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P0004-1 Quick Look Final Report

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Introduction

The LDEF (Long Duration Exposure Facility) mission accumulated an unprecedented exposure to the space radiation environment in low earth orbit (LEO). LDEF was deployed on 6 April 1984 on STS-41C and returned to Earth on 20 January 1990 on STS-32 for a total mission duration of 2115 days or 5.790 years. LDEF was deployed into an 28.5°, 480×474 km orbit. Orbital altitude decayed over the duration of the mission.

The P0004-1 "Seeds in Space" experiment consited of six sealed aluminum canisters which contained tomato seeds and a variety of other seeds for the investigation of space radiation effects on the seeds. The seeds were contained in cloth bags. Interspersed among the bags of seeds were ten dosimeter packets to monitor the accumulated ionizing radiation exposure of the seeds. In addition to the ten flight dosimeter packets, four ground control packets and one ground movement packet were also included as part of the experiment. The P0004-1 experiment was mounted on the F2 tray, near the trailing edge of the LDEF orbiter (see Figure 1).

The P0004-1 dosimeter packets contained four types of radiation detecting materials - TLDs, CR-39 PNTDs, Tuffak polycarbonate PNTDS, and ^{6}LiF/CR-39 neutron detectors. Thermoluminescent Detectors (TLDs) measured the total absorbed dose of ionizing radiation. CR-39 plastic nuclear track detectors (PNTDs) are sensitive to ionizing radiation of $LET_{\infty}\cdot H_2O \geq 5$ keV/μm. Tuffak polycarbonate PNTDs are sensitive to ionizing radiation of $LET_{\infty}\cdot H_2O \geq 250$ keV/μm. ^{6}LiF/CR-39 detectors record exposure to thermal and resonance neutrons. All four detector types are passive and record accumulated radiation exposure.

Experiment

The ten radiation dosimeter packets included in the P0004-1 experiment were distributed among the six aluminum canisters containing seeds. Each dosimeter packet contained four types of radiation sensitive detectors. These detectors measure difference portions of the space radiaton environment. Thermoluminescent Detectors (TLDs) are sensitive to a wide spectrum of ionizing radiation though they record radiation of high LET with lower efficiency than low LET radiation. TLDs are used to measure total absorbed dose. CR-39 plastic nuclear track detectors (PNTD) are sensitive to ionizing radiation of $LET_{\infty}\cdot H_2O \geq 5$ keV/μm and are used to obtain LET spectra in a region from 5 keV/μm to >1000 keV/μm. Tuffak polycarbonate PNTDs are sensitive to ionizing radiation of $LET_{\infty}\cdot H_2O \geq 250$ keV/μm are used to measure the high LET tail of the space radiation environment. ^{6}LiF/CR-39 neutron detectors record neutron induced alpha particles through the ^{6}Li(n,α)T reaction. These detectors are used to measure the flux of thermal and resonance neutrons. Table 1 lists the

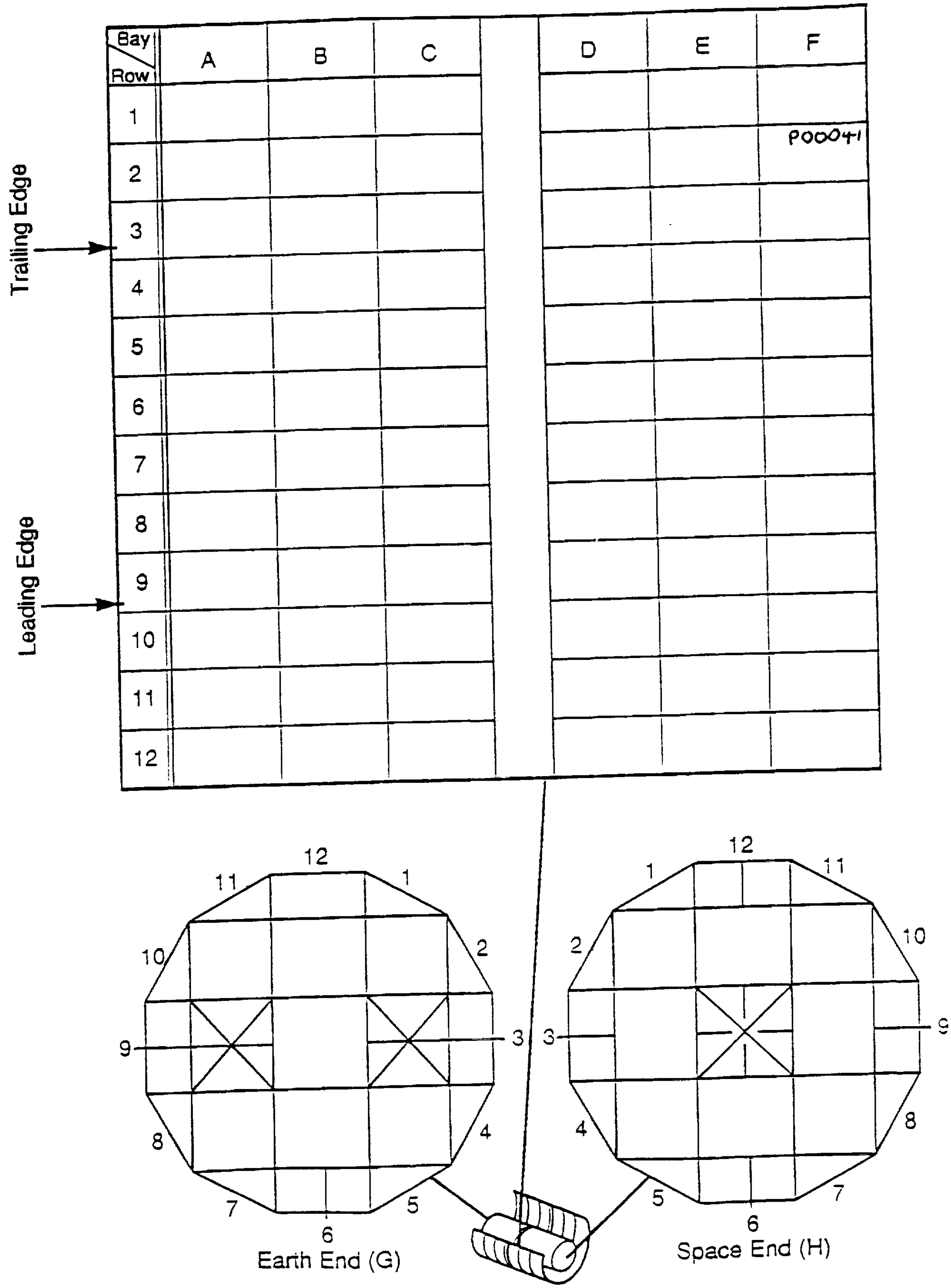

Figure 1: Position of the P0004-1 experiment on the LDEF spacecraft.

distribution of the various types of radiation detectors in the different dosimeter packets. Each detector packet consisted of an acrylic TLD holder containing the TLD chips and the ^{6}LiF/CR-39 neutron detectors, a pair of CR-39 PNTDs and a pair of Tuffak polycarbonate PNTDs.

Thermoluminescent Detectors

Each flight dosimeter packet contained several TLD chips to measure the total absorbed dose. Packets 1–8 contained four TLD-200 chips and four TLD-700 chips. Packets 9 and 10 contained six TLD-600 chips. The TLD chips were mounted in a 3.1 cm × 4.9 cm acrylic holder. The TLD holder is pictured in Figure 2. TLDs of the same manufactured batch as the flight TLDs were also included in the four ground control packets and in the ground movement packet.

Three different types of TLDs were used in the P0004-1 Dosimeter packets, TLD-200, TLD-600 and TLD-700. The distribution of the different TLD types can be seen in Table 1. TLD-200 is made of extruded CaF_2 crystal. TLD-600 and -700 are made of extruded ^{6}LiF and ^{7}LiF, respectively. Generally the LiF TLD chips show a flatter response to γ-rays. LiF is also less subject to signal fading and produced better defined glow peaks during readout.

In order to carry out the TLD analysis, it was necessary to establish TLD calibrations over the duration of the mission. Studies were undertaken to address two potential problems in the analysis of the LDEF TLDs. One study focused on the potential fading of latent TLD signal over the nearly six year exposure time. A second study focused on potential problems of high accumulated doses in the TLDs and a corresponding supralinearity in TLD response.

TLD Fading Study

A study has been undertaken to ascertain the extent of fading of signal in TLD-700 as a function of storage time at elevated temperatures. TLDs were irradiated with a dose of 1.053 rad ^{137}Cs γ-rays and stored in an oven in air at a constant temperature of 38°C. This was projected to be the highest temperature that the LDEF spacecraft and experiments would attain during the mission. A group of six TLDs are periodically removed and read out. Another group of six TLDs from the same manufactured bath is irradiated to the same 1.053 rad γ-ray dose and read out at the same time for comparison. The ratio of doses from the stored TLDs to newly irradiated TLDs is calculated. Figure 3 is a plot of the dose ratio as a function of storage duration at 38°C.

