TL Response of Single Crystal TLD-100 to
70 eV - 5 keV Electrons and Comparison with TSEE Glow Curves

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Abstract

A "TL effective" energy-range relationship was found which agrees with the universal curve above 2 keV but becomes nearly constant at about 300°A for energies between 1 keV and 100 eV. The glow curve shape obtained from single crystal TLD-100, after irradiation with 70 eV to 30 keV electrons, is essentially the same as that obtained after irradiation with cesium γ -rays, (i.e. TL emitted from bulk of sample) as long as 1) the dose is well below saturation and 2) irradiations are performed on freshly cleaved crystals or vacuum annealed crystals. This result shows that there is no intrinsic difference between TL traps near the surface and in the bulk. Irradiation with electron energies less than 1 keV results in the TL signal being emitted from the same region from which TSEE electrons are emitted. The usual TSEE glow curve, found by other investigators, is different from the TL glow curve obtained from vacuum annealed crystals. However, if the TL sample is given the same "standard annealing" as is customary in TSEE experiments, the TL glow curve obtained after irradiation with low energy electrons is altered and there is then good agreement between this TL glow curve and the TSEE curve found by others. This altered glow curve is a result of hydroxyl ions which diffuse into the sample during annealing.

The TL efficiency was comparable to cesium γ -rays for 30-5 keV electrons, decreased rapidly between 5 and 1 keV and remained constant at about 20% of the efficiency of cesium γ -rays below 1 keV. Half of this decrease in efficiency can be attributed to the higher LET of low energy electrons. The cause for the remaining decrease is not known but it may have its origin in the same mechanism proposed to account for the large range of low energy electrons.

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COO-1105-239

TL Response of Single Crystal TLD-100 to
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1. INTRODUCTION

The work reported here is a continuation of the work reported in COO-1105-234. Here we report the glow curve shape and sensitivity of single crystal TLD-100 to 70 eV - 4 keV electrons. To the best of our knowledge, the glow curve shape has not been investigated at these low irradiation energies and the sensitivity has only been investigated for samples which have been given the standard annealing of 400°C for 1 hour in air. As was reported in COO-1105-234 this standard annealing drastically alters the glow curve shape and sensitivity. The glow curve shape induced by irradiation with low energy electrons is of great interest since these electrons deposit their energy in a depth similar to that from which thermally stimulated exo-electrons (TSEE) are emitted. For vacuum-annealed samples, the glow curve shape for less than saturation dose of electrons with energies as low as 70 eV is essentially the same as for the cesium induced, bulk sample glow curve. On the other hand, a typical TSEE glow curve made on TLD-100 powder which has been given the standard annealing looks much like the TL glow curve from an electron irradiated sample which has been given the same pre-irradiation air annealing. One reason proposed for the discrepancy between the glow curve shapes produced

by TSEE electrons, which are emitted from the surface of the sample, and TL, which is emitted by the bulk of the sample after γ -ray exposure, is that TSEE traps have different structure due to their proximity to the surface (Zimmerman, 1971). In view of the present finding, however, it is felt these differences are not intrinsic to traps near the surface but are caused by impurities diffused into the sample during the pre-irradiation annealing.

The depth in which the electrons deposit their energy was estimated by irradiating a constant cross section of the sample with 100 eV to 30 keV electrons and recording the TL at saturation as a function of the irradiating electron energy. At saturation, all electron traps in the irradiated volume are filled; consequently, the number of filled traps, and therefore the TL, will be proportional to the "TL effective" depth of penetration of the electrons. The results for energies greater than 2 keV show that the TL "effective range" of electrons follows the universal curve, $R = aE^n$, where R is the range, E the electron's energy and a and n are constants. But, below 500 eV the range remains approximately constant at 300 Å. This is related to data on the escape depths of true secondary electrons from LiF.

The efficiency with which electrons produce TL, in samples not annealed in air, is the same as cesium γ -rays above 5 keV. Between 5 and 1 kV the efficiency decreases to one fifth of that of γ -rays and below 1 kV it remains constant at this value. Part, but not all of the decrease in efficiency, is explained by the increasing LET of the lower energy electrons.

2. MATERIALS AND METHODS

All experiments were done on single crystal TLD-100 purchased from Harshaw Chemical Co. in 1975 (Control No. 1-KK-1). Samples measuring $1/8$ inch x $1/8$ inch x 1 mm were cleaved from a single crystal and annealed at 400°C for 1 hour in a vacuum of 10^{-6} torr. These samples were further cleaved to $1/8$ inch x $1/8$ inch x .2 mm and read out once to 400°C in a He atmosphere to remove the TL signal induced by cleaving. All samples were flushed for a minimum of 5 minutes before being read out to minimize the diffusion of impurities into the sample. To verify that the read out process did not alter the concentration of traps near the surface, the TL at saturation for 200 eV electrons was measured using samples which were read out and also samples not read out after cleaving. No difference was found. Henceforth all irradiations were done on the freshly cleaved surface after one read-out.

The irradiation chamber has been described in detail in COO-1105-234. The only modification was to reduce the voltage to minus 15 volts on the sample-side disc (the disc which repels secondary electrons). This was done to minimize any perturbing fields that the irradiation electrons might encounter after passing through the two 1 mm collimating ports. To verify that this change did not cause an apparent change in sensitivity by decreasing the fraction of secondary electrons collected, samples were irradiated with 2 and 5 kV electrons with both -15 and -45 volts applied to the sample-side disc. No change in the apparent sensitivity was observed. The TL reader and glow curve recording instruments were the same as described in COO-1105-234.

For the experiment in which the TL at saturation was measured as a function of energy, it was important to know the beam was not changing

shape after passing through the irradiation port. If this were the case, and the extent of the change was different for various irradiation energies, the cross-sectional area that would be irradiated at these energies and the volume irradiated would therefore not be simply proportional to the depth of penetration of the electrons. At 10 and 30 keV, the TL produced by a saturation dose was photographed during read-out and the spot size measured. It was the same size as the irradiation port, the uncertainty in the measurement being $\pm 10\%$. At lower energies there was not sufficient light to photograph, so an alternate method was devised. Samples were given saturation doses of 100 eV electrons and then cleaved into strips .5 mm wide. These strips were read out individually. The results were consistent with the beam not spreading at all. An increase in the diameter of 20% or more would have been easily detected.

3. RESULTS

A. Glow curve shape

The glow curve shape obtained for a dose well below saturation for all electron energies used (70 eV to 5 keV) was quite similar to the glow curve produced by the bulk of the sample after irradiation with cesium γ -rays (see Fig. 1). The changes in glow curve shape which occur at low energies as the dose approaches saturation will be discussed in section 3D.

B. Range of electrons

One surprising result observed while investigating glow curve shapes at 70 eV was that the TL at saturation doses was a factor of ten greater than expected from estimates of the depth of penetration of 70 eV electrons. These estimates were based on data for the ranges of electrons in aluminum (Kobitch, et al., 1967) and plastic (Cole, 1969) and were then scaled to

the relative stopping power of LiF above 10 keV (Berger, et al., 1966). To determine the relative depth of penetration at various energies, the TL at saturation was determined for these energies. Since the irradiated cross sectional area is the same at all energies, the volume irradiated is proportional to the depth of penetration of the electrons. The TL at saturation is proportional to the number of traps in the irradiated volume (Jain, et al., 1974); thus, if we assume a uniform distribution of traps, the TL at saturation would be proportional to the depth of penetration of the electrons. The number of electrons required to achieve saturation was determined (Fig. 2) and the TL from peaks 3-5 at saturation was plotted as a function of the electron irradiation energy. The results have been scaled so the TL at 10 keV is numerically equal to the depth of penetration of 10 keV electrons as determined by Morbitzer and Scharmann (1964). Agreement on the shape of the two curves is good. Unfortunately there has been very little work done on the range of electrons in insulators at irradiation energies below 1 keV and no information is available for LiF. The data in Fig. 3 shows that the "TL effective" range becomes approximately constant below 1 keV and, assuming the normalization to Morbitzer's data is valid, its value below 1 keV is $300\text{\AA}$.

