Relative Efficiency of TLD-100 to High Linear Energy Transfer Radiation - Correction to Astronaut Absorbed Dose

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Abstract

Response of thermoluminescent detectors (TLD-100) to high linear energy transfer (LET) particles has been studied using helium, carbon, silicon, and iron ions from the Heavy Ion Medical Accelerator at Chiba (Japan), iron ions from the Brookhaven National Laboratory (NY) Alternate Gradient Synchrotron , and 53, 134, 185, and 232 MeV protons from the Loma Linda accelerator. Using the measured relative (to ^{137}Cs) dose efficiency, and measured LET spectra from a tissue equivalent proportional counter (TEPC) on 20 Space Shuttle flights, and 7 Mir flights, the underestimation of absorbed dose by these detectors has been evaluated. The dose underestimation is between 15-20% depending upon the flight inclination and shielding location. This has been confirmed by direct correlation of measured dose by TEPC and TLD-100 at a low shielded location in the Shuttle mid-deck. A comparison of efficiency- LET data with a compilation of similar data from TLD-700, shows that shapes of the two curves are nearly identical, but that the TLD-100 curve is systematically lower by about 13%, and is the major cause of dose underestimation. These results strongly suggest that TLDs used for crew dose estimation be regularly calibrated using heavy ions.

Introduction

Thermoluminescent detectors (TLD-100) are used to measure the astronauts flight integrated absorbed dose . The relative efficiency of TLD-100, and TLD-700 to high LET particles have previously been measured (Tochilin and Goldstein, 1968, Jahnert, 1972, Hoffman and Prediger, 1983, Patrick et al., 1976, Henson and Thomas, 1977). Recently, Yasuda et al. (1999) have measured the efficiencies of TLD-600, and TLD-700 at the HIMAC facility. All of these measurements show that the efficiency for measuring the absorbed dose drops off as the linear energy transfer (LET) of the charged particles increases. The measurements of crew radiation exposures thus are under estimations of the true value of crew exposures. The relative dose efficiency of TLDs depends on the activator (Mg, Ti) concentrations, batch to batch variation, and on the annealing process. Thus, it should be determined for the particular TLD batch used in each specific dose measurement. Inspite of the long history of use of these detectors for determination of astronaut absorbed doses, and their proposed use for the ISS astronauts, the efficiency of the TLD-100 for high LET radiation has not been experimentally determined.

Experimental Details and Analysis

The relative absorbed dose efficiency of TLD-100 was studied at HIMAC using ions of helium, carbon, silicon, and iron, at the AGS using iron ions, and at Loma Linda using protons. The relative efficiency measurements cover the LET (L) range of 0.4 to 200 keV/micron, and was determined by integrating the main TL peak. Table 1 gives the details of various exposures. Figure 1 plots the relative absorbed dose efficiency as a function of LET. The exposures were made at two dose values for each ion energy, with doses typically of 10 mGy and 100 mGy. This covers the range of many Shuttle doses, measured Mir doses, and expected ISS doses. The agreement between the iron exposures done at HIMAC and BNL, is very good. Cross calibration of these TLDs with a ^{137}Cs source showed an agreement within 3%. For comparison, the available data on the efficiency of TLD-700, some of which were in powder form, and using different estimation procedures, are plotted in Figure 1 also. The solid line is a least square fit to the square root of a four order polynomial in logarithm of LET to all of TLD-700 data, and covers most of the LET range observed in space. The data of Tochilin et al. and Henson and Thomas were normalized downwards by a few percent to account for their efficiency of more than 1 for LET < 0.3 keV/μm. The fit curve is given by the expression:

$$\varepsilon (L)=[0.9085-.1135\ln(L)+0.0414(\ln(L)+.0418(\ln(L))^3-.0027(\ln(L))^4)]^{-1/2} \quad L \geq 0.3\ \text{keV}/\mu\text{m}$$

and

$$\varepsilon =1 \text{ for LET} < 0.3\ \text{keV}/\mu\text{m}. \qquad (1)$$

The dashed line in Figure 1, is the above expression, Equation 1, scaled down by 13% and fits our TLD-100 measurements very well, suggesting that the functional LET dependence of efficiency for TLD-700 and TLD-100 is the same, but the absolute efficiency is lower. Data acquired by Yasuda et al. (1999) on their TLD-700 and TLD-600 dosimeters shows nearly identical LET dependence. The cause of lower TLD-100 efficiency could be some unknown source of calibration difference or something peculiar to this batch of TLDs. It could also be related to the annealing procedure or differences related to the glow curve analysis. Further investigation will be required to assess the effect of each parameter.

