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TEM SCALE MODEL INVESTIGATIONS
FEBRUARY–MARCH, 1979

by

B.R. Spies

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ABSTRACT

A series of transient electromagnetic (TEM) scale model studies was carried out by the Bureau of Mineral Resources in February and March 1979 using the Macquarie University TEM modelling facility.

The model studies can be divided into four categories: studies to gain an understanding of the range of situations for which two-layer master curves can be used; studies of the effect of a finite ramp width of the transmitter current waveform on the received transient signal; studies of the effects of vertical lateral discontinuities on the response of two-loop systems; and studies of the effects of a conductive host rock on the response from a conductive dyke.

The results are presented as curves and profiles, and provide guidelines for TEM interpretation of several different models.

INTRODUCTION

A series of transient electromagnetic (TEM) scale model studies was carried out by the Bureau of Mineral Resources (BMR) during the three-week period 16 February to 10 March 1979 using the Macquarie University TEM modelling facility which is described in detail by Spies (1979). These studies were conducted as a joint BMR-Macquarie University-CSIRO project, with BMR providing salary and personnel and CSIRO covering travelling and accommodation expenses. For information on the TEM method the reader is referred to Velikin & Bulgakov (1967) and Spies (1976).

The models studied can be divided into four categories:

1. Truncated one-dimensional (1D) structures

A 1D structure is one in which variations in electrical properties are restricted to the vertical axis of the model. In some situations with other structures, for example those listed in Table 1, the effects of the edges or ends can be neglected, and these structures can be considered as 1D approximations. To gain an understanding of the range of situations for which two-layer master curves can be used, a series of measurements was made on square and rectangular aluminium sheets of various sizes.

2. Ramp width

With the possibility of introducing high-powered transmitters to enhance the signal-to-noise ratio with TEM, it is useful to know the effect of a finite ramp width at the end of the transmitter current waveform on the received transient signal. Although this problem can best be studied by numerical methods, the model facility offered a fast means of investigating the likely effects.

3. Lateral discontinuity.

In several field surveys difficulties have been reported in interpreting two-loop data in areas of relatively simple geological conditions. A model consisting of a half-space with a vertical interface separating regions with a conductivity contrast of 30.1 was investigated.

4. Dyke in conductive host rock.

To supplement suites of curves for the TEM response of dykes in air presently being carried out by CSIRO (G. Buselli, pers. comm), it will be necessary to investigate the effect of a conductive host rock, and in particular to assess the significance of current-gathering or enhancement effects. A technique that is often used to simulate a conductive host is to immerse a graphite slab in a brine or acid solution, resulting in conductivity contracts of greater than 1000:1. There is a need to develop techniques of simulating lower conductivity contrasts than this. A method investigated in the study described here is to use a highly conductive metal, such as copper, enclosed in a type-metal host.

RESULTS

1. TRUNCATED 1D STRUCTURES

Description of models

The models consisted of square and rectangular sheets of aluminium (conductivity, σ = 2 x 107 s/m) with physical parameters as shown in Figure 1 and Table 1. Measurements were made at heights of 1.6 mm and 20.5 mm using loop sizes of 27 mm and 60 mm diameter.

Table 1: Model Parameters -Truncated 1D Structures

Figure	Structure	2a (cm)	d (mm)	W (cm)	a/d	a/h
2	2D	6	4	20 (∞)	7.5	19
3	2D	6	1	20 (∞)	30	19
4	2D	2.7	4	20 (∞)	3.4	8.5
5	2D	2.7	1	20 (∞)	13.5	8.5
6	3D	6	4	L	7.5	19
7	3D	6	1	L	30	19
8	3D	2.7	4	L	3.4	8.5
9	3D	2.7	1	L	13.5	8.5
10	3D	6	4	20 (∞)	7.5	1.5
11	3D	6	1	20 (∞)	30	1.5
12	3D	6	4	L	7.5	1.5
13	3D	6	1	L	30	1.5

Results

The results are presented in Figures 2 to 13 as graphs of percentage change of response against normalised time, for various values of L/a (see Fig. 1).

Percentage change is defined as

$$\% \text{ change} = \frac{[e(t)_L - e(t)_\infty]100}{e(t)_\infty}$$

where $e(t)_L$ is the response over the model, of truncated dimension L, and

$e(t)_\infty$ is the response for an infinite sheet.

Normalised time is defined as

$$T' = t/\sigma a^2,$$

where t = sample time, σ = conductivity, and

a = loop radius.

The curves can be used to estimate the correction, when doing a 1D interpretation, that needs to be applied to the measured TEM response of layered structures of limited lateral extent.

The general features can be seen in Figures 2 and 4, for the 4 mm thick plate and both loop sizes. When L is greater than 2a, $e(t)_L = e(t)_\infty$ at early times. At later times $e(t)_L$ becomes greater and then finally decreases rapidly with time. This process can be understood by considering the behaviour of eddy currents with time. At early times the response is controlled only by the parts of the plate near the loop, so the response is identical to that of an infinite plate. At late times the response is less than that of an infinite plate because of the decrease in total volume. At intermediate times the response is greater than for an infinite

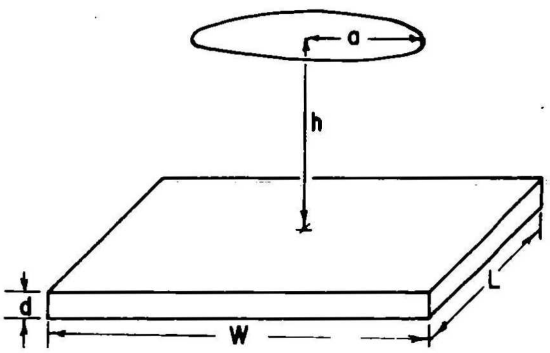


Fig.1 Definition of parameters used in truncated 1D model study

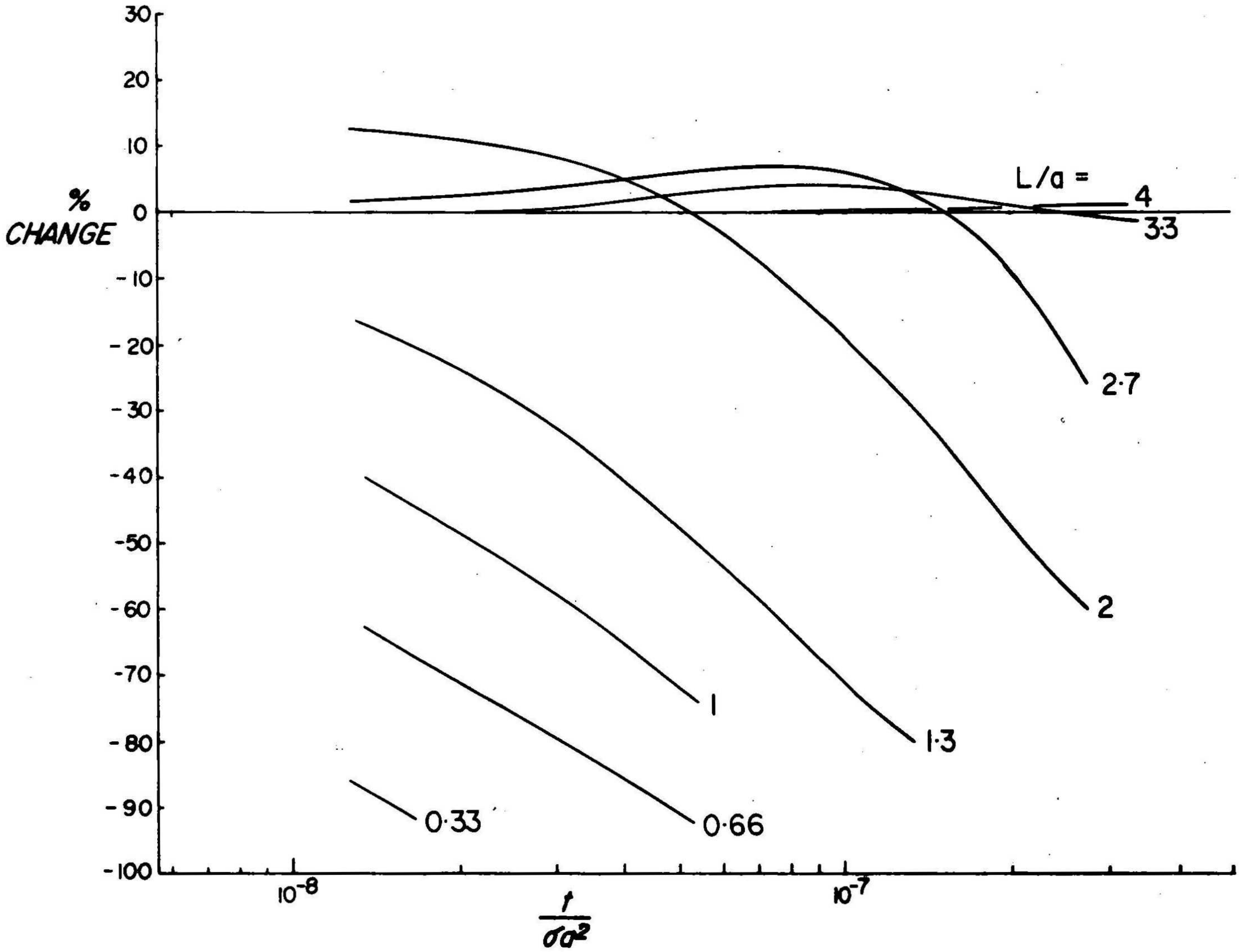


Fig.2 Correction curves for rectangular structure,
loop diam. = 6cm, d=4mm, W=20cm, 1·6mm height

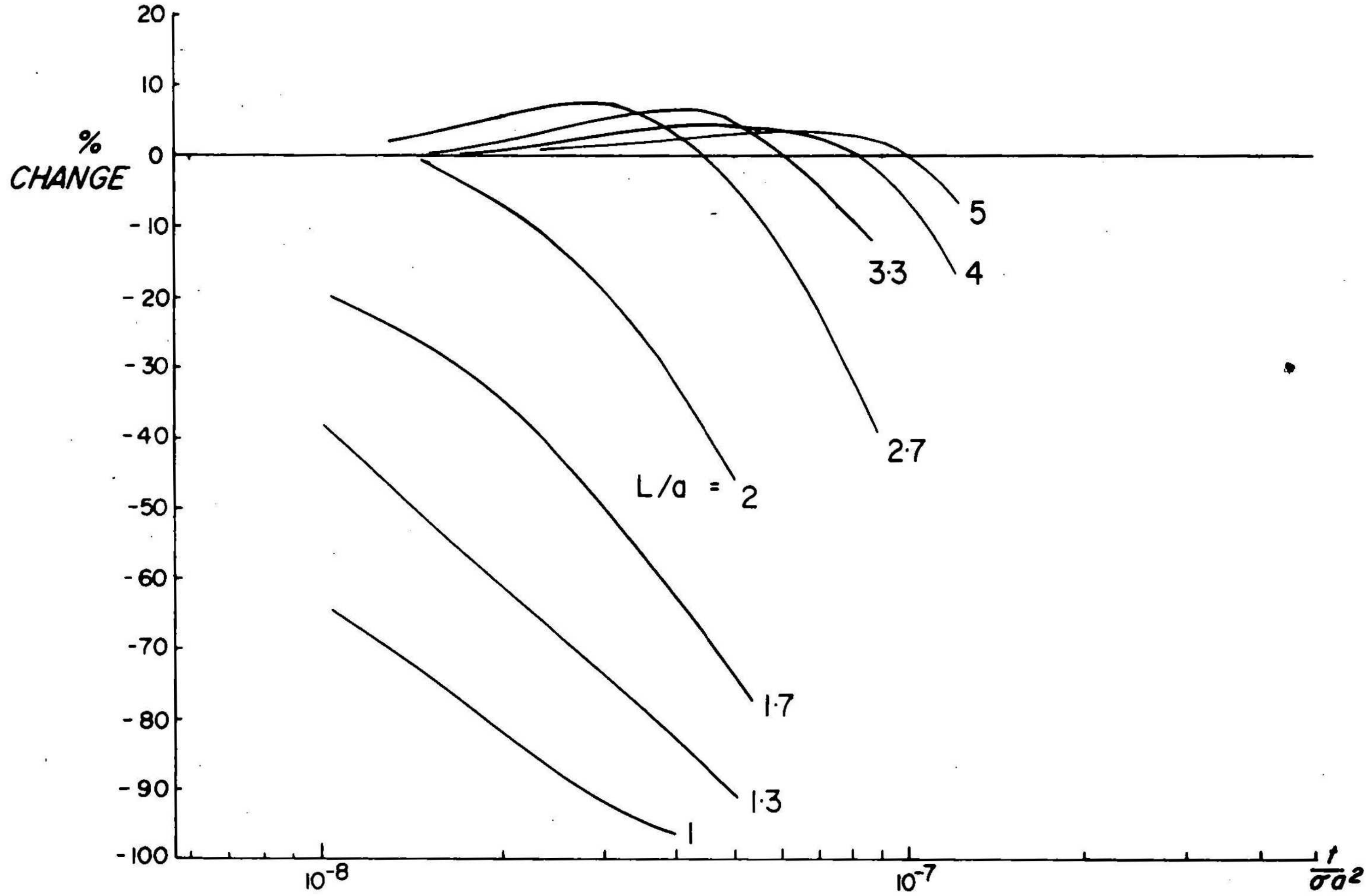


Fig. 3 Correction curves for rectangular structure, loop diam. = 6 cm, d = 1 mm, W = 20 cm, 1·6 mm height

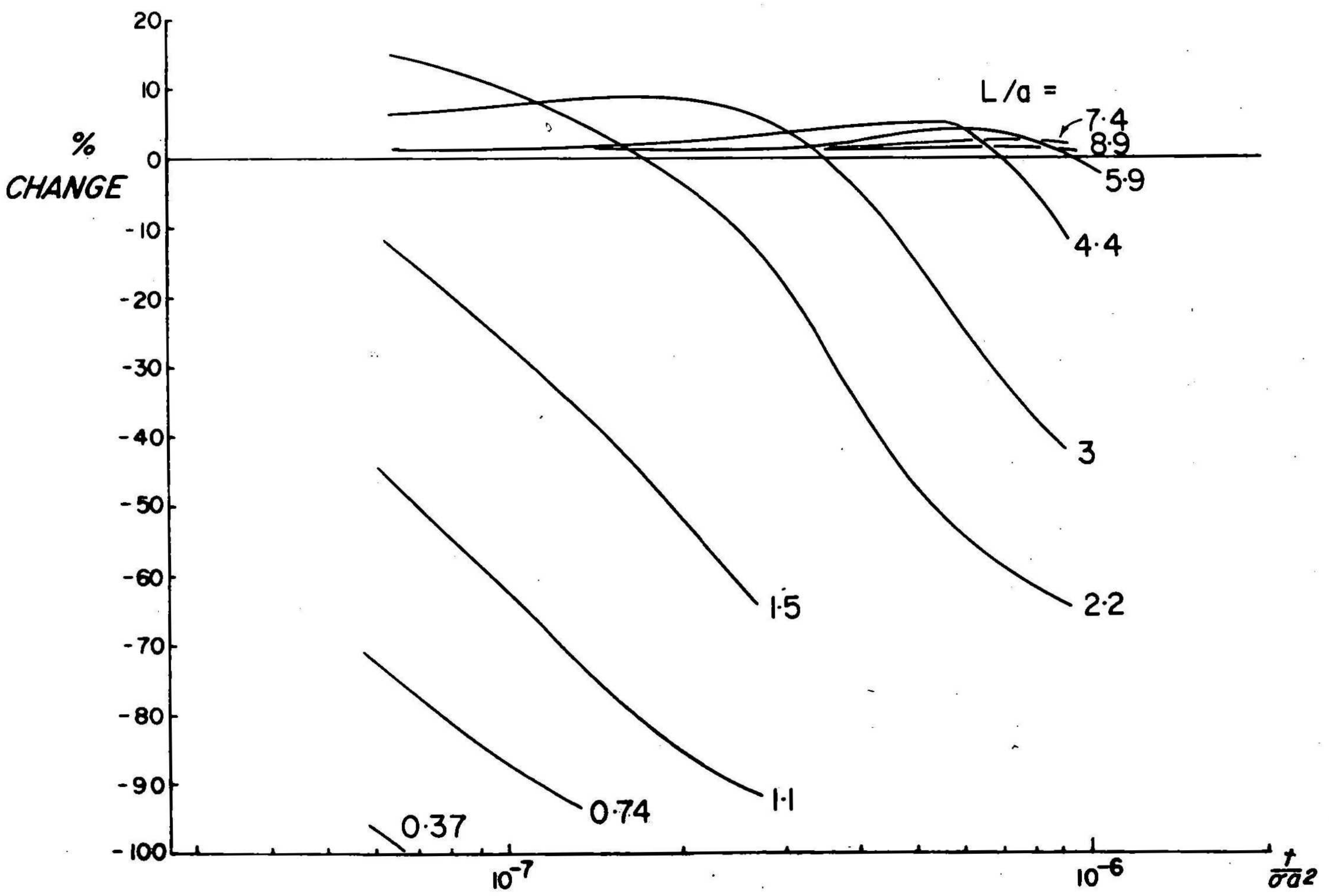


Fig. 4 Correction curves for rectangular structure, loop diam. = 2·7 cm, d = 4 mm, W = 20 cm, 1·6 mm height

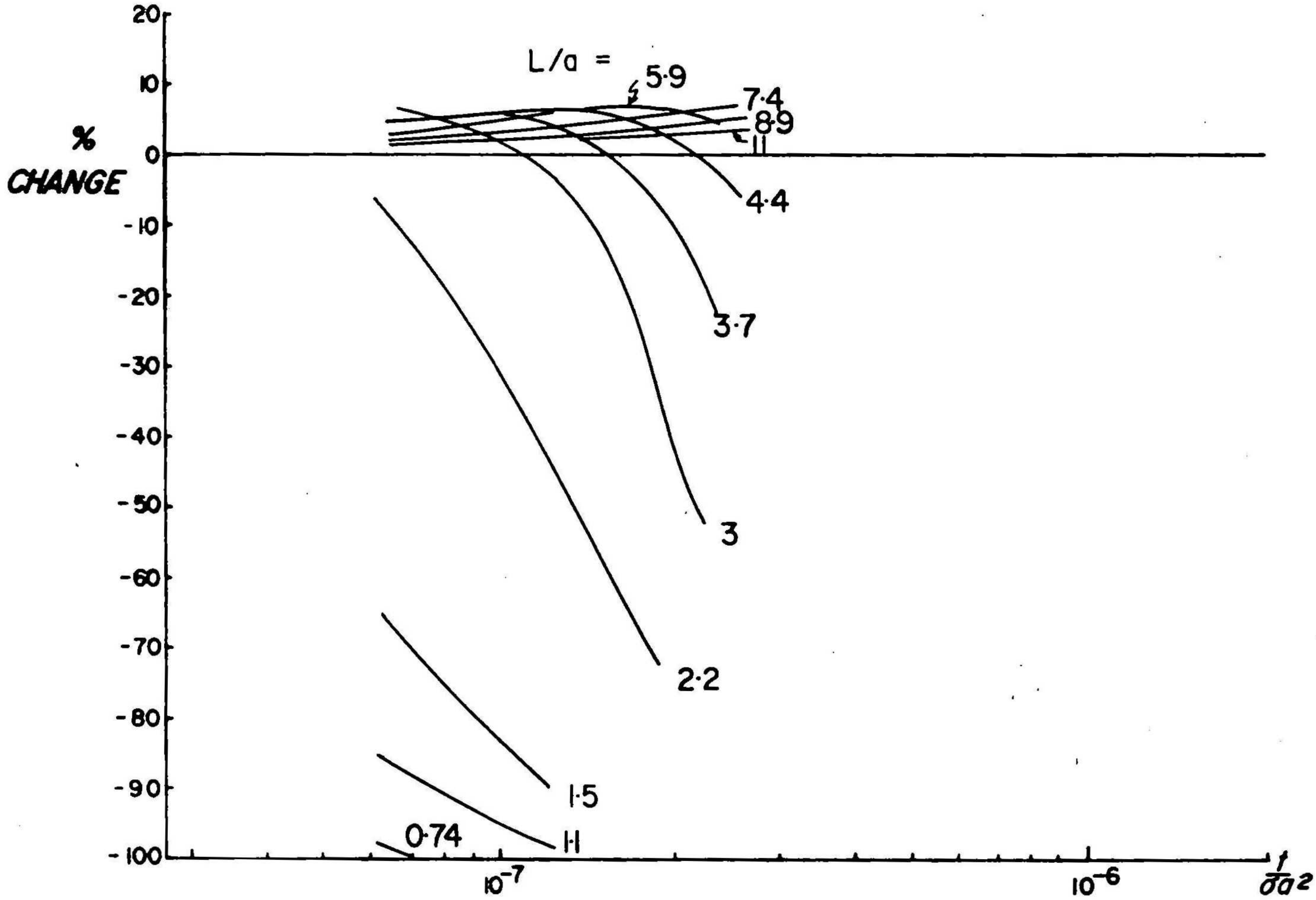


Fig.5 Correction curves for rectangular structure, loop diam.= 2·7cm, d=1mm, W= 20cm, 1·6mm height.

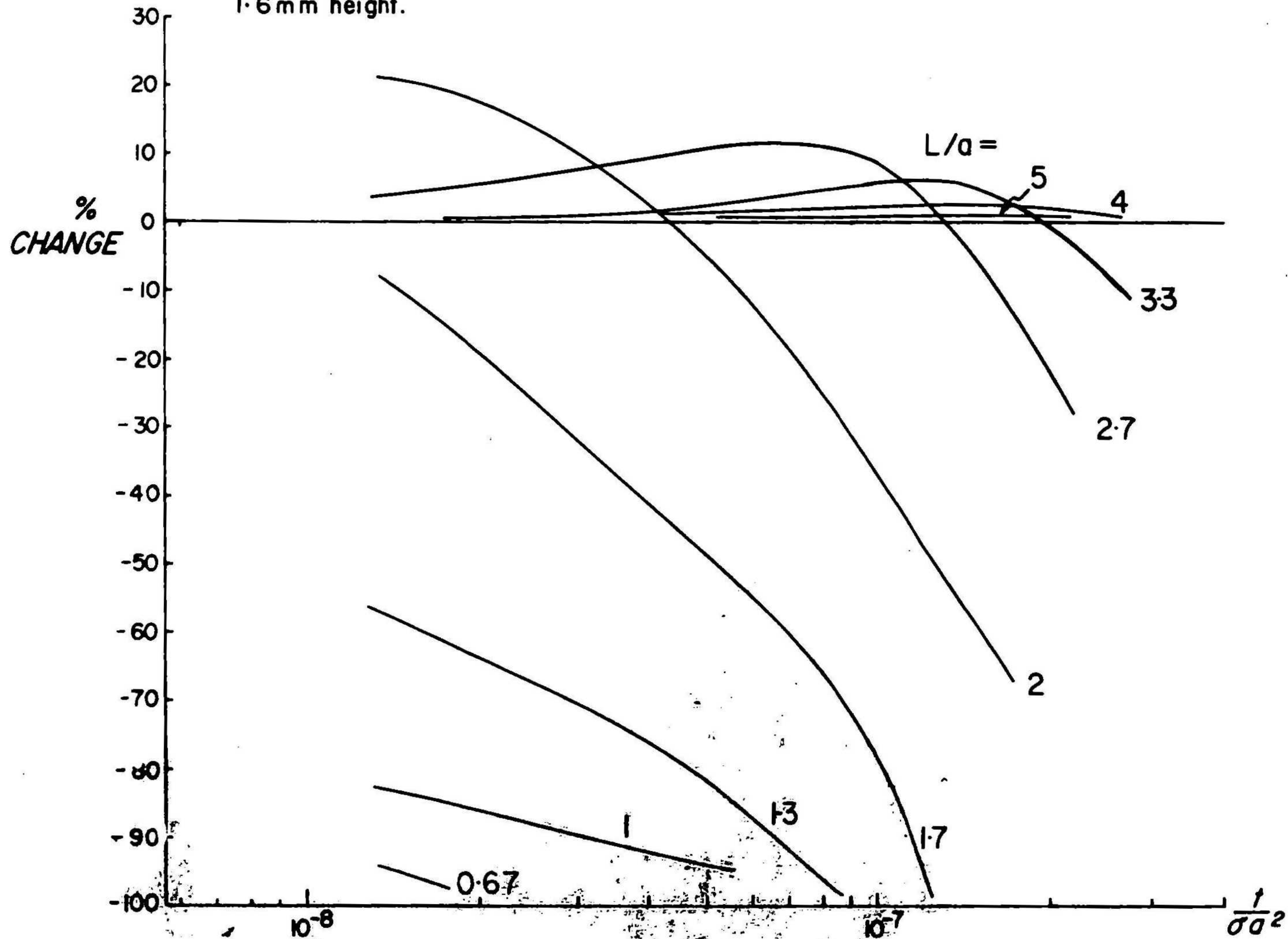


Fig.6 Correction curves for square structure, loop diam.= 6cm, d=4mm, W=L, 1·6mm height

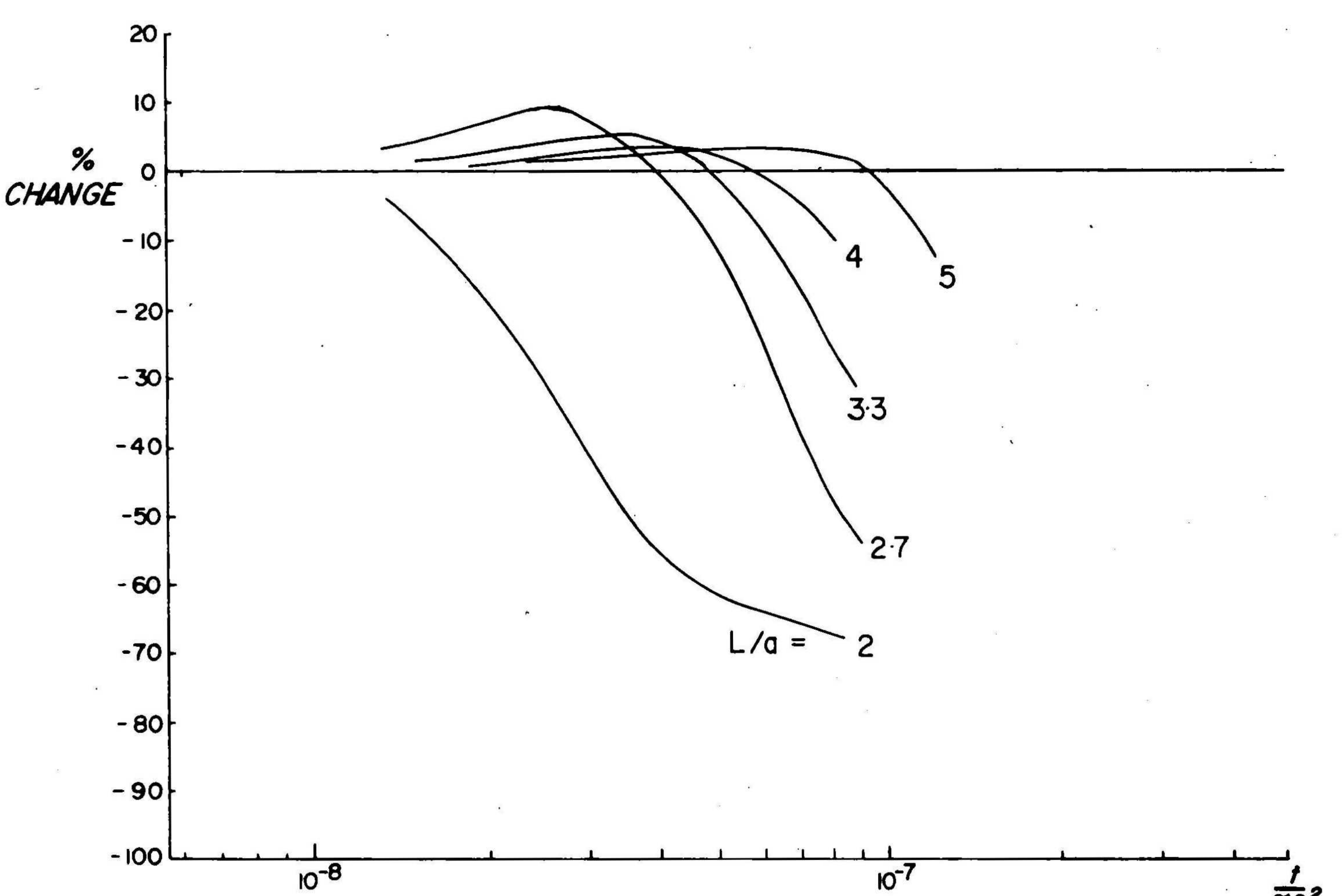


Fig. 7 Correction curves for square structure, loop diam. = 6cm, d = 1mm, W = L, 1·6mm height

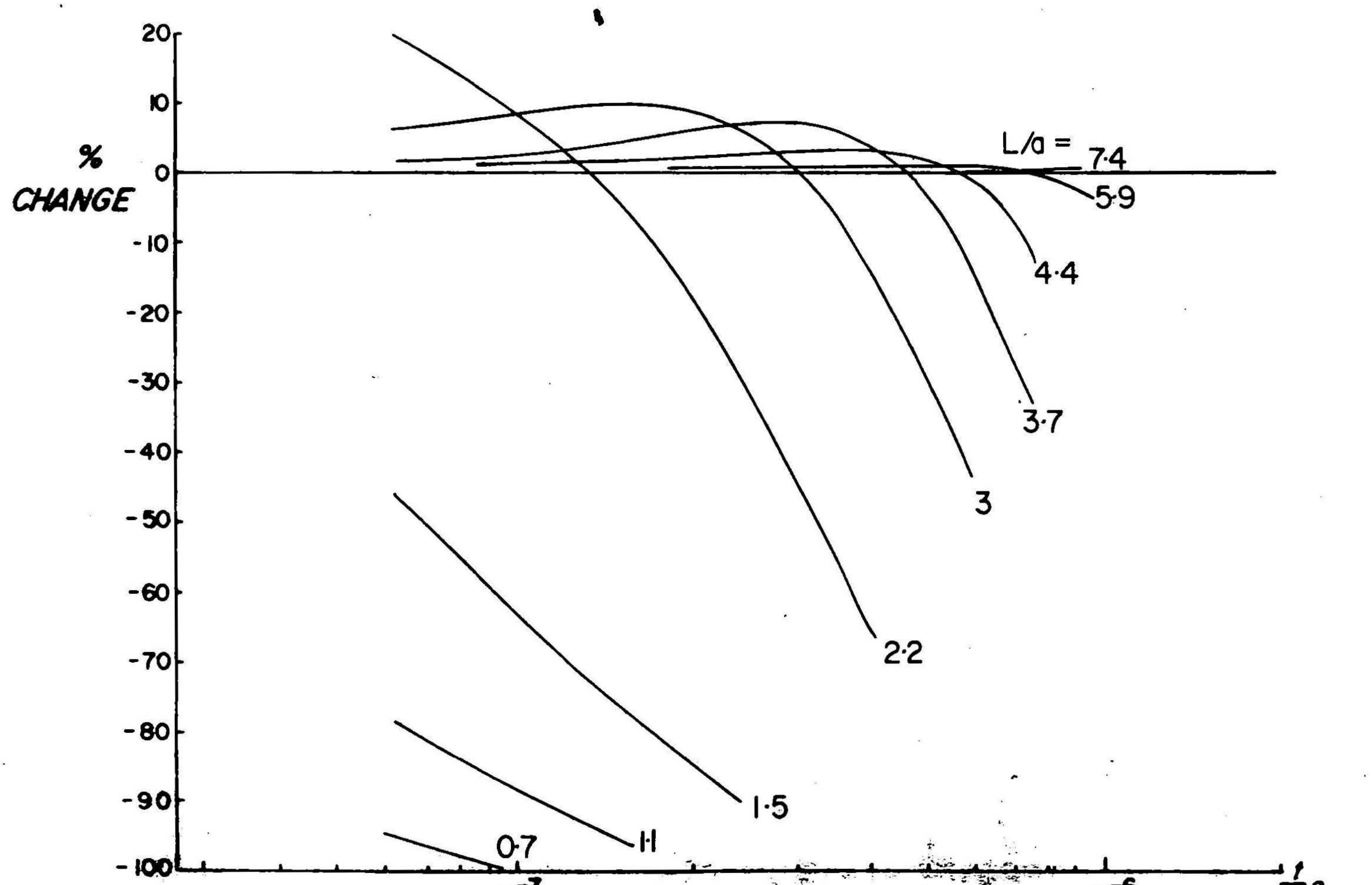


Fig. 8 Correction curves for square structure, loop diam. = 2·7cm, d = 4mm, W = L, 1·6mm height

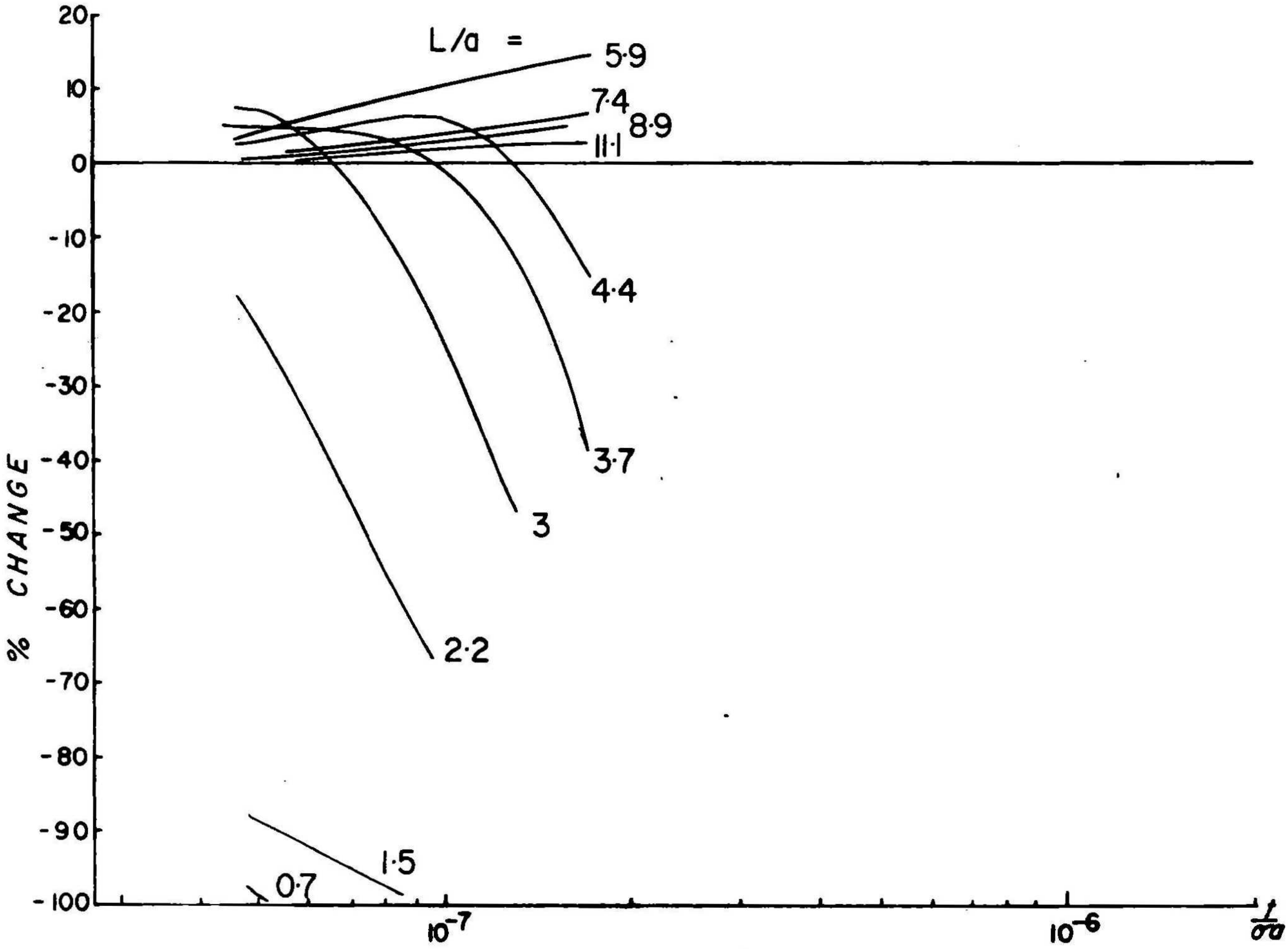


Fig. 9 Correction curves for square structure, loop diam. = 2·7cm, d = 1 mm, W=L, 1·6mm height.

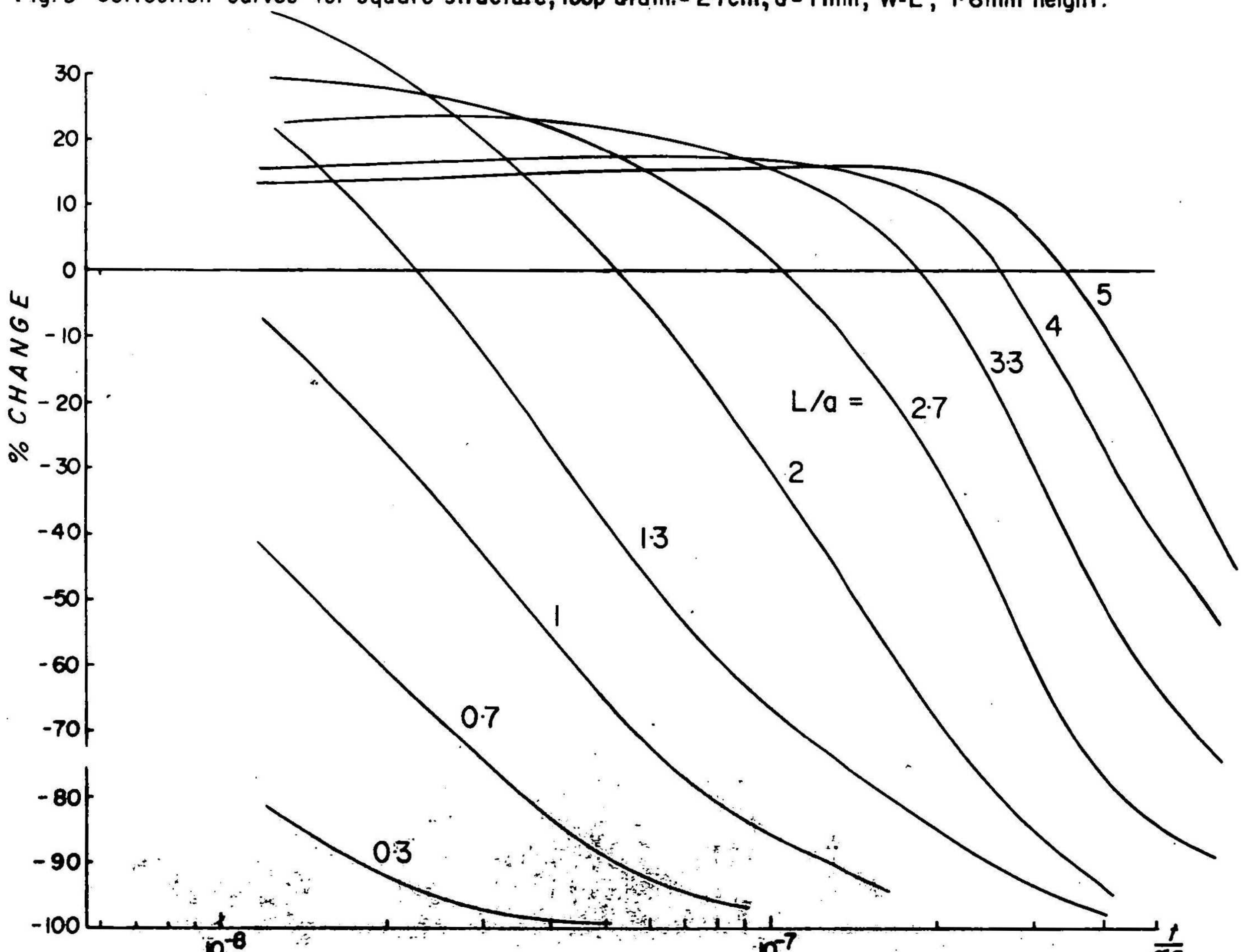


Fig. 10 Correction curves for rectangular structure, loop diam. = 6cm, d = 4 mm, W=20cm, 20mm height

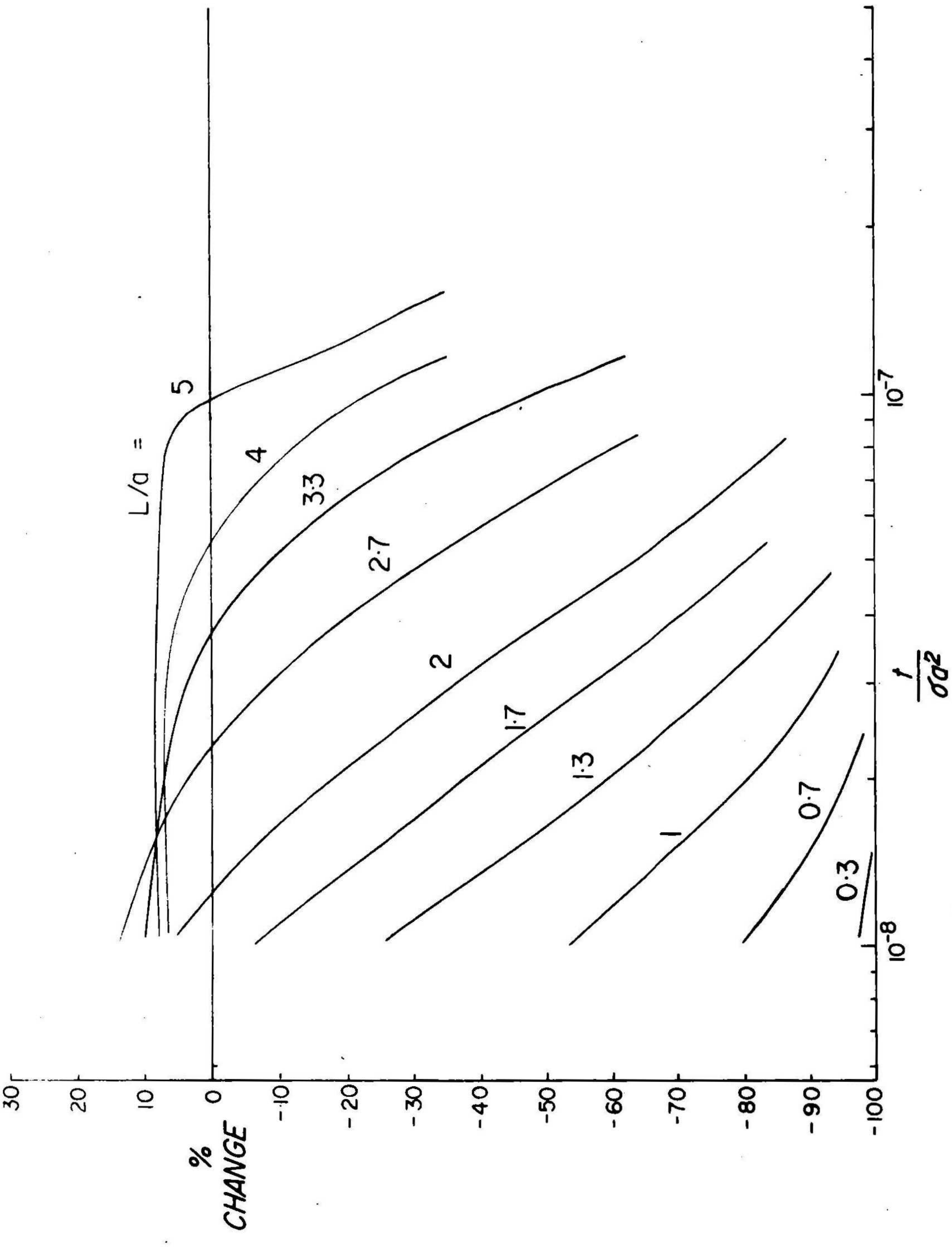


Fig. 11 Correction curves for rectangular structure, loop diam. = 6cm, d = 1mm, W = 20cm, 20mm height