C. Sensitivity to 100 eV to 5 keV electrons

The TL for 3 ergs deposited in the sample is given in table 1, column 3. The data in Fig. 2 shows that for this energy deposited in the sample the response is linear at 2 keV and below. The data, presented in a previous report (Lasky, 1976), shows that no supralinearity is expected for radiation which has a LET greater than 25 keV/micron; that is electrons with energy less than 3 keV. For electron energies above 3 keV, supralinearity is present. Ideally one would like to compare the efficiencies of different

energy electrons to produce TL at a dose for which there is no supralinearity at any energy; that is, at doses corresponding to less than 10^3 R for 5 keV electrons. Since there was not sufficient signal for this when irradiation was carried out with electron energies less than 5 keV, all measurements were made for 3 ergs deposited. This corresponds to 2×10^4 R at 5 keV. The response obtained at 5 keV and above (table 1, column 3) have been corrected to the value they would have if no supralinearity were present (column 5). This was done by determining the ratio of the response per rad below 10^3 R to the response at the dose delivered (using data presented in COO-1105-234, Fig. 3) and multiplying the measured response (column 3) by these values. The efficiency relative to ^{137}Cs γ -rays (column 6) was found by dividing the values in column 5 by the response of TLD-100 to 3 ergs deposited by ^{137}Cs γ -rays. The efficiency (column 6) is approximately constant below 1 keV, the same energy region for which the depth of penetration is constant. It rapidly increases between 1 and 5 keV. At 5 keV and above the degree to which electrons are less efficient in producing TL can be completely attributed to their having a higher LET than cesium γ -rays. This point has been thoroughly discussed in a previous report (Lasky, 1976).

D. Changes in the shape of the glow curve at saturation doses

As the dose deposited at any given energy approaches the saturation dose, peak 5 saturates more rapidly than peak 2 and 3. This is most evident at lower irradiation energies (see Figs. 4-9). A peak at about 250°C becomes pronounced at saturation doses for irradiation energies greater than 1 keV. This peak is also observable for saturation doses of x-rays (Jain, 1974) but is much more pronounced for higher LET radiation (Aitken, 1967). It is attributed to multiple ionizations of a trapping

center by one high LET particle or, for lower LET radiation, multiple ionization caused by overlapping adjacent tracks (Attix, 1974). The absence of this peak at saturation doses of electrons with energy less than 500 eV indicates the minimum energy needed for the ionization responsible for this trap is between 500 and 1000 eV.

4. DISCUSSION

A. Range of electrons in LiF

Prior to discussing the data obtained in the present study for electron ranges, a brief review will be given of some relevant facts found in the literature. Figure 10 shows the ranges of electrons obtained by investigators using different methods in a variety of materials. Several points are illustrated by these data.

1. Agreement of ranges obtained in LiF using different methods is not good.
2. There is good agreement between the universal curve $R = aE^n$ and all data for energies above 2 keV. (R is the range, E the electron's energy and a and n are constants. The universal curve is represented by a straight line on the log - log plot.)
3. Below 2 keV the range of electrons in insulators breaks from the universal curve, being larger than expected. This break is most evident in the results of Bronstein (1969a) who obtained the ranges in Mg and MgO using the same method.

Good agreement between the results of Bronstein and Morbitzer for the range of electrons in LiF is not expected (Fig. 10 b, e) since very different methods were used. Bronstein used the "break away" method of the ξ -Ep curve, that is, he deposited a thin layer of the material being

studied on a substrate having a very different inelastic reflection coefficient and noted the incident electron energy for which a large change in the number of reflected electrons occurred. The electron range is twice the deposited sample thickness since the electrons must penetrate this layer, be reflected and repenetrate it before being detected. In this experiment a pulsed low current electron beam was used to avoid charging of the sample. One would expect the range measured by this method to correspond most closely with the maximum range of electrons since the break in the number of inelastically reflected electrons occurs when the first reflected straggling electrons can repenetrate the deposited layer. Morbitzer and Scharmann (1964) measured the electron range by a luminescence excitation technique. This consisted of vacuum depositing a known thickness of LiF on a glass slide and monitoring the luminescence produced by a continuous electron beam. As the beam energy is increased, the luminescence will increase as long as the electrons deposit all their energy in the LiF. When the electron beam range exceeds the LiF thickness the luminescence remains constant. The important parameter here is the range in which electrons deposit their energy. Straggling electrons which have a large range but do not make an appreciable contribution to the energy deposition will be detected in a "break away" measurement of the range but not a luminescence measurement of the range. Kobetich and Katz's (1967) data on aluminum indicates this difference is appreciable. From the above considerations one would expect the luminescence range to be smaller than the "break away" range which is indeed born out by the data in Fig. 10.

Kobetich and Katz (1967) gave a semiempirical formula for the extrapolated range of electrons in aluminum, which agrees very well with the copious amounts of data available for that metal. The relative stopping power

for LiF and Al for energies down to 10 keV has been calculated by Berger and Seltzer (1964) to be 1.10 at 10 keV. If the data for Al is scaled by this factor the agreement between Morbitzer's and Kobetich's data is admirable. However, again we are dealing with two different methods of measurement and, although the luminescence range is more closely related to the extrapolated range than the maximum range, this close agreement may perhaps be regarded as much a coincidence as well as a check on the accuracy of the two sets of data.

The experimental method used in the present work most closely parallels that of Morbitzer's luminescence excitation method. For this reason the data for the relative ranges of 100 eV to 30 keV electrons shown in Fig. 3 were scaled to agree with his value for the range of 10 keV electrons. Clearly an absolute measurement of the "TL effective" range is called for to set this curve. Such an experiment is planned for the near future. For the present, the values obtained from Fig. 3 will be used. The confidence in their accuracy, however, is sufficient for the purpose of verifying, in Sec. 3B, that the TL emitted after very low energy electron bombardment is emanating from a depth comparable to the escape depth of TSEE electrons.

Below 1 keV there is data available for the range of electrons in metals but very little data for insulators. This is largely due to the difficulties encountered in preparing the extremely thin samples required for these measurements. The data which are available show that the energy-range relationships for insulators deviate from those for metals at energies below 2 keV. The range decreases less with decreasing energy for insulators (see Fig. 10). No data are available for insulators at energies below 500 eV. The present data show the "TL effective" range (Fig. 3)

breaks from the universal curve below 2 keV and becomes almost constant at about $300\text{\AA}$ for energies below 500 eV. This is surprising at first but, as will be shown, not inconsistent with other facts known about LiF. Mayhugh (1968) has shown through U.V. repopulation studies, that electrons need only be in the conduction band to be effectively trapped. No additional energy is required for the trapping process. At this point it is useful to consider the range of electrons in two parts as is done by Bronstein (1970).

ℓ is the range in which the incident electrons' energy is reduced to 50 eV.

λ is the range over which its energy is reduced from 50 eV to 0. Bronstein has found λ for LiF to be $200\text{\AA}$ for incident energies greater than 500 eV. For energies below 500 eV, λ apparently decreases but Bronstein warns that it is difficult to tell if this is real or an artifact of the method used. He has made a more extensive study of CsI (1969b) and found that the range of slow secondary electrons (λ) increases from $230\text{\AA}$ to $900\text{\AA}$ as the incident electron's energy is increased from 0.3 keV to 2.2 keV. At 0.5 keV, λ is three times as large as ℓ . Most true secondary electrons have an energy of 1 eV (Bronstein, 1969; Bruining, 1954). These secondary electrons have a large range because there are very few ways they can lose energy. For example, they do not have sufficient energy for creation of plasmons (Kunz, 1969) and there are not many conduction band electrons with which they can interact to lose energy. The main mechanism left for energy loss is production of phonons. In metals, where there are many conduction band electrons to which they may lose energy, λ is typically 10 atomic layers or less (Bronstein, 1960). Thus, although there is not yet data for the range of electrons in insulators for energies below

500 eV, it is likely that the entering electron will lose most of its energy close to the surface but will diffuse a good deal further into the crystal. In view of the value of λ found by Bronstein, a total range of about $300\text{\AA}$ for low energy electrons in LiF is reasonable.

A check on the above line of reasoning may be made by adding a constant "low energy electron diffusion length" to the range of electrons in air and comparing this to the range measured in LiF. Since arguments of electrons diffusing in the conduction band do not apply to air, the range in air should correspond to the distance required to slow electrons to low energies, ℓ . Cole (1969) has measured the range in which electrons produce 99% of their ionization. In curve (a) Fig. 11 these data have been scaled to agree with Morbitzer's luminescence range for a 10 keV electron in LiF. This was done to 1) correct for the different stopping powers of air and LiF and 2) adjust for the different ranges measured by the luminescence technique and the ionization of air. If $180\text{\AA}$ is added to these values the resultant curve (b) in Fig. 11 shows admirable agreement with the present data (c) and Morbitzer's data (d) for the range of electrons in LiF. The cause for the structure at low energies on "TL effective" range is not known but it probably reflects details of slowing down process at low energies for incident electrons. The ionization energy of the core electrons in fluorine is 670 eV. For incident electron energies below this value the core electrons cannot contribute to the electron stopping cross section. This may be the source of the slight increase in the electron range below this energy.

B. Comparison of TL glow curve produced by irradiation with low energy electrons to TSEE glow curves

In general there is good correspondence between thermally stimulated exo-electron emission (TSEE) glow curves and TL glow curves, particularly

A_1 , B_{v11} and A_{11} (B_{v11})₂ compounds (Käämbre, 1973). However, the lack of complete correspondence has spurred debate whether the same traps are responsible for the two phenomena (Becker, 1973; Nash, 1971; Zimmerman, 1971). Holzapfel (1969) estimated that TSEE electrons are emitted from the first $100\text{\AA}$ of ionic compounds. The present experiment is the first known to us in which TL has been stimulated from a similar region. Figure 12 shows the TSEE glow curve obtained by Zimmerman (1971) from TLD-100 powder. The sample was given the standard annealing of 1 hour at 400°C in air and this is the procedure generally used when taking TSEE glow curves. The TSEE glow curve obtained has the same shape as the TL glow curve obtained from samples irradiated with low energy electrons after being given the same pre-irradiation air-annealing (Lasky, 1976). The cause for the lack of detailed numerical agreement of the glow peak temperatures is probably the different thermal contact between the sample and heater pan for the two apparatus. TL and TSEE glow curves taken on the same apparatus show excellent correspondence in peak positions (Petel, et al., 1973). In section 3A it was reported that the TL glow curve response to low energy electrons, which deposit their energy in a region similar to that responsible for TSEE, is the same as the glow curve obtained after irradiating with higher energy electrons or x-rays as long as all annealings are done in vacuum. In a previous report (Lasky, 1976) it was shown that diffusion of hydroxyl ions into the sample during annealing is responsible for changes in the TL glow curve response to low energy electrons. In view of the good correspondence between this altered TL glow curve shape in air-annealed samples and the TSEE glow curve, and the fact that vacuum annealed samples do not exhibit any change in shape, it seems likely that the diffusion of hydroxyl ions

into TLD-100 is also responsible for the glow curve shape observed for TSEE. Support is given to this interpretation by experiments performed by Scharmann (1968). He found that the height of the 120°C TSEE peak in LiF was greatly reduced if experiments were performed on freshly cleaved samples.