Initially there is a decline in the dose ratio extending over the first six weeks of storage. The ratio then levels off for the remainder of the study carried out to date. During readout, there was no preheating phase and the low temperature glow peak is present in the measurement. A preheating phase would have eliminated this low temperature glow peak. The initial decrease in dose ratio is due to the annealing out of this low temperature glow peak

Table 1: P0004-1 Seeds in Space Experiment. LDEF Seed Exposure Dosimeters

Dosimeter No.	Canister No.	CR-39 Pairs	Tuffak Pairs
01	6	8A-SE-1 / 8A-SE-2	TU-SE-1 / TU-SE-2
02	6	8A-SE-3 / 8A-SE-4	TU-SE-3 / TU-SE-4
03	6	8A-SE-5 / 8A-SE-6	TU-SE-5 / TU-SE-6
04	4	8A-SE-7 / 8A-SE-8	TU-SE-7 / TU-SE-8
05	2	8A-SE-9 / 8A-SE-10	TU-SE-9 / TU-SE-10
06	5	8A-SE-11 / 8A-SE-12	TU-SE-11 / TU-SE-12
07	7	8A-SE-13 / 8A-SE-14	TU-SE-13 / TU-SE-14
08	3	8A-SE-15 / 8A-SE-16	TU-SE-15 / TU-SE-16
09	6	8A-SE-17 / 8A-SE-18	TU-SE-17 / TU-SE-18
10	3	8A-SE-19 / 8A-SE-20	TU-SE-19 / TU-SE-20

	TLD-200, TLD-700 – Batch 2 chips
01–08	8 units, 4 chips of each type
09–10	2 units – 6 TLD-600 chips – 2 CR-39, one with Gd
#1–#4	4 ground control
	1 transportation background test unit

Ground Controls	
#1, #2	5 TLD-700, 2 TLD-600 with CR-39
#3, #4	4 TLD-200

Transportation Background	
	4 TLD-600

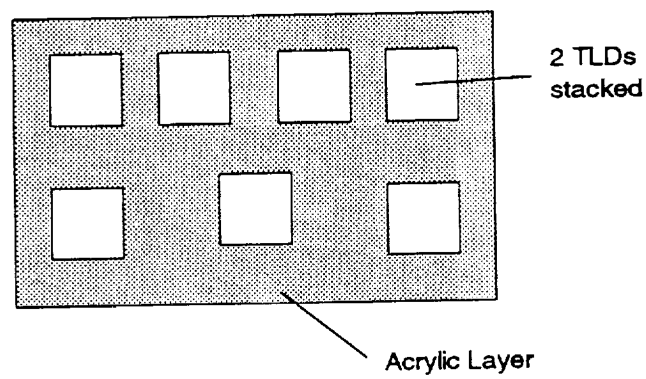

Figure 2: Configuration of TLDs and ^{6}LiF/CR-39 neutron detectors in acrylic TLD holder.

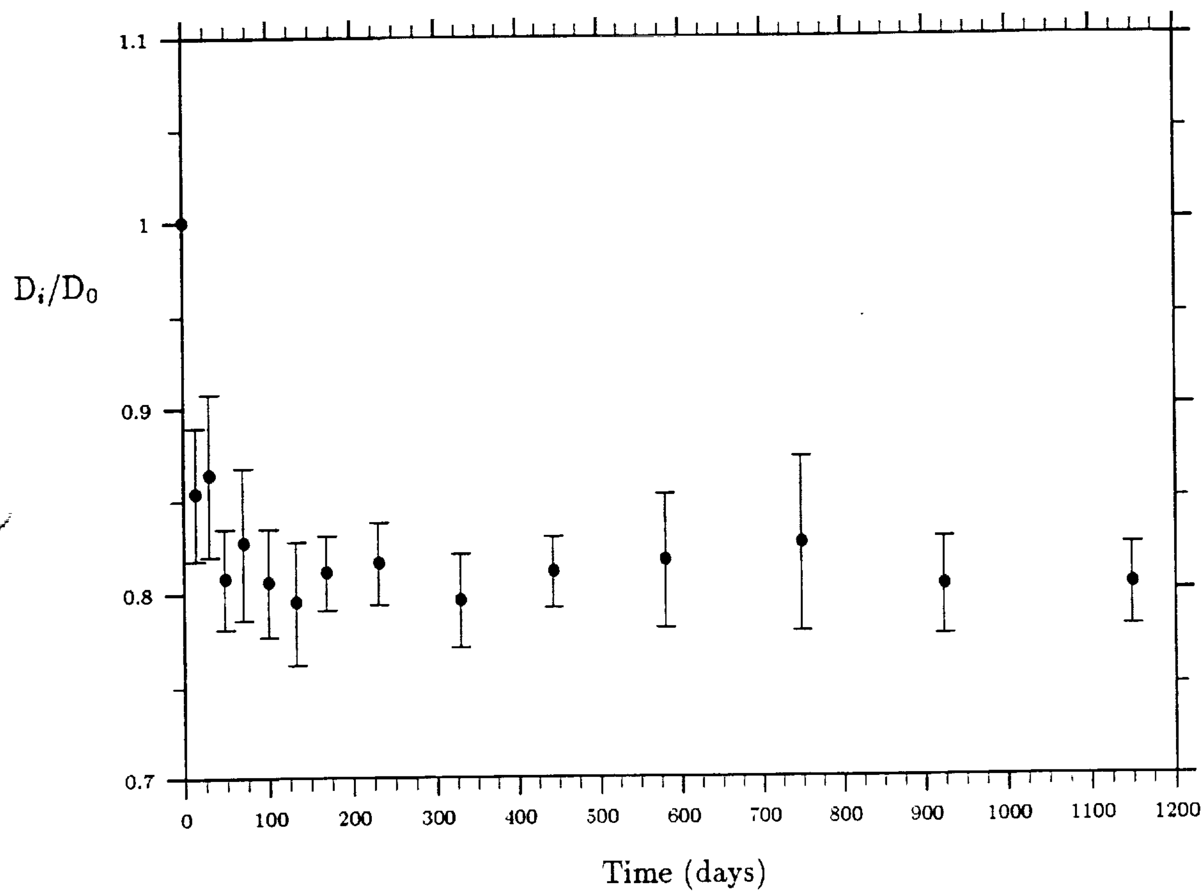

Figure 3: The fading of thermoluminesence in TLD-700 chips irradiated to 1.053 rad, then stored at 38°C, where D_i and D_0 were the doses measured from the stored TLDs and newly irradiated TLDs, respectively.

during the first several weeks of storage at elevated temperature. If a preheating step were included in the readout cycle (heating the TLDs at 120°C for 10 seconds before readout) the low temperature glow peak would anneal out and the dose ratio would appear approximately level during the entire duration of the study. These results indicate that for TLD-700, signal fading is not a serious problem for temperatures less the 38°C.

TLD Calibrations

TLDs of the same manufactured batches as those included in the P0004-1 experiment were used for purposes of calibration. TLDs were irradiated with an average dose of 6.284 rad ^{137}Cs γ-rays at intervals of two months during the length of the LDEF mission for a total dose of 207.36 rads. Following the retrieval of LDEF, these calibration TLDs were read out along with the flight TLDs. The purpose of the calibration TLDs was to simulate the fading of stored signal taking place in the TLDs contained in the experiment.

The TLD reader results are in units of nanocoulombs (nC). Dose calibration factors for types TLD-200 and TLD-700 were calculated in rad/nC. These dose calibration factors were then used during the readout of experimental TLDs, taking the fading of stored signal into account.

TLD High Dose Supralinearity

For large doses (>100 rads), supralinearity of TLD response becomes significant. A study was undertaken to measure this effect (see Figure 4). TLDs of type -200 and -700 were exposed to indentical high doses and read out. For the largest dose (10^3 rad), TLD-200 gave an erroneously high result due to the high light output. This was a problem even when a 100/1 neutral density filter was employed between the heated planchet and the photomultiplier tube to reduce light intensity. For large doses, for TLDs of the same dimensions, TLD-200 yields a signal/dose ratio approximately 20 times greater than that of TLD-700. It would appear that the output of the photomultiplier tube also becomes supralinear with respect to incident light intensity if too large a current in generated.[1]

To compensate for the supralinearity of TLD response for large doses, the high dose calibration points for TLD-200 were rejected. The dose response for TLD-200 at lower doses was extended in constant relationship to the TLD-700 response.

TLD Readout

Flight, background and calibration TLDs were read out together using a Harshaw Model 4000 reader. Due to the high doses accumulated during the length of the mission, a 100/1 neutral density filter was used to reduce light intensity from the heated TLDs to the photomultiplier tube. The readout cycle used consisted of a 10 second preheating phase at 120°C followed by a 7°C/sec heating rate to a maximum temperature of 325°C. The photomultiplier current output was integrated between 120°C and 260°C for determination of dose. Data

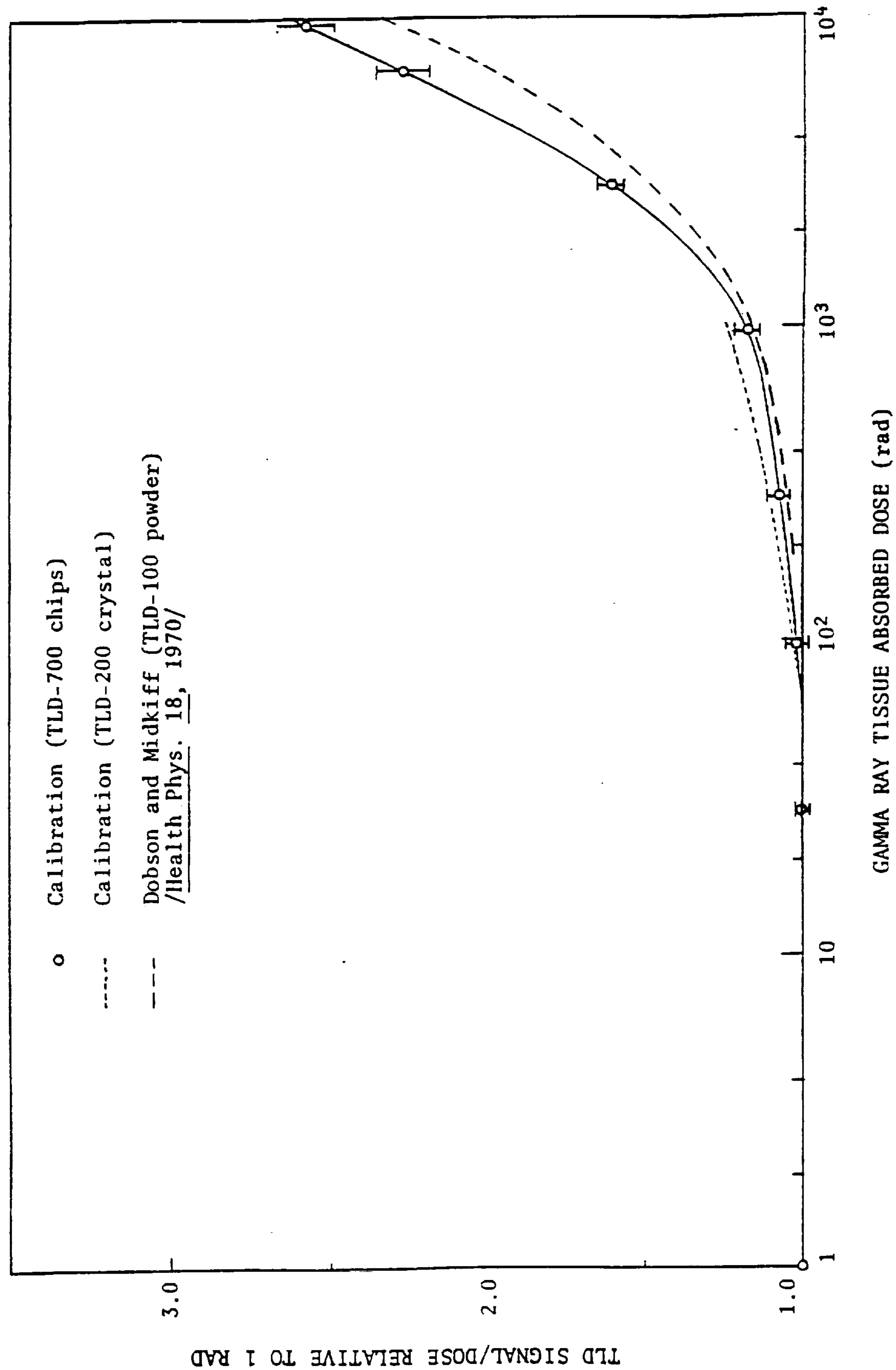

Figure 4: Calibrations of TLDs demonstrating the supralinearity at high doses.

Table 2: P0004: 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	0.42
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		$3.2 \pm 0.2 \times 10^{-3}$	1.3×10^{-3}*	
GC2		$3.2 \pm 0.2 \times 10^{-3}$	1.3×10^{-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.

from glow curves were measured up to 325°C for later examination of possible dose and LET dependent effects.

TLD Results and Discussion

The TLD dose measurements are given in Table 2. Mission doses from TLD-700 are seen to vary between 291 rad (maximum shielding) and 664 rad (minimum shielding). In each of the 8 detectors, which included both TLD-200 and -700, the -700 dose was higher. The average ratio of TLD-200 and -700 was 0.939. The reason for this discrepance is not clear, but we have elected to publish the TLD-700 results based on the flatter and more stable response. The standard deviations of the measurements were derived from the scatter in individual experimental and calibration readings. The accuracy of the doses is expected to be within ±5%.

The tissue absorbed dose measurements made with the TLDs showed that the dose under the least shielding (0.42 g/cm^2) for TLD-700 was 664 rad (314 mrad/d). In comparison with

Table 3: P0006: 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.

other LDEF TLD measurements, the highest P0006 dose was 648 rad (0.48 g/cm^2 shielding) while that from M0004 was 248 rad (1.37 g/cm^2 shielding). Table 3 lists the results from the TLDs contained in the P0006 experiment. Both the P0004 and the P0006 were on the trailing edge of the orbiter while the M0004 was on the leading edge. The dose ratio of ~2.5 between the trailing and the leading edge was mainly due to the anisotropy of trapped protons in the South Atlantic Anomaly where a large fraction of the total mission dose was accumulated.

The smallest TLD-700 dose from P0004 was 291 rad (138 mrad/d) behind the greatest shielding (1.11 g/cm^2) in the experiment. For the TLDs in different canisters, but with the same shielding, the TLD-700 doses were similar, with a minimum of 293 rad and a maximum of 315 rad. The No. 3 and No. 9 detectors were in the middle of canister No. 6 which was filled with 120 different types of seeds and where the shielding was not well known.

CR-39 PNTDs

CR-39 Plastic Nuclear Track Detector was included in the P0004-1 experiment to measure the LET spectra. CR-39 PNTD is sensitive to ionizing radiation of $LET_\infty \cdot H_2O \geq 5$ keV/μm. CR-39 has never before been used in a space mission of such long duration. It was therefore necessary to carry out studies on the long duration effects of the space environment on latent particle tracks in CR-39. In addition, due to the high fluence of tracks in the CR-39, it was necessary to establish a different etching protocol to avoid over-etching the detectors and losing the track data.

Environmental Studies of CR-39

The CR-39 PNTDs included in the P0004-1 experiment were exposed to environmental conditions which might have affected their performance as track detecting materials. The principle environmental factor which might have affected the track recording properties of CR-39 was long duration storage of the material at elevated temperatures. Temperature aboard LDEF was not regulated and was predicted to range from -22°C to 38°C. Several studies were carried out to assess the effect of long duration storage at elevated temperatures on latent tracks in CR-39.

CR-39 was exposed to a variety of ions and energies at the Lawrence Berkeley Laboratory Bevalac accelerator. The CR-39 samples were stored in air in an oven at a constant temperature of 38°C. This was predicted to be the highest temperature aboard LDEF during the mission. Table 4 gives a summary of the results of these studies. In all cases, the bulk etch rate V_G and the track etch rate V_T increased as functions of storage time. The reduced track etch rate V_R remained fairly constant over the duration of the study. Figure 5 illustrates V_G, V_T, and V_R as functions of storage duration for 900 MeV/amu Fe tracks in CR-39. After a period of annealing, the material deteriorated to a point where is was no longer possible to distinguish the tracks from the background.

Temperatures aboard LDEF rarely reached annealing temperatures. The "LDEF Post-Flight Thermal Analysis" report indicates that during the first year of the mission, temperature aboard LDEF remained on average well below 38°C.[2] Those samples of CR-39 which have been etched as part of the preliminary analysis procedure show none of the material degradation seen in the CR-39 samples used in the thermal annealing studies. A more complete description of the environmental studies of latent tracks in CR-39 can be found in USF TR-78.[3]

Calibration

CR-39 PNTDs from two of the flight dosimeter packets were irradiated to heavy ion beams at the Lawrence Berkeley Laboratory Bevalac accelerator for the purpose of calibration. Table 5 is a list of the ions and energies to which P0004-1 CR-39 detectors were exposed. All irradiations were made at a 90° angle of incidence. Following processing, track diameters corresponding to each ion/energy combination were measured and a plot of reduced etch rate V_R as a function of LET was generated. Figure 6 shows the calibration plot of V_R and LET. The line is a best fit 4th order polynomial to the calibration points. Points marked A are from a calibration plot of the same material which has not been aged for six years, scaled to fit the newly added points. The equation of the polynomial is the detector response function for this particular batch of CR-39, adjusted for age of material, and will be used in calculating the LET from measured track parameters.

Table 4: Summary of CR-39 Annealing Studies

CR-39	Ion	Energy	Maximum Annealing Duration
Batch 7 U4	Fe	900 MeV/n	14 months
16 U4	Fe	900 MeV/n	8 months
BDOP	Fe	900 MeV/n	no annealing
18 U4	Ne	282 MeV/n	4.3 months
18 U4	Ne	400 MeV/n	4.3 months
18 U4	Fe	1.7 GeV/n	4.3 months

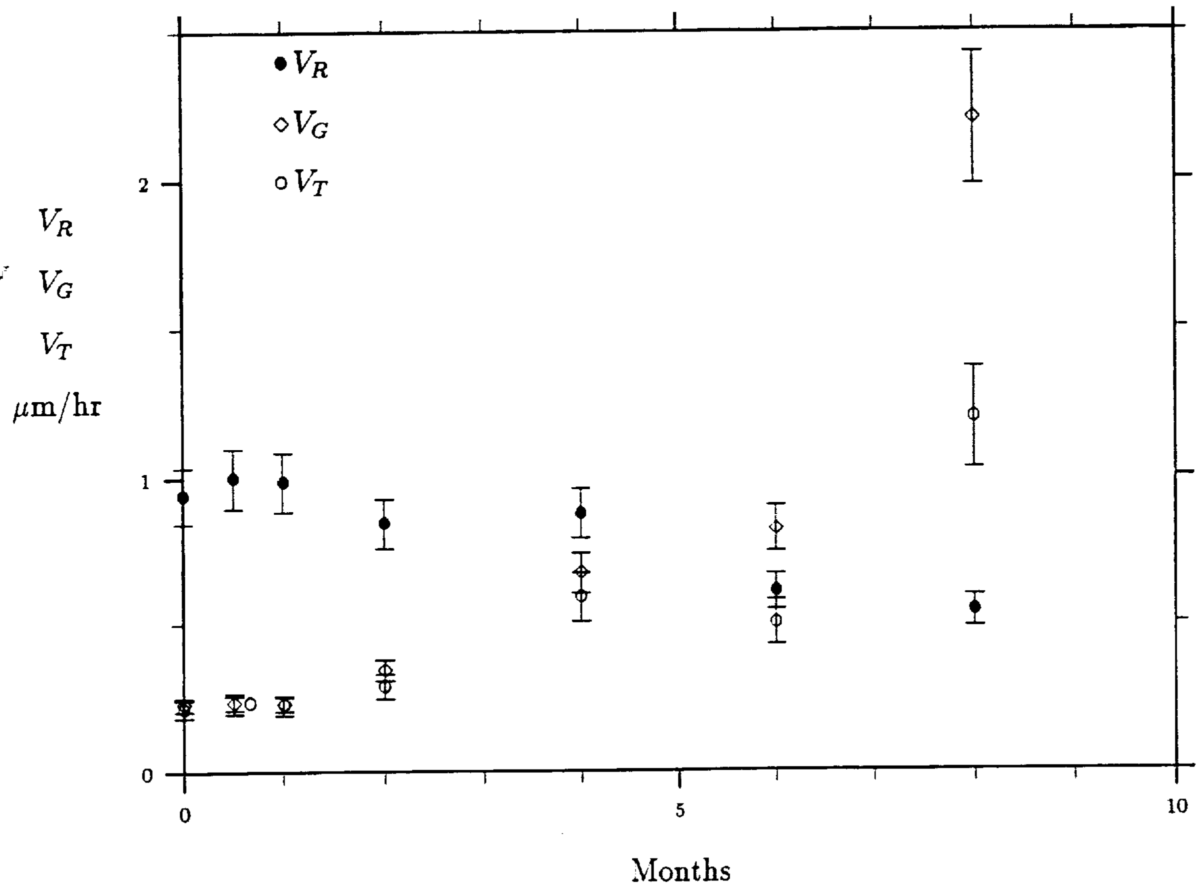

Figure 5: Bulk etch rate V_G, track etch rate V_T, and reduced etch rate V_R as functions of annealing time for 900 MeV/amu Fe tracks in CR-39. Tracks were no longer visible after 8 months for this sample.

Table 5: Summary of Accelerator Irradiations of LDEF Flight and Ground Control PNTDs.

Ion	Energy MeV/amu	Range (cm H_2O)	$LET_{\infty} \cdot H_2O$ (keV/μm)
Kr	1367	32.3	266
Au	1150	12.6	1320
Fe	1691	54.5	136.2
U	928	8.36	1882
Ag	1452	26.7	451
Fe	1700	55.1	135.7

Preliminary Processing of CR-39

Due to the unprecedented length of the LDEF mission, CR-39 PNTDs were expected to have fluences approaching saturation levels. A nominal value for saturation of CR-39 is 10^6 tracks/cm^2. Fluences greater than this value lead to overlapping tracks and the track parameters (semi-minor b and semi-major a axes) are no longer measurable. In order to avoid the problem of overlapping tracks, a reduced etch time is used. This leads to smaller tracks which cannot be as easily measured. It is optimal to establish an etch time where few tracks are overlapping, but where track parameters are large enough to be easily measured. Samples of CR-39 from the P0006 experiment on LDEF from the same manufactured batch as the P0004-1 CR-39 detectors, were etched for intervals of 24, 36, 48, and 168 hours. 168 hours is the etch time for CR-39 flown on typical STS missions. Fluences from these test samples were measured as was the bulk etch B, the thickness of material removed from each surface during the etching process. Table 6 lists the CR-39 samples, duration of etch, bulk etch and fluence measured on the top and bottom surfaces of the test etch samples.

An assessment was made of the surface quality, fluence and track size on each CR-39 test sample. Since the P0004-1 CR-39 PNTDs were located near the P0006 experiment, the P0006 test samples are a good indicator of what is expected for the P0004-1 CR-39 detectors. It was determined that a 36 hour etch time in 6.25 N NaOH at 50°C was optimal for processing of P0004 CR-39.

Initial Analysis and Results

One pair of CR-39 PNTDs, 8A-SE-1,2, from the P004-1 experiment were processed in 6.25 N NaOH at 50°C for 36 hr. After etching, the pair of detectors was reassembled into its original experimental configuration, forming a PNTD doublet. The doublet was scanned for two surface short range (SR) and four surface galactic cosmic ray (GCR) events. A short range event is a pair of tracks made on the inner two surfaces of the CR-39 doublet by one

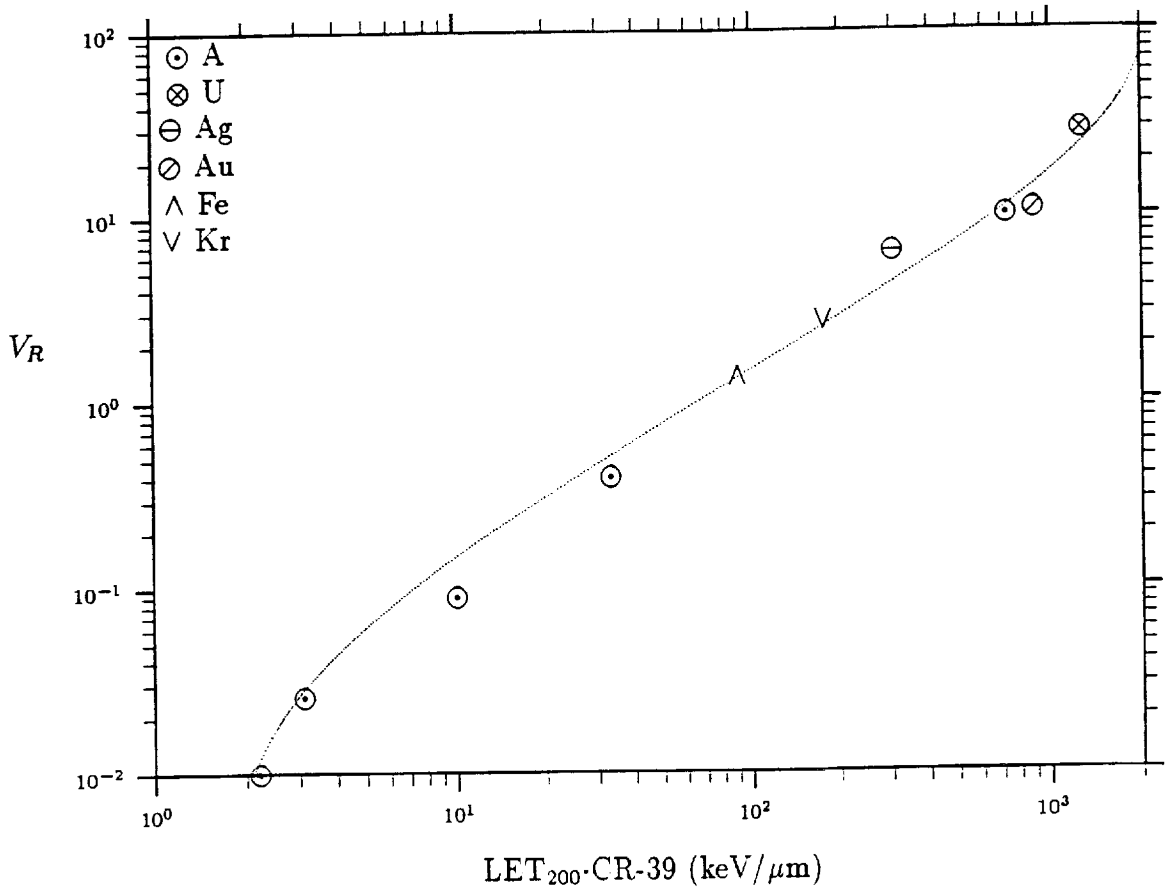

Figure 6: Calibration Plot of V_R and LET for CR-39 test irradiations. Points marked by A are from a previous calibration curve for this same batch of material, adjusted to fit the new points due to aging of the material.

Table 6: Fluences and Etch Parameters of CR-39 Test Etch Samples.

Sample Name	Etch (hours)	Bulk Etch (μm)	Fluence (tracks/cm^2)
7-204-C1 (top)	24	4.994	$1.5 \pm 0.04 \times 10^5$
7-204-C1 (bottom)	24	4.994	$1.0 \pm 0.02 \times 10^5$
7-204-C2 (top)	168	40.220	$1.5 \pm 0.03 \times 10^5$
7-204-C2 (bottom)	168	40.220	$1.3 \pm 0.03 \times 10^5$
7-204-C3 (top)	48	15.414	$2.1 \pm 0.05 \times 10^5$
7-204-C3 (bottom)	48	15.414	$1.5 \pm 0.03 \times 10^5$
7-204-C4 (top)	36	9.533	$1.4 \pm 0.03 \times 10^5$
7-204-C4 (bottom)	36	9.533	$0.72 \pm 0.02 \times 10^5$

particle. These events are the result of primary trapped protons and energetic secondaries. A four surface GCR event is a set of tracks on all four surfaces of the CR-39 doublet created by one particle. Four surface events are usually the result of GCR. Figure 7 shows a cross sectional diagram of two layers of CR-39 PNTD with a four surface Galactic Cosmic Ray event and a two surface Short Range event.

The preliminary results from the 8A-SE-1,2 CR-39 doublet are listed in Table 7. A thickness of 8.2 μm was removed from each CR-39 surface by the etching process. A fluence of 1.43×10^5 tracks/cm^2 of SR events was measured. The fluence of GCR was 5.59×10^3 tracks/cm^2. Fluences and bulk etch B were sufficiently small to prevent overlapping tracks. Table7 also lists the SR and GCR fluences measured from a CR-39 doublet in the P0006 experiment. P0006 was located on the same LDEF tray, F2, as the P0004-1 experiment. The P0006 experiment consisted of thick stacks of different detector materials separated by aluminum plates. The lower fluences seen for the P0006 CR-39 detector pair are therefore most likely the result of greater shielding. LET flux, dose rate, and dose equivalent rate spectra will be measured and plotted for this sample. The remaining P0004-1 CR-39 detectors will be processed and analyzed.

Tuffak Polycarbonate PNTDs

Tuffak polycarbonate plastic nuclear track detector was included in the P0004-1 experiment to measure the LET spectra above 250 keV/μm. Tuffak polycarbonate has never before been used for an experiment of such long duration. It was therefore necessary to carry out studies on possible effects of long term exposure of the space environment on the nuclear track recording properties of Tuffak. Most of the high LET tracks that registered in Tuffak were from short range (on the order of several microns) secondaries. High LET primaries

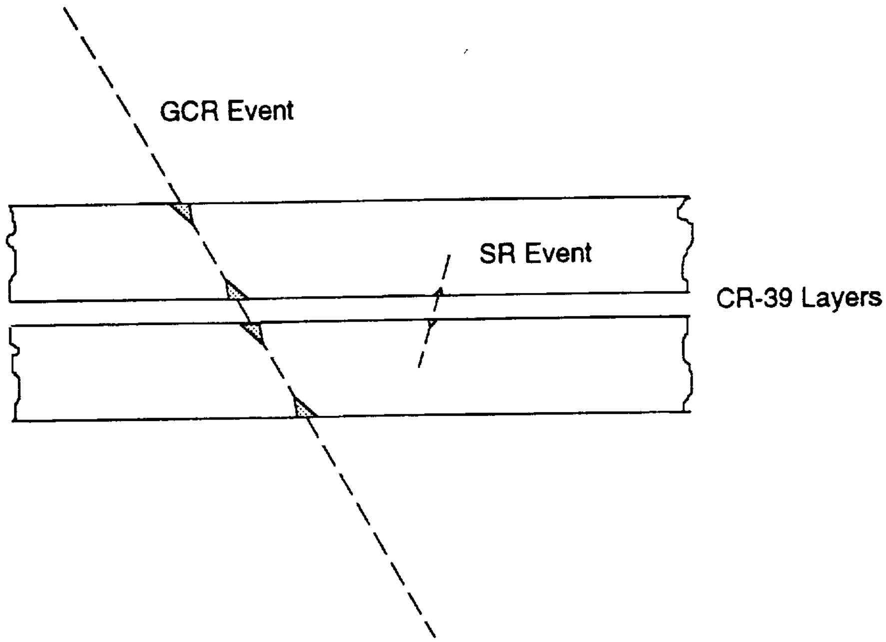

Figure 7: Cross sectional view of two layers of CR-39 PNTD with four surface Galactic Cosmic Ray event and two surface Short Range event.

Table 7: Results from preliminary analysis of P0004-1 and P0006 CR-39.

Sample Name	Etch (hours)	Bulk Etch (μm)	Fluence tracks/cm^2	Comments
8A-SE-1,2	36	8.243	1.43×10^5	SR Events
			5.59×10^3	GCR Events
7-119/120	36	8.574	2.08×10^4	SR Events
			9.44×10^2	GCR Events

are found in much lower fluence. Testing of chemical etch times was carried out in order to determine the optimal etch for locating and measuring short range secondary particle tracks and primary HZE tracks.

Environmental Studies of Tuffak PNTD

The temperature aboard LDEF was not regulated and was predicted to range from -22°C to 38°C. A study was undertaken to determine the effect of prolonged storage at elevated temperatures on the etching characteristics and on latent particle tracks in Tuffak PNTD. Samples of Tuffak PNTD were exposed to a beam of 570 MeV/nucleon Ar ions from the Lawrence Berkeley Laboratory Bevalac accelerator. The Tuffak PNTDs were placed behind a brass wedge at a 45° angle of incidence. The brass wedge served to slow down the Ar ions, increasing the LET of the particles above the 250 keV/μm threshold needed for registration. The Tuffak PNTD samples were stored in air at a constant temperature of 38°C for varying lengths of time. After the storage period, the samples were removed from the oven and etched in a solution of 6.25 N NaOH at 50°C for 16 hours. Measurements were made of the detector dimensions in order to determine the bulk etch B.

After etching, the detectors were examined under an optical microscope. Tracks were selected that had a range of

$$r = \sqrt{2}T - 1/2B, \tag{1}$$

where T is the thickness and B is the bulk etch. All units are in microns. This insured that all measured tracks had the same LET. Figure 8 is a plot of $V_R - 1$ as a function of annealing duration for the Tuffak polycarbonate. V_R is reduced track etch ratio, the ratio of track etch rate V_T to bulk etch rate V_G:

$$V_R = \frac{V_T}{V_G}. \tag{2}$$

V_R is unitless while V_T and V_G are in units of μm/hr. Track etch rate V_T and bulk etch rate V_G are plotted as functions of annealing time in Figures 9 and 10, respectively.

There is a decrease in track etch rate V_T and bulk etch rate V_G during the first two months on annealing. The reduced track etch ratio V_R also decreases during the first several months due to the faster rate of decease in V_T. After this initial decease, the three curves level off. Track etch rate, bulk etch rate, and consequently reduced track etch ratio, remain relatively unchanged for the remainder of the study. These results can be interpreted as being caused by a change in the Tuffak polycarbonate material during the initial period at elevated temperatures. After a period of approximately two months at 38°C, the material stabilizes and no further significant change is seen. A more complete description of the environmental effects of prolonged storage at elevated temperatures on the track recording properties of Tuffak polycarbonate can be found in USF TR-78.

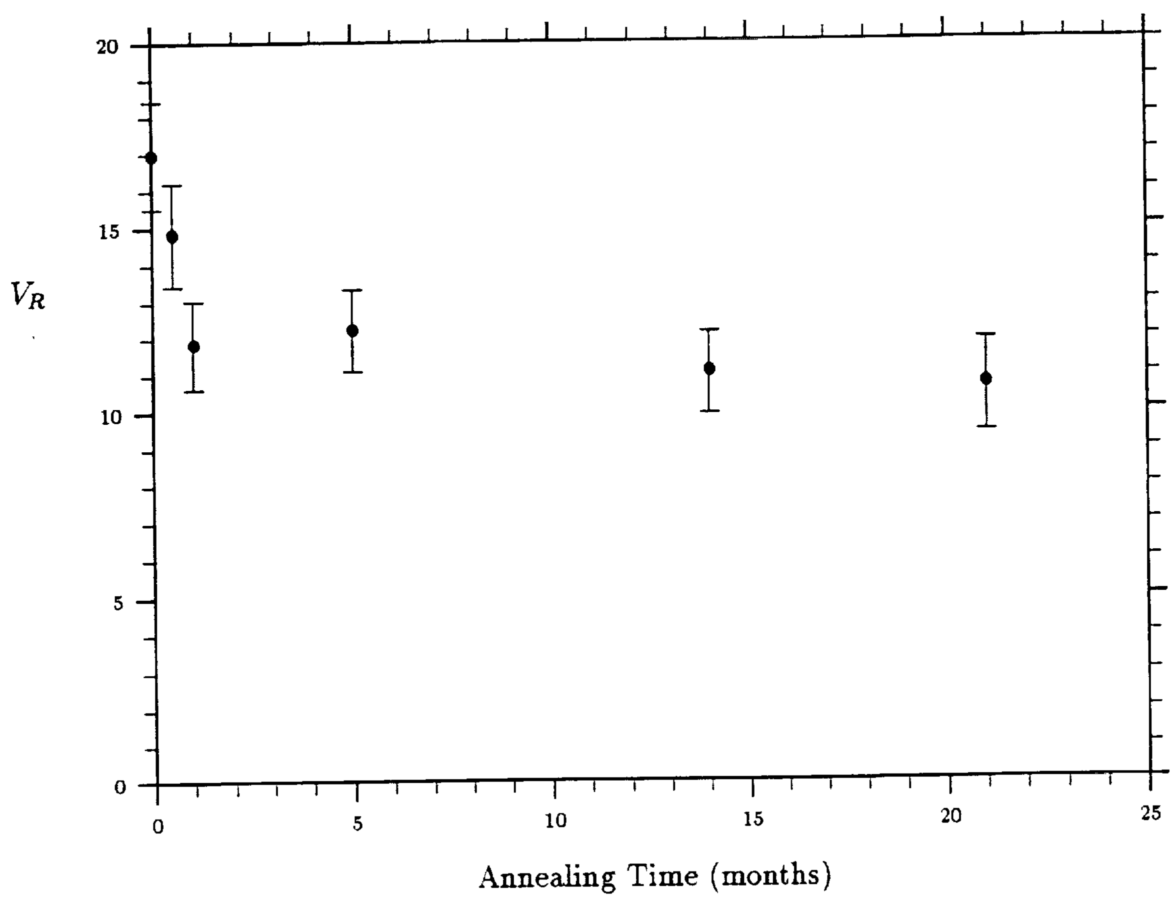

Figure 8: Reduced track etch ratio V_R as a function of annealing time at 38°C for tracks of stopping Ar in Tuffak polycarbonate PNTD.

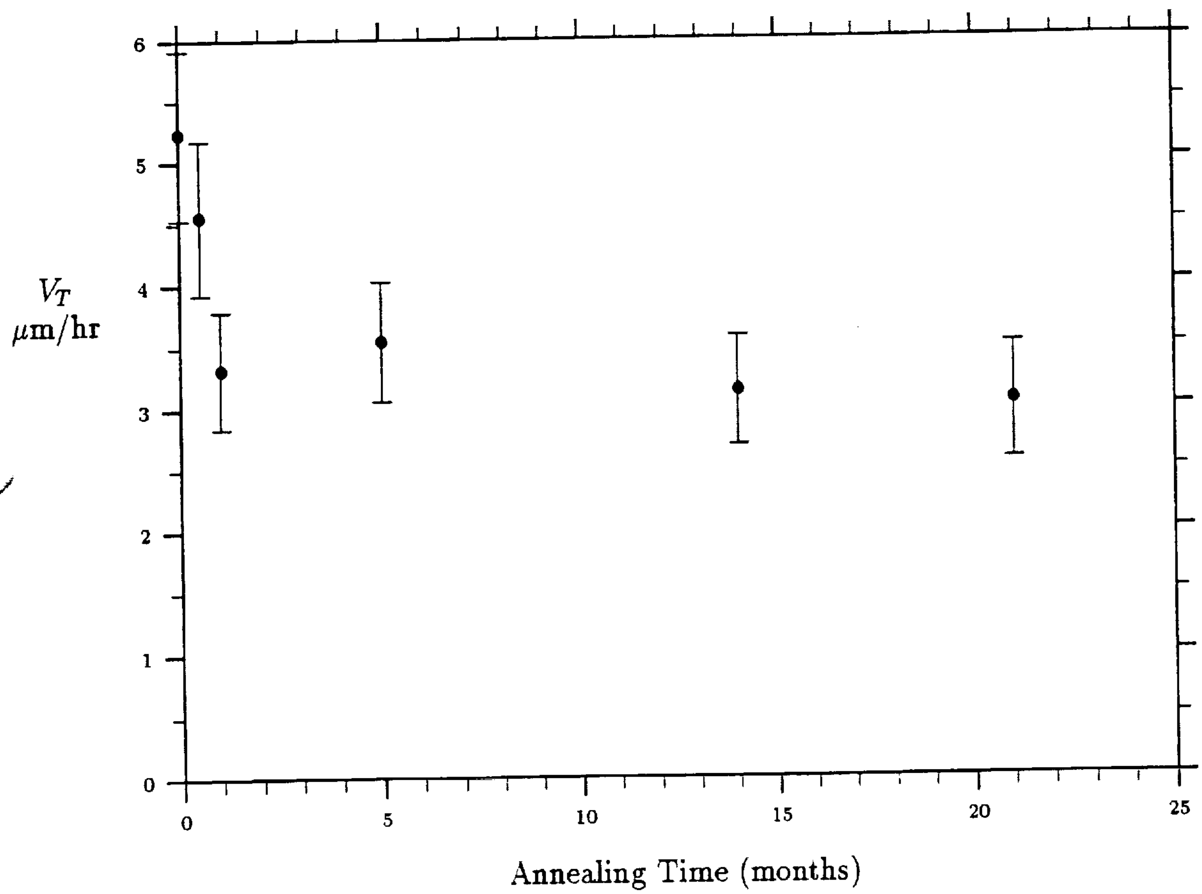

Figure 9: Track etch rate V_T as a function of annealing time at 38°C for tracks of stopping Ar in Tuffak polycarbonate PNTD.

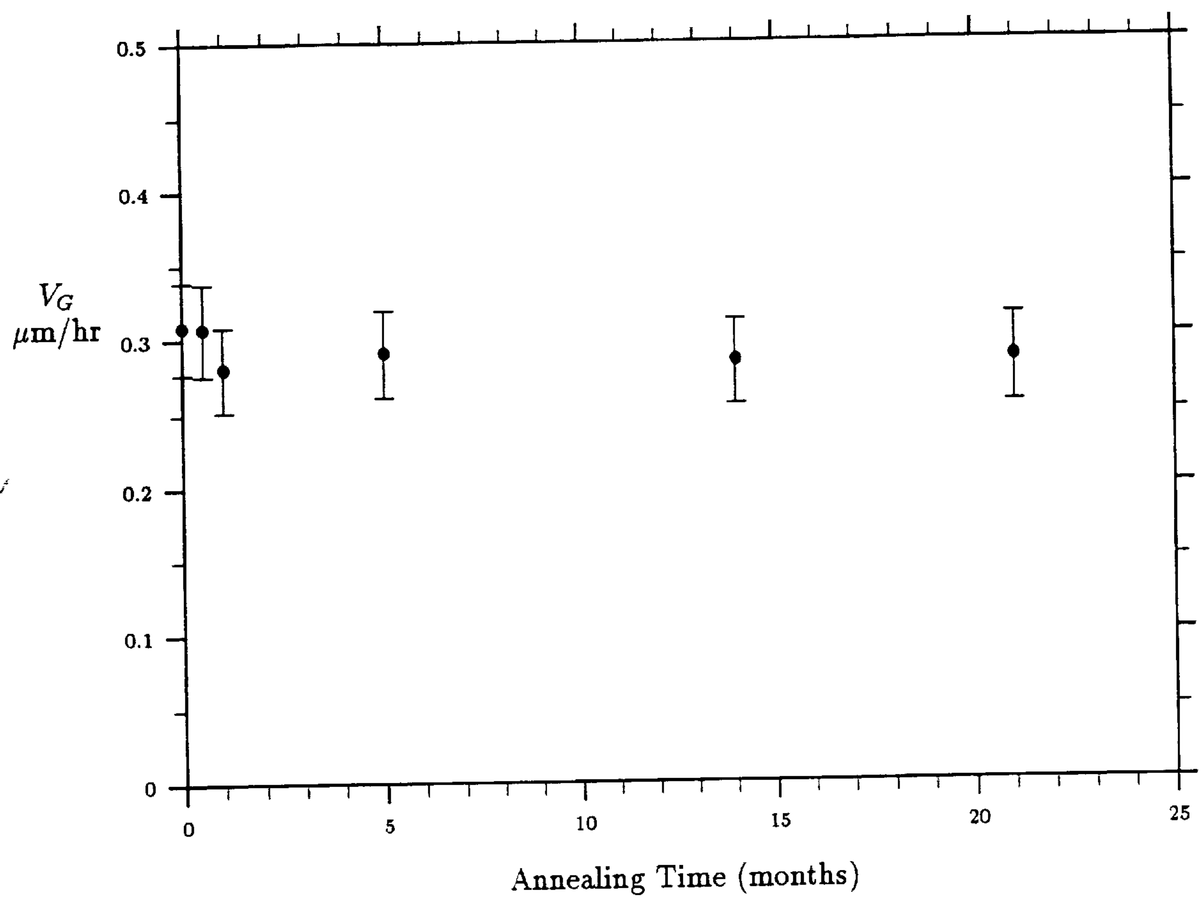

Figure 10: Bulk etch rate V_G as a function of annealing time at 38°C for Tuffak polycarbonate PNTD.

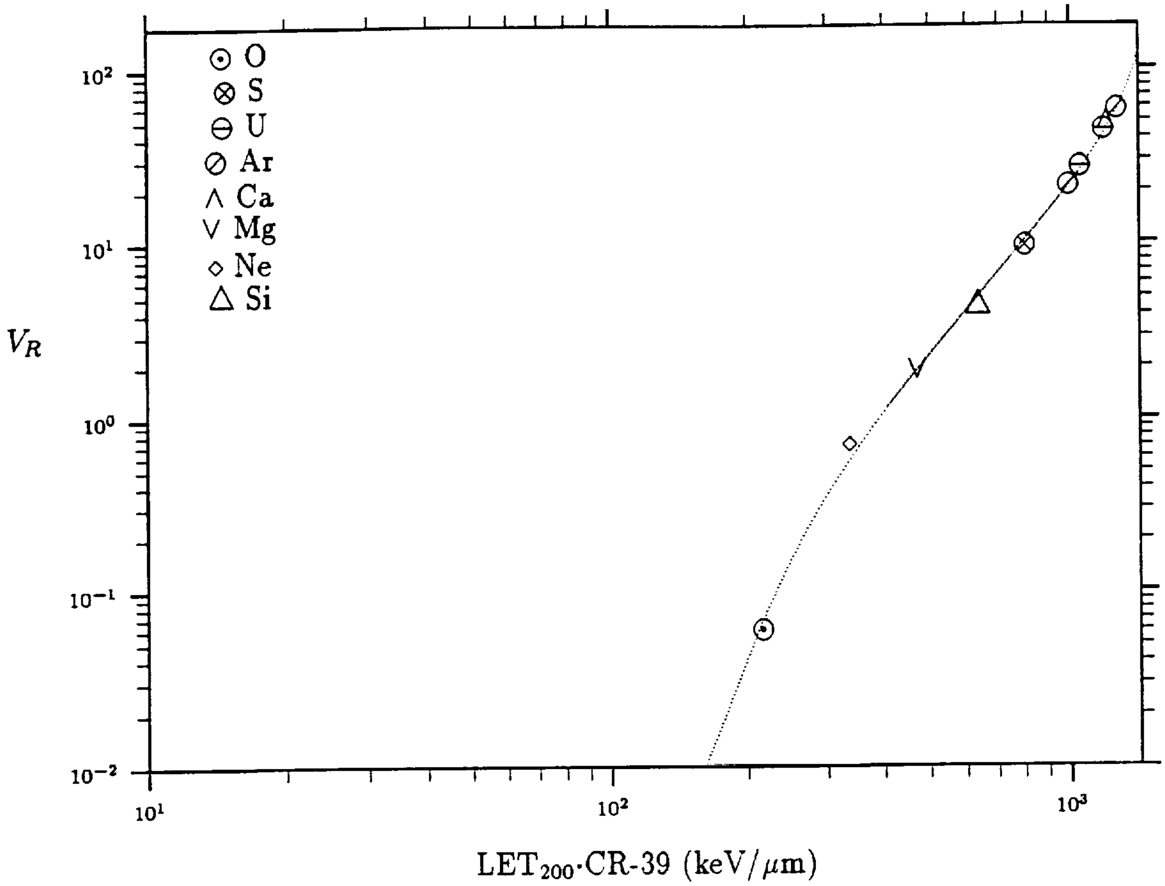

Figure 11: Calibration response function for polycarbonate PNTD.

Calibration of Tuffak Polycarbonate

The conversion of measured values of the reduced track etch ratio V_R to LET is done via a detector response function for the particular detector material. Figure 11 is a plot of the detector response function for polycarbonate PNTDs like Tuffak. The points on the curve are the individual responses of Tuffak to various high LET heavy ions. A fourth order polynomial is fitted to these points. The equation of this curve is then used to convert the measured V_R of the particle tracks to LET.

Tuffak polycarbonate PNTDs from two of the ten flight dosimeter packets included in the P0004-1 experiment were irradiated to heavy ion beams at the Lawrence Berkeley Laboratory Bevalac accelerator for the purpose of calibration. Table 8 is a list of the ions and energies to which the Tuffak PNTDs from P0004-1 were exposed. All irradiations were made at a 90° angle of incidence. These detectors will be processed and the track diameters measured in order to obtain information on the response of the P0004-1 Tuffak PNTDs to heavy ions.

Table 8: Summary of accelerator irradiations of P0004-1 Tuffak PNTDs.

Ion	Energy MeV/amu	Range (cm H_2O)	$LET_\infty \cdot H_2O$ (keV/μm)
Ag	1452	26.7	451
Au	1150	12.6	1320
U	928	8.36	1882

The detector response function in Figure 11 will be adjusted to fit these points. The previous detector response function is for polycarbonate used in standard laboratory conditions. Adjusting the curve to the points measured from the P0004-1 detectors exposed to heavy ions will compensate for the prolonged storage and the temperature environment of the flight exposed Tuffak PNTDs.

Preliminary Processing of Tuffak PNTDs

Due to the unprecedented length of exposure of the P0004-1 Tuffak PNTDs, it was not known what fluences of particles the detectors may have recorded. It is important not to over-etch the Tuffak PNTDs so that particle tracks will not overlap. Overlapping tracks make the measurement of track parameters (semi-major and semi-minor axes, a and b) difficult or impossible, and hence make the LET measurement more difficult. Samples of Tuffak PNTD of the same manufactured batch flown on LDEF as part of the P0006 experiment were etched for periods of 24, 48, and 96 hours, respectively. Etching was done in a solution of 6.25 N NaOH at 50°C. The fluences of these detectors are tabulated in Table 9. Due to the high registration threshold of Tuffak polycarbonate, fluence of primary cosmic ray tracks was low and no significant overlap in tracks was seen. Two samples of P0004-1 Tuffak PNTD were etched for 144 hours. Results from the P0004-1 Tuffak samples, TU-SE-1,2, are also listed in Table 9. After a 144 hour etch, there was still no significant overlapping of tracks.

Initial Analysis and Results

Two adjacent layers of Tuffak PNTD included in P0004-1, TU-SE-1 and 2, have been etched. Processing was in a solution of 6.25 N NaOH at 50° for 144 hours. After etching, the two adjacent detectors were reassembled into their original experimental configuration forming a PNTD doublet. The bulk etch was 40.5 μm removed from each surface.

The largest number of tracks took the form of spherical etch pits. These are the result of extremely short range secondary particles. These particles have a high LET, but a range that is generally much shorter than the bulk etch. Initially these tracks etch at a rate V_T proportional to the LET of the particle. Etching continues the length of the latent damage trail. After this, etching continues at the bulk etch rate V_B, transforming the conical tracks

Table 9: Summary of preliminary Tuffak PNTD test etching.

Sample Name	Etch (hours)	Bulk Etch (μm)	Fluence (tracks/cm^2)
P0006:			
212R1	24	6.4	4080 ± 90
212R3	48	15.5	8500 ± 190
212R2	96	22.6	10340 ± 230
P0004-1:			
TU-SE-1,2	144	40.5	17340 ± 340

into convex shaped pits. The fluences listed in Table 9 are from these short range secondary tracks.

During a scan of a 2.73 cm^2 area of the detector surface, only two long range galactic cosmic ray (GCR) tracks were found. In order for a particle track to be classified as long range, it must have formed conical tracks on all four surfaces of the two Tuffak PNTD layers. This small number of tracks is in keeping with the expected fluence of high LET long range Galactic Cosmic Rays.

Both long range GCRs and the short range secondary tracks contribute significantly to the high LET portion of the space radiation environment. The etching parameters can be altered in order to enable measurement of one of these two high LET components. A long etch such as the 144 hour etch for the first pair of P0004-1 Tuffak PNTDs enlarges all the features on a detector surface, enabling the large long range GCR tracks to be quickly located and measured. However, a long etch time overetches the small secondary particle tracks, making it impossible to measure these tracks. A very short etch, ~24 hours, will produce only very small tracks, but these tracks can be successfully measured. Further work on the P0004-1 Tuffak PNTDs will focus on developing a method to measure these short range secondary particle events in order to measure their contribution to dose and dose equivalent in the LDEF orbit.

^{6}LiF/CR-39 Neuton Detectors

In addition to the plastic nuclear track detectors (PNTDs) and thermoluminescent dosimeters (TLDs) contained in the 10 flight packets, packets No. 9 and No. 10 also contained neutron detectors composed of ^{6}LiF radiator foils and CR-39 PNTDs. The No. 1 and No. 2 Ground Control packets also held neutron detectors for background comparisons.

The ^{6}LiF foils were 0.64 cm × 0.64 cm × 0.09 cm in dimensions. Each foil was placed against a square of CR-39 of equal area. The detectors were exposed in pairs with one being covered by Gd foil of 0.0025 cm thickness. The Gd foil has a high cross section for absorption of thermal neutrons with an effective cutoff at a neutron energy of 0.2 eV. This allows the measured neutron fluences to be separated into thermal and resonance regions.

The function of the CR-39 is to record alpha particle tracks resulting from the ^{6}Li(n,α)T reaction. The ^{6}LiF therefore serves as an alpha particle radiator foil. The ^{6}Li neutron capture cross section peaks at thermal energy (σ_{Th} =950 b) and declines with increasing neutron energy $\sigma \simeq E_n^{-1/2}$. By methods previously discussed (Benton *et al.* 1978; Benton *et al.* 1981) the responses for thermal and resonance neutrons were found to be 3.57×10^2 thermal neutrons/track and 5.6×10^3 resonance neutrons/track. This assumes a well-thermalized neutron peak below 0.2 eV and a E_n^{-1} moderated neutron spectrum above 0.2 eV.

The P0004 experiment was located in tray F-2 at the trailing edge of the LDEF orbiter. As such, it was expected to receive a higher fluence of trapped protons than experiments at the leading edge due to the East-West effect in trapped protons in the South Atlantic Anomaly (SAA). A difference of approximately 2.5 was projected for the two positions. This should also be reflected in neutron fluences since collisions between protons and target nuclei in the orbiter materials was a major source of neutrons.

Processing Procedures

Because of the abundance of tracks on the surfaces of the flight detector CR-39, it was necessary to process them for a short period only. The standard processing used with the detectors after space missions of a few days would have resulted in overlapping of the particle tracks and an inability to determine track densities. The processing was done in steps to a total of 1.25 hr in 6.25 N NaOH solution at 70°C. This was 25% of the standard processing time.

Detector Readout

The track densities of alpha particle tracks on the CR-39 were counted manually at 430× under an optical microscope. The tracks of the short-range alpha particles (alpha particle energy from the ^{6}Li(n,α)T reaction is 2.057 MeV plus (kinetic energy ÷ 2.327)) were discriminated from the greater part of the background tracks on the basis of track size. For those background tracks within the size and range criteria of the alpha particles, a background was determined by counting the back surface of the CR-39. The subtracted backgrounds were due mainly to secondaries from reactions involving GCRs or the trapped protons. The track densities from the detectors are given in Table 10.

Neutron Measurements

The track densities were converted to neutron fluences using procedures and calibration factors discussed above. The errors introduced in the neutron fluences by the assumptions made regarding the spectral shapes of the neutrons cannot be determined but probably fall within ±20% for the thermal neutrons and ±50% for the resonance neutrons.

Table 10: Track Densities Measured on the Neutron Detectors.

Canister	Detector	Track Density (cm^{-2})
3	10	$2.76 \pm 0.07 \times 10^5$
	10 (Gd)	$4.96 \pm 0.22 \times 10^4$
6	9	$1.45 \pm 0.04 \times 10^5$
	9 (Gd)	$3.20 \pm 0.17 \times 10^4$
GC	1+2	285 ± 39
	1+2 (Gd)	81 ± 30

Backgrounds have been subtracted for all track densities.
(Gd) denotes that the detector was covered with 0.0025 cm thick gadolinium foil.
GC denotes ground control detectors.

The dose equivalents were determined from the fluences using conversion factors based on the recommendations of NCRP (1971). The factors (1.016×10^{-6} mrem-cm^2/neutron for thermal; 4.92×10^{-6} mrem-cm^2/neutron for resonance) incorporate QF values of 2 and 6.4 for thermal and resonance neutrons, respectively.

The neutron fluences and dose equivalents are given in Table 11. The dose equivalent rates given are based on the LDEF orbit duration (2115 days) for the mission detectors and on total assembly time (2418 days) for the ground controls.

Similar neutron detectors were also placed in the P0006 experiment which shared tray F-2 with P0004. The P0006 canister was much smaller in size than those used in P0004 but the contents had a higher average density. The measurements are given in Table 12 for comparison.

Discussion and Conclusions

From Tables 11 and 12 it is seen that the neutron fluences were higher in the P0004 canisters than in that of P0006. The difference was much greater for thermal than resonance neutrons. This is consistent with the shielding. The detectors in the P0004 canisters had less vertical shielding to space but greater shielding to the sides. They were surrounded by the seed packages which consisted of a sizable mass (approximately 6 kg) of hydrogenous material. This material effectively scatters and moderates the higher energy neutrons produced in collisions of cosmic rays with target nuclei. The effect of this moderation should correspond with the mean free paths of the measured neutrons fluences and, thus, vary inversely with neutron energy, which explains the greater differences seen in the thermal fluences.

Table 11: Thermal and Resonance Neutron Measurements for P0004.

Canister No.	Neutron Energy Range	Fluence (cm^{-2})	Dose Equiv. (mSv)	Dose Equiv. Rate (μSv/d)
3	≤0.2 eV	$8.1 \pm 1.6 \times 10^7$	0.82 ± 0.16	0.38 ± 0.07
	0.2 eV - 1 MeV	$2.9 \pm 1.4 \times 10^8$	14.2 ± 7.1	6.7 ± 3.4
6	≤0.2 eV	$4.0 \pm 0.8 \times 10^7$	0.41 ± 0.08	0.19 ± 0.04
	0.2 eV - 1 MeV	$1.9 \pm 0.9 \times 10^8$	9.2 ± 4.6	4.3 ± 2.2

Minimum shielding above the detector was 6.1 g/cm^2 Al equivalent. To the side it was approximately 12.4 g/cm^2 plus shielding external to the canister.

Table 12: Thermal and Resonance Neutron Measurements for P0006.

Neutron Energy Range	Fluence (cm^{-2})	Dose Equiv. (mSv)	Dose Equiv. Rate (μSv/d)
≤0.2 eV	$1.22 \pm 0.24 \times 10^7$	0.124 ± 0.024	0.059 ± 0.011
0.2 eV - 1 MeV	$1.43 \pm 0.72 \times 10^8$	7.0 ± 3.5	3.3 ± 1.6

Minimum shielding above the detector was 16.8 g/cm^2 Al equivalent. To the side it was 3.3 g/cm^2 plus shielding external to the canister.

There is also a difference between P0004 canisters No. 3 and No. 6. There were different types of seeds in the two canisters and the vertical shielding of the detectors in No. 6 was somewhat uncertain. It should be noted that TLD doses at the locations of the neutron detectors were 3.15 and 3.88 Gy for canisters No. 3 and No. 6, respectively, which is in inverse relationship to the neutron fluences. This suggests less vertical shielding to space for the canister No. 6 detectors, and perhaps less moderating influence from the seeds.

Dose equivalents of 0.82 and 0.41 mSv, for thermal neutrons, and 14.2 and 9.2 mSv, for resonance neutrons, were measured in P0004 canisters No. 3 and No. 6, respectively, during the LDEF mission. Comparisons with measurements from the P0006 experiment indicate that the seed mass had a significant effect in moderating the neutron energies and increasing the lower energy neutron fluences. The differences seen between the two canisters may be due to uncertainty in the position of the detectors in canister #6. The dose equivalent from the thermal and resonance neutrons is less than 0.5% of the total charged particle dose equivalent as measured with TLDs at the same positions.

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