PHYSICAL PARAMETERS OF GLOW PEAKS 4,5 AND 6 IN TLD — 100 (LiF:Mg)

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ABSTRACT

In order to determine more precise values of the trap depth and the frequency factor of the so called peak 6 in magnesium doped LiF, produced by Harshaw Chemical Co., which is commercially known as TLD-100, an appropriate pre - as well as post-annealing treatment was used to isolate the peak 6 from the peak 5. Further post-annealing for different intervals of time at 109, 129, 140, and 145°C has shown a decay curve that can be fitted with continuous trap model, but, not with the original Randall-Wilkins model. It was found E_6 = 1,38 eV, $s_6 = 8{,}0 \times 10^{11}$ sec^{-1}.

The trial to fit the observed glow curve comprising peak 4 and 5 using E - and s - values determined from decay data of each peak when isolated, and using also experimental values of peak 4 and 5 temperature, T_4 and T_5, did not reproduce the observed glow curve. By representing the experimental glow curve, around T_5, by a 6-terms polynomial function and by identifying its coefficients with corresponding coefficients in a power expansion, around T_5, of the expression $I(T) = I_4(T) + I_5(T)$, where $I_i(T)$ is Randall-Wilkins formula for peak i, more accurate values of activation energy E, frequency factors, T_4, T_5, and the ratio $n(E_4,0)/n(E_5,0)$ were determined. $n(E_i,0)$ is the density of filled traps of kind i.

1. INTRODUCTION

TLD-100 is the dosimetric LiF doped with 300 ppm of Mg and grown by Harshaw Chemical Co., Cleveland, Ohio, USA. It has a characteristic glow curve consisting mainly of 5 glow peaks[1] (Fig. 1). Each one has its maximum at a given temperature for a given heating rate to produce the glow curve. Several other peaks at higher temperatures[2] have also been reported which will not be considered here, except for the one very close to the fifth peak. This peak, called peak 6, was first found by pre-irradiation annealing at 120 to 145°C for time longer than 3 hours[1]. It can also be isolated from peak 5 by post-annealing at about 130°C for more than 3 hours. To this date, there is only one determination of the activation energy E_6 and frequency factor s_6 of peak 6 by Zimmerman et al[1]. These values are $E_6 \sim 2.1$ eV and $s_6 \sim 10^{22}$ sec^{-1}, which appears much larger than one expects. Even for peaks 4 and 5, there are considerable variations between the E- and s-values determined by different workers, as can be seen in Table I.

In the present work we tried to obtain reasonable values of E_6 and s_6, as well as, values of E_4, s_4, E_5, and s_5 to be compared with values listed in Table I. For the obtention of isothermal decay data we used different techniques to isolate each one of the peaks.

2. Experimental Methods

TLD-100 powder purchased from Harshaw Chemical Co. and Harshaw TL detector Model 2000 A coupled to an Automatic Integrating Picoammeter Model 2000 B were used in this experiment. The usual heat treatment of 400°C for 1 hour and 80°C for 24 hours was given to

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Table I

Peaks	E(eV)	s(sec^{-1})	authors
4 5	1,19 ± 0,5 1,25 ± 0,6	(1.0 - 15) x 10^{11} (0,5 - 14) x 10^{11}	Zimmerman et al[1]
5	2.4	5 x 10^{23}	Gorbics et al[3]
4 5	1,15 ± 0,06 1,36 ± 0,07	(1.2 ± 0.06) x 10^{12} (2,2 ± 0.11) x 10^{15}	Grant et al[4]
5	$E(T_{low})$ = 1,3 $E(T_{high})$ = 0,8	10^{12}	Moran and Podgorsak[5]

Observ. Moran and Podgorsak used heating rate = 35° C/min.
Gorbics et al obtained above values of E and s from the dependence between peak temperature and heating rate.

the samples. A ^{137}Cs gamma-source was employed for irradiation. Each experimental point in the graphs is an average of about 10 readings.

3. Results

a. Pre - and post-irradiation annealing for observation of peak 6 for isolation of peaks 4 and 5.

Zimmerman et al[1] showed that 3 to 5 hours annealing at temperature in the range of 125°C to 145°C enables peak 6 to be seen distinctly. Another way to isolate peak 6 from peak 5 is to perform post-irradiation annealing at temperatures around 120°C to 165°C. Figure 2 shows glow curves after 0, 2, 4, 6, 8, 10, 20, and 30 hours post-annealing at 127°C. After 2 hours the peak 4 decays almost completely and the peak 5 predominates. After 7 to 8 hours heating, the peak 6 becomes observable together with the peak 5. After 30 hours, the peak 5 decays almost completely, leaving peak 6. The glow curve in Fig. 3 shows peak 6 after the decay of peak 5. A peak at still higher temperature namely at about 320°C can also be seen.

In order to isolate peak 4 we used the optical bleaching method[6], 310 nm UV light bleaches peak 5, little affecting peak 4. The result is shown in Fig. 4. For a bleaching time longer than 3 to 4 hours the height of peak 5 becomes smaller than that of peak 4.

b. Post-annealing decay curves

Starting with these isolated peaks, isothermal decay data were obtained. For peak 4 the post-annealing was carried out at 103, 109, and 120°C for different intervals of time; at 127, 137, 140 and 165°C for peak 5, and at 129, 140 and 145°C for peak 6. The decay curves are shown in Fig 5, 6, and 7, respectively.

c. Supralinearity, peak position of peak 6

Several samples of TLD-100 were irradiated to cesium gamma-rays, varying its exposures from 100 to 7×10^4 R. Subsequently, they were annealed at 130°C for 20 hours and then its TL was read out to obtain TL response vs. exposure. The result shows that the peak 6 is more supralinear than the peak 5, which is in agreement with Sunta et al[2], i.e., higher the peak temperature T_p, more supralinear is the behaviour of this peak (Fig. 8).

The position in degree C of the peak 6 is a function of time intervals of pre-as well as post-annealing. In both cases there is a maximum shift of about 10°C for a pre-annealing at a temperature in the range of 125 to 145°C and, for a post-annealing at a temperature in the range of 120 to 165°C, used in this work.

d. Correlation of peak 6 to some absorption band

As further property of peak 6 we searched for some absorption band connected to that peak. TL measurements and optical absorption were carried out on single crystal of LiF:Mg with a similar characteristic of TLD-100. For the optical absorption, Zeiss spectrophotometer model DMR 21, with double beam, in the range of 2500 to 190 nm wave length was used.

No specific absorption band correlated to peak 6, in this wave length range was found.

4. Randall-Wilkins model and determination of trap depth E and frequency factor s.

From the decay curves of Fig. 5, 6, and 7, we can compute trap depths and frequency factors of peaks 4, 5, and 6.

If we designate by p, the escaping probability of electrons from traps of a given kind, n(t) the number of electrons in the traps at the instant t, $\beta(t) = dT/dt$ the heating rate, we can write in accordance with Randall-Wilkins model[7]

$$p = s \exp(-E/KT)$$
$$K = \text{Boltzmann constant} \qquad (1)$$

or

$$\frac{dn}{dt} = -np \qquad (2)$$

$$\frac{dn}{dT} = -np/\beta(T) \qquad (2a)$$

The glow curve due to a group of traps, each with a definite E-value, is then described by the equation

$$I(T) = n(E,0)\, s \exp\left[-\frac{E}{KT} - \int_{T_o}^{T} \frac{s}{\beta(T)} \exp\left(-\frac{E}{KT'}\right) dT'\right] \qquad (3)$$

T_o can be taken as the room temperature.