C. TL sensitivity of single crystal TLD-100 to 100 eV - 30 keV electrons

Table 1, column 6 gives the TL efficiency for various energy electrons relative to the efficiency of cesium γ -rays. Column 7 shows the relative sensitivity expected if the larger LET of the electrons were the only factor contributing to their reduced efficiency. (The dose averaged LET, defined in report COO-1105-234, needed to find the relative efficiency for electrons from Wingate's data was obtained by scaling Cole's data for plastic (1969) to the relative stopping power of LiF (Berger, et al., 1966)). The decrease in efficiency for 30-5 keV electrons is completely explained by the effect of the LET of this radiation. Below 2 keV the loss in efficiency is a factor of two greater than can be explained by the LET effect for these electrons. The efficiency is constant below 1 keV. This is consistent with the theory that at low irradiation energies most of the traps are filled by electrons at the bottom of the conduction band which are diffusing beyond the primary range into the crystal. The efficiency of these electrons would not depend on the energy of the primary electrons which created them. The higher efficiency above 2 keV might indicate an increased probability of filling traps which are predominantly within the range of the primary beam.

5. CONCLUSION

A "TL effective" energy-range relationship was found which agrees with the universal curve above 2 keV and becomes nearly constant at about 300Å for energies between 1 keV and 100 eV. The glow curve shape obtained from single crystal TLD-100, after irradiation with 70 eV to 30 keV electrons, is essentially the same as that obtained after irradiation with cesium γ -rays, as long as 1) the dose is well below saturation and 2) irradiations are performed on freshly cleaved crystals or vacuum annealed crystals. This result shows that there is no intrinsic difference between TL traps near the surface and in the bulk. Irradiation with low energy electrons results in the TL signal being emitted from the same region from which TSEE electrons are emitted. The usual TSEE glow curve is different from the TL glow curve obtained from vacuum annealed crystals. However, if the TL sample is given the same "standard annealing" as is customary in TSEE experiments, there is good agreement. This altered glow curve is a result of hydroxyl ions which diffuse into the sample during annealing. It would be interesting to see if better sample preparation procedures in TSEE experiments would lead to a glow curve which agrees with the "unaltered" glow curve obtained from TLD-100. The lack of correspondence between these two glow curves has been a topic of discussion in the literature for several years and, to the best of our knowledge, this is the first time a specific cause for the discrepancy has been isolated.

The TL efficiency was comparable to cesium γ -rays for 30-5 keV electrons, decreased rapidly between 5 and 1 keV and remain constant at about 20% of the efficiency of cesium γ -rays below 1 keV. Half of this decrease in efficiency can be attributed to the higher LET of low energy

electrons. The cause for the remaining decrease is not known but it may have its origin in the same mechanism proposed to account for the large range of low energy electrons.

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Figure Captions

- Fig. 1 TL glow curve for freshly cleaved crystals irradiated with, A: 2×10^{-11} coulombs 70 eV. electrons. B: 3×10^{-10} coulombs 1 keV. electrons, and C: 1 rad cesium γ -rays.
- Fig. 2 TL vs. coulombs delivered to sample for 100 eV - 5 eV electrons. Note: TL for 100 eV - 1 keV electrons has been successively multiplied by 2 to separate these curves.
- Fig. 3 TL from peaks 3-5 at saturation vs. electron irradiation energy and range as determined by Morbitzer and Scharman (1964). The TL curve has been scaled so as to coincide with the range at 10 keV as determined by Morbitzer's luminescence technique.
- Fig. 4 TL glow curve for irradiation with 100 eV electrons. A: two decades before saturation (10^{-10} C), B: at saturation (10^{-8} C), and C: one decade into saturation (10^{-7} C).
- Fig. 5 TL glow curve for irradiation with 200 eV electrons. A: two decades before saturation (10^{-10} C), B: at saturation (10^{-8} C), and C: one decade into saturation (10^{-7} C).
- Fig. 6 TL glow curve for irradiation with 500 eV electrons. A: one decade and a half decades before saturation (4×10^{-10} C), B: at saturation (10^{-8} C), and C: one decade into saturation (10^{-7} C).
- Fig. 7 TL glow curve for irradiation with 1 keV electrons. A: one decade before saturation (3×10^{-10} C), B: at saturation (3×10^{-8} C), and C: one decade into saturation (3×10^{-7} C).
- Fig. 8 TL glow curve for irradiation with 5 keV electrons. A: one decade before saturation (5×10^{-11} C), B: at saturation (5×10^{-9} C), and C: one decade into saturation (4×10^{-8} C).
- Fig. 9 TL glow curve for irradiation with 20 keV electrons. A: one decade before saturation (10^{-10} C, 2×10^{-9} R), B: at saturation (2×10^{-8} C, 4×10^{-7} R), C: one decade into saturation (3×10^{-8} C, 6×10^{-7} R).
- Fig. 10 Electron ranges in Al, LiF, Mg and MgO by different techniques. A: Semi-empirical formula for transmission of electrons in Al (Kobetich and Katz, 1967) B: range in LiF as determined by the "break away" method for inelastically scattered electron (Bronstein and Protchenko, 1970), C: range in Mg, D: MgO as determined by the "break away" method for inelastically scattered electrons (Bronstein and Brozdichenko, 1969), and E: range in LiF determined by luminescence excitation technique. (Morbitzer and Scharmann, 1964).
- Fig. 11 Electron range vs. irradiation energy. A: data for electron range in air (Cole, 1969) scaled to agree with Morbitzer's luminescence measurement of the range of 10 keV electrons in LiF, B: $a + 180 \lambda$ C: present data for TL from peaks 3-5 at saturation, scaled to numerically agree with Morbitzer's measurement of the range of 10 keV electrons in LiF, and D: Morbitzer's data (1967).

Fig. 12 TSEE glow curve for TLD-100 powder as determined by J. Zimmerman (1971).

Table

Table 1. TL efficiency for 30 keV - 100 eV electrons relative to cesium γ -rays.

Fig. 1

Fig. 3

Fig. 2

Fig. 4

Fig. 5

1 KeV

Fig. 7

500 eV

Fig. 6

Fig. 8

Fig. 9

Fig. 10

Fig. 11

(1) IRRADIATING ELECTRON ENERGY (keV)	(2) DOSE DEPOSITED	(3) TL FROM PEAKS 3-5 [ARBITRARY UNITS]	(4) SUPRALINEARITY FACTORS AT THIS DOSE	(5) (3) CORRECTED FOR SUPRALINEARITY	(6) TL EFFICIENCY RELATIVE TO Co γ -RAYS. (OBSERVED)	(7) TL EFFICIENCY RELATIVE TO Co γ -RAYS ATTRIBUTABLE TO LET EFFECTS (MINGATE, 1967)
30	1×10^{-11}	6.9 $\pm$ 5%	1.23	5.6	.95	.93
10	3×10^{-11}	7.8 $\pm$ 5%	1.50	5.1	.88	.84
5	6.0×10^{-11}	5.5 $\pm$ 5%	1.17	4.7	.80	.77
2	1.5×10^{-10}	2.3 $\pm$ 10%	1.00	2.3	.30	.65
1	3.0×10^{-10}	1.3 $\pm$ 15%	1.00	1.3	.22	.58
.500	6.0×10^{-10}	.78 $\pm$ 15%	1.00	.78	.13	.48
.300	1.0×10^{-9}	1.4 $\pm$ 15%	1.00	1.4	.24	.46
.200	1.5×10^{-9}	1.0 $\pm$ 15%	1.00	1.0	.17	.45
.150	2.0×10^{-9}	1.3 $\pm$ 20%	1.00	1.3	.22	.44
.100	3.0×10^{-9}	1.1 $\pm$ 30%	1.00	1.1	.19	.43

Table 1

Fig. 12