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CHARACTERISTICS OF THERMOLUMINESCENCE GLOW CURVES FOR MATERIALS EXHIBITING MORE THAN ONE GLOW PEAK*

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ABSTRACT

The properties of thermoluminescence glow curves, containing one or more glow peaks, have been determined for situations where the assumptions invoked to obtain the usual first and second order kinetics do not apply. First order kinetics occurs only when retrapping is negligible. If more than one glow peak is present and retrapping occurs between different types of traps the glow peaks can be approximated, except in the "wings," by the usual first and second order expressions; but often physically unrealistic parameters are obtained. These studies indicate that dating is best accomplished with minerals exhibiting first order kinetics.

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INTRODUCTION

The thermoluminescence (TL) properties of materials exhibiting a single glow peak that is not described by the usual first and second order kinetics were described previously (Levy, 1980). Described here are TL systems with more than one glow peak that are not subject to the assumptions invoked to obtain the usual first and second order kinetics. Simple generalized kinetic equations have been obtained, for systems with more than one glow peak, which are analogous to the equations which are the basis for the usual first and second order expressions. The properties of these systems have been studied by obtaining numerical solutions of the generalized equations. In turn, glow curves computed from the general expressions were subjected to a best-fit procedure to obtain the usual first and second order kinetic parameters. The results show that glow peaks, that are neither first nor second order, are often approximated by first and second order kinetics in a way that provides misleading kinetic information.

As emphasized previously (Levy 1980), the usual first and second kinetic expressions are based on a number of assumptions. These are contained in the original papers, Randall and Wilkens (1945) for first order and Garlick and Gibson (1948) for second order, and described—with varying degrees of emphasis—in a number of books (Garlick, 1949; Curie, 1963; Bräunlich, 1979). Inasmuch as the properties of a single glow peak, not subject to the usual assumptions, was described previously (Levy 1980), only those earlier results needed for comparison with glow curves with more than one peak will be reviewed here. This will be followed by a derivation of the simplest possible equations, for materials with more than one glow peak, which describes the glow curves obtained when none of the usual equations apply. The more obvious properties of these glow curves will be described. Finally, these computed glow curves will be regarded as measured curves and analyzed as if they were "data." This demonstrates the degree that glow curves, for materials not subject to the usual assumptions, are—or are not—described by the usual first and second order kinetics. It also provides the kinetic parameters, the E and s values, which would be obtained from the commonly used methods for determining glow peak kinetics parameters, e.g those described by Chen (1969,1976).

PROPERTIES OF GLOW CURVES WITH A SINGLE GLOW PEAK

In a material exhibiting a single glow peak, the simplest equation describing the shape, peak temperature and other properties of the TL curve is based on the equations

$$\frac{dn_1}{dt} = (-1)[n_1 s_1 \exp(-E_1/kt)]\left[1 - \frac{\sigma_{t1}(N_1-n_1)}{\sigma_{t1}(N_1-n_1)+\sigma_r n_r}\right] \qquad (1)$$

and

$$I(t) = -dn_1/dt \quad \text{or} \quad I(t) = -dn_r/dt, \qquad (2)$$

where n_1 = trapped electron concentrationat time, t

n_{10} = trapped electron concentration at time $t = 0$

s_1 = preexponential or "attempt-to-escape" frequency

E_1 = activation energy for thermal untrapping, in eV.

k = Boltzmann's constant

T = temperature, in degrees Kelvin for all computations and in degrees Celcius for all figures

σ_{t1} = cross section for electron retrapping by empty electron traps

σ_r = cross section for electron-hole recombination resulting in light emission

N_1 = electron trap concentration

N_r = hole trap concentration; N_r does not appear explicitly in the simple cases considered in this paper

n_{ro} = trapped hole concentration at $t = 0$

$\sigma_1 = \sigma_{t1}/\sigma_r$.

For linear heating $T = T_0+\beta t$, where T_0 = temperature when heating commences and β = heating rate.

As mentioned above, the use of equations (1) and (2) includes the implied assumption that there is only one type of hole trap and one type of electron trap. It is also implicitly assumed that s and E are constants.

The usual first order TL glow curve expression:

If it is assumed that $\sigma_r n_r \gg \sigma_{t1}(N_1-n_1)$, i.e. if retrapping is negligible, then eqs. (1) and (2) become

$$I(t) = -dn/dt = n_1 s_1 \exp(-E/kT). \qquad (3)$$

Using $T = T_0+\beta t$ the well-known first order glow curve expression is obtained

$$I(t) = n_0 s_1 \exp(-E_1/kT)\exp\left(-\int_0^T \frac{s_1}{\beta}\exp(-E_1/kT)dt\right). \qquad (4)$$

The usual second order TL glow curve expression:

If retrapping occurs and if, in addition, it is assumed: 1) The cross section for electron retrapping is equal to the cross section for hole retrapping, i.e. $\sigma_{t1} = \sigma_r$, and, 2) The number of trapped electrons is equal to the number of trapped holes, i.e. $n_1 = r_r$, or equivalently, $n_{10} = n_{ro}$ then eqs. (1) and (2) become

$$I(t) = -dn_1/dt = n_1^2 s_1 \exp(-E/kT). \qquad (5)$$

Using $T = T_0+\beta t$ one obtains the usual second order glow curve expression

$$I(t) = \frac{n_{01} s_1^* \exp(-E_1/kT)}{\left(1 + \frac{s^*}{\beta} \int_0^T \exp(-E_1/kT)dT\right)^2}, \text{ where } s_1^* = \frac{n_{01}}{N_1} s. \qquad (6)$$

<u>Properties of the usual first and second order glow curve expressions:</u>

Glow curves computed from eqs. (4) and (6) are shown in Fig. 1 for $E_1 = 1.0$, 1.25 and 1.50 eV, the trap concentrations $N_1 = N_2 = N_3 = 10^{16}$, and all other parameters unchanged. For comparison with glow curves to be described below, one or more of the curves will be included. In these cases the shape and position on the temperature axis is significant but the size or peak height is <u>not</u> significant. As emphasized earlier (Levy 1979, 1980), the shape and peak temperature of a single first order curve is independent of the initial trapped charge concentration. However, the height—or area—is proportional to the initial trapped charge concentration. In contrast, while the area—not the height—of a single second order glow peak is proportional to the initial trapped charge concentration, other properties depend strongly on the initial trapped charge concentration. As the initial trapped charge concentration increases 1) the peak temperature occurs at lower temperature, 2) the <u>shape</u> of the glow curve changes, and 3) the glow curves tend to superimpose at high temperatures.