If we denote by t_a the length of the post-annealing time at temperature T_a, the glow curve is given by

$$I(T,t_a) = n(E,0)s \exp\left[-\frac{E}{KT} - t_a s \exp\left(-\frac{E}{KT_a}\right) - \int_{T_o}^{T} \frac{s}{\beta(T')} \exp\left(-\frac{E}{KT'}\right) dT'\right] \qquad (4)$$

From experimental curves of Log $I(T,t_a)$ vs. t_a and (4) we can obtain $s \exp(-E/KT_a)$ for different values of T_a, and from this, s and E. The semi-logarithmic plot of eq. (4) is a straight line; this fact characterizes Randall-Wilkins assumption that E is a well defined value. There are several instances, like for peak 6 in Fig. 7, where this hypothesis is not obeyed. Morato and Watanabe[8] assumed that E has a continuous distribution around a given value E_o and half-width. Assuming a Gaussian distribution, the glow curve and the isothermal decay for a post-annealing at T_a for a time t_a can be described by the equation:

$$I(T,t_a) = \frac{n(E_o)s}{\sqrt{2\pi}\,\sigma} \int_{E_1}^{E_2} \exp\left[-\frac{|E - E_o|^2}{2\sigma^2} - t_a\, s \exp\left(-\frac{E}{Kt_a}\right) - \frac{E}{KT} \right.$$

$$\left. - \int_{T_o}^{T} \frac{s}{\beta(T')} \exp\left(-\frac{E}{KT'}\right) dT' \right] dE \qquad (5)$$

By a best fit of experimental points in Fig 5 and 6 and using eq. (4) we obtained the values of E and s listed in Table II.

Table II

Peak n°	E(eV)	$s(sec^{-1})$
4	1.10 ± 0.05	$(1 - 10) \times 10^{10}$
5	1.24 ± 0.04	$(1 - 10) \times 10^{11}$
6	1.36 ± 0.12	$(1 - 10) \times 10^{12}$

In this calculation for peak 6, the slope of the curves in Fig 7 for large t_a end was considered. Since, it is obvious that these curves do not obey rigorously eq. (4), we used eq. (5). As starting values of parameters we used those listed in Table II. In Fig. 7 solid lines are the theoretical ones with the following values of the parameters

$$\begin{aligned} E_6 &= 1.38 \pm 0.07 \text{ eV} \\ s_6 &= (8.0 \pm 0.10) \times 10^{11} \text{ sec}^{-1} \\ \sigma_6 &= 0.06 \text{ eV} \\ T_6 &= 272^\circ\text{C (peak temperature)} \end{aligned} \qquad (6)$$

Connected to the non-exponential decay behaviour of the peak 6 it is found experimentally that there is a shift in peak temperature as the isothermal annealing proceeds. In Fig. 9 the solid line is the theoretical shift as predicted by the continuous model, while the crosses are the experimental points.

5. Theoretical best fit to actual glow curve

Having obtained above parameters we tried to fit the actual experimental glow curve

(peak 4 + peak 5), taking the ratio of the heights of these two peaks as adjustable parameters. We always obtained a broad single peak without the observed peak 4 shoulder. This was proved to be due to the small value of $\Delta T = T_5 - T_4$, where T_5 and T_4 are the peak 4 and peak 5 temperatures determined from experimental heating curve. Actually, besides usual experimental error, there is an intrinsic difficulty in determining the real experimental peak temperature. For this determination if we solder the tip of thermocouple to the heating planchet, we obtain a heating curve distinct from a simple contact to the surface of planchet. Gorbics et al[2] immersed the tip of thermocouple in the hot pressed TL powder under measurement mixed with gold powder to have better thermal contact. Probably this is the most correct way to determine the phosphor temperature during heating procedure. Of course, keeping the thermocouple immersed in the phosphor powder without mixing gold powder one obtains a different temperature reading.

It is evident that the actual temperature of TL phosphor is always lower than the planchet temperature. In most of the cases the peak temperature is taken from the planchet heating curve.

A second factor that contributes to the error in ΔT - value is the fact that the peak 4 always appears as a shoulder of peak 5, therefore it is difficult to define the exact position of its peak.

Hence, starting from values listed in Table II for peaks 4 and 5 and keeping T_5 and T_4 as variable parameters we tried a direct fit of the experimental glow curve to

$$I(T) = I_4(T) + I_5(T) \tag{7}$$

I_4 and I_5 are Randall-Wilkins formulae for peak 4 and peak 5, respectively. Two methods were employed for this calculation.

A. Power series expansion around T_5

This method consists of:

i) Finding coefficients A_i in the power series

$$I(T) = \Sigma_i A_i (T - T_5)^i \tag{8}$$

that reproduce the observed glow curve around T_5

ii) Expanding eq. (7) in a power series similar to (8) and equating corresponding coefficients

iii) Extracting the values of parameters from the identification of these coefficients.

In practice eq. (8) is truncated, keeping k terms and then proceed with least square fitting[9] minimizing

$$Y = \sum_{i=0}^{m} W_i [F'(X_i) - F(X_i)]^2 \tag{9}$$

where

$$X_i = T_i - T_5$$

$F'(X_i)$ = experimental value of $I(T)$ at X_i

$$F(X_i) = \sum_{j=0}^{k} A_j X_i^j \qquad (10)$$

$W_i = \sigma_i^{-2}$

σ_i = mean square deviation associated with X_i. In the present case σ_i was varied between 2 and 5% and k = 5. We obtained

$$\begin{aligned} A_0 &= 1.0645 \times 10^{1} & A_3 &= -0.2874 \times 10^{-2} \\ A_1 &= 0.7613 \times 10^{-2} & A_4 &= -0.1698 \times 10^{-4} \\ A_2 &= -0.6195 \times 10^{-1} & A_5 &= 0.2056 \times 10^{-5} \end{aligned} \qquad (11)$$

These values were equated to the corresponding coefficients in the expansion

$$I(T) = \sum_{i=0}^{k} (n!)^{-1} I^{(n)}(T_5) (T - T_5)^i \qquad (12)$$

There are several sets of solutions of the resulting set of equations for which E_4, s_4, T_4, E_5, s_5, and T_5 are unknowns. Decay curves were used to select the most reasonable set. We obtained

$$\begin{aligned} E_4 &= 1.07 \pm 0.03 \text{ eV} & E_5 &= 1.29 \pm 0.04 \text{ eV} \\ s_4 &= (3.0 \pm 0.1) \times 10^{10} \text{ sec}^{-1} & s_5 &= (6.0 \pm 0.2) \times 10^{11} \text{ sec}^{-1} \\ T_4 &= 197^{\circ}\text{C} & T_5 &= 237^{\circ}\text{C} \end{aligned} \qquad (13)$$

Gorbics et al[3] obtained $T_5 = 235^{\circ}$C using $\beta = 2,3^{\circ}$C/sec.

Figure 10 shows theoretical curves (solid lines). Dots are experimental points. First glow curve is for 0 hour post-annealing, second one for 2 hours and third one for 4 hours post-annealing at 127°C.

B. Least square best fit for a non-linear function of several variables[10].

In eq. (7) let us consider as variables, the temperature T, TL response I(T), post-annealing time t_a and the error σ associated to I(T) at temperature T; trap depth E, frequency factor s, and the ratio between initial number of filled peak 4 and peak 5 traps as adjustable parameters.

In the actual computation we consider a discrete set of T values. If we designate by T_i the i th value of T, σ_i the mean square deviation at T_i, Y_i experimental value of TL at T_i $X_1 \ldots\ldots X_n$ the n variables and $E_1 \ldots\ldots E_m$ the m parameters of the problem in hand, we can construct the following difference

$$g_i = (I(T_i) - Y_i) / \sigma_i \qquad (14)$$

which is a non linear function of n variables and m parameters. The least square best-fit consists in minimizing the sum

$$G = \sum_{i=1}^{k} g_i^2 \qquad (15)$$

r is the number of discrete T values appropriately chosen. σ was varied between 3 and 5%. For peak temperatures T_4 and T_5 we used the values found in the previous computation.

In Fig. 11, solid lines represent theory and dots have the same meaning as in Fig. 10. This result corresponds to the following set of parameters.

$$\begin{aligned} E_4 &= 1.05 \pm 0.03 \text{ eV} & E_5 &= 1.29 \pm 0.04 \text{ eV} \\ s_4 &= (1.00 \pm 0.05)\ \text{sec}^{-1} \times 10^{10} & s_5 &= (6.8 \pm 0.4) \times 10^{11}\ \text{sec}^{-1} \\ & n(E_4,0)/n(E_5,0) = 0{,}38 \end{aligned} \qquad (16)$$

In both cases A and B the heating rate was taken constant and equal to 2.3°C/sec.

