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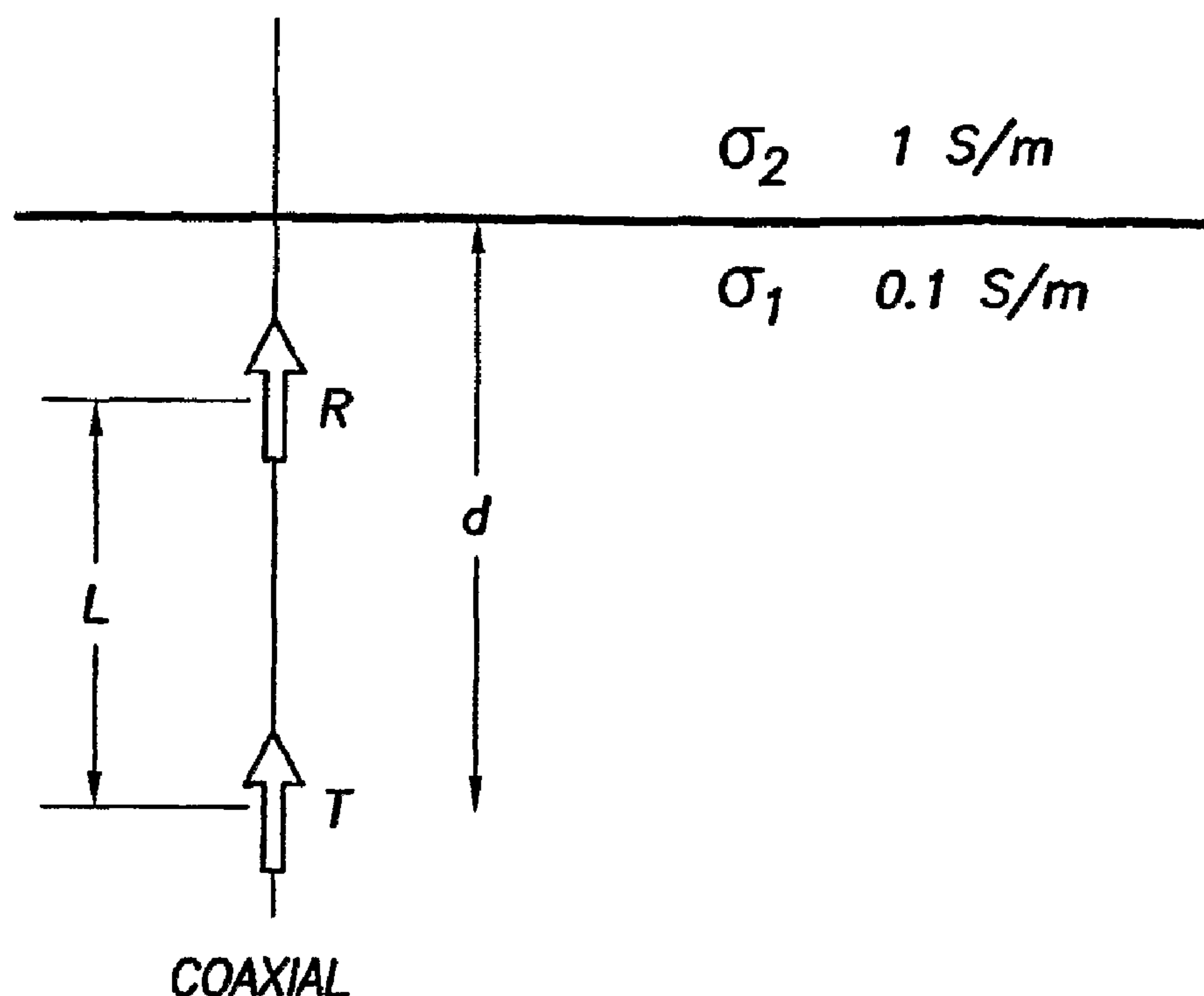
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A method and a system are provided for allowing determination of a distance from a tool to anomaly ahead of the tool. The apparatus for performing the method includes at least one transmitter and at least one receiver. An embodiment of the method includes transmitting electromagnetic signals from the at least one transmitter through the formation surrounding the wellbore and detecting voltage responses at the at least one receiver induced by the electromagnetic signals. The method includes calculating apparent conductivity or apparent resistivity is monitored over time, and the distance to the anomaly is determined from the apparent conductivity or apparent resistivity values

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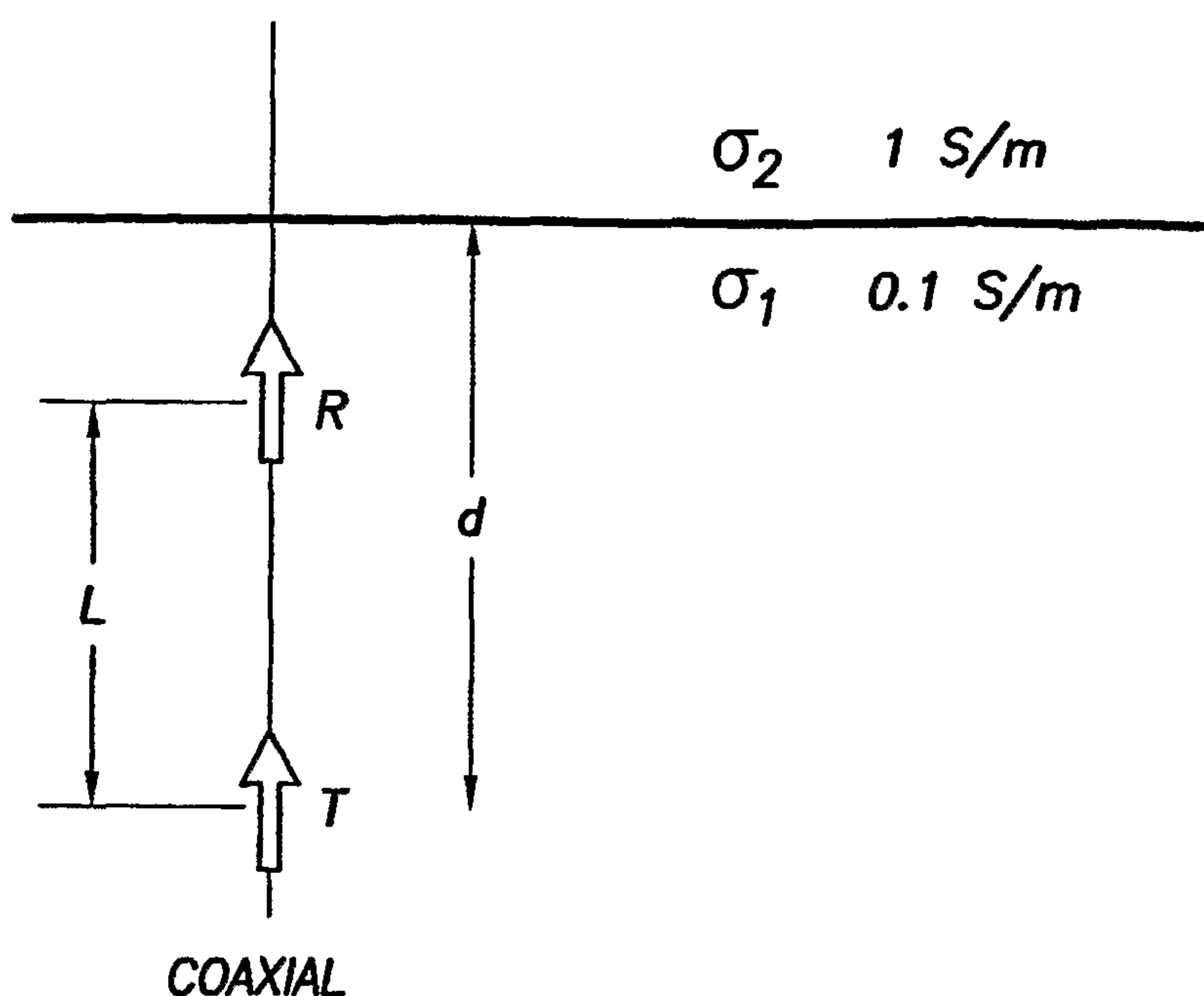
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(54) Title: METHOD FOR LOCATING AN ANOMALY AHEAD OF A DRILL BIT



(57) Abstract: A method and a system are provided for allowing determination of a distance from a tool to anomaly ahead of the tool. The apparatus for performing the method includes at least one transmitter and at least one receiver. An embodiment of the method includes transmitting electromagnetic signals from the at least one transmitter through the formation surrounding the wellbore and detecting voltage responses at the at least one receiver induced by the electromagnetic signals. The method includes calculating apparent conductivity or apparent resistivity is monitored over time, and the distance to the anomaly is determined from the apparent conductivity or apparent resistivity values

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METHOD FOR LOCATING AN ANOMALY AHEAD OF A DRILL BIT

The present invention relates to a method for locating an anomaly ahead of a device. In a particular embodiment, the invention relates to finding the location of a resistive or conductive anomaly ahead of a drill bit in a formation surrounding a borehole, or ahead of a borehole, in drilling applications. In a particular embodiment, the device may be located within a wellbore.

10 In logging while drilling (LWD) geo-steering applications, it is advantageous to detect the presence of a formation anomaly ahead of or around a bit or bottom hole assembly. There are many instances where "Look-Ahead" capability is desired in LWD logging environments. Look-ahead logging is to detect an anomaly at a distance ahead of the drill bit. Some look-ahead examples include predicting an over-pressured zone in advance, or detecting a fault in front of the drill bit in horizontal wells, or profiling a massive salt structure ahead of the drill bit. While currently available techniques are capable of detecting the presence of an anomaly, they are not capable of determining the location of the anomaly with sufficient depth or speed, they are not capable of detecting an anomaly at a sufficient distance ahead of a bit or bottom hole assembly.

25 When logging measurements are used for well placement, detection or identification of anomalies can be critical. Such anomalies may include for example, a fault, a bypassed reservoir, a salt dome, or an adjacent bed or oil-water contact. It would be beneficial to determine both the distance and the direction of the anomaly from the drilling site.

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In formation evaluation, the depth of investigation of most logging tools, wire line or LWD has been limited to a few feet from the borehole.

U.S. Patent No. 6,181,138 to Hagiwara discloses a technique for locating an anomaly adjacent to a logging device, utilizing tilted coil induction tools and frequency domain excitation techniques. In order to achieve a depth of investigation with such a tool, a longer tool size would be required. However, longer tools generally result in poor spatial resolution.

In order to increase depth capabilities, transient electromagnetic (EM) methods have been proposed. One such method for increasing the depth of investigation is proposed in U.S. Patent No. 5,955,884 to Payton, et al. The tool disclosed in this patent utilizes electric and electromagnetic transmitters to apply electromagnetic energy to a formation at selected frequencies and waveforms that maximize radial depth of penetration into the target formation. In this transient EM method, the current is generally terminated at a transmitter antenna and temporal change of voltage induced in a receiver antenna is monitored. This technique has allowed detection of an anomaly at distances as deep as ten to one hundred meters. However, while Payton discloses a transient EM method enabling detection of an anomaly, it does not provide a technique for detecting anomalies ahead of a drill bit.

Accordingly, a new solution is needed for determining the distance from a tool to an anomaly ahead of that tool. Particularly such a solution is needed for looking ahead of a drill bit. Furthermore, a real time solution having an increased depth of analysis is needed so that the measurements can be immediately useful to equipment operators.

In one aspect, in accordance with an embodiment of the present invention there is provided a method for determining a distance to an anomaly in a formation ahead of a device in a wellbore. The method may be implemented using a device including at least one transmitter and at least one receiver. The method includes calculating at least one of an apparent conductivity and an apparent resistivity based on a detected response, which may include a voltage response. The at least one of apparent conductivity and apparent resistivity is monitored over time, and the distance to the anomaly is determined based on an observed change of the one of apparent conductivity and apparent resistivity.

In a particular embodiment of the invention, a voltage response is measured over time, and the response is utilized to calculate the apparent conductivity or the apparent resistivity over a selected time span. A time at which the apparent conductivity deviates from a constant value is determined, and this time may be utilized to ascertain the distance that an anomaly is ahead of a wellbore.

In a particular embodiment of the invention, the distance to the anomaly is determined when the at least one of apparent conductivity and apparent resistivity reaches an asymptotic value.

The device may comprise a logging tool and/or it may be provided in a measurement-while-drilling section or a logging-while-drilling section of a drill string trailing a drill bit.

The present invention will now be illustrated by means of example by the detailed description below with reference to the attached drawing figures, wherein:

FIG. 1 is a block diagram showing a system in accordance with embodiment of the invention;

FIG. 2 is a flow chart illustrating a method in accordance with an embodiment of the invention;

FIG. 3 is a schematic showing apparent conductivity with a coaxial tool

5 FIG. 4 is a graph showing voltage response of the coaxial tool of FIG. 3 in a homogeneous formation for various formation resistivities;

FIG. 5 is a graph showing voltage response in a homogeneous formation as a function of formation resistivity
10 at different times (t) for the same coaxial tool;

FIG. 6 is a graph showing voltage response in a homogeneous formation as a function of formation resistivity for a larger transmitter-receiver spacing than in FIG. 5;

FIG. 7 is a graph showing voltage response as a function
15 of t as given by the coaxial tool of FIG. 3 at different distances from the bed;

FIG. 8 is a graph showing the voltage response data of FIG. 7 in terms of the apparent conductivity ($\sigma_{app}(t)$);

FIG. 9 is similar to FIG. 8 except that the
20 resistivities of layers 1 and 2 have been interchanged;

FIG. 10 presents a graph comparing $\sigma_{app}(t)$ of FIG. 8 and FIG. 9 relating to $d = 1$ m.

FIG. 11 presents a graph of the same data as displayed in FIG. 8 but now on a linear scale of apparent conductivity;

25 FIG. 12 shows a graph of $\sigma_{app}(t)$ on a linear scale for various transmitter/receiver spacings L in case $d = 1$ m;

FIG. 13 shows a graph of late time conductivity as a function of d for various transmitter/receiver spacings L ;

FIG. 14 shows the $\sigma_{app}(t)$ plots for $d = 5$ m and $L = 01$ m
30 for various resistivity ratios;

FIG. 15 shows a graph of the $\sigma_{app}(t)$ for the case $d = 5\text{ m}$ and $L = 01\text{ m}$, but for different resistivity ratios while the target resistivity is fixed at $R_2 = 1\text{ ohm-m}$;

FIG. 16 graphically shows a comparison of the late time apparent conductivity at $t = 1\text{ second}$ with a model calculation, for the case target resistivity $R_2 = 1\text{ ohm-m}$;

FIG. 17 graphically shows the same data as FIG. 16 plotted as the late time apparent conductivity at $t = 1\text{ second}$ versus ratio of the late time apparent conductivity at $t = 1\text{ second}$ over local environment conductivity;

FIG. 18 graphically shows distance to anomaly ahead of the tool verses transition time (t_c) as determined from the data of FIG. 8;

FIG. 19 shows a plot of the apparent conductivity ($\sigma_{app}(z; t)$) in both z - and t -coordinates;

FIG. 20 is a schematic showing apparent conductivity with a coplanar tool;

FIG. 21 graphically shows voltage response of the coplanar tool of FIG. 20 with a transmitter/receiver separation of $L = 1\text{ m}$, in a homogeneous formation as a function of formation resistivity at different times (t);

FIG. 22 graphically shows voltage response in a homogeneous formation as a function of formation resistivity for a larger transmitter-receiver spacing than in FIG. 21;

FIG. 23 is a graph showing voltage response data in terms of the apparent conductivity ($\sigma_{app}(t)$) as a function of t as provided by the coplanar tool of FIG. 20 at different distances from the bed;

FIG. 24 shows a comparison of the late time apparent conductivity ($\sigma_{app}(t \rightarrow \infty)$) for coplanar responses where $d = 05\text{ m}$ and $L = 01\text{ m}$ as a function of conductivity of the local layer while the target conductivity is fixed at 1 S/m ;

FIG. 25 graphically shows the same data as FIG. 24 plotted as the ratio of target conductivity over local layer conductivity versus ratio of the late time apparent conductivity over local layer conductivity; and

5 FIG. 26 graphically shows distance to anomaly ahead of the tool verses transition time (t_c) as determined from the data of FIG. 23.

Embodiments of the invention relate to a system and method for determining distance to an anomaly in a formation
10 ahead of a device in a wellbore. Both frequency domain excitation and time domain excitation have been used to excite electromagnetic fields for use in anomaly detection. In frequency domain excitation, a device transmits a continuous wave of a fixed or mixed frequency and measures
15 responses at the same band of frequencies. In time domain excitation, a device transmits a square wave signal, triangular wave signal, pulsed signal or pseudo-random binary sequence as a source and measures the broadband earth response. Sudden changes in transmitter current cause signals
20 to appear at a receiver caused by induction currents in the formation. The signals that appear at the receiver are called transient responses because the receiver signals start at a first value and then decay or increase with time to a constant level. The technique disclosed herein implements the
25 time domain excitation technique.

As set forth below, embodiments of the invention propose a general method to determine a distance to a resistive or conductive anomaly using transient EM responses. As will be explained in detail, the distance to the anomaly is found by
30 monitoring an apparent conductivity over time based on transient voltage response. The distance to the anomaly is determined based on the variation of the apparent conductivity over time. Time-dependent values for apparent

conductivity can be obtained from coaxial and coplanar measurements, and can respectively be denoted as $\sigma_{coaxial}(t)$ and $\sigma_{coplanar}(t)$. Both read the conductivity around the tool.

FIG. 1 illustrates a system that may be used to
5 implement the embodiments of the method of the invention. A surface computing unit 10 may be connected with an electromagnetic measurement tool 2 disposed in a wellbore 4 and supported by a cable 12. The cable 12 may be constructed of any known type of cable for transmitting electrical
10 signals between the tool 2 and the surface computing unit 10. One or more transmitters 16 and one or more receivers 18 may be provided for transmitting and receiving signals. A data acquisition unit 14 may be provided to transmit data to and from the transmitters 16 and receivers 18 to the surface
15 computing unit 10.

Each transmitter 16 and each receiver 18 may be tri-axial and thereby contain components for sending and receiving signals along each of three axes. Accordingly, each transmitter module may contain at least one single or multi-
20 axis antenna and may be a 3-orthogonal component transmitter. Each receiver may include at least one single or multi-axis electromagnetic receiving component and may be a 3-orthogonal component receiver.

A tool/borehole coordinate system is defined as having
25 x, y, and z axes. The z-axis defines the direction from the transmitter T to the receiver R. It will be assumed hereinafter that the axial direction of the wellbore 4 coincides with the z-axis, whereby the x- and y-axes correspond to two orthogonal directions in a plane normal to
30 the direction from the transmitter T to the receiver R and to the wellbore 4.

The data acquisition unit 14 may include a controller for controlling the operation of the tool 2. The data

acquisition unit 14 preferably collects data from each transmitter 16 and receiver 18 and provides the data to the surface computing unit 10.

5 The surface computing unit 10 may include computer components including a processing unit 30, an operator interface 32, and a tool interface 34. The surface computing unit 10 may also include a memory 40 including relevant coordinate system transformation data and assumptions 42, an optional direction calculation module 44, an optional
10 apparent direction calculation module 46, and a distance calculation module 48. The optional direction and apparent direction calculation modules are described in more detail in US patent application 10/897,585 of which priority is presently claimed and which is herewith incorporated by
15 reference.

The surface computing unit 10 may further include a bus 50 that couples various system components including the system memory 40 to the processing unit 30. The computing system environment 10 is only one example of a suitable
20 computing environment and is not intended to suggest any limitation as to the scope of use or functionality of the invention. Furthermore, although the computing system 10 is described as a computing unit located on a surface, it may optionally be located below the surface, incorporated in the
25 tool, positioned at a remote location, or positioned at any other convenient location.

The memory 40 preferably stores module 48 and optional modules 44 and 46, which may be described as program modules containing computer-executable instructions, executed by the
30 surface computing unit 10. The program module 44 contains the computer executable instruction necessary to calculate a direction to an anomaly within a wellbore. The program module 48 contains the computer executable instructions necessary to

calculate a distance to an anomaly. The stored data 42 includes data pertaining to the tool coordinate system and the anomaly coordinate system and other data required for use by the program modules 44, 46, and 48.

5 For further details on the computing system 10, including storage media and input/output devices, reference is made to US patent application 10/897,585 of which priority is presently claimed and which is herewith incorporated by reference. Accordingly, additional details concerning the
10 internal construction of the computer 10 need not be disclosed in connection with the present invention.

FIG. 2 is a flow chart illustrating the procedures involved in a method of the invention. Generally, in procedure A, the transmitters 16 transmit electromagnetic
15 signals. In procedure B, the receivers 18 receive transient responses. In procedure C, the system processes the transient responses to determine a distance to the anomaly, and optionally also a direction.

In case a 3-orthogonal component receiver is employed,
20 magnetic field transient responses at the receivers $[R_x, R_y, R_z]$ which are oriented in the $[x, y, z]$ axis direction of the tool coordinates, respectively, are noted as

$$(1) \begin{bmatrix} V_{xx} & V_{xy} & V_{xz} \\ V_{yx} & V_{yy} & V_{yz} \\ V_{zx} & V_{zy} & V_{zz} \end{bmatrix} = \begin{bmatrix} R_x \\ R_y \\ R_z \end{bmatrix} \begin{bmatrix} M_x & M_y & M_z \end{bmatrix}$$

from a magnetic dipole source in each axis direction, $[M_x,$
25 $M_y, M_z]$.

When the resistivity anomaly is distant from the tool, the formation near the tool is seen as a homogeneous formation. For simplicity, the method may assume that the formation is isotropic. Only three non-zero transient
30 responses exist in a homogeneous isotropic formation. These

include the coaxial response and two coplanar responses. Coaxial response $V_{zz}(t)$ is the response when both the transmitter T and the receiver R are oriented in the common tool axis direction. Coplanar responses, $V_{xx}(t)$ and $V_{yy}(t)$,
5 are the responses when both the transmitter T and the receiver R are aligned parallel to each other but their orientation is perpendicular to the tool axis. All of the cross-component responses are identically zero in a homogeneous isotropic formation. