October 1980, control number T-1409-S(1). A Harshaw Model 3000 was used for readout. The procedures recommended by Harshaw were followed carefully.

The configuration of the first experiment consisted of two identical packets of 16 TLDs arranged in planar arrays. One array was placed on the leading edge of the spacecraft, the other on the trailing edge. These arrays were installed in opaque packets of 1-mil aluminum foil and Kapton tape mounted behind an aluminum plate of 30-mil thickness. The aluminum shield and foil wrapping of the TLDs were approximately 0.22 gm/cm^2. In addition to the flight arrays, two control arrays were prepared that were kept with the flight

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arrays as long as possible during experiment integration, and then stored in our laboratory. After recovery, the flight detectors were read out in groups of four, alternating with the control detectors.

The TLDs were calibrated before flight with a Co^{60} gamma source. The flight and control detectors were re-calibrated after the flight using a 55-MeV proton beam at the Lawrence Berkeley 88" Cyclotron. It was decided to use protons for the re-calibration because the flight data, discussed below, suggested that the majority of the dose observed in this first experiment was due to energetic protons that impinged upon LDEF in the region of the South Atlantic Magnetic Anomaly. The proton beam fluence was monitored using a plastic scintillator and an ion chamber. Figure 1 is a plot of the calibration data and a least-squares fit to these data. These new data are in good agreement with our earlier calibration data.

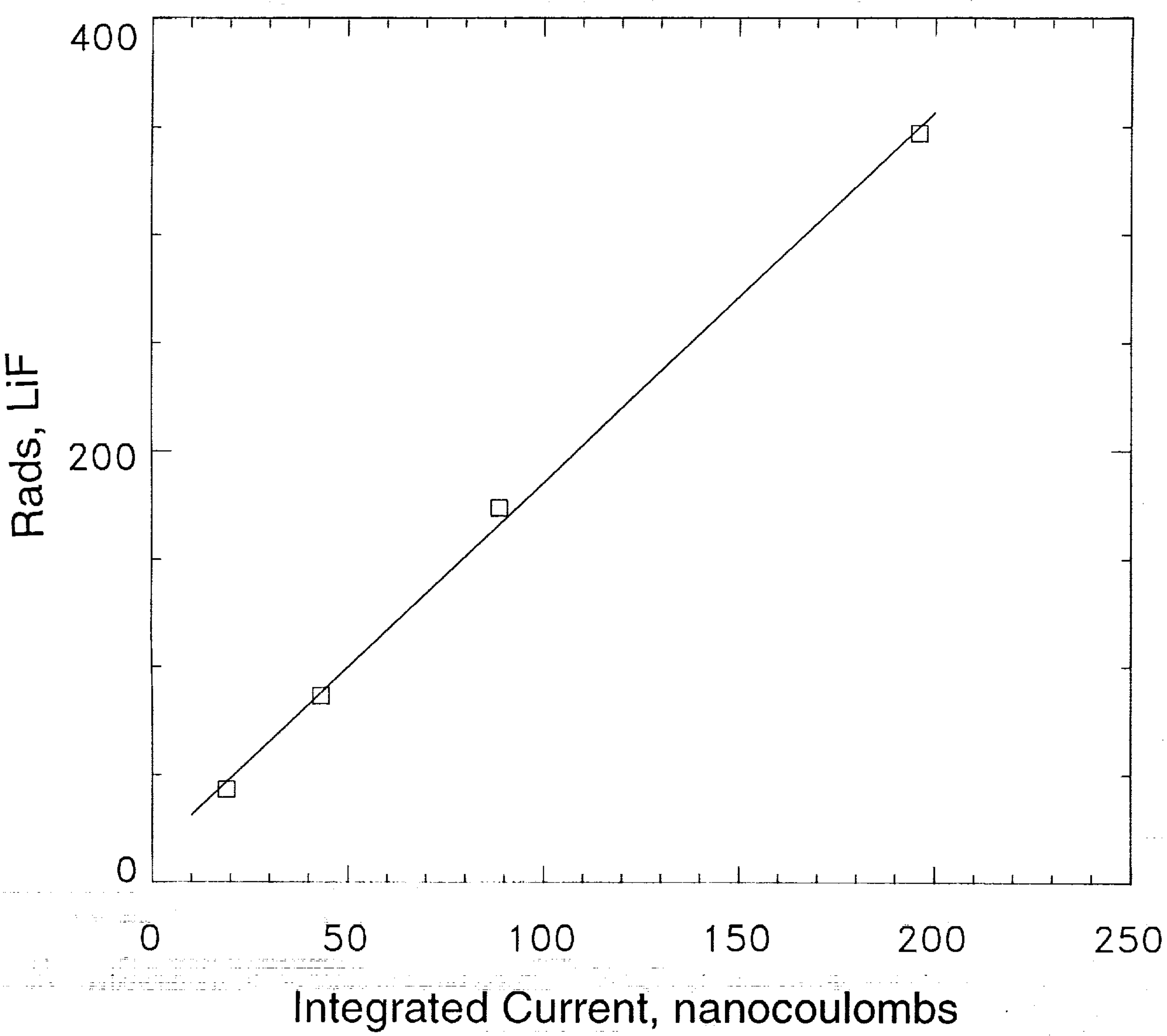

Figure 1. A plot of dose from 55-MeV protons vs integrated current as measured with the Harshaw 3000. The actual flight detectors were used in this calibration run.

The configuration of the second experiment consisted of 12 LiF TLDs, each mounted behind a different thickness of metal shield. Figure 2 is a photograph of the assembly; Table 1 gives the shield thicknesses and the shield material. Three of these assemblies were mounted on the leading edge of LDEF and exposed to the ambient radiation for the entire 69-month mission. A fourth assembly also was mounted on the leading edge, but was covered after 40 weeks with a shield of stainless steel almost 2 cm thick. Thus, during most of the LDEF mission, the dose received by the fourth assembly was determined by the much thicker cover. A fifth assembly was mounted on the trailing edge of LDEF and exposed for the entire mission while the sixth assembly also was on the trailing edge and recovered after 40 weeks. The assembly locations are summarized in Table 2.

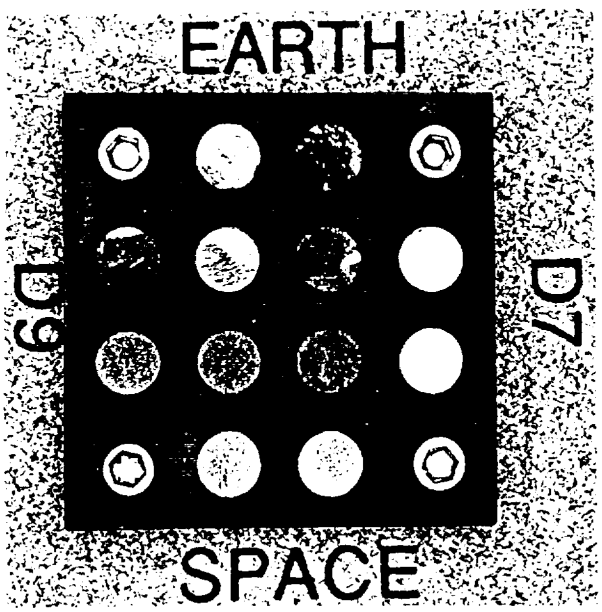

Figure 2. One of the flight assemblies used in Experiment 2.

Table 1. Shield Thicknesses

Shield Number	Material	Shield Thickness (mil)
1	Al	.0295
2	Ti	.096
3	Stainless steel	.20
4	Al	1.0
5	Stainless steel	.57
6	Stainless steel	.80
7	Stainless steel	1.0
8	Stainless steel	1.5
9	Stainless steel	2.2
10	Stainless steel	4.4
11	Stainless steel	8.0
12	Stainless steel	16

Table 2. Exposure Time and Location on LDEF

Assembly Number	Location on LDEF	Exposure Time
1	Leading edge	69 months
2	Leading edge	69 months
3	Leading edge	69 months
4	Leading edge	40 weeks
5	Trailing edge	69 months
6	Trailing edge	40 weeks

RESULTS

Experiment 1

Table 3 gives the results of the readout measurements for the flight and control arrays in nanocoulombs. These readings are shown in detail so the reader can get a feel for the scatter in the measurements.

It can be seen that the control dose is negligible. The LDEF flight doses were:

$$\text{Leading Edge} = 88.9 \pm 11.5 \text{ rads} \quad (1)$$

$$\text{Trailing Edge} = 147 \pm 21.1 \text{ rads} \quad (2)$$

$$\text{Dose Ratio} = 1.65 \pm 0.32 \quad (3)$$

Table 3. TLD Readings for LDEF Flight and Control Detectors

Sample #	Leading Edge (nC)	LE Control (nC)	Trailing Edge (nC)	TE Control (nC)
1	†	0.05 nC	70.87	0.03
2	42.54	0.02	89.02	0.02
3	37.62	0.02	83.43	0.03
4	39.09	0.02	85.88	0.02
5	46.76	0.03	73.62	0.02
6	42.41	0.03	62.95	0.02
7	42.14	0.03	78.85	0.02
8	50.55	0.02	67.43	0.02
9	38.14	0.02	76.46	0.02
10	46.00	0.03	76.91	0.03
11	42.84	0.02	95.53	0.02
12	50.22	0.03	82.07	0.02
13	37.24	0.03	62.80	0.02
14	40.36	0.03	71.97	0.02
15	38.08	0.03	61.22	0.03
16	56.19	0.02	96.88	0.03
	43.35 ± 5.59		77.24 ± 11.09	

† A malfunction in the readout apparatus interfered with the measurement of the first leading edge TLD.

Experiment 2

Experiment 2 differed from Experiment 1 in that it consisted of single LiF TLDs under a variety of shield thicknesses and materials rather than several TLDs under a single shield thickness. As a consequence, it is convenient to show the observations in graphical form. Figure 3 is a plot of the dose vs shielding thickness for the three arrays exposed on the leading edge of LDEF for 69 months. Three different symbols are used; the solid line shows the average value. The results for all shields are reduced to the equivalent gm/cm^2 of aluminum. It can be seen that the measured dose reaches an asymptotic value at about 0.01 gm/cm^2; a smaller shield thickness did not increase the measured dose.

Figure 4 shows the results for the leading-edge exposure of 40 weeks at the beginning of the LDEF mission. It can be seen that the depth-dose profile for the 40-week mission shows the same shape as for the 69-month mission. Figure 5 shows the ratio of the two exposures; the solid line is simply the ratio of 69 months to 40 weeks. The ratio of doses shown in Figure 5 clearly is not a simple function of shielding thickness. Figure 6 shows the measured and predicted dose on the leading edge for the 69-month mission. The predicted dose (ref. 1) is over 300,000 rads for zero shield thickness (not plotted).

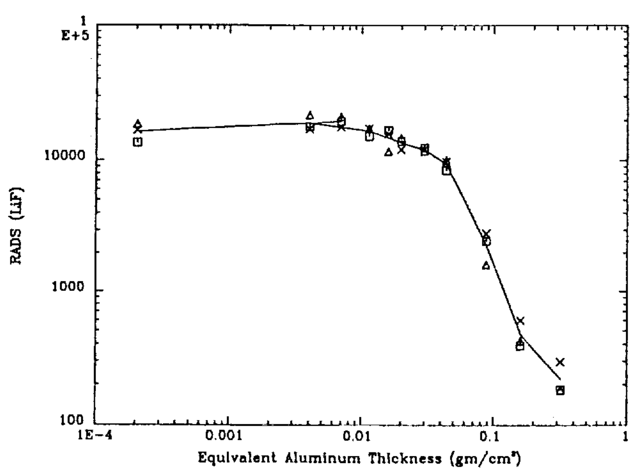

Figure 3. The measured dose vs shielding thickness for the three arrays exposed on the leading edge of LDEF for a 69-month period. The solid curve gives the average of the three measurements.

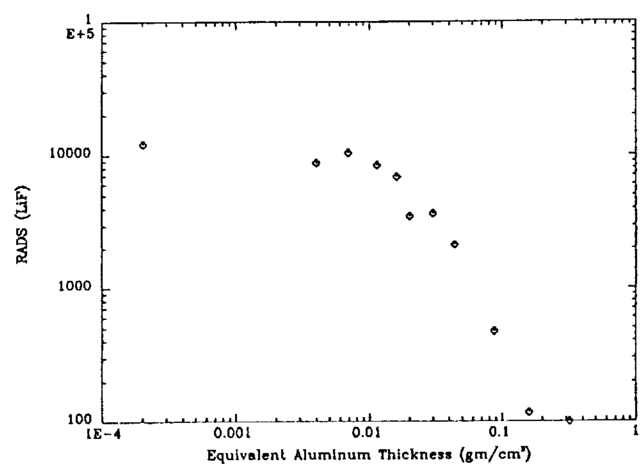

Figure 4. The depth-dose profile for the single leading edge exposure of 40 weeks.

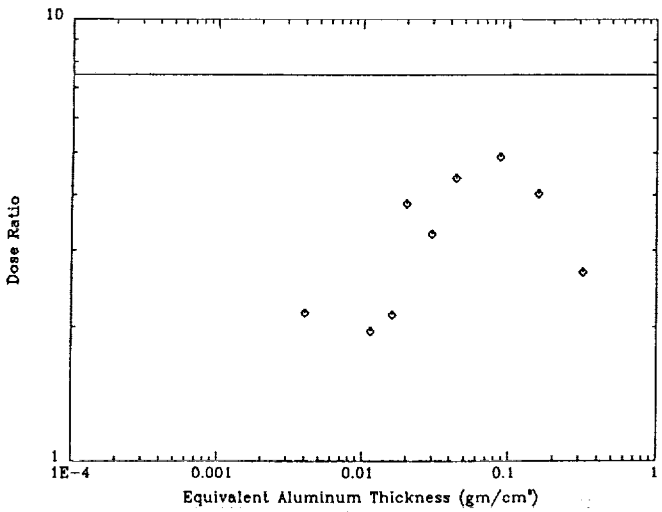

Figure 5. The ratio of the results given in Figures 3 and 4 are shown as well as the ratio of exposure times, solid curve.

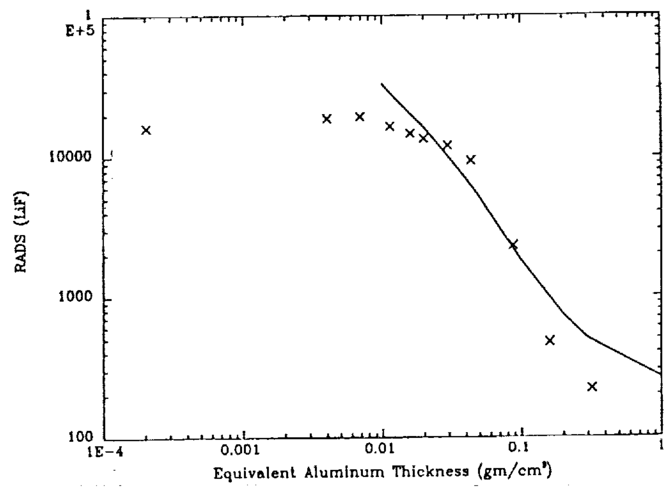

Figure 6. A comparison of the dose measured on the leading edge of LDEF and the predicted dose for the entire mission (69 months).

DISCUSSION

Experiment 1

A difference between the leading-edge and trailing-edge dose was expected, the so-called East-West effect, but was larger than expected. The predicted dose is about 690 rads with 380 rads due to protons and 310 rads due to electrons (ref. 1). Thus, the observed dose is of the order of 15% of the predicted value.

It has been suspected for some time that the NASA AE-8 model over-predicts the electron dose for modest shielding such as used in Experiment 1. Gussenhoven et al. (ref. 2) have shown from observations made aboard CRRES that this suspicion is correct, in general. A much smaller electron dose than the predicted 140 rads would mean that the dose observed in Experiment 1 was due almost entirely to protons. Support for this supposition is given by the observed East-West effect. The large observed value of 1.65 is in agreement with the predictions if the electron dose is negligible compared to the proton dose. The electrons, because of their small gyro-radii in the geomagnetic field, show no East-West effect and, thus, lessen the observed dose asymmetry.

Even if the measured dose were entirely due to protons, it was less than 40% of the predicted proton dose. However, the prediction used the NASA AE-8 model. This model is based upon data acquired in the late 1960s to early 1970s time period. The model contains two environments, one for solar minimum and one for solar maximum. The differences of course are based upon the magnitude of the solar-cycle effect during the time period of data acquisition. The increase in atmospheric density increases the drag upon the protons as well as the spacecraft. The solar activity during the later part of the LDEF mission was substantially higher than during the solar maximum when the model data were acquired. Therefore, it is expected that the proton fluxes during the later part of the LDEF mission would have been significantly less than predicted by the AP-8 model.

Experiment 2

Figure 5 shows that the ratio of the dose received over 69 months of exposure to that experienced over the first 40 weeks of the LDEF mission is substantially less than the ratio of exposure times. Furthermore, Figure 6 shows that the measurements agree fairly well with the predictions for shielding thicknesses between ≈ .03 gm/cm^2 and ≈ .10 gm/cm^2. For thicknesses greater or less than this shielding range, the predicted dose is significantly higher than the observations. Note that both experiments show a substantially lower dose at 0.3 gm/cm^2 than given by the predictions. How could we explain these differences?