6. Conclusions

a. By singling out the peak 5 as better as one can by post-annealing at temperature between 125 and 135°C and by isolating peak 4 by optical bleaching with 310 nm UV light, we obtained from isothermal decay curves, trap depths and frequency factors for peaks 4 and 5 as it follows:

$$E_4 = 1.10 \pm 0.05 \text{ eV and} \quad s_4 = (1 - 10) \times 10^{10}\ \text{sec}^{-1}$$
$$E_5 = 1.24 \pm 0.04 \text{ eV and} \quad s_5 = (1 - 10) \times 10^{11}\ \text{sec}^{-1}$$

b. Pré-annealing at temperature in the range 100 to 125°C or post-annealing at any temperature between 120 to 165°C eliminate peak 5 leaving peak 6 almost isolated. The isothermal annealing shows that the decay curve is not exponential as expected by Randall and Wilkins model. Further-more the peak position shifts as the annealing proceeds. The continuous trap model predicts both behaviour and following values of parameters:

$$\begin{aligned} E_6 &= 1.38 \pm 0.07 \text{ eV} \\ s_6 &= (8.0 \pm 0.01) \times 10^{11}\ \text{sec}^{-1} \\ \sigma_6 &= 0.06 \text{ eV} \\ T_6 &= 272°\text{C} \end{aligned}$$

c. The peak 6 is markedly more supralinear than the peak 5 and this supralinearity starts at about 100 R; the saturation takes place in the vicinity of 10^5 R. The peak 6 height is, however much smaller than of the peak 5.

In the range of 2500 nm to 190 nm no specific absorption band correlated to the peak 6 was found.

d. After failure to reproduce the observed glow curve comprising peaks 4 and 5, using the values of trap depth, frequency factor and peak temperature found in this work, the experimental curve was fitted with polynomial function around T_5°, the peak 5 temperature. Six terms were used and the coefficients of the power series expansion of $I(T) = I_4(T) + I_5(T)$, where $I_i(T)$ is Randall Wilkins formula for peak i. The values of trap depth, frequency factor and peak temperature are:

$$\begin{aligned} E_4 &= 1.07 \pm 0.03 \text{ eV} & E_5 &= 1.29 \pm 0.04 \text{ eV} \\ s_4 &= (3.0 \pm 0.1) \times 10^{10}\ \text{sec}^{-1} & s_5 &= (6.0 \pm 0.2) \times 10^{11}\ \text{sec}^{-1} \end{aligned}$$

T_4 = 197°C T_5 = 237°C

The merit of this process is that, if we have a well defined heating rate, the peak temperature can be determined from the calculation. It gives, however, several sets of solutions. Isothermal decay data can be used to select the most reasonable one.

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RÉSUMÉ

Afin de déterminer avec plus de précision la profondeur de piège et la facteur de fréquence du pic n° 6 dans le LiF dopé au magnésium (fourni par Harshaw Chemical Co. sous le nom commercial de TLD-100) un recuit avant irradiation (pré recuit) et un recuit après irradiation (post-recuit) ont été utilisés pour isoler la pic 6 du pic 5. Les post-recuits de durée variable à 109, 129, 160 et 145°C ont montré que les courbes de decroissance ne peuvent pas être ajustées par la théorie de Randall-Wilkins, mais elles s'accordent avec la théorie de distribution continue des pièges. Les valeurs E_6 = 1,38 eV et $s_6 = 8{,}0.10^{11}$ sec^{-1} ont été trouvées.

Il n'a pas été possible de reproduire la courbe d'émission contenant les deux pics 4 et 5 en utilisant la théorie de Randall-Wilkins, les valeurs de l'energie d'activation E et du facteur de fréquence s, et les températures T_4 et T_5 des pics 4 et 5 obtenus expérimentalement. Le courbe d'emission expérimentale a été alors representée par un polynôme de 6 terms au voisinage de T_5 et ses coefficients identifiés avec les coefficients correspondants du développement en série au voisinage de T_5 de l'expression $I(T) = I_4(T) + I_5(T)$, où $I_i(T)$ est la formule de Randall-Wilkins pour le pic i. Cette identification a permis de calculer, pour les pics 4 et 5, les valeurs de l'energie d'activation, du facteur de frequence, de la température et la relation $n(E_4,0)/n(E_5,0)$. $n(E_i,0)$ représente la densité de pièges occupés d'espèce i.

RESUMO

Afim de determinar valores mais precisos da profundidade das armadilhas e fator de frequência do assim chamado pico 6 no LiF ativado com magnésio, preparado por Harshaw Chemical Co., que é comercialmente conhecido com o nome de TLD-100, um tratamento pré e pós-recozimento apropriado foi usado para isolar o pico 6 do pico 5. Pós-recozimentos em 109°, 129°, 140° e 145°C dão origem a curvas de decaimento que podem ser ajustadas com o modelo contínuo, porém, não com o de Randall-Wilkins. Foram obtidos E_6 = 1,38 eV e $s_6 = 8{,}0 \times 10^{11}$ s^{-1}.

A tentativa de ajustar a curva de emissão contendo os dois picos 4 e 5, usando os valores de E e s determinados das curvas de decaimento de cada um dos picos isolados, e usando as temperaturas dos picos 4 e 5, T_4 e T_5, obtidos experimentalmente, não reproduz a curva de emissão observada. Ajustando a curva experimental a uma função polinomial com 6 termos, em torno de T_5, e identificando seus coeficientes com os coeficientes correspondentes na série de potência em torno de T_5, da expressão $I(T) = I_4(T) + I_5(T)$, onde $I_i(T)$ é a fórmula de Randall Wilkins para o pico i, foram determinados a energia de ativação, fator de frequência, T_4, T_5 e a razão o $n(E_4,0)/n(E_5,0)$. $n(E_i,0)$ é a densidade de armadilhas preenchidas do tipo i.

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FIGURE CAPTIONS

Fig. 1 - Typical glow-curve of TLD-100 after annealing 1 hr at 400°C and γ-irradiating to 800 R of ^{137}Cs. Heating-rate: 60°C/min.

Fig. 2 - Post-annealing effects at 127°C on peaks 4, 5 and 6, after

a) 0 hrs
b) 2 hrs
c) 4 hrs
d) 6 hrs
e) 8 hrs
f) 10 hrs
g) 20 hrs
h) 30 hrs

Fig. 3 - Peak 6 isolated by post-annealing at 130°C/ 20 hours

Fig. 4 - Peak isolated after post-annealing 103°C and optical bleaching ultraviolet 310 nm light for 90 minutes

a) 0 hrs at 103°C
b) 2 hrs at 103°C
c) 4 hrs at 103°C
d) 6 hrs at 103°C
e) 8 hrs at 103°C

Fig. 5 - Exponential decay of peak 4.
Post-annealings at: 103°C, 109°C, 120°C.

Fig. 6 - Exponential decay of peak 5
Post-annealings at 127°C, 137°C, 140°C and 165°C

Fig. 7 - Decay of peak 6
Post-annealings at: 129°and 140°C

Fig. 8 - TL response of TLD-100 vs. gamma-rays exposure

Fig. 9 - Peak 6 temperature shift for post-annealing at 137°C.
Solid line – theory; (x) experiments.

Fig.10 - Best fit to actual glow curve of TLD-100, around peaks 4 and 5, by expanding Randall-Wilkins two peaks formulae into power series (6 terms are retained)

Fig.11 - Peaks 4 and 5 simultaneous fit using Randall-Wilkins Model.

Fig. -1

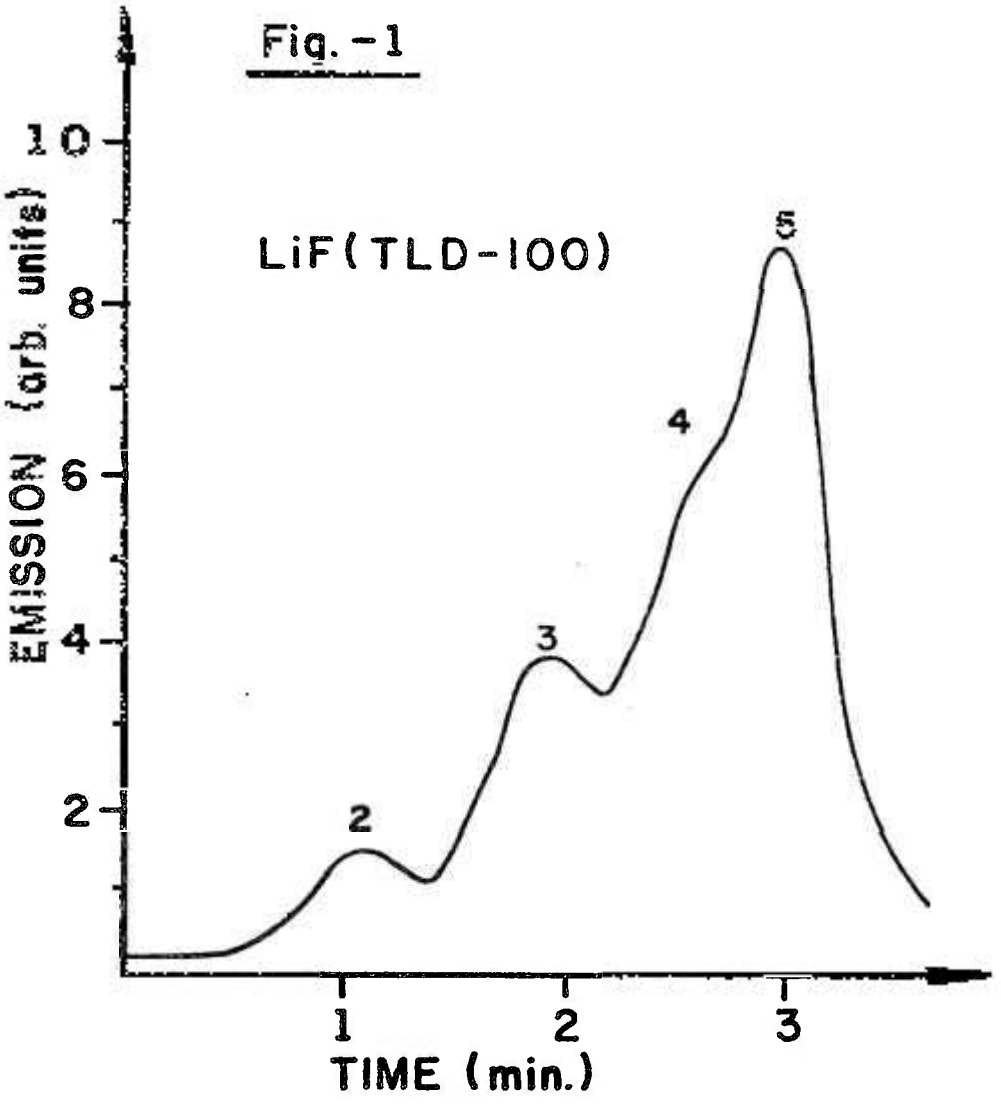


Fig.-2

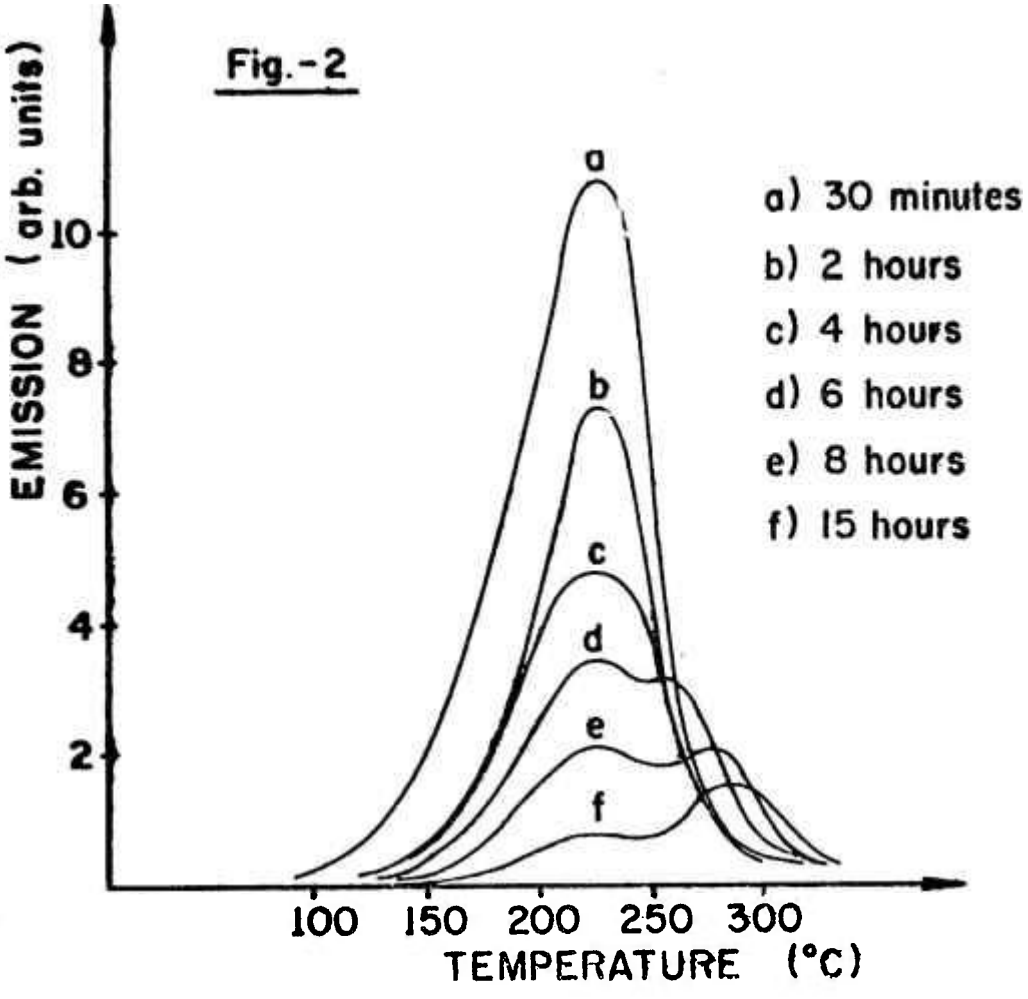

EMISSION (arb. units)
10
8
6
4
2
a
b
c
d
e
f
a) 30 minutes
b) 2 hours
c) 4 hours
d) 6 hours
e) 8 hours
f) 15 hours
100
150
200
250
300
TEMPERATURE (°C)

Fig.-3

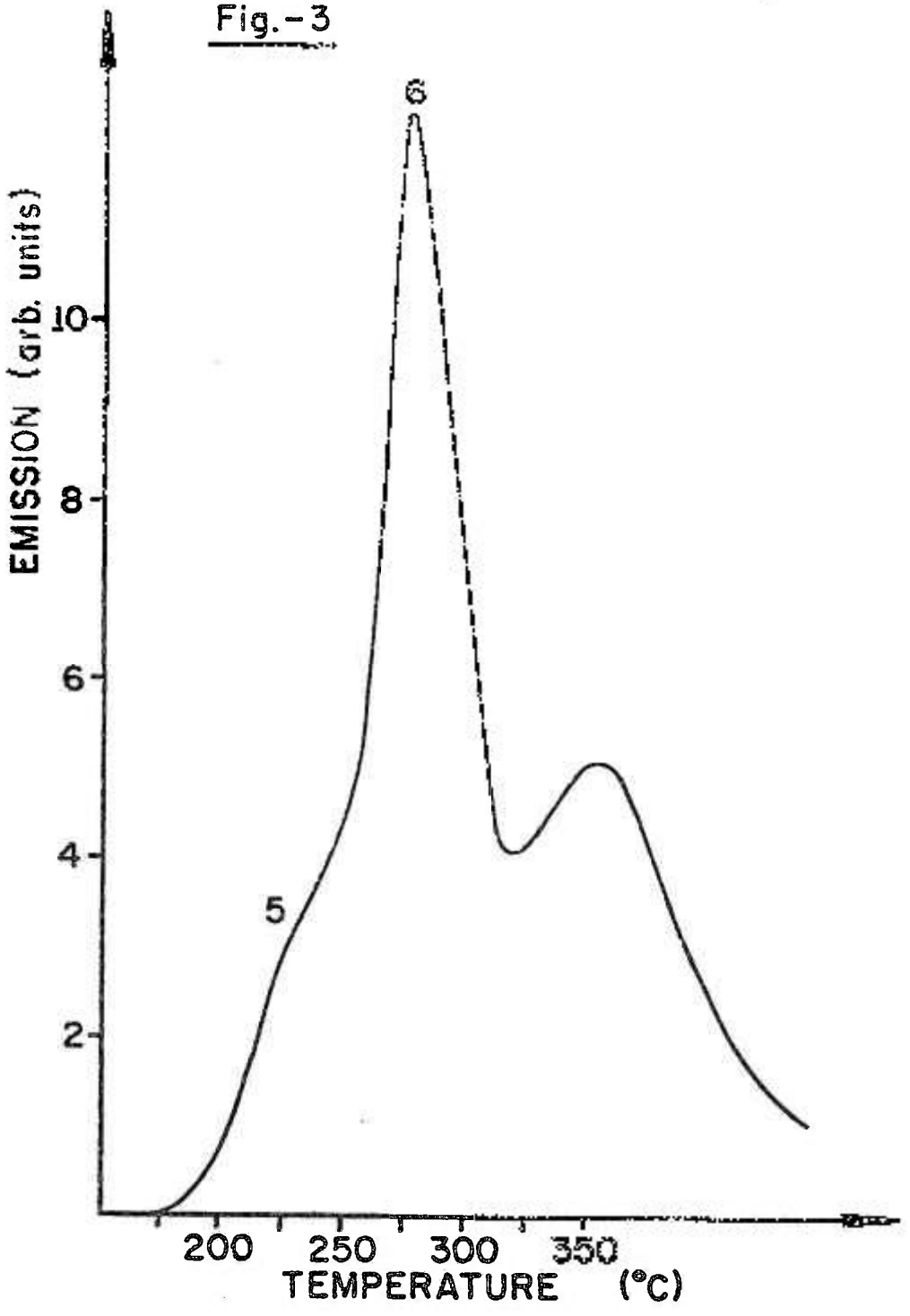
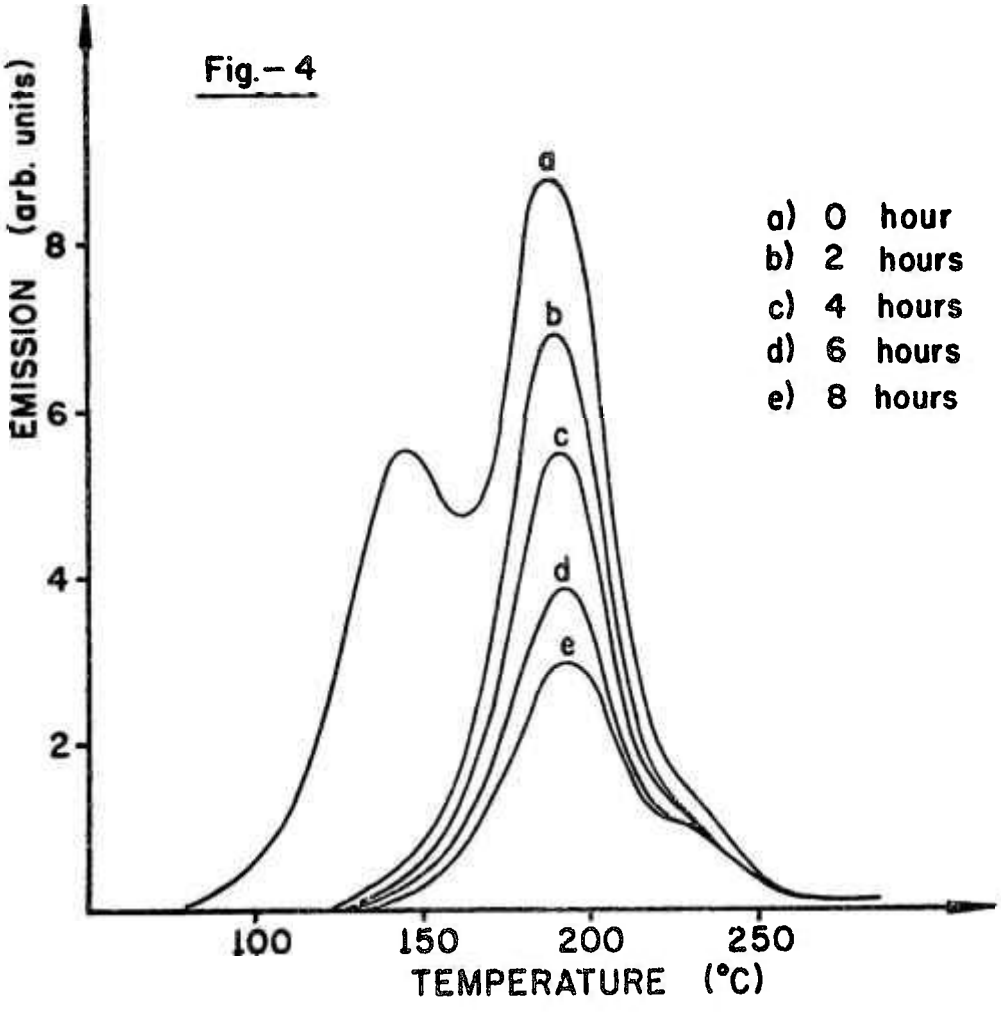


Fig.– 4


EMISSION (arb. units)
8
6
4
2
a
b
c
d
e
a) 0 hour
b) 2 hours
c) 4 hours
d) 6 hours
e) 8 hours
100
150
200
250
TEMPERATURE (°C)