In order to determine the magnitude of the effect of decreased efficiency on measured astronaut dose, a knowledge of the differential LET spectrum, J(L), (particles/cm^2 sr day keV/μm)$^{-1}$, incident on TLDs is needed. Given a measurement of J(L), the true dose, D, is given by:

$$D = k \int J(L)\, L\, dL \qquad (2)$$

where k is the proportionality constant for conversion to appropriate absorbed dose units. If the detector is not fully sensitive to particles of all LETs, then measured dose, D_ε , is less, and given by:

$$D_\varepsilon = k \int J(L)\, L\, \varepsilon(L)\, dL \qquad (3)$$

where ε (L) is the dose efficiency for particles of a given LET, L.

The skin LET spectra for the individual astronauts are not measured. However a surrogate for the these measurements is provided by a tissue equivalent proportional counter (TEPC) that flies on Shuttle flights (Badhwar et al., 1994) has been used to determine the magnitude of the correction. Using TEPC data acquired on 20 Shuttle flights, the underestimation of crew doses on these missions was calculated from equations (2) and (3). These results, sorted by flight inclination, are given in Table 2. The error ratio, $f = (D - D\varepsilon)/ D\varepsilon$, is given in column 13, as a % in the TLD-100 measured doses. Averaging by inclination only, f is 18.5 % for 28.5, and 20.8% for >51.6 degree inclination flights. The same analysis using the TLD-700 data (Equation 1) shows that f varies from a low of 0.7 to 5.4%.

Table 3 gives the results of the analysis for the NASA-Mir astronauts. Using equation (1) for TLD-700, the correction is rather small, between 2.2 and 3.8%. However, using the TLD-100 calibration the correction varies from 18.2 to 20%, and is about the same if only the ^{137}Cs and HIMAC heavy ion calibrations are used (Loma Linda proton data not included). Contributions of neutrons to the crew exposures still needs to be included.

Figure 2 is a plot of measured absorbed doses using the TEPC (D_{TEPC}) and TLD-100 (D_{TLD}) on both 28.5° and 57° Shuttle flights, on which the TEPC and TLDs were mounted at the mid-deck Dloc2 position. A least square fit to the data gives: $D_{TEPC} = (3.26 \pm 23.35) + (1.30 \pm 0.022)\, D_{TLD}$. This means that the absorbed dose measured by TEPC was 30% higher than the TLD measured absorbed dose. It is to be noted that the TEPC measures neutrons that are almost completely missed by the TLD-100. These results confirm that the inefficiency of the TLD-100 to high LET particles leads to lower measured absorbed doses for astronauts.

It is worth noting that the differential LET spectrum is a complex function of flight inclination, flight altitude, solar activity, and shielding. Since the flight crews move into areas of different shielding during missions, this spectrum becomes an even more complex function.

Conclusions

A study of the TLD-100 efficiency has shown that: (1) the absorbed dose efficiency of TLD-100 crew passive dosimeters decreases as the LET of particles increases; (2) combining these efficiency measurements with the TEPC measured LET spectrum, the crew radiation absorbed doses are shown to be underestimated by 15-20% depending on the flight inclination and other factors; (3) the main reason for this underestimation is due to the reduced overall efficiency, and to a lesser extent, the LET dependence; (4) this underestimation does not include the neutron dose missed by such detectors; and (5) other TLDs with better LET response should be investigated to reduce the magnitude of this correction.

Acknowledgment

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Figure Captions

Figure 1: Plot of absorbed dose efficiency as a function of linear energy transfer. Solid line is a least square fit to the TLD-700 data.

Figure 2: Plot of absorbed dose rate measured by TEPC and that measured by TLD-100.

Table 1: Details of TLD exposure and efficiency

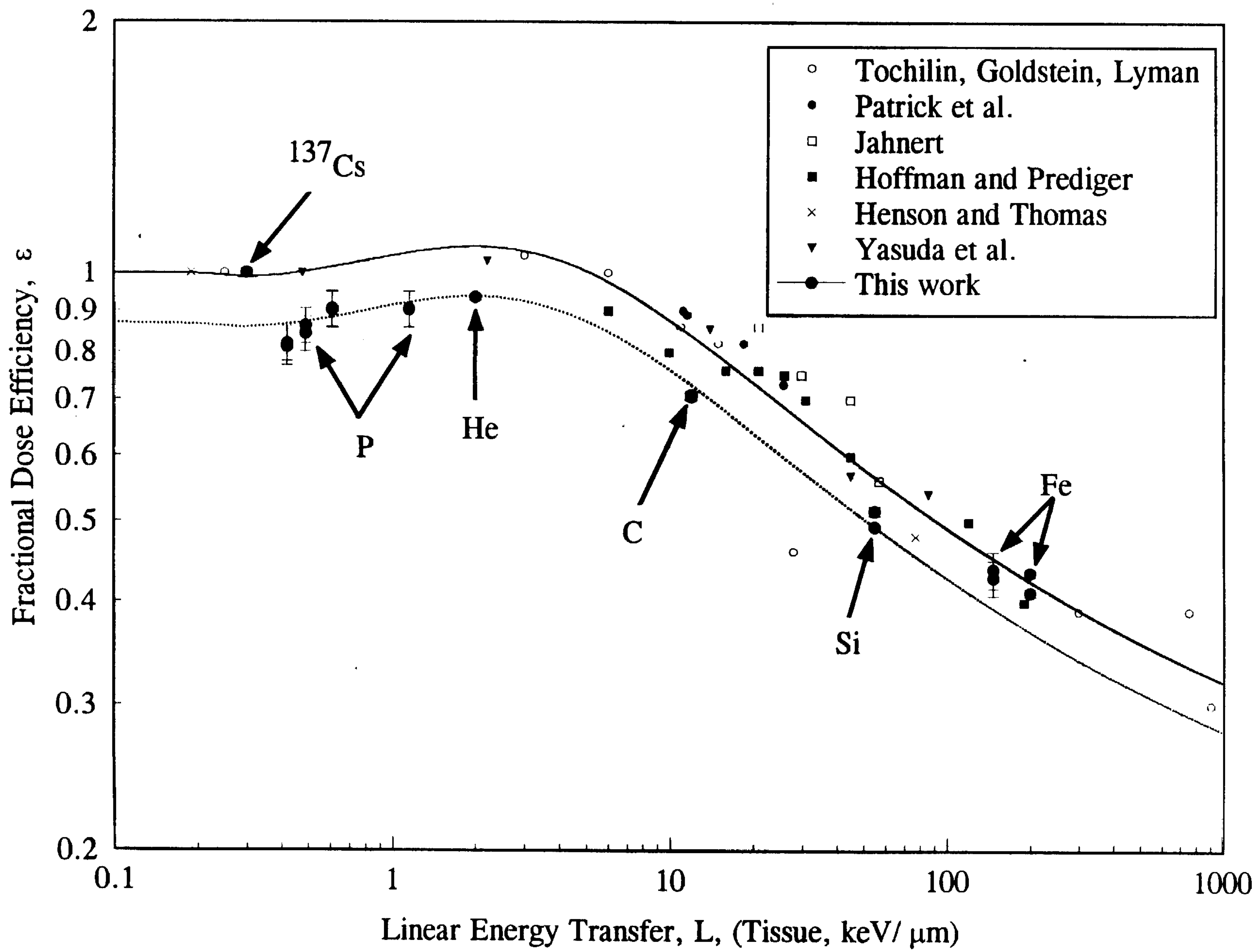
Particle/Source	Energy/nucleon MeV/amu	LET (keV/μm)	Z^2/β^2	Delivered Dose (mGy)	Normalized Efficiency
^{137}Cs	.662 MeV γ-ray	0.4	-	10	0.972±0.01
H	232 ± 2	0.42	2.8	16.3	0.811±0.05
H	232 ± 2	0.42	2.8	103.8	0.820±0.05
H	185 ± 2	0.49	3.31	14.1	0.863±0.05
H	185 ± 2	0.49	3.31	102.3	0.843±0.05
H	134 ± 2	0.61	4.27	16.9	0.905±0.06
H	134 ± 2	0.61	4.27	105.6	0.902±0.06
H	53 ± 3	1.15	9.61	14.7	0.902±0.06
H	53 ± 3	1.15	9.61	105.6	0.904±0.06
He	150	2	15.58	10	0.934±0.01
He	150	2	15.58	100	0.839±0.01
C	290	12	86.44	10	0.709±0.007
C	290	12	86.44	100	0.706±0.007
Si	490	55	344.79	10	0.515±0.007
Si	490	55	344.79	100	0.493±0.003
Fe	500	200	1176.78	10	0.428±0.021
Fe	500	200	1176.78	100	0.438±0.022
Fe	1000	147	882.86	10.6	0.434±0.0044
Fe	1000	147	882.86	108	0.411±0.0041

Table 2: Corrected astronaut exposures for selected Shuttle flights

Flight	Launch Date	Inclination (Degrees)	Days	Altitude (km)	ϕ (MV)	Density (g/cm^3)	F10.7 (10^4 Jansky)	Location	Min TLD-100 Crew Dose (mGy)	Avg TLD-100 Crew Dose (mGy)	Max TLD-100 Crew Dose (mGy)	Error (%)	Corrected Avg Crew Dose (mGy)
STS-57	6/21/93	28.5	10.0	470	782	7.54E-16	118	LOCKER	3.541	4.620	5.213	16.7	5.392
STS-51	9/12/93	28.5	9.8	296	703	1.26E-14	83	PAYLOAD BAY 2	0.641	0.647	0.656	18.6	0.767
STS-61	12/2/93	28.5	10.8	594	662	7.81E-17	97	PAYLOAD BAY 2	13.71	16.196	21.070	17.6	19.046
STS-69	9/7/95	28.5	10.9	370	591	1.73E-15	70	PAYLOAD BAY 2	2.085	2.960	4.901	18.9	3.519
STS-80	11/19/96	28.5	17.7	350	541	2.91E-15	82	PAYLOAD BAY 2	2.864	3.717	5.711	18.9	4.420
STS-82	2/11/97	28.5	10.0	607	561	3.01E-17	70	MS005	24.83	32.047	43.10	16.7	37.399
STS-83	4/4/97	28.5	4.0	296	496	9.60E-15	78	MS005	0.334	0.381	0.437	21.8	0.464
STS-94	7/1/97	28.5	15.7	296	483	9.10E-15	71	MS005	1.396	1.594	2.105	19.9	1.911
STS-95	10/29/98	28.5	8.9	556	576	2.86E-16	130	MS005	13.891	21.002	30.679	17.6	2.4698
STS-62	3/4/94	39	14.0	259	645	3.52E-14	89	PAYLOAD BAY 2	1.265	1.320	1.36	17.2	1.547
STS-63	2/2/95	51.6	8.3	355	602	2.90E-15	81	DLOC2	1.962	2.266	2.790	18.1	2.676
STS-74	11/12/95	51.6	8.2	394	582	1.10E-15	73	PAYLOAD BAY 2	1.774	2.191	2.955	19.6	2.620
STS-81	1/12/97	51.6	10.2	354	553	2.50E-15	72	SPACEHAB	2.081	2.625	3.431	21.0	3.176
STS-89	1/22/98	51.6	8.8	296	493	1.34E-14	94	SPACEHAB	2.038	2.408	3.152	21.0	2.914
STS-91	6/2/98	51.6	9.8	320	467	1.06E-14	116	SPACEHAB	2.014	2.223	2.984	20.8	2.685
STS-91	6/2/98	51.6	9.8	320	467	1.06E-14	116	MS005	2.014	2.223	2.984	22.3	2.719
STS-88	12/4/98	51.6	11.8	320	605	1.44E-14	141	MS005	2.022	2.468	2.856	21.3	2.994
STS-56	4/8/93	57	9.3	302	731	1.75E-14	110	PAYLOAD BAY 2	1.048	1.084	1.103	21.1	1.313
STS-60	2/3/94	57	8.3	352	644	4.34E-15	93	DLOC2	1.307	1.428	1.566	20.3	1.718
STS-85	8/7/97	57	11.9	296	486	1.00E-14	80	PAYLOAD BAY 2	1.824	1.933	2.046	22.3	2.364

Table 3: Corrected crew exposure for NASA-Mir Program.

Mission	Start Date	Inclination (Degrees)	Days	Altitude (km)	ϕ (MV)	Density (g/cm^3)	F10.7 (10^4 Jansky)	Location	Q	Dose (mGy)	Error (%)	Corrected Dose (mGy)
NASA Mir 1	3/16/95	51.6	115	394	556	1.34E-15	79	Core	2.61	41.60±1.00	20.0	49.9
NASA Mir 2	3/22/96	51.6	188	388	498	1.19E-15	72	Core/Spektr	2.46	59.01±0.75	19.2	70.3
NASA Mir 3	9/16/96	51.6	128	381	503	1.40E-15	73	Spektr	2.43	36.83±0.44	19.2	43.9
NASA Mir 4	1/12/97	51.6	133	387	501	1.27E-15	74	Spektr	2.40	38.98±0.54	19.1	46.4
NASA Mir 5	5/15/97	51.6	144	389	482	1.30E-15	81	Spektr	2.38	56.75±0.50	18.9	67.5
NASA Mir 6	9/24/97	51.6	127	384	486	2.04E-15	92	KvantII/Priroda/Kristall	2.29	37.82±0.56	18.2	44.7
NASA Mir 7	1/22/98	51.6	141	378	489	2.84E-15	105	Priroda	2.35	30.62±0.25	18.5	36.3



Tochilin, Goldstein, Lyman
Patrick et al.
Jahnert
Hoffman and Prediger
Henson and Thomas
Yasuda et al.
This work
137Cs
P
He
C
Si
Fe
Fractional Dose Efficiency, ε
Linear Energy Transfer, L, (Tissue, keV/ μm)
2
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
1
10
100
1000

Figure 1

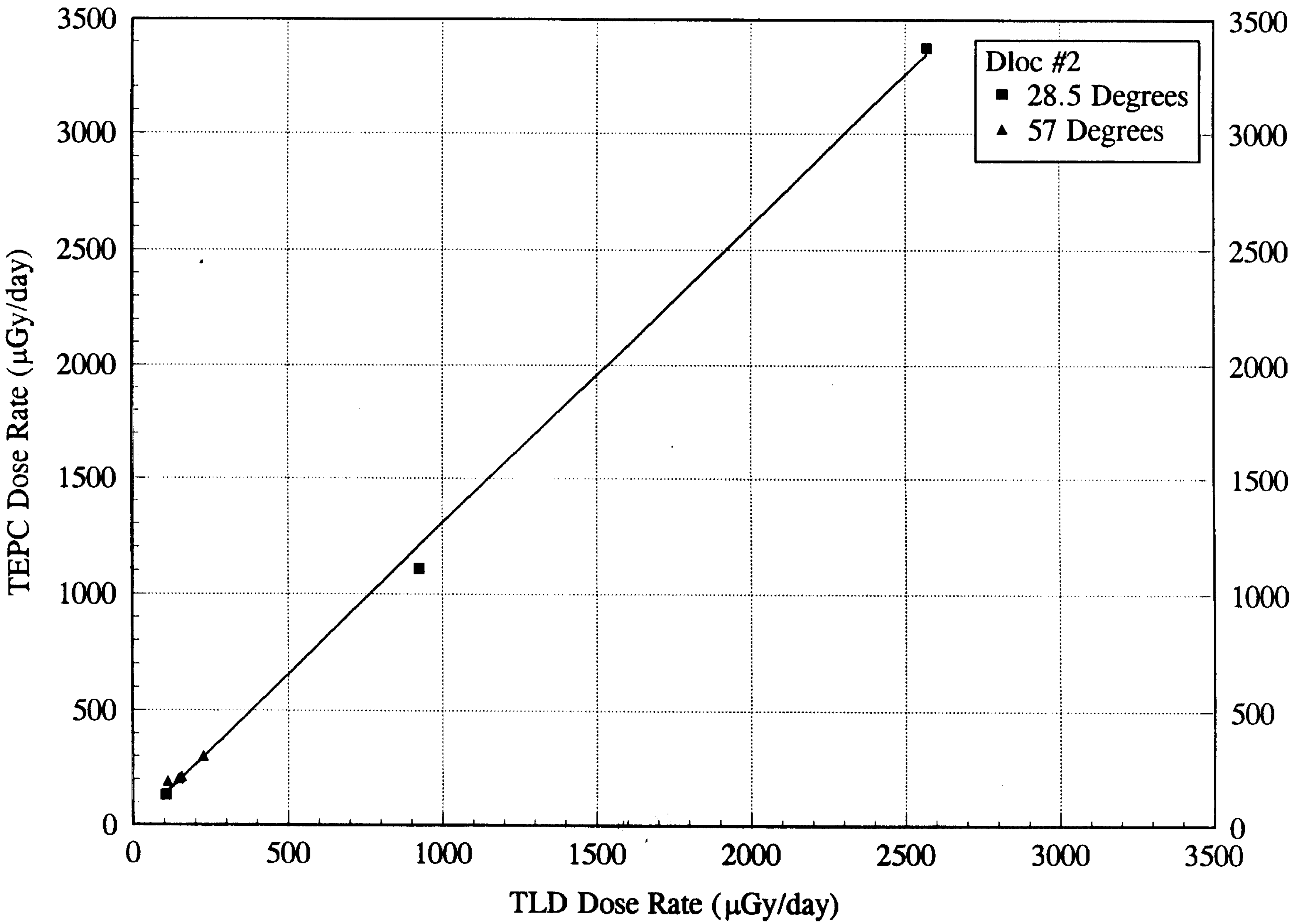

Dloc #2
28.5 Degrees
57 Degrees
TEPC Dose Rate (µGy/day)
TLD Dose Rate (µGy/day)
0
500
1000
1500
2000
2500
3000
3500

Figure 2