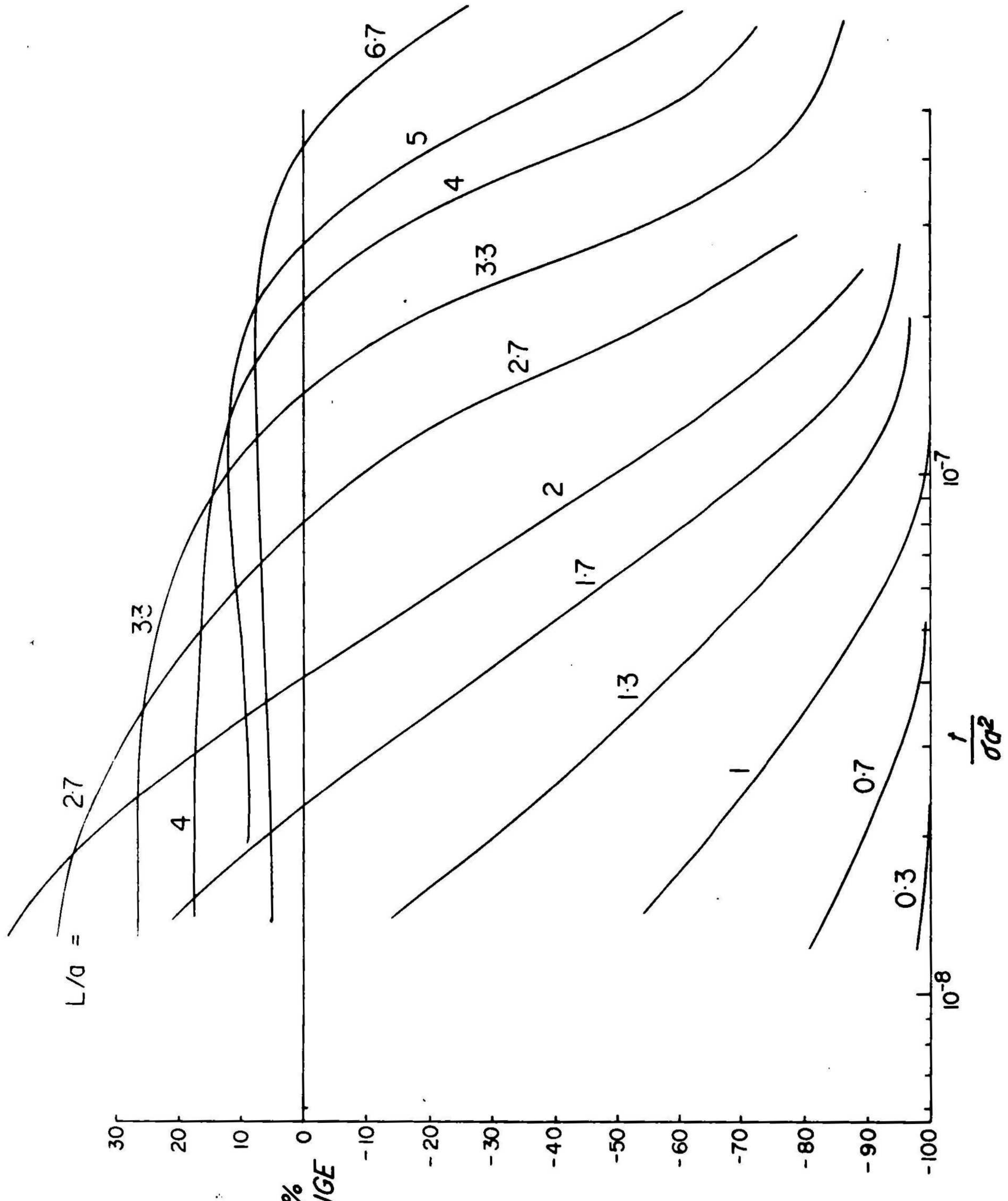


Fig. 12 Correction curves for rectangular structure, loop diam. = 6cm, d = 4mm, W = L, 20mm height

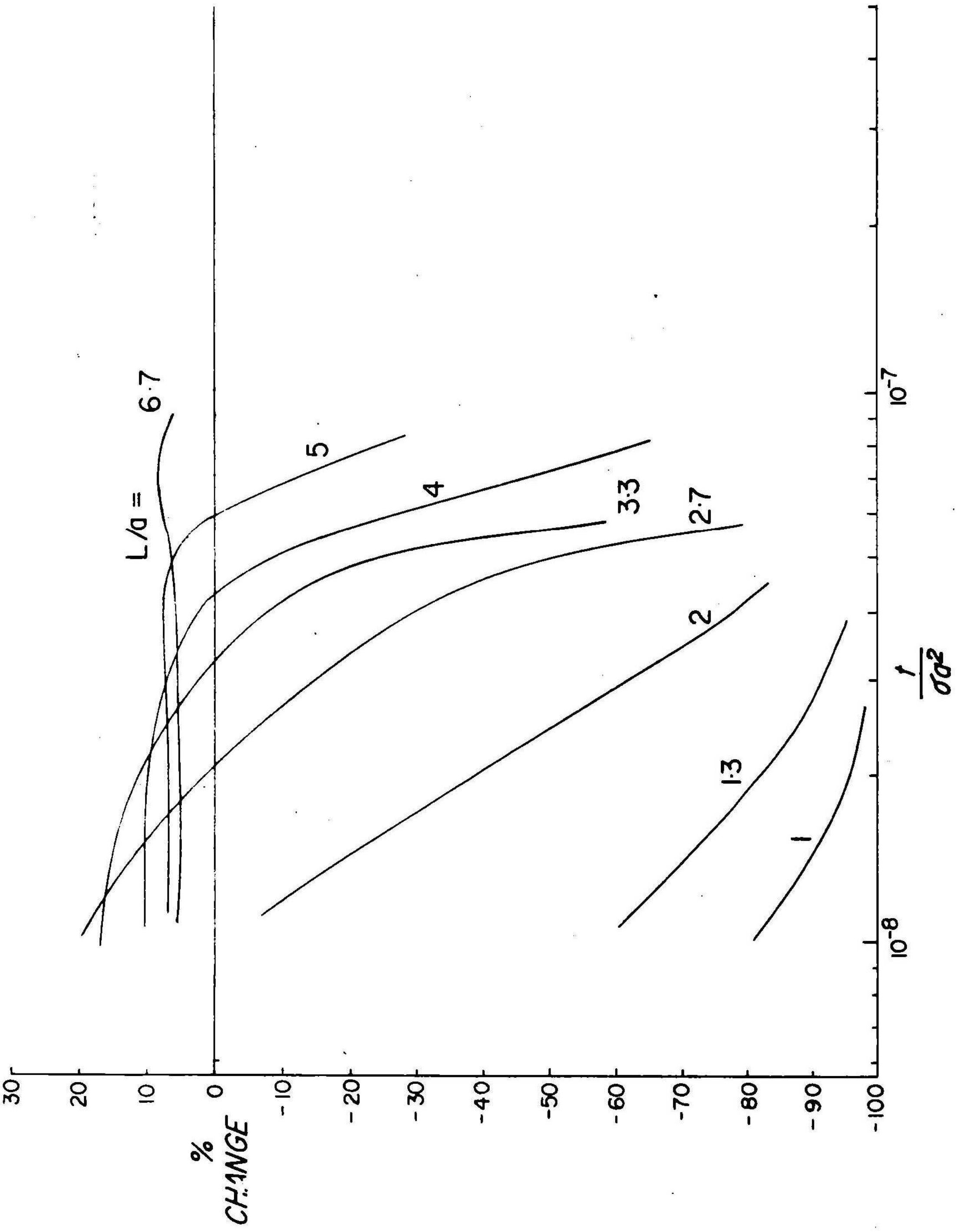


Fig. 13 Correction curves for rectangular structure, loop diam. = 6cm, d = 1mm, W = L, 20mm height

plate owing to reflections from the edges of the plate which concentrates the eddy currents. This is called the "edge effect".

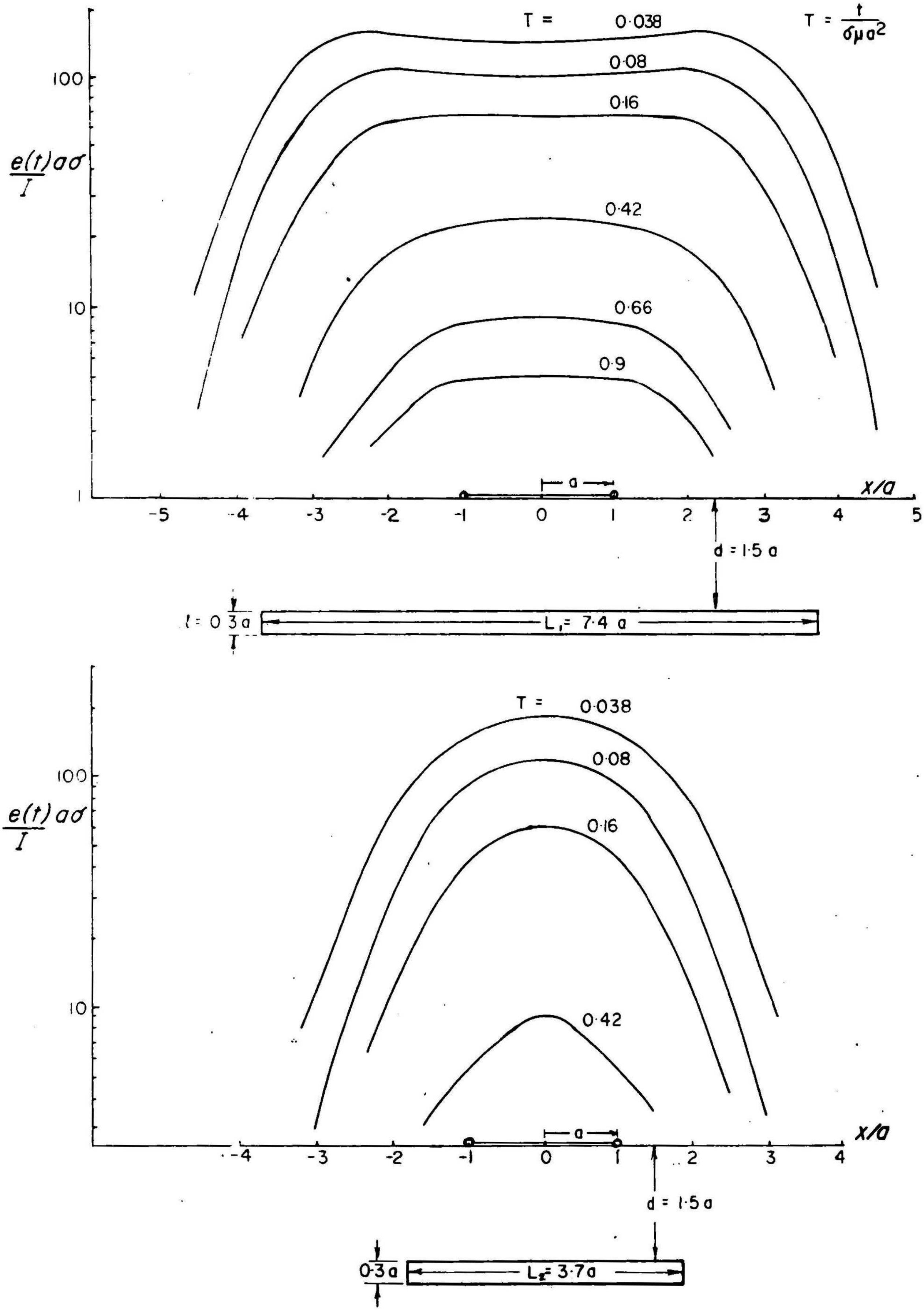
When L is much less than the loop diameter, 2a, the response falls off rapidly with time and is less than $e(t)_\infty$ for all times. If L is slightly smaller than 2a, the response at early times can still be greater than $e(t)_\infty$.

Figures 3 and 5 show the results for a 1 mm thick plate. The general features are the same as for the 4 mm thick plate that the response falls off earlier. This would also happen if the conductivity was decreased.

Results for squares of side L are shown in Figures 6 to 9. The time of departure from the infinite plate response is roughly the same as for the rectangles (Figs. 2-4), but the percent change for L less than a is greater owing to the decreased volume of the body.

Rectangular models are placed at a depth of 20 mm in Figures 10 to 13. The main features can be seen by comparing Figures 2 and 10, which are identical models at different depths. The most obvious results is that at early times the response $e(t)_L$ is larger for the cases where the depth is increased, and that none of the truncated models appear infinite, even for L/a = 5. At later times the features are generally similar.

An example of the edge effect mentioned earlier can bee seen by examination of the profiles over 4 mm square plates of sides 5 cm and 10 cm shown in Figure 14. For the larger plate, the response at early times is greater when the loop is near the edge of the plate than when it is in the centre of the plate. When the loop is over the centre of the small plate, the response is larger than when the loop is at the edges, because of the combined contribution of the two edges.



Model dimensions: a = 13·5 mm L_1 = 100 mm
d = 20·5 mm L_2 = 50 mm
l = 4 mm $\sigma = 2{\cdot}2 \times 10^7$ s/m
t = 0·19 to 4·6 ms

Fig. 14 Profiles over square plates of different sizes

Discussion

The edge effect explains why the response at early times over a plate with dimensions similar to the loop is greater than for either larger or smaller plates. At late times the effect of the total volume of the plates plays a more important role, and the response decreases monotonically as the loop size.

The models shown give an idea of the situations where two-layer master curves, such as those of Raiche & Spies (in prep.), can be used. Generally it is necessary that the layers have a lateral extent at least as large as the loop size for early times, and several loop sizes at later times. The connection between lateral extent, conductivity, and sample time is closely related to the diffusion of eddy currents in the ground.

Lewis & Lee (1978) describe the annular pattern of eddy current diffusion, and give expressions for determining the position of the maximum electric field. Although these expressions can be used as a guide, it must be recognised that the perturbation in response due to an edge (either lateral or at depth) will be obtained at least half a decade in time earlier than given by Lewis & Lee's formulae.

2. TRANSMITTER RAMP TURN-OFF

Description of model

The transient decay test set transmitter used in the model facility includes an option to vary the turn-off time from almost zero to several hundred milliseconds. For this study turn-off times of 0.5 ms and 0.9 ms were used. The model setup consisted of a 2.7 cm loop lying on a type-metal block, which simulates a half-space of conductivity 3×10^6 S/m.

Results

Transient decay curves for two different turn-off ramps, plotted using normalised parameters, are shown in Figures 15 and 16. Three different curves are shown:

(i) the true transient decay curve obtained from the model with no ramp;

(ii) the transient decay, measured in the receiver coil, due to the turn-off ramp with the modal removal; and

(iii) the transient decay curve obtained over the model, with the ramp turn-off (the "combined curve").

Referring first to Figure 15, it can be seen that for a transmitter pulse with ramp, at early times the transient response is decreased by the introduction of the modal. At later times this situation is reversed. When the true transient decay curve has the same amplitude as the ramp-only curve, $e(t)_1$, the combined curve (model with ramp) is larger than $e(t)_1$ by a factor of five. Even when the ramp-only curve has decayed to a very small value, e.g. 0.002, the combined curve is still over two times as large as the true transient decay curve.

At late times the combined curve approaches the true curve. The error in response is 50% at a time approximately twice that at which the equivalent response is measured on the ramp-only curve. For the error to be insignificant, at least half a decade of time needs to have elapsed between the time at which the ramp response

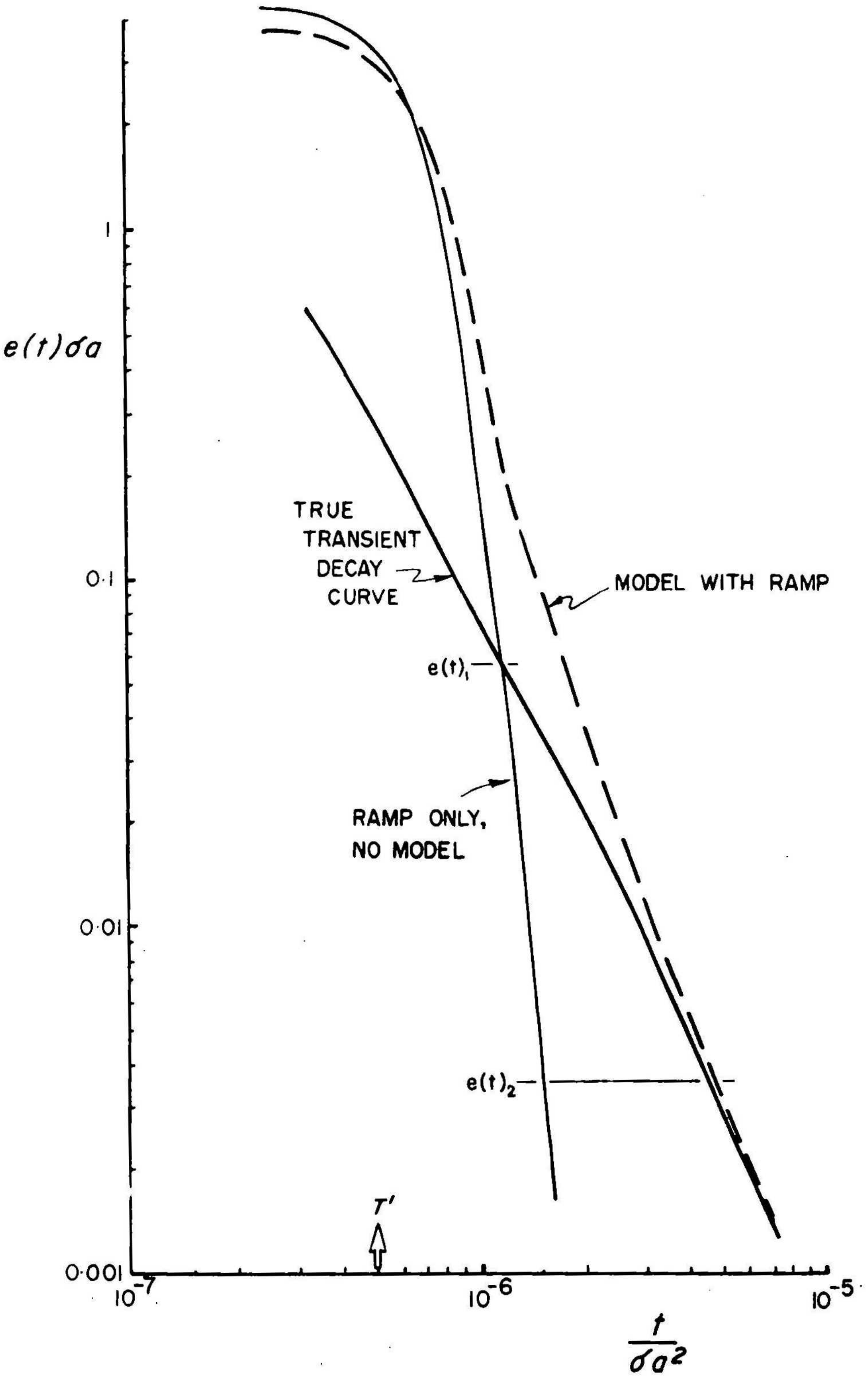


Fig. 15 Transient decay curves obtained over a half-space model with a ramp turn-off. σ = half-space conductivity.

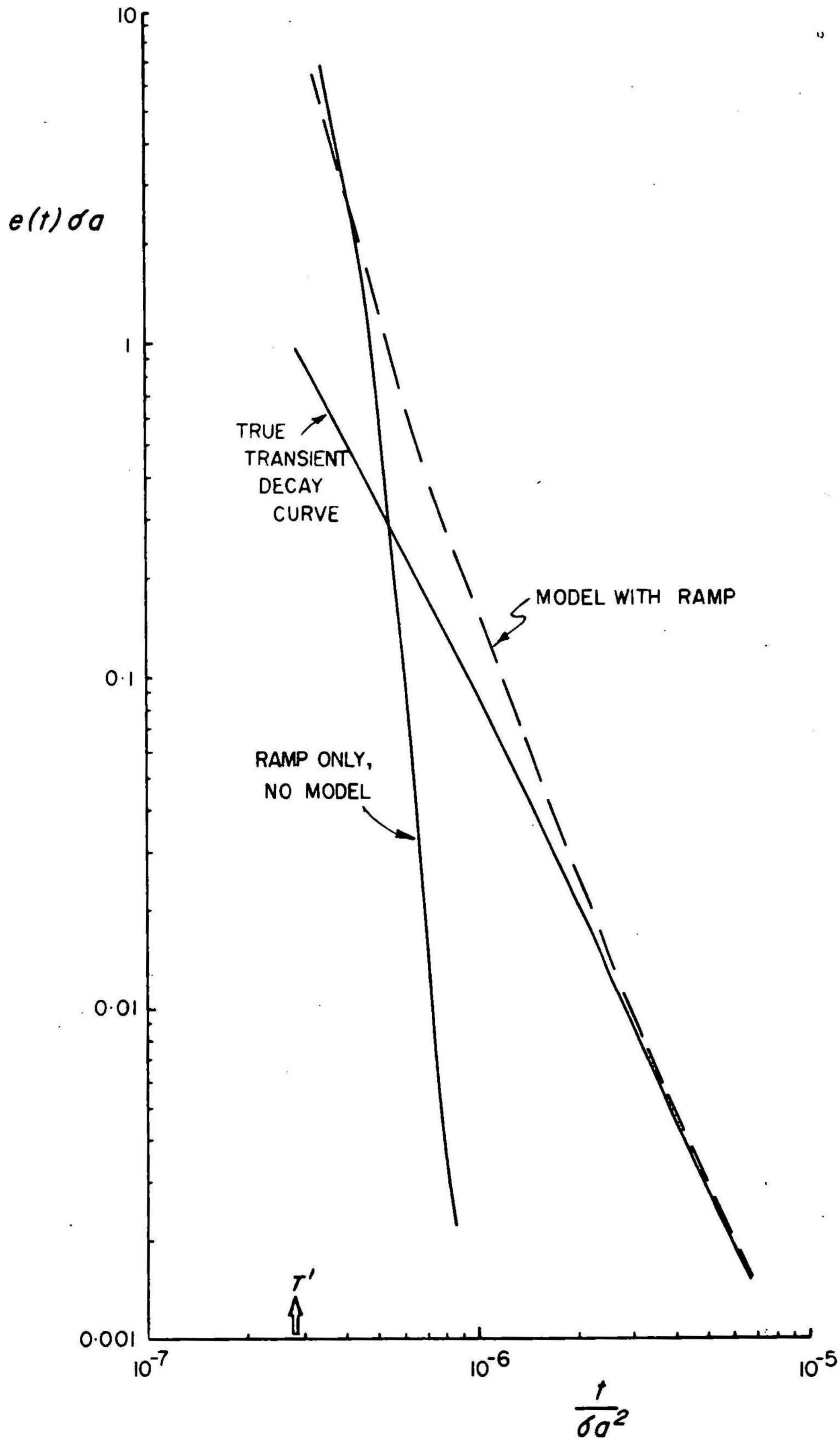


Fig. 16 Transient decay curves obtained over a half-space model with a ramp turn-off

has decayed to a certain level, say $e(t)_2$, and measurement of the model transient decay at the same signal level. These features are also true for the faster ramp turn-off shown in Figure 16.

Discussion

These studies show that if the transmitted waveform has an appreciable turn-off time, large errors can be introduced in the measured response for at least half a decade of time after the end of the ramp. At late times the effect of the ramp is negligible. This is because the ramp contains mainly high-frequency components, which have the greatest effect on the early parts of the transient.

In some transient electromagnetic systems, such as PEM, the time reference $t = 0$ is defined as being near the end of the ramp. For the PEM system, this zero-time is found by measuring the signal induced in the receiver and adjusting a timing potentiometer until the signal just starts to fall away. It is assumed that this is the edge of the ramp. This procedure is very dependent on the shape of the ramp, which will change with loop size and the conductivity of the ground. For the PEM system the ramp is a simple LR decay governed by the inductance and resistance of the loop.

It is interesting to note, however, that there is a simple time correction that can be applied to the data in Figures 15 and 16. For the model in Figure 15 there is an apparent time difference of 5×10^{-7} s/Sm between the model with ramp curve and the true transient curve at medium to late times. If the numerical value of this time difference (T') is used for the zero time reference $t = 0$, then the measured curve based on the adjusted sample times would be relatively free of error. For the model shown in Figure 16, T' is equal to 2.7×10^{-7}. As well as being dependent on the ramp shape, T' may also depend on the type of model.

There does not appear to be any easy method of determining T' in practical field conditions. Clearly the time reference lies between the start of the turn-off assumed in some systems (MPPO-1 and SIROTEM) and the end of the turn-off. For accurate results to be obtained, measurements should not be made until at least half a decade of time later than that at which the transmitter turn-off signal can be detected in the receiver.

3. LATERAL DISCONTINUITY: TWO-LOOP SYSTEM

Description of model

The model consists of two blocks of differing conductivity joined by means of a conductive epoxy resin. The model parameters are shown in Table 2.