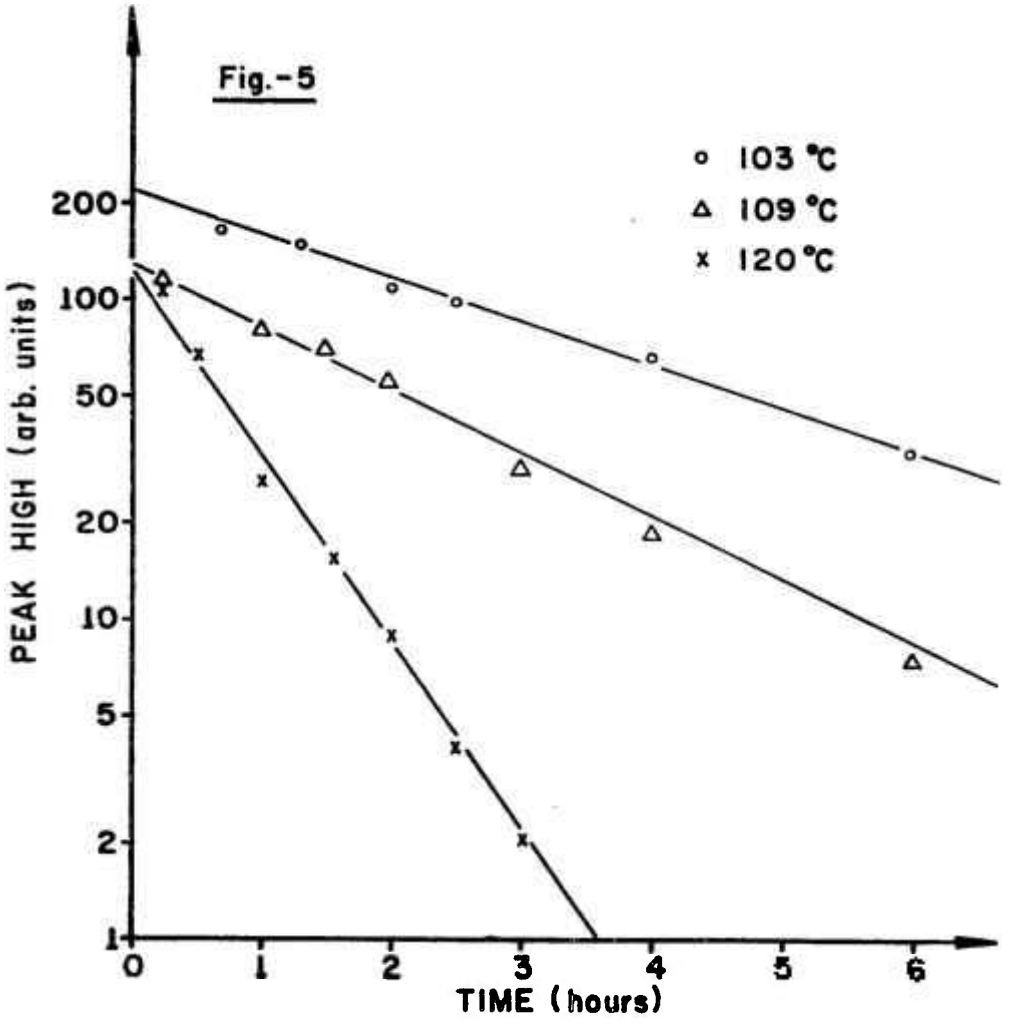
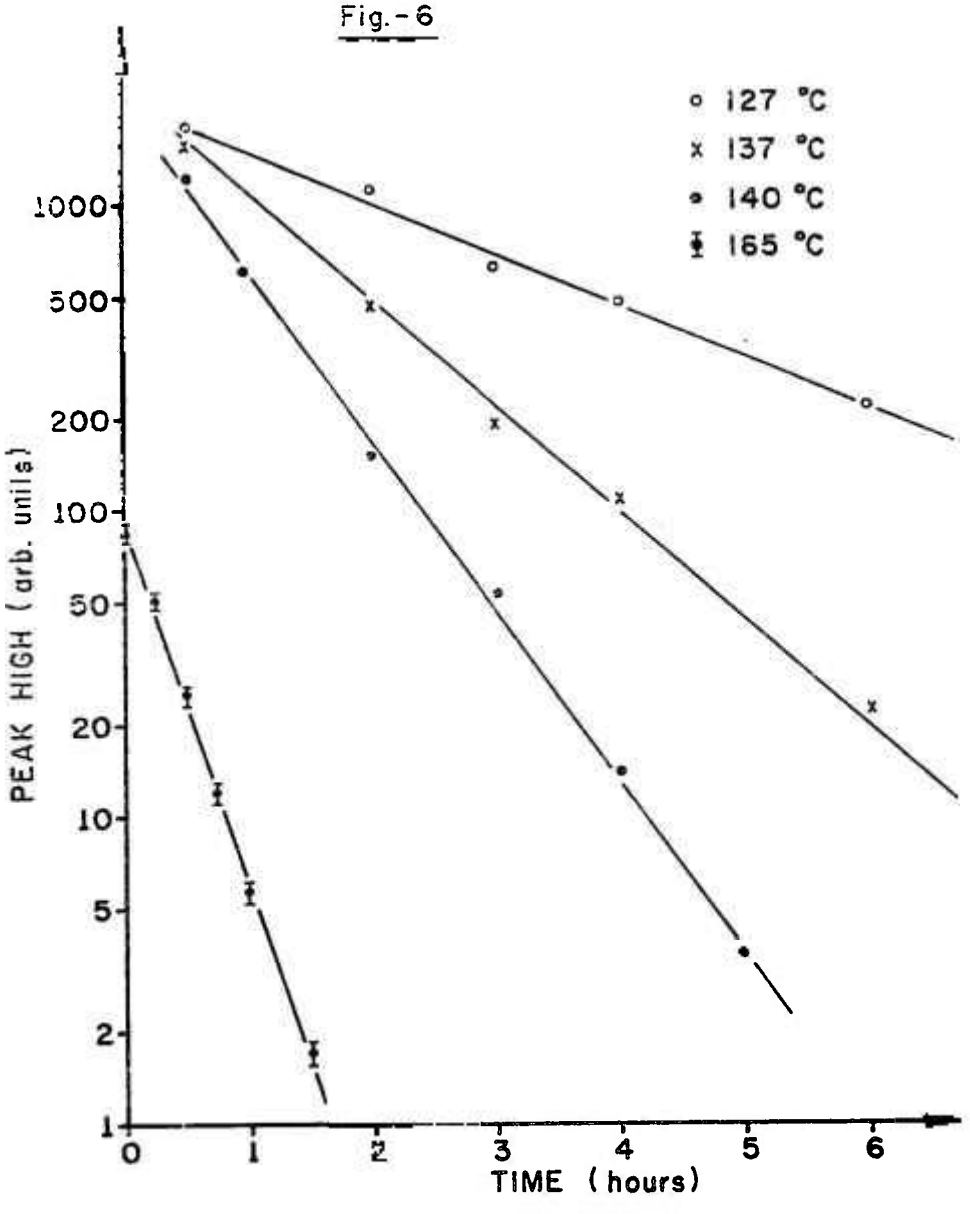


Fig.-5
o 103 °C
Δ 109 °C
x 120 °C
PEAK HIGH (arb. units)
200
100
50
20
10
5
2
1
0
1
2
3
4
5
6
TIME (hours)

Fig.-6


127 °C
137 °C
140 °C
165 °C
PEAK HIGH (arb. units)
1000
500
200
100
50
20
10
5
2
1
0
1
2
3
4
5
6
TIME (hours)