Properties of single glow peaks not restricted to the assumptions made to obtain the usual first and second order kinetic expressions:

Glow curves computed from the general kinetic expression for a single peak, eqs. (1) and (2) are Figs. 1 to 5 in the 1980 paper (Levy, 1980). These figures demonstrate that the glow peak properties depend on the σ_r/σ_{t1} ratio, i.e. on the degree of retrapping. The first order curve is obtained when $\sigma_r \gg \sigma_{t1}$. When $\sigma_r/\sigma_{t1} = 1$ the usual second order curve is obtained. The usual second order TL expression requires that $n_1 = n_r$ (or, $n_{10} = n_{ro}$). Figure 3 in the 1980 paper demonstrates that the glow peak shape is a strong function of the n_1/n_r ratio. To reiterate, all results for single glow peak are described in considerable detail in the earlier paper.

THERMOLUMINESCENCE IN MATERIALS EXHIBITING MORE THAN ONE GLOW PEAK

All of the single peak results described above invoke an important assumption that is seldom mentioned explicitly. Namely, it is assumed that, in materials exhibiting more than one peak, there are no interactions between the different peaks. In other words, it is assumed that thermally released charges producing one peak do not become trapped by, or otherwise interact with, the traps associated with the other peaks. In this section equations will be derived which describe glow curves with more than one peak and, most importantly, includes cases in which charges released from one type of trap can be trapped by other types of traps.

Glow curves with two types of interacting traps:

Consider the simplest possible situation which will permit interactions between different types of traps, a material containing two types of electron traps and a single type of hole trap. Also, TL is produced when thermally released electrons recombine with holes at the hole traps. Let E_1 and s_1 and E_2 and s_2 be the kinetic parameters describing thermal untrapping at the two types of electron traps. Let σ_{t1} and σ_{t2} be the cross sections for electron trapping on the (N_1-n_1) and (N_2-n_2) empty electron traps of each type. Of course N_1 and N_2 are the trap concentrations, assumed independent of t, and n_1 and n_2 are the trapped electron concentrations at time t. The corresponding quantities for the single type of hole trap are N_r and n_r. The constant N_r will not appear in the simple cases considered here. The initial trapped charge concentrations are n_{10}, n_{20} and n_{ro} and $n_{10}+n_{20} = n_{ro}$. Assume that the material was irradiated at a temperature where thermal untrapping is negligible.

Then, after heating is begun, the equations describing the trapped charge concentrations in the two types of traps are

$$\frac{dn_1}{dt} = -n_1 s_1 \exp(-E_1/kT)$$

$$+[n_1 s_1 \exp(-E_1/kT)+n_2 s_2 \exp(-E_2/kT)] \times [\frac{\sigma_{t1}(N_1-n_1)}{\sigma_{t1}(N_1-n_1)+\sigma_{t2}(N_2-n_2)+n_r\sigma_r}] \quad (7)$$

$$\frac{dn_2}{dt} = -n_2 s_2 \exp(-E_2/kT)$$

$$+[n_1 s_1 \exp(-E_1/kT)+n_2 s_2 \exp(-E_2/kT)] \times [\frac{\sigma_{t2}(N_2-n_2)}{\sigma_{t1}(N_1-n_1)+\sigma_{t2}(N_2-n_2)+n_r\sigma_r}] \quad (8)$$

$$I(t) = -\frac{dn_r}{dt} = -(\frac{dn_1}{dt} + \frac{dn_2}{dt}) \quad (9)$$

The first terms in eqs. (9) and (10) represent the release of electrons to the conduction band by thermal untrapping. The second terms represent the charges retrapped. The first part of the second term is the total charge released and the second part is the fraction of charge retrapped. Equation (11) gives the TL intensity, I(t), as heating progresses. The intensity is proportioned to the total hole concentration charge change, i.e. $dr = dn_1+dn_2$, in time dt. As is usual, $T = T_0+\beta T$.

Glow curves with two or more interacting traps:

Quite general kinetic equations for materials exhibiting two or more glow peaks can be obtained by considering a material with j different types of electron traps and one type of hole trap. To consider the simplest possible case, it will be assumed that the hole trap concentration is equal to or greater than the sum of the electron trap concentrations. Then, in strict analogy with the two trap derivation given above, the corresponding equations for j different types interacting electron traps, i.e. for j interacting glow peaks are:

$$\frac{dn_i}{dt} = -n_i s_i \exp(-E_i/kT) + \left(\sum_{i=1}^{j} n_i s_i \exp(-E_i kT)\right) \frac{\sigma_i(N_i-n_i)}{\left[\sum_{i=1}^{j} \sigma_i(N_i-n_i)\right]+n_r} \qquad (10)$$

where

$$i = 1,2,\ldots,j, \qquad \sigma_i = \sigma_{ti}/\sigma_r, \qquad \sum_{i=1}^{j} n_{io} = n_r \qquad (11)$$

and

$$I(t) = -dn_r/dt = -\sum_{i=1}^{j} dn_i/dt. \qquad (12)$$

The term interacting kinetics will be used to describe the kinetics of glow curves obtained when retrapping occurs between different types of traps.

THERMOLUMINESCENCE PROPERTIES OF MATERIALS EXHIBITING THREE INTERACTING GLOW PEAKS

To illustrate the TL properties of materials in which charges released from one type of trap can be retrapped on the same type and other types of traps, a number of different situations will be considered.

Role of the retrapping to recombination cross section ratios:

Consider a material with three types of electron traps having equal concentrations, i.e. $N_1 = N_2 = N_3$. Also, let the initial trapped charge concentrations be equal, i.e. $n_{10} = n_{20} = n_{30}$ and $n_{10} + n_{20} + n_{30} = n_r$. The corresponding glow curves, computed from eqs. (10)-(12), are shown in Fig. 2 for various retrapping-recombination cross section ratios, i.e. for various values of $\sigma_1 = \sigma_2 = \sigma_3$. Clearly the glow curves depend very strongly on the σ_i values. When retrapping is large almost all of the charges released by the low temperature traps are retrapped and the intensity of the low temperature peaks is very low. Clearly, when trapping predominantes thermally released charges have a tendency to become retrapped until light emitting recombination is the only available process.

Glow curves computed from the three trap equations, Fig. 2, for various $\sigma_{t1}/\sigma_r = \sigma_{t2}/\sigma_r = \sigma_{t3}/\sigma_r$ ratios illustrate two important points. First, for $\sigma_r \gg \sigma_{t1}, \sigma_{t2}, \sigma_{t3}$ the curves resemble those for first order peaks that do not interact, i.e. the computed curves resemble first order kinetic curves. Second, even if $\sigma_1 = \sigma_2 = \sigma_3 = 1$, which might be expected to produce curves approximating second order kinetic curves, the computed curves are quite different from the usual second order kinetic curves.

Dependence of the glow curves on the initial trapped charge concentration:

The dependence of the glow curves on the initial trapped charge concentration in the lowest temperature trap is shown in Fig. 3. The peak temperature, shape, and intensity (area) of all of the peaks is related to the initial low temperature charge. Similar changes occur when only the initial high temperature trap charge concentration is changed (Fig. 4). Finally, Fig. 5 describes the three trap situation when the initial trapped charge concentrations are equal but are at different initial concentrations. The glow peak characteristics depend on the initial trapped charge levels. Also, a new feature appears. At low initial charge levels the relative peak heights increase from low to high temperature. At high initial charge levels the opposite occurs. Together, Figs. 3 to 5 demonstrate that the height (area), relative height, shape, peak temperature, etc. are functions of the initial trapped charge concentrations when interactive retrapping occurs. In practical terms these results show that the glow curves depend on the dose received by the sample, and any untrapping which might occur prior to measurement. A relatively large number of additional cases could be considered, e.g. cases with the initial charge concentration at three different levels. However, space is not available to include them here.

FIRST AND SECOND ORDER KINETIC PARAMETERS DESCRIBING GLOW CURVES COMPUTED FROM INTERACTIVE KINETICS

In practice, one would not know—at least initially—if a measured glow curve was described by interactive retrapping kinetics or the usual first and second order kinetics. If the measured glow peaks were described by the usual kinetics any of the well-known procedures should establish the kinetics and provide E and s values; assuming that the individual peaks were "separated" sufficiently. Also, if they are not well separated computerized best-fit procedures will, most likely, determine the order of the kinetics and the E and s values. For examples of these computerized procedures see Mattern et al. (1970, 1975) and Fairchild et al. (1978).

Furthermore, it is important to determine if <u>interactive kinetics</u> glow peaks are approximated by the usual first and second order expressions. To obtain information on this point the four computed glow curves shown in Fig. 5 were regarded as "data" and analyzed using the best-fit procedure referenced above. An example of the resulting "best-fit" first and second order glow peaks, and the parameters obtained are shown in Figs. 6. The parameters obtained by "analyzing" all four curves in Fig. 5 are summarized in Table I. Numerous comments can be made about Fig. 5 and Table I.

1) The first and second order glow peaks match the interactive kinetic "data" quite well in a number of respects. The peak temperatures, the full width at half maximum and the upper half of the peaks nearly coincide.

2) Neither the first nor second order curves account for the intensity occurring in the "tails" or "wings" of each peak. An additional comment on this point is included below.

3) As might be expected, since it is the situation leading to the least retrapping, the higher the initial trapped charge concentration, for a fixed trap concentration, the more closely the first and second order parameters resemble those used to compute the curves.

4) Table I demonstrates that the first and second order parameters depend on the initial charge level. The values range from physically realistic ones to some that are very unlikely. Furthermore, these values change in a regular way, becoming more unlikely as the initial charge concentration decreases.

5) As mentioned above, the first and second-order curves match the computed "data" quite well at the peak, at the half-height and over the upper half—or more—of the peaks. Thus, any of the methods regularly used to determine kinetic order and kinetic parameters that are based on peak temperature and full and/or half-width, e.g. those summarized by Chen (1969, 1976), and to a lesser extent any best-fit results which do not account for observed intensity in the glow peak "wings" are likely to give the impression that a measured glow curve is described by first or second order kinetics when, in fact, it contains too much intensity in the wings to be attributable to either kinetics. Also, the usual kinetic procedures are likely to provide physically unrealistic parameters. These conclusions appear to apply to previous measurements on quartz (Fuller and Levy, 1977a ; 1977b, and 1978) and the granite TL results included in these proceedings (Schwartzman et al. 1982).

APPLICATIONS TO DATING AND AUTHENTICATION

The results described above indicate that TL materials used for dating and authentication can be divided into categories. First, the ideal TL dating material should exhibit a single first order glow peak at a temperature sufficiently above ambient temperature to preclude ambient temperature thermal untrapping over a period appreciably longer than the dating time span. Second, since materials exhibiting only one glow peak appear to be extremely rare, the next best substance could contain several first order glow peaks. It would be best if these peaks did not overlap and occurred at the highest measurable temperatures. Third, in principle materials exhibiting single or multiple second order glow peaks can be used for dating; probably more easily for authentication than for accurate dating. In fact, a material exhibiting a single second order glow peak can be used for accurate dating if the peak area, not the height at the peak or at a fixed temperature, is carefully measured. However, it is likely that a material exhibiting more than one second order peak would exhibit <u>interactive</u> kinetics. The retrapping producing second order kinetics in a single peak is the same process giving rise to interactive kinetics when more than one type of trap is present.