Table 2: Parameters of Lateral Discontinuity Model

Material	Width	Length	Thickness	Conductivity
Type-metal	170 mm	200 mm	25 mm	3×10^6 S/m
Graphite	250 mm	200 mm	50 mm	10^5 S/m
Conductive resin	~ 0.5 mm	-	-	~ 10^4 S/m

Measurements were made with loops of 13.5 mm radius with separation l = 32, 57, and 87 mm. For comparison a coincident loop profile was also measured.

Results

Profiles obtained with the coincident loop are shown in Figure 17 using normalised parameters. The values of normalised time would represent milliseconds for models where $\sigma\mu a^2 = 10^{-3}$. These profiles could be easily interpreted using intuitive means.

For a separated-loop system, however, the results are more complicated. The profiles shown in Figure 18 are for a loop separation, l, of 2.4 a, where a is the loop radius. The response over the more conductive block is negative at early times and positive at late times. Over the more resistive block the response is positive over the whole time range measured.

This is the normal two-loop half-space response, as described by Spies (in prep.). Briefly, the response of a half-space is negative at early times, decays and changes sign at a time which depends on the loop separation and ground conductivity, and finally decays with positive sign at late times.

Referring again to Figure 18, it can be seen that directly over the contact the response is complex, especially in the medium tim range (T = 0.58 and 1.2). This complexity could lead to considerable difficulties in interpretation.

When the loop separation is increased to l/a = 4.2 (Fig. 19) the half-space responses on the left and right are similar to those for l/a = 2.4, except that the sign change occurs later. Over the contact, the response is negative for all times. This response zone is the same width as the loop separation. Similar features can be seen when the loop separation is increased to 6.4 a, as shown in Figure 20.