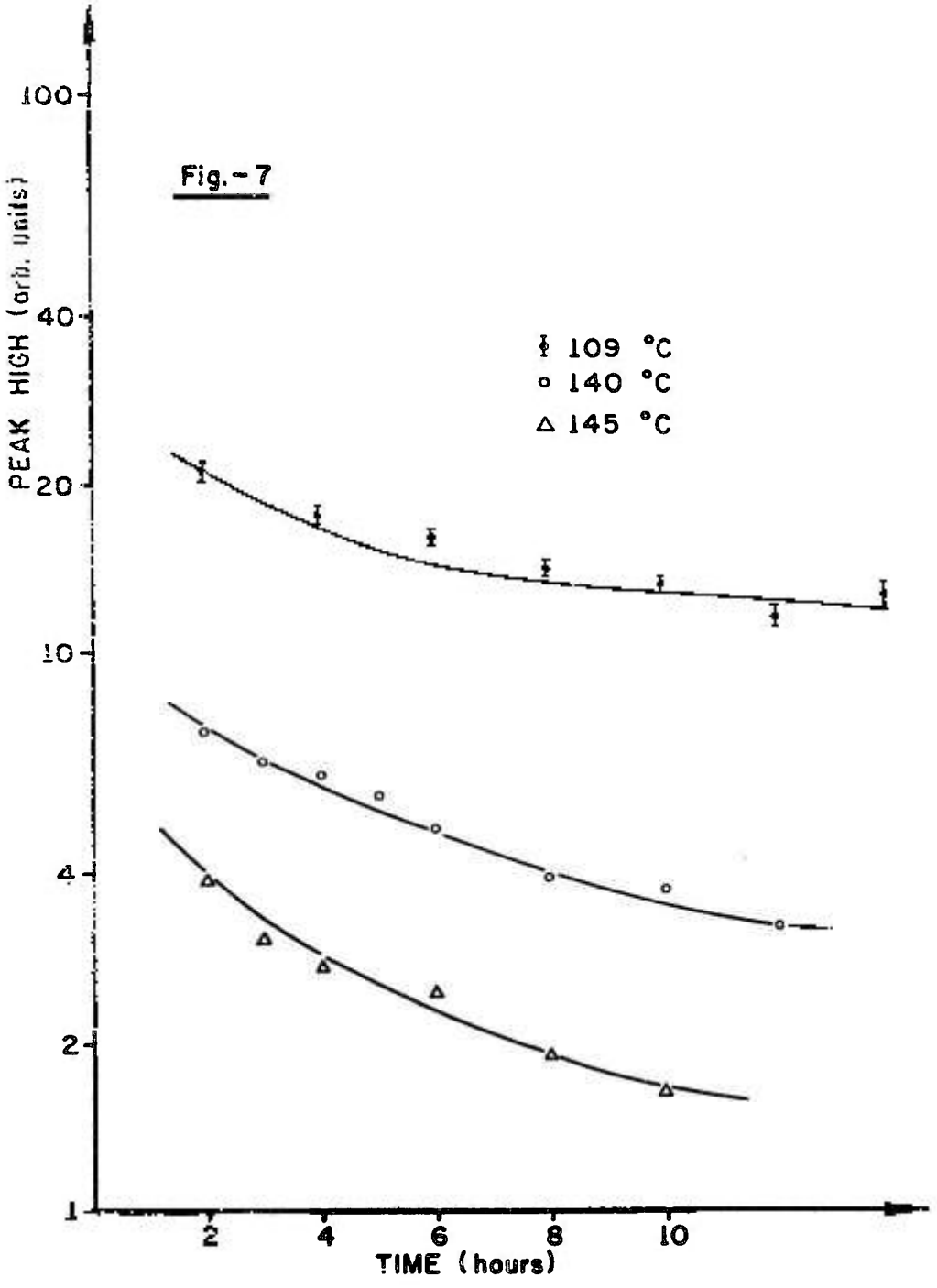
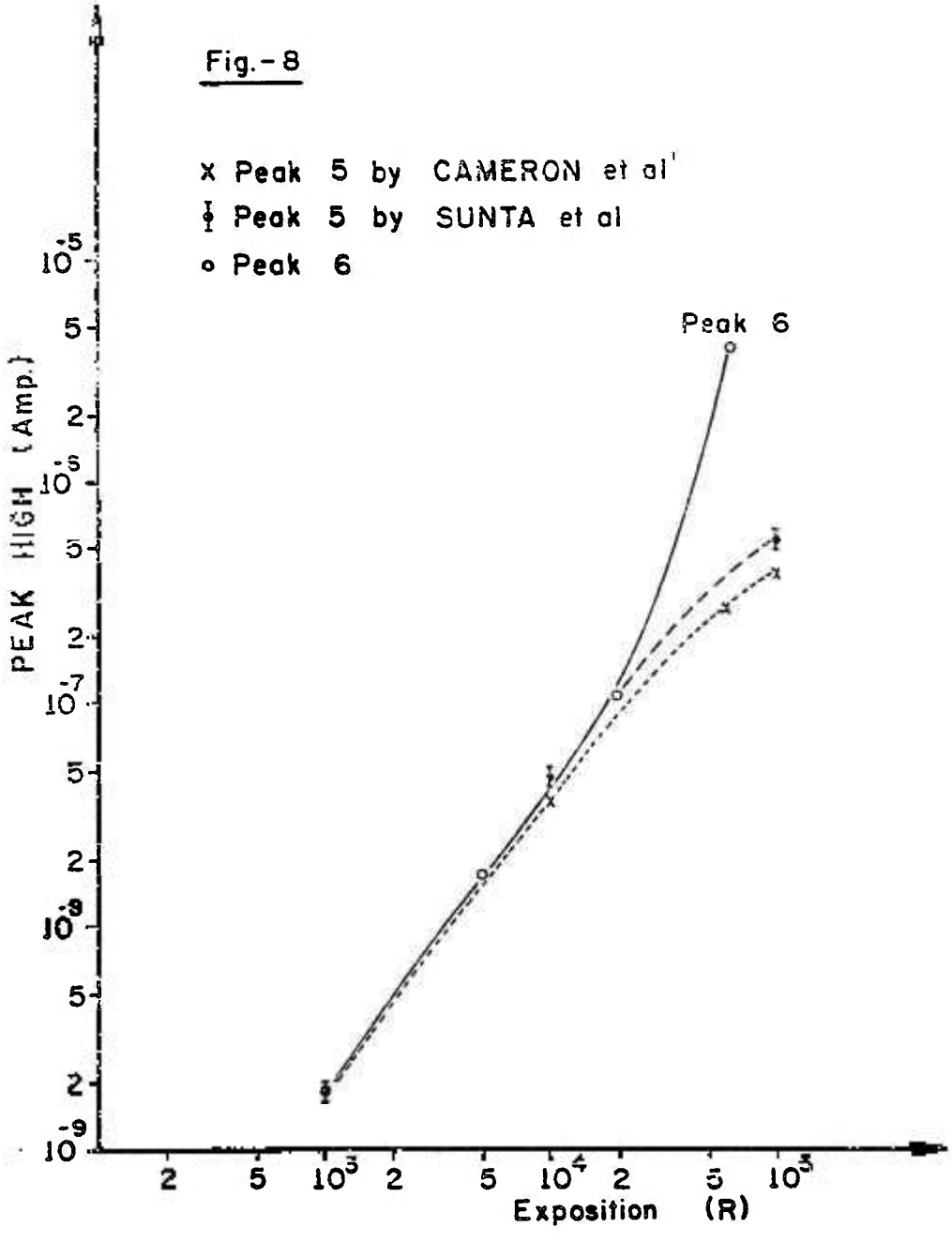


Fig.-7
PEAK HIGH (arb. units)
100
40
20
10
4
2
1
109 °C
140 °C
145 °C
2
4
6
8
10
TIME (hours)

Fig.-8


x Peak 5 by CAMERON et al
Peak 5 by SUNTA et al
o Peak 6
Peak 6
PEAK HIGH (Amp.)
Exposition (R)