An obvious question is that of the linearity of the response of the TLD dosimeters over the long LDEF mission. The literature on LiF TLDs gives a large scatter in values for fading in LiF (refs. 3,4,5). Values range from several percent per month to a percent per year. The higher values would significantly affect the LDEF results. If, for example, the fade were 20% per year, the real dose would have been around twice the measured dose for the samples exposed over the entire mission. However, fading does not explain the results shown in Figures 4 and 5 unless one were to postulate that the fading is a complex function of radiation exposure. Other studies have indicated a supralinearity in the response of TLDs (ref. 6); such behavior would worsen the fit between predictions and measurements.

A second question is that of the useful range of absorbed dose for LiF. Bull (ref. 4) gives a range of 5 x 10^{-3} to 10^5 rads. This useful dose range covers the expected dose to the LDEF experiments. However, at low energy, the electrons and protons do not uniformly irradiate the entire TLD, but are absorbed in a small portion of the TLD that faces outboard. Saturation could have occurred in the near-surface region of a TLD without the entire device being adversely affected. A simple range estimate indicates that it takes on the order of 600 keV for an electron to penetrate a TLD-100 and 13 MeV for a proton. An accurate calculation of the depth-dose profile in a TLD-100 would require detailed knowledge of the electron and proton energy spectra, which are at best poorly known. The flattening in the observed dose occurs around 2 x 10^4 rads, which is 20% of the maximum useful range of LiF dosimeters (ref. 4); therefore, the hypothesis that saturation effects are at least a partial cause of the deviation between predictions and observations for the thin shields cannot be ruled out.

Figure 5 further supports the saturation hypothesis — the reason that the dose ratio below 0.01 gm/cm^2 is much less than the ratio of exposure times is due to the onset of saturation effects. Once saturation begins, the effectiveness of further exposure is reduced, and, eventually, more radiation has no further effect on the TLD response. The dose ratio never equals the ratio of exposure times of approximately 7.5.

However, since LDEF moved to a more benign environment at lower altitude as the mission progressed, the dose ratio would be expected to be less than the exposure time ratio.

The discussion of the results of Experiment 2 given above suggest that fading is not a major factor in these experiments. Thus, it is concluded that the radiation dose in the LDEF orbit resulting from higher energy particles is more benign than predicted by the NASA models. Furthermore, since the observed East-West effect is equal to that predicted for protons alone, it suggests that the electron dose is negligible compared to that from protons.

PRESENT CONCLUSIONS

The results of this experiment suggest that for the LDEF mission:

1) The dose due to electrons that can penetrate 0.22 gm/cm^2 or more was an order of magnitude lower than predicted.

2) The dose due to protons that can penetrate 0.22 gm/cm^2 or more was a factor of 3 lower than predicted.

3) The total dose for shielding thicknesses between ≈ 0.01 gm/cm^2 and 0.1 gm/cm^2 agreed well with the predictions based upon the NASA models.

4) For shielding thicknesses less than ≈ 0.01 gm/cm^2 no conclusion has been reached at the present time.

ONGOING WORK

Saturation and fading effects are being studied. In order to estimate the magnitude of fading in our TLDs, 20 were irradiated again at the Lawrence Berkeley Laboratory with a 55-MeV proton beam. They will be read out over a year or more to determine the magnitude of fading. We will study saturation effects by irradiating some TLDs with low-energy electron and proton beams. It should be possible to determine if the apparent dose saturation is really due to saturation effects or indicates an absence of very-low-energy electrons and protons in the LDEF orbit.

It should be noted that the data base used in generating the NASA models does not go down to zero energy. Thus, the predictions given for LDEF are extrapolations into the unknown as the shielding thickness goes to zero. The LDEF environment is expected to be different at the lowest energies from two earlier low-altitude dosimetric missions — COSMOS 1887 (ref. 7) and COSMOS 2044 (ref. 8). These two Soviet missions had inclinations of 82.3° and 62.8°, respectively, and thus regularly traversed auroral latitudes, whereas LDEF remained below and was not exposed to auroral particles.

It is hoped that the activation experiments will lead to a quantitative value for the integrated proton flux over the LDEF mission that can be compared with the TLD results.

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