Materials exhibiting more than one glow peak and interactive kinetics can, in principle, be used for dating if the response to radiation, the redistribution of charge during ambient temperature thermal charge release and retrapping, and other parameters in the kinetics can be established or closely approximated. It is possible, or even likely, that reasonable dating can be accomplished with materials showing interactive kinetics in special cases. For example, if the initial trapped charge concentrations are much smaller than the trap concentrations, and the retrapping-recombination cross section ratio is high, nearly all of the trapped charge may appear as a single high temperature peak; see Fig. 2. Such a peak may appear to be a single second order peak. To some extent, these possibilities are supported by measurements indicating that reasonable dates are obtained by materials, e.g. the feldspars, which exhibit second order kinetics, light induced charge redistribution, exhibit glow curve shapes and other indications that they follow interactive kinetics.

At this stage in the development of TL dating techniques, there is little point in further speculation about the TL characteristics that materials must possess to be useful for accurate dating unless they exhibit first order kinetics. The usefulness, for dating, of materials not exhibiting first order kinetics can be ascertained only by determining the details of the TL kinetics of each mineral used for dating.

Table I

Activation energies, E_i, in eV, and pre-exponential factors, s_i for first order and $s^* = (n_0/N)s$ for second order, obtained from a "best-fit" of the usual first and second order TL kinetic expressions to a 3 glow peak glow curve computed from <u>interactive</u> TL kinetics

		E_1	E_2	E_3	s_1	s_2	s_3
Assumed Values[(a)]		1.00	1.25	1.50	10^{10}	10^{10}	10^{10}
					First Order		
Initial Trapped Charge, n_0	Fraction of Traps Initially Filled, n_0/N						
5×10^{15}	0.5	0.984	1.225	1.311	6.1×10^{9}	5.4×10^{9}	2.4×10^{8}
1×10^{15}	0.1	0.978	1.236	1.158	4.6×10^{9}	6.0×10^{9}	8.9×10^{6}
5×10^{14}	0.05	0.981	1.259	1.106	4.7×10^{9}	9.3×10^{9}	2.6×10^{6}
10^{14}	0.01	0.989	1.361	1.032	5.2×10^{9}	8.2×10^{10}	3.2×10^{5}
					Second Order		
		E_1	E_2	E_3	$s_1^{*(b)}$	s_2^*	s_3^*
5×10^{15}	0.1	1.432	1.778	2.125	2.7×10^{15}	2.1×10^{15}	1.8×10^{15}
10^{15}	0.05	1.413	1.754	1.850	1.3×10^{15}	9.4×10^{14}	5.7×10^{12}
5×10^{14}	0.05	1.410	1.758	1.745	1.1×10^{15}	9.0×10^{14}	5.7×10^{11}
10^{14}	0.01	1.399	1.808	1.576	6.6×10^{14}	2.1×10^{15}	8.7×10^{9}

(a) Values used in the <u>interactive</u> TL kinetic expressions, eqs. (10)-(12) in the text, to compute the glow curves analyzed on the basis that they contain <u>non-interactive</u> first or second order glow peaks.

(b) The trap concentration N is 10^{16} for all cases. The values of s_i^* which should be obtained from <u>non-interacting</u> second order kinetics is given by $s_i^* = (n_0/N)s_i$, i.e. s_i^* is always less than 10^{10}.

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FIGURE CAPTIONS

Figure 1. Glow curves computed from the usual first and second order kinetics on the basis that charges released from one type of trap are not retrapped by other types of traps. For comparison, these curves are shown on other figures. The trap concentration is 10^{16}.

Figure 2. Glow curves computed from interactive kinetics, in which charges released from one type of trap may be retrapped by other types of traps, for various values of the trapping-recombination cross section ratios. Except where indicated, the kinetic parameters shown in Fig. 1 are used for all curves.

Figure 3. Glow curves computed from interactive kinetics for different initial charges in the lowest temperature trap. Note that both the relative intensities and peak temperatures change.

Figure 4. Glow curves computed from interactive kinetics for different initial charges in the highest temperature trap.

Figure 5. Interactive kinetic glow curves for different initial trapped charge levels. Figures 3-5 and additional curves (not shown) demonstrate that the glow peak properties are strong functions of the initial charge levels when interactive kinetics apply.

Figure 6. The $n_{01} = n_{02} = n_{03} = 10^{15}$ interactive kinetics glow curve in Fig. 5 regarded as "data" and best-fitted to the usual first and second order kinetics. Also shown are the best-fit parameters. The usual kinetics fit the upper half of the glow peaks quite well, but not the "wings" at the base of the glow peaks.

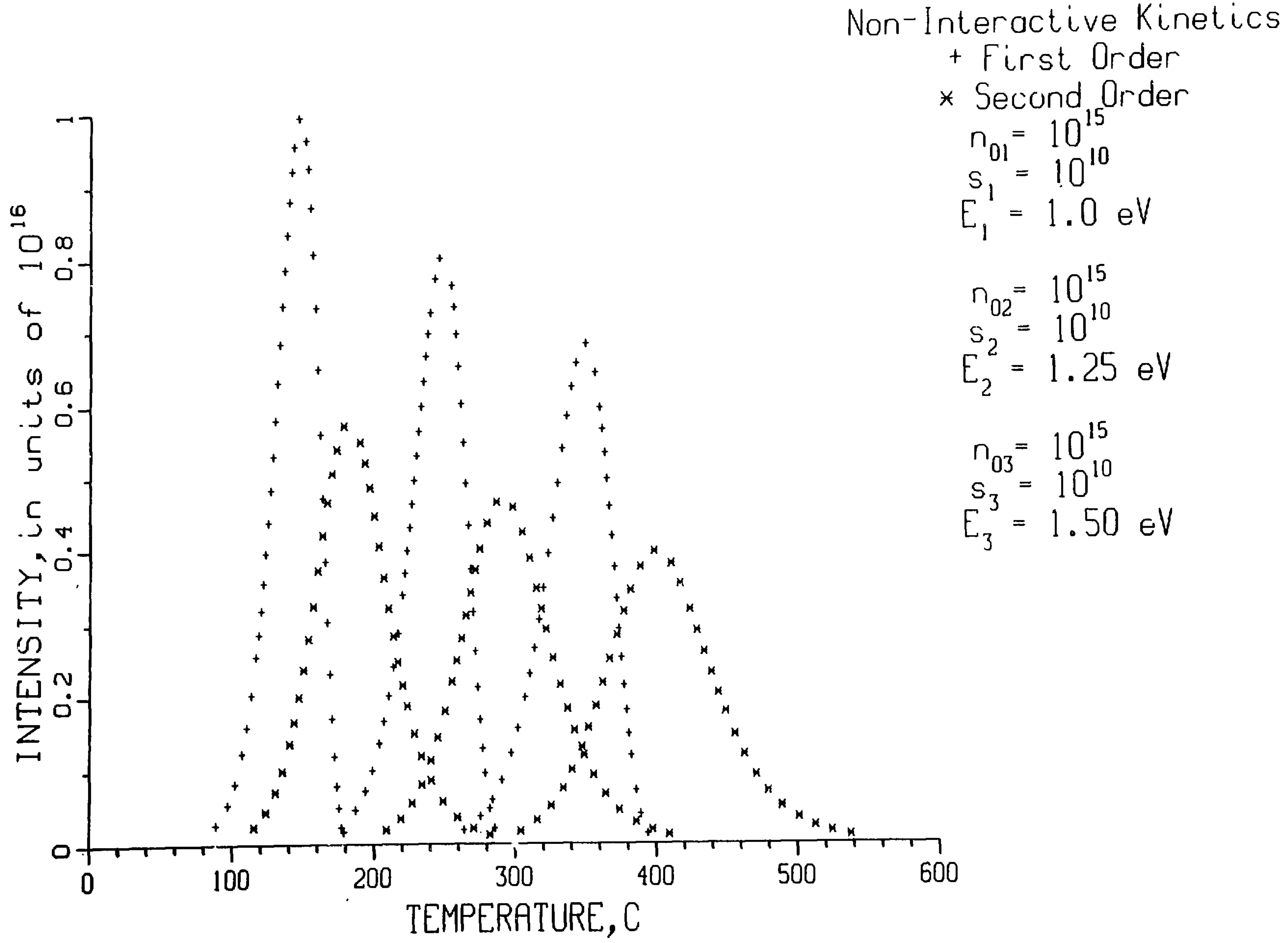

Non-Interactive Kinetics
+ First Order
× Second Order
$n_{01} = 10^{15}$
$s_1 = 10^{10}$
$E_1 = 1.0$ eV
$n_{02} = 10^{15}$
$s_2 = 10^{10}$
$E_2 = 1.25$ eV
$n_{03} = 10^{15}$
$s_3 = 10^{10}$
$E_3 = 1.50$ eV
INTENSITY, in units of 10^{16}
0
0.2
0.4
0.6
0.8
1
0
100
200
300
400
500
600
TEMPERATURE, C

FIGURE 1

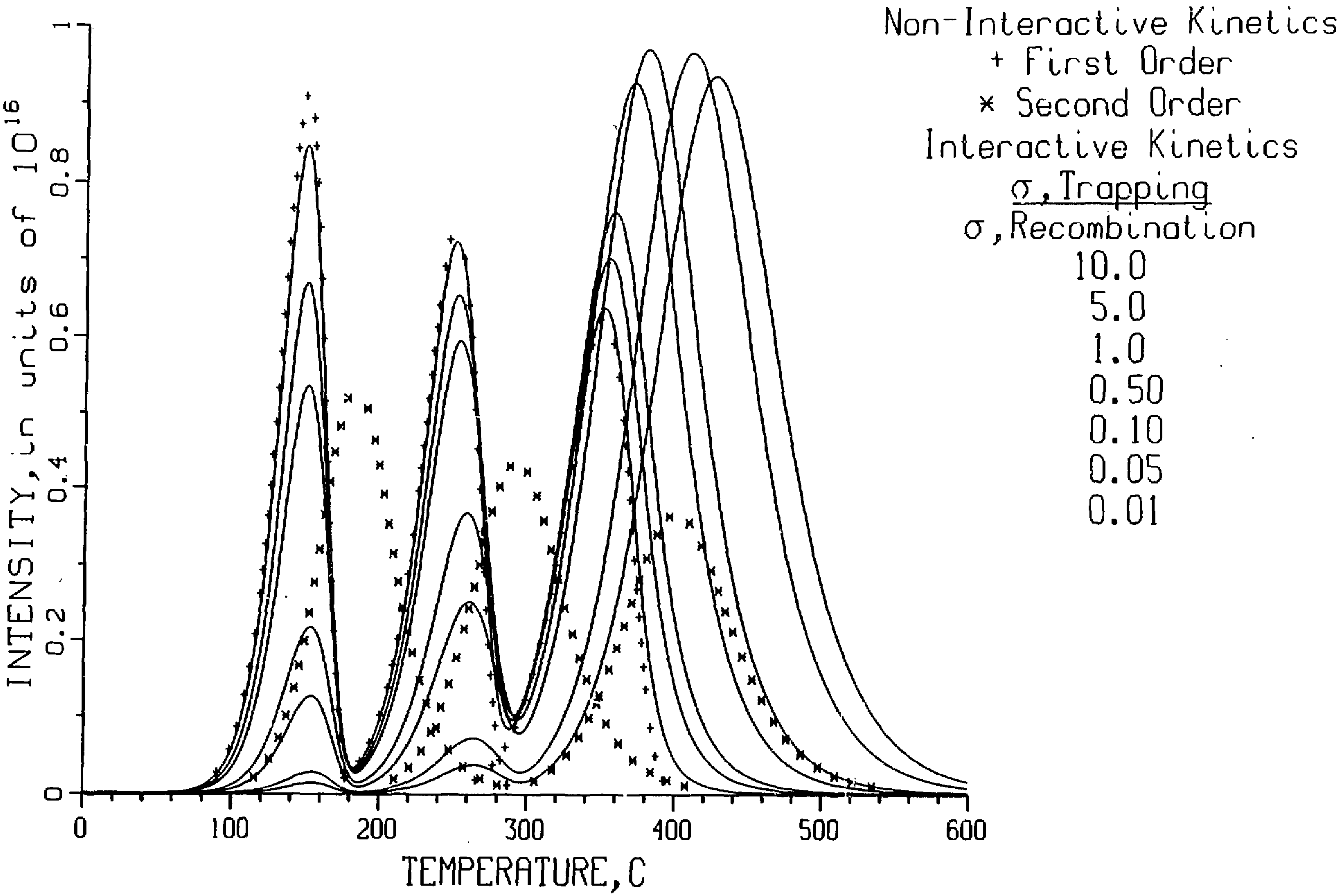

Non-Interactive Kinetics
+ First Order
* Second Order
Interactive Kinetics
σ, Trapping / σ, Recombination
10.0
5.0
1.0
0.50
0.10
0.05
0.01
INTENSITY, in units of 10^{16}
0
0.2
0.4
0.6
0.8
1
0
100
200
300
400
500
600
TEMPERATURE, C

FIGURE 2

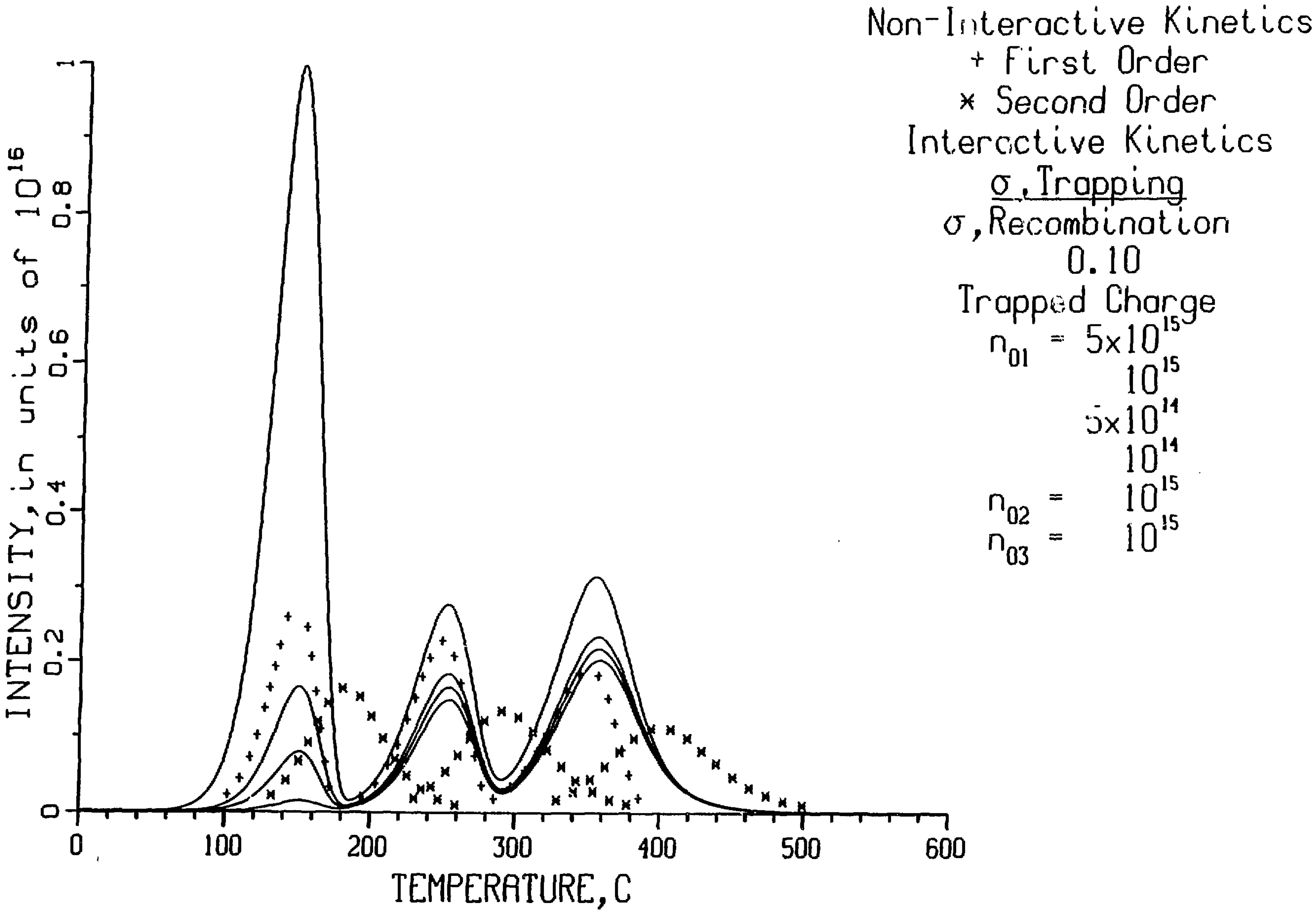

Non-Interactive Kinetics
+ First Order
* Second Order
Interactive Kinetics
σ, Trapping
σ, Recombination
0.10
Trapped Charge
n_{01} = 5×10^{15}
10^{15}
5×10^{14}
10^{14}
n_{02} = 10^{15}
n_{03} = 10^{15}
INTENSITY, in units of 10^{16}
0
0.2
0.4
0.6
0.8
1
0
100
200
300
400
500
600
TEMPERATURE, C

FIGURE 3

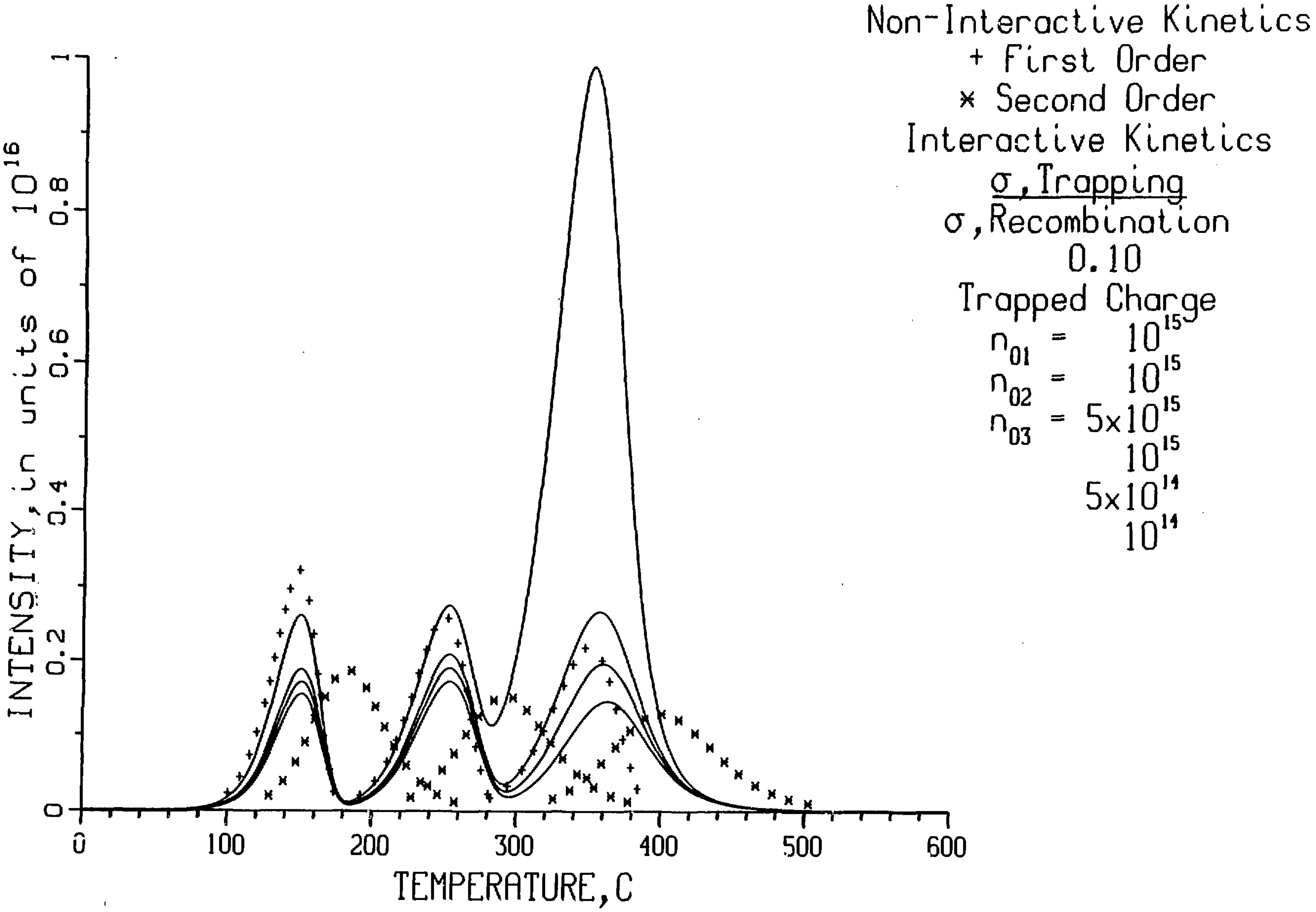
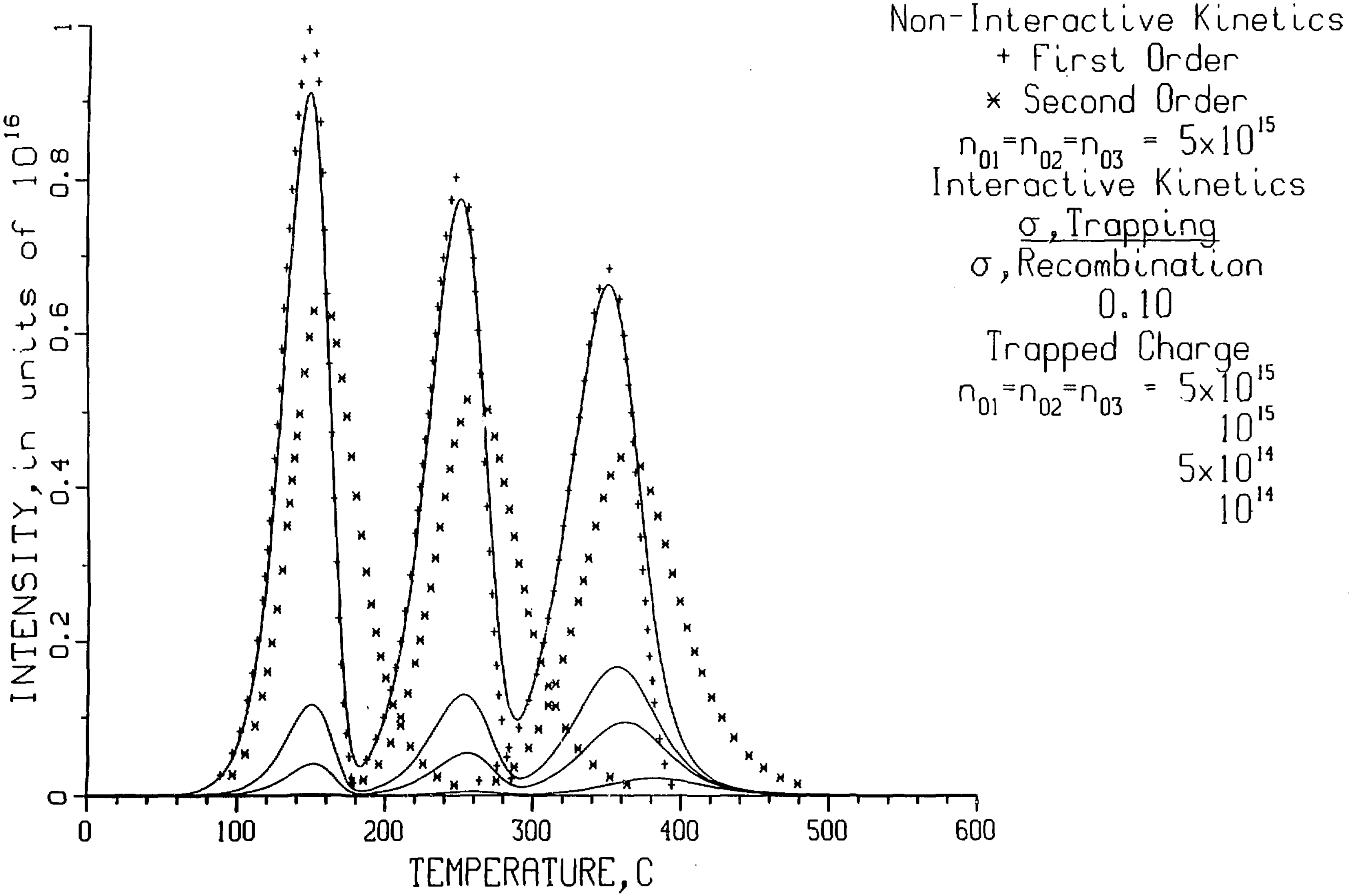
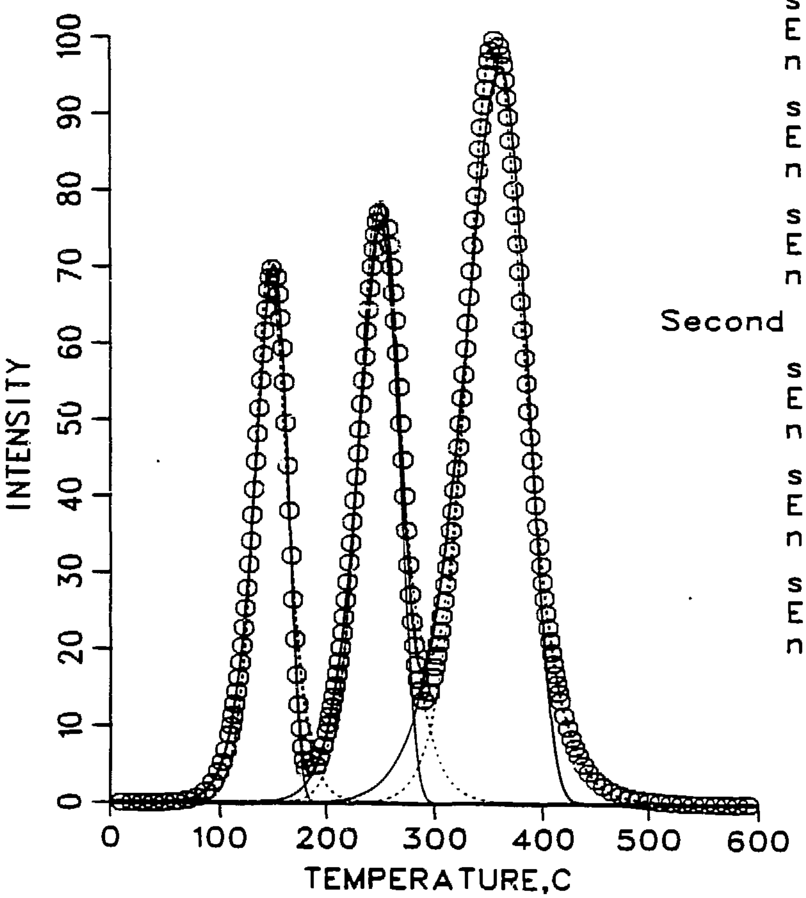

Non-Interactive Kinetics
+ First Order
× Second Order
Interactive Kinetics
σ, Trapping
σ, Recombination
0.10
Trapped Charge
n_{01} = 10^{15}
n_{02} = 10^{15}
n_{03} = 5×10^{15}
10^{15}
5×10^{14}
10^{14}
INTENSITY, in units of 10^{16}
0
0.2
0.4
0.6
0.8
1
0
100
200
300
400
500
600
TEMPERATURE, C

FIGURE 4



Non-Interactive Kinetics
+ First Order
* Second Order
$n_{01}=n_{02}=n_{03} = 5\times10^{15}$
Interactive Kinetics
σ, Trapping
σ, Recombination
0.10
Trapped Charge
$n_{01}=n_{02}=n_{03} = 5\times10^{15}$
10^{15}
5×10^{14}
10^{14}
INTENSITY, in units of 10^{16}
0
0.2
0.4
0.6
0.8
1
0
100
200
300
400
500
600
TEMPERATURE, C

FIGURE 5



First Order Parameters

$s = 4.59 \times 10^{9}$
$E = 0.978$
$n_0 = .60 \times 10^{-1}$
$s = 6.01 \times 10^{9}$
$E = 1.236$
$n_0 = .79 \times 10^{-1}$
$s = 8.87 \times 10^{6}$
$E = 1.158$
$n_0 = .15 \times 10$

Second Order Parameters

$s^* = 1.31 \times 10^{15}$
$E = 1.413$
$n_0 = .62 \times 10^{-1}$
$s^* = 9.40 \times 10^{14}$
$E = 1.754$
$n_0 = .86 \times 10^{-1}$
$s^* = 5.67 \times 10^{12}$
$E = 1.850$
$n_0 = .15 \times 10$

FIGURE 6