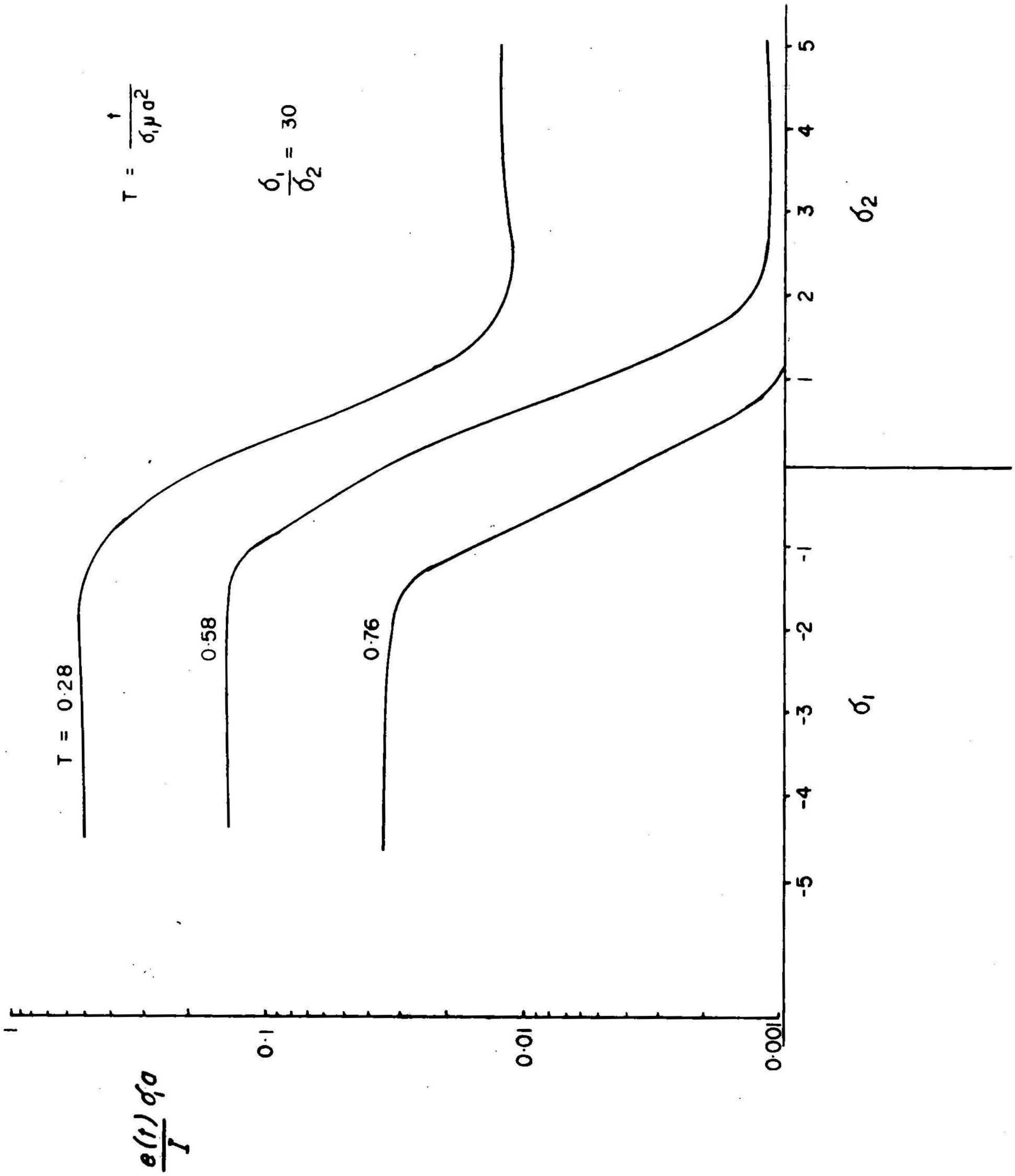


Fig.17 Coincident-loop profiles over lateral contact model

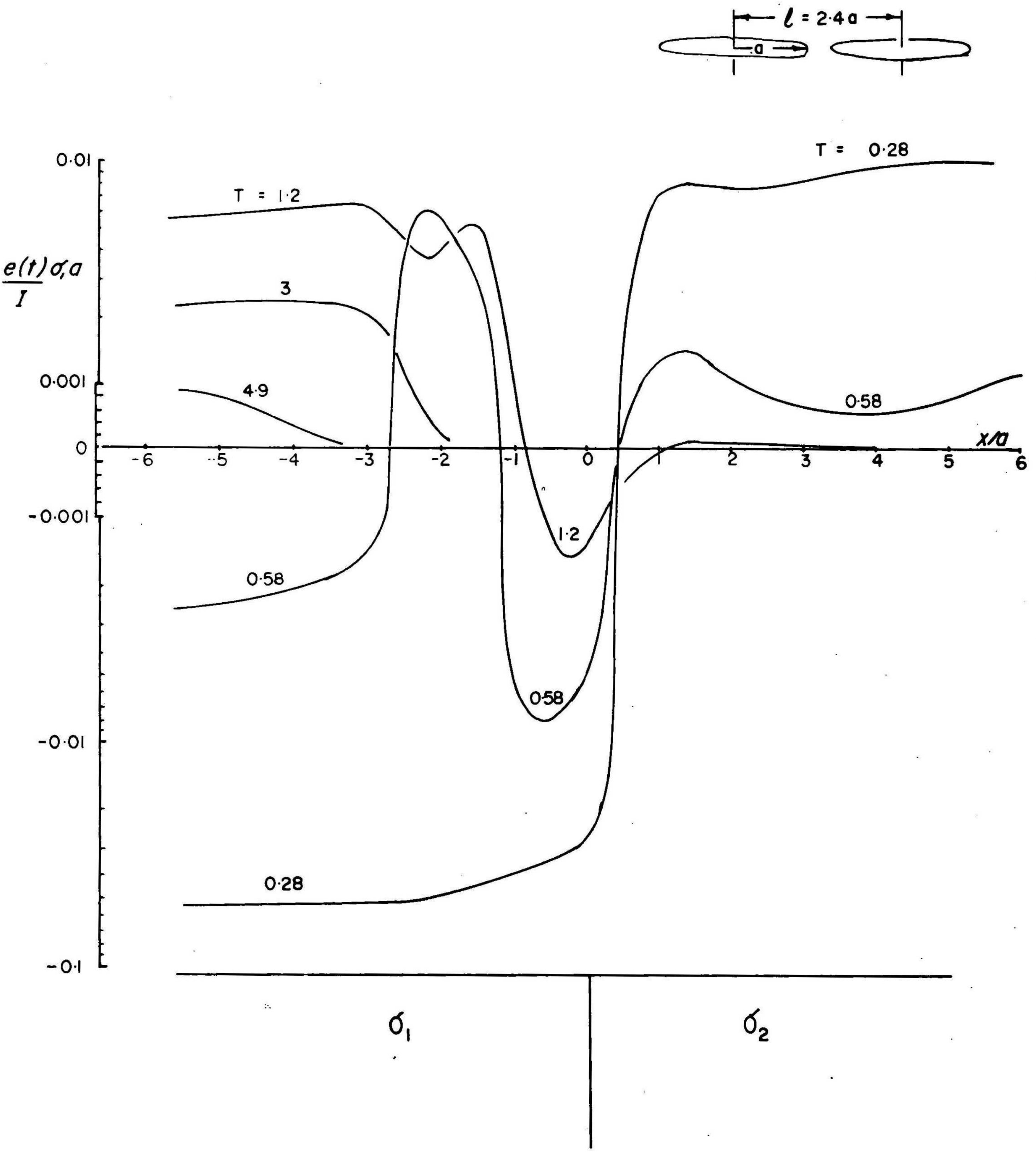


Fig. 18 Two-loop profiles over lateral contact model, l/a = 2.4

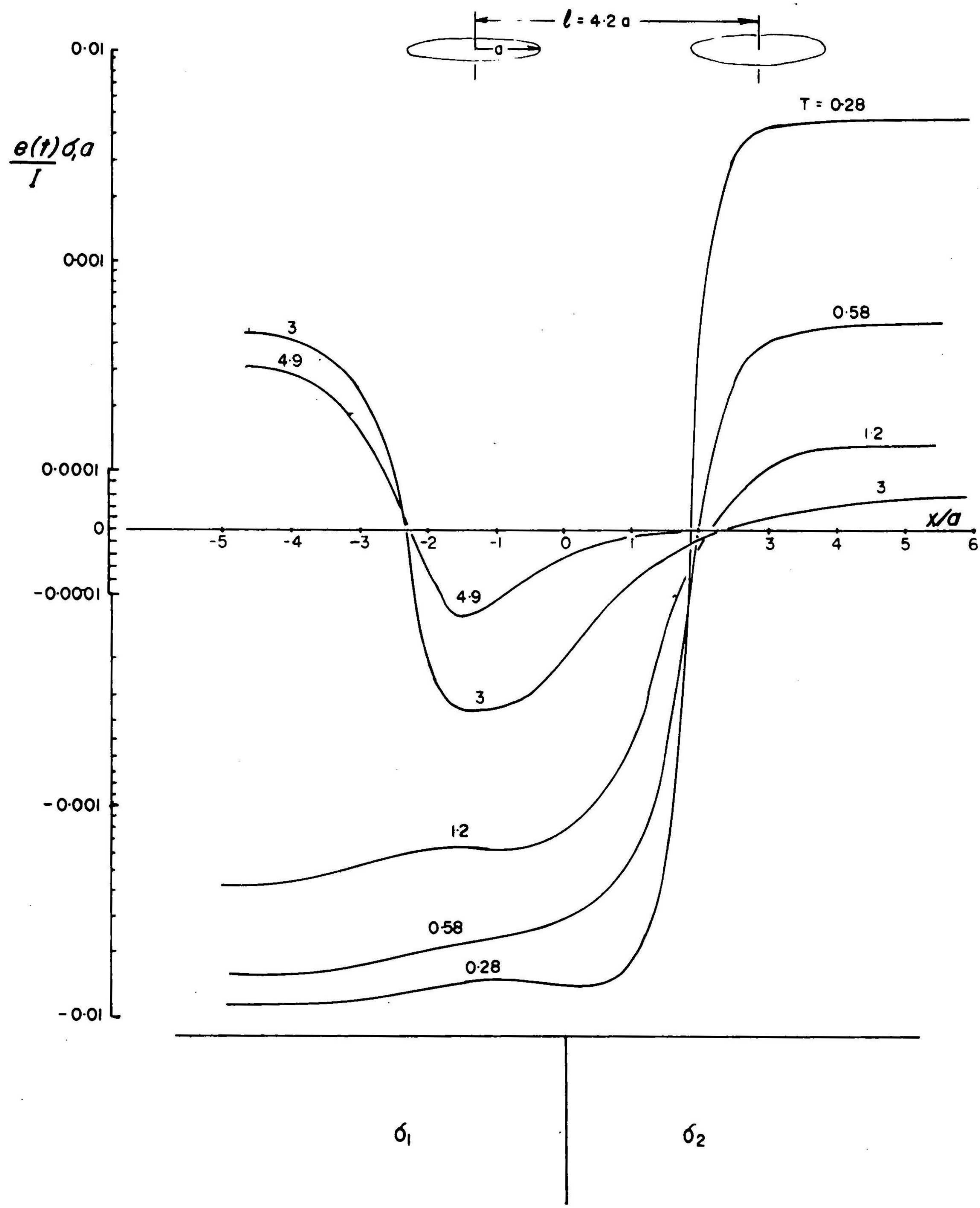


Fig.19 Two-loop profiles over lateral contact model, 1/a = 4.2

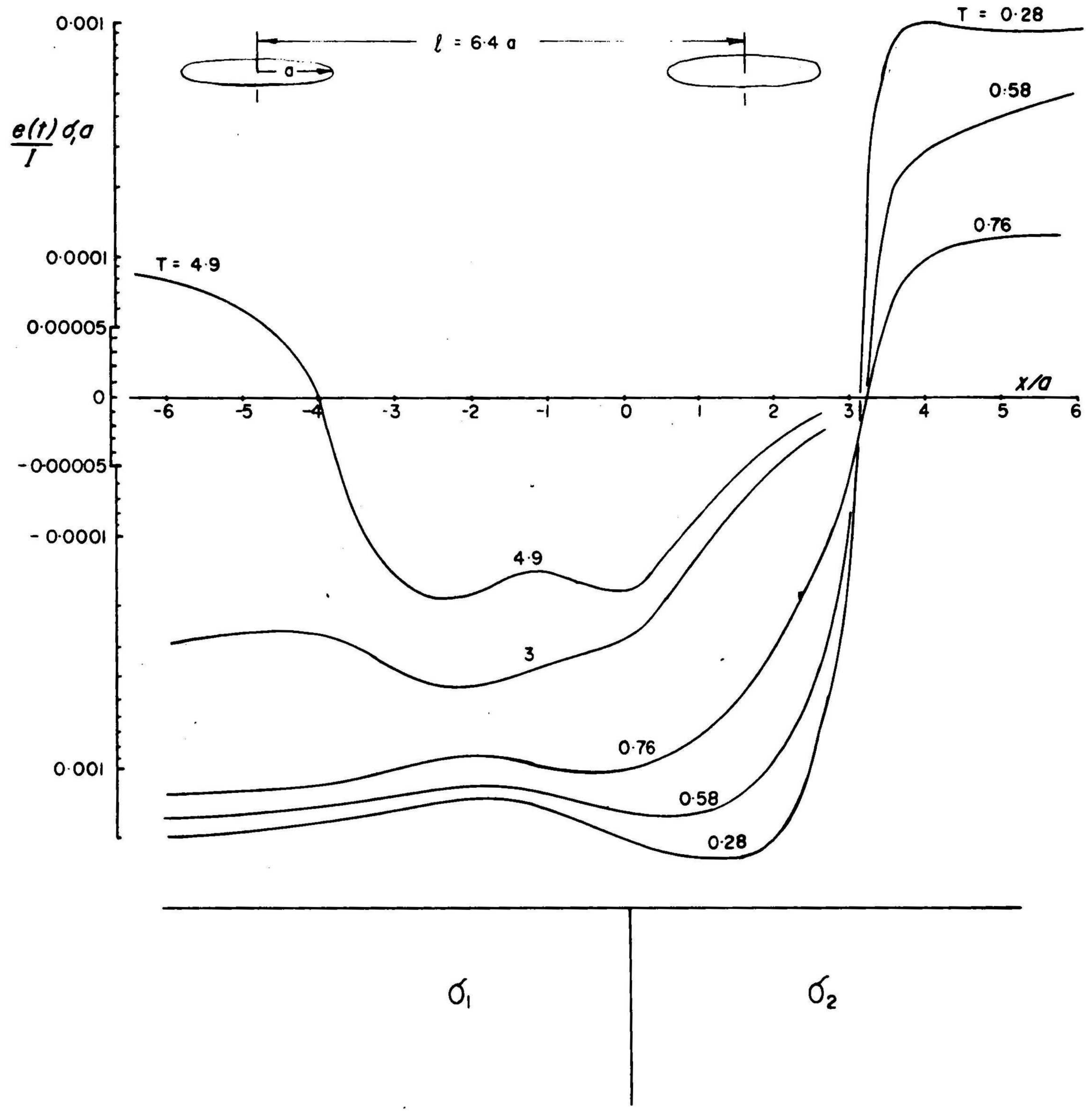


Fig. 20 Two - loop profiles over lateral contact model, 1/a = 6.4

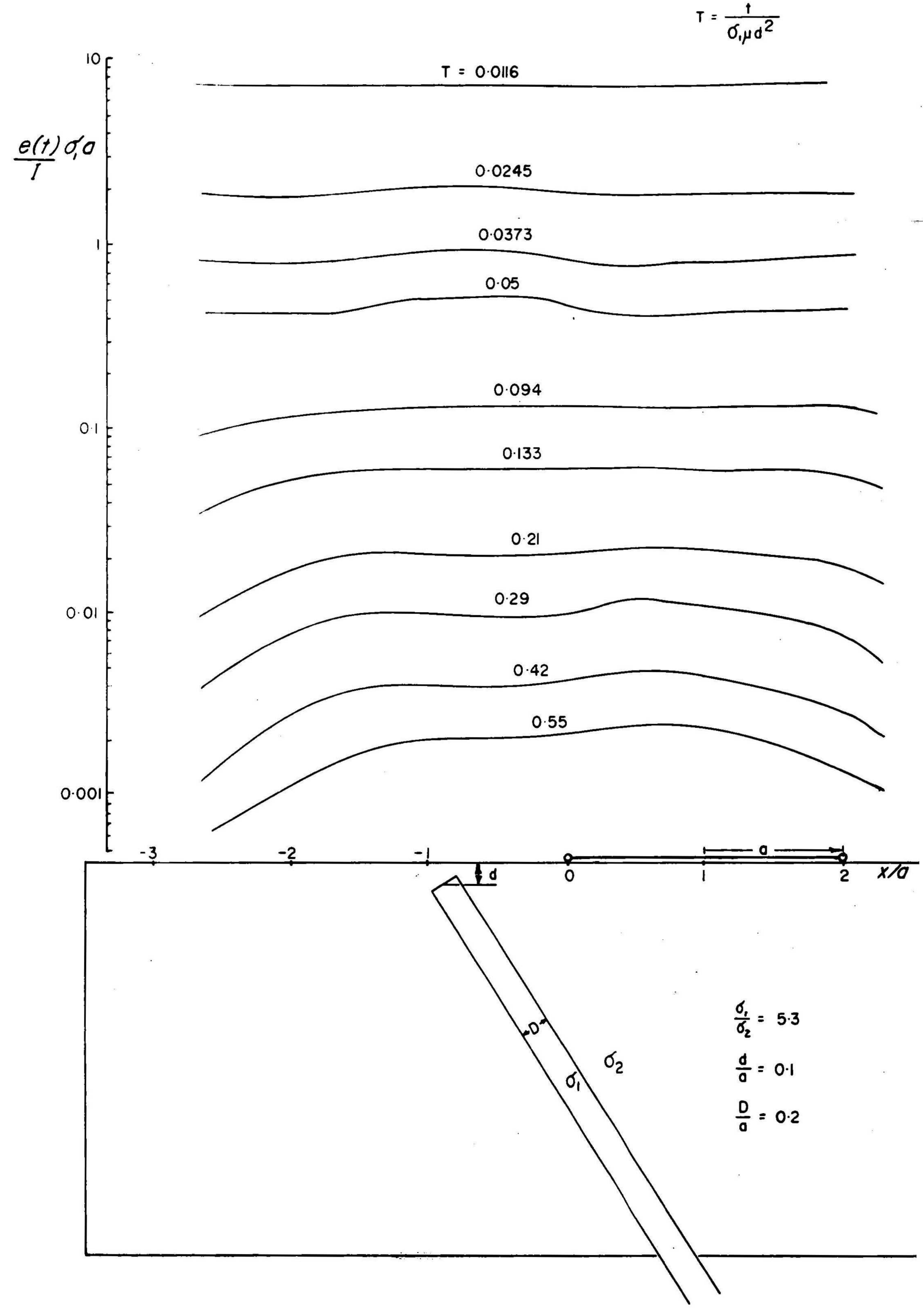


Fig. 21 Coincident loop profiles over a dyke in a conductive host rock

Discussion

Although the vertical contact is a very simple model, the two-loop TEM response can be seen to be fairly complex. The response can be positive or negative depending on loop separation, ground conductivity, and sample time. Under some conditions (for example T = 3.0 and 4.9 in Figure 19) the profile is not dissimilar to that expected over a vertical dyke-like model.

Thus it can be seen that lateral changes in conductivity can cause complex two-loop TEM anomalies which are difficult to interpret, even qualitatively. By contrast, the coincident-loop profile shown in Figure 17 is simple, and would be unlikely to result in misinterpretation.

4. DYKE IN A CONDUCTIVE HOST ROCK

Description of model

The dyke model consisted of a brass plate ($\sigma = 1.6 \times 10^7$ S/m) with dimensions 12 cm x 20 cm x 6 mm. The surfaces were thoroughly cleaned, a flux (Bakers fluid) applied and the plate preheated before immersing in a stainless steel mould, 20 cm x 20 cm x 10 cm, containing molten type-metal ($\sigma = 3 \times 10^6$ S/m). The posit coefficient of expansion (upon solidification) of type-metal and the soldering compatability of the two metals ensured that good electrical contact was achieved.

Results

Tem profiles for a range of times are shown in Figure 21. At early times the block responds as a half-space and the dyke is not seen. At later times (T = 0.03) eddy currents diffuse into the block and a small anomaly is obtained over the top of the plate. At later times still, edge effects become important and the block no longer behaves like a half-space near the edges (e.g. at x = 2a, the block does not respond as a half-space for T greater than 0.09). At T = 0.546 eddy currents have diffused deep into the block and a response attributed to deeper parts of the plate can be seen at x = 0.5 a.

The plate response is small at all times, however, owing to the small conductivity contrast of only 5.3 between the plate and host.

Discussion

The modelling technique described above appears to be an effective method of simulating small conductivity contrasts between a conductive body and host rock. The technique is relatively straightforward, but requires a certain amount of expertise and caution in the casting of molten metal. The alternative method is to use a salt-water tank, but small conductivity contrasts would be difficult to achieve. Also, the tank would be much too small to simulate a half-space.

CONCLUSIONS

The model studies carried out in this report were conducted in a short time span (3 weeks) on the Macquarie University facility, and provided guidelines for TEM interpretation of several different models.

The facility is being moved temporarily to BMR and will be used to model a wider range of EM and electrical techniques. Suggestions from industry and other governmental departments on particular problems which could be studied are welcome.

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