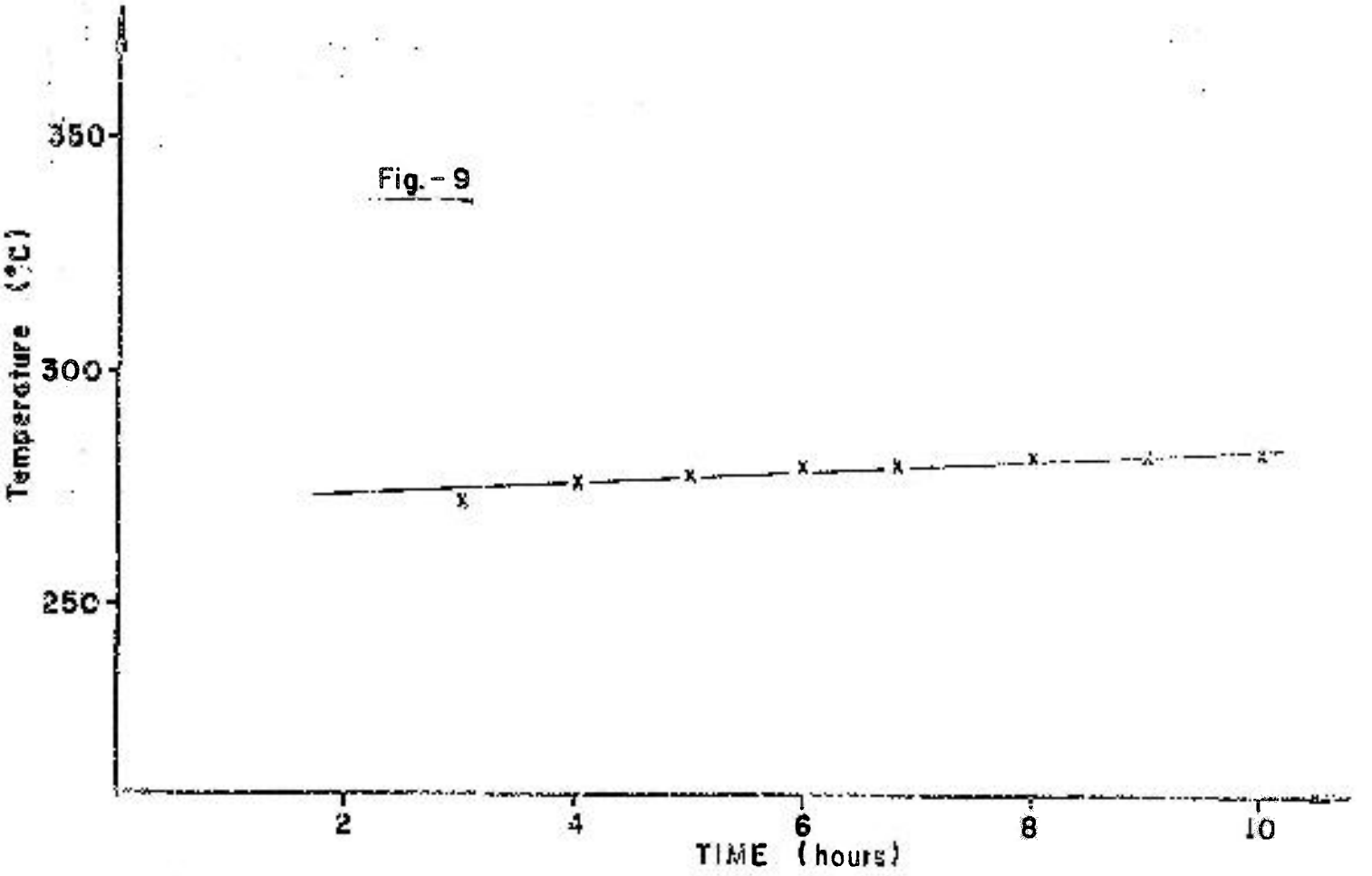
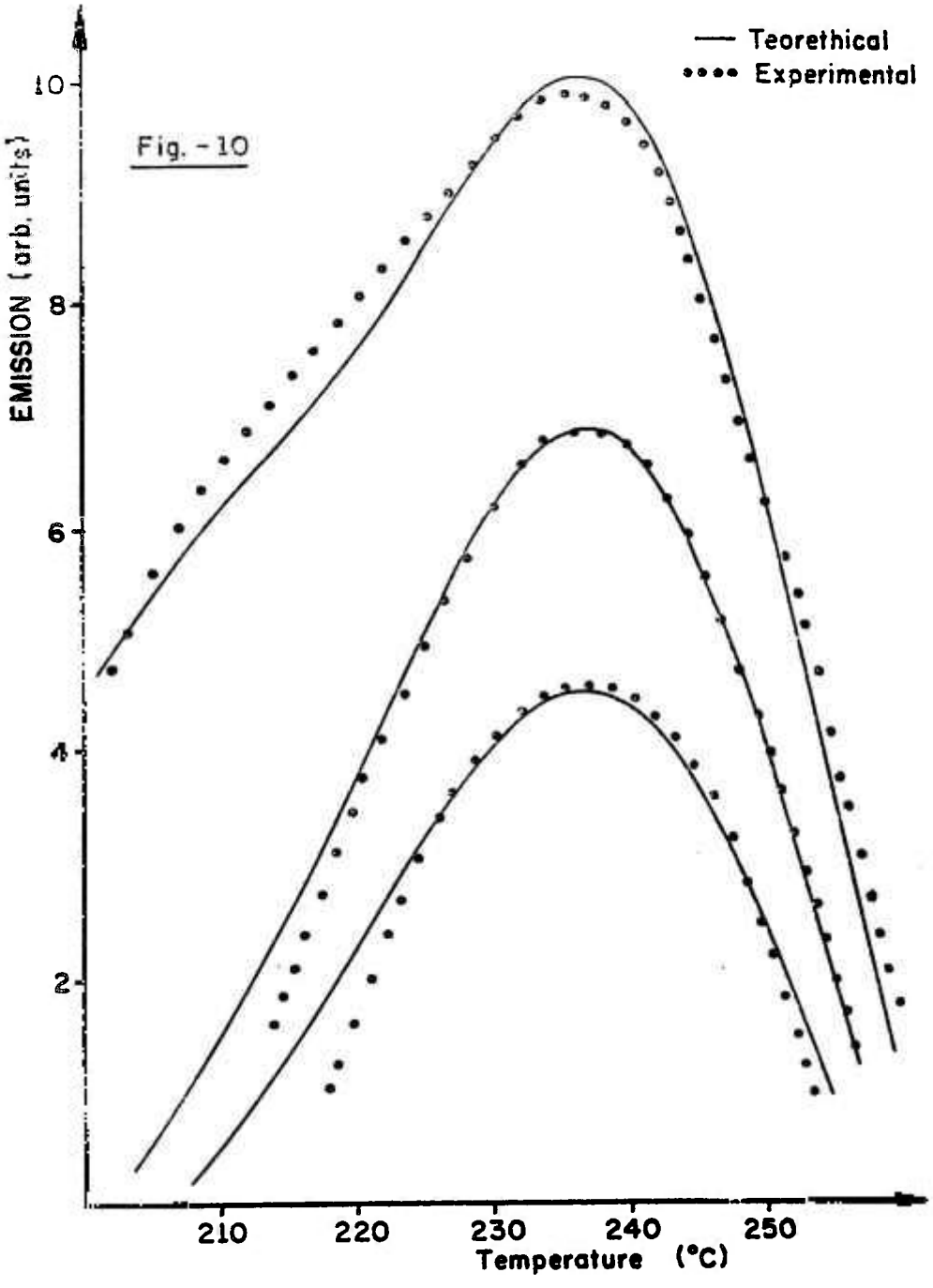


Fig. - 9
350
300
250
Temperature (°C)
2
4
6
8
10
TIME (hours)


Teorethical
Experimental
Fig. - 10
EMISSION (arb. units)
10
8
6
4
2
210
220
230
240
250
Temperature (°C)

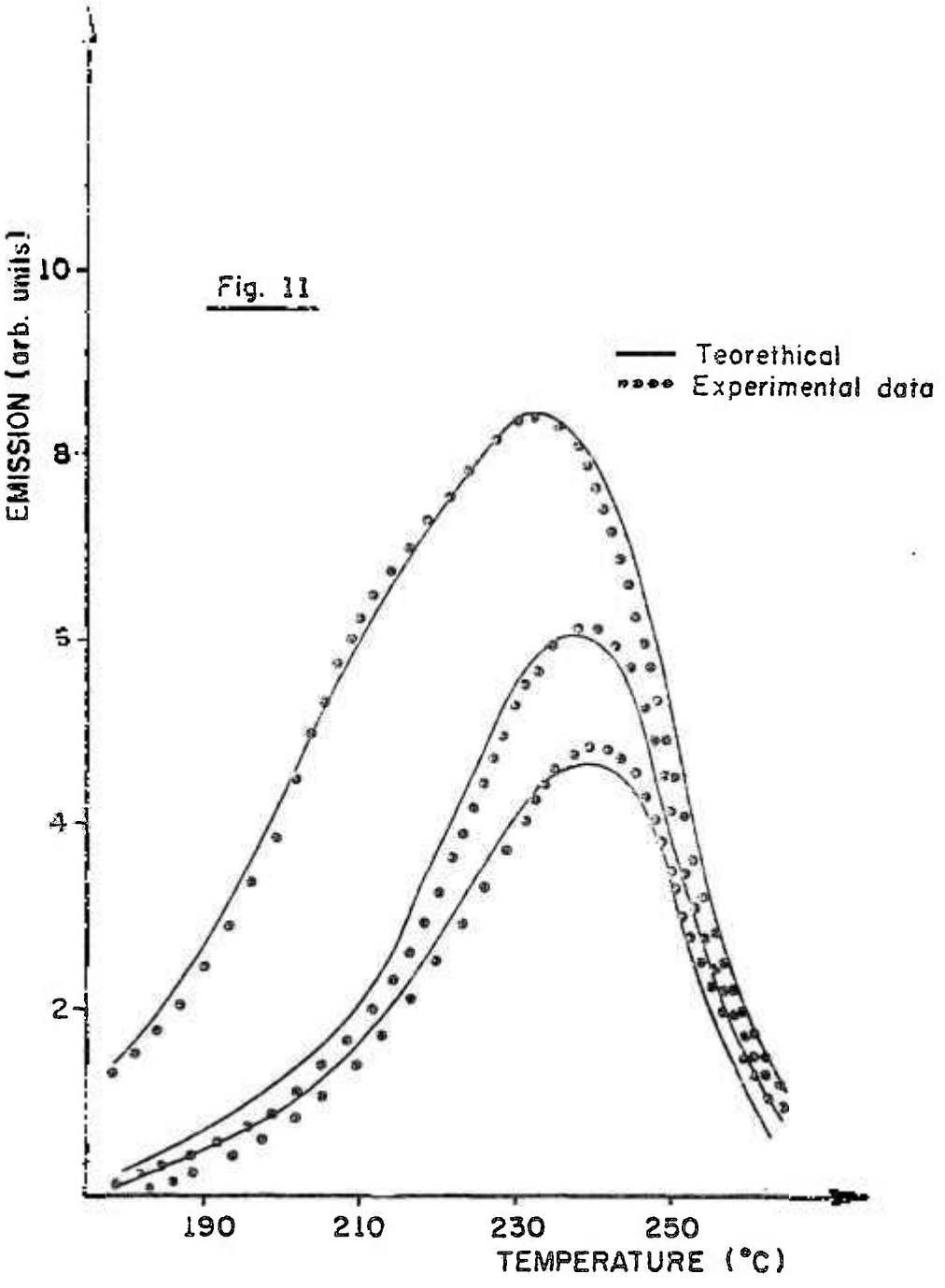


Fig. 11
Teorethical
Experimental data
EMISSION (arb. units)
10
8
6
4
2
190
210
230
250
TEMPERATURE (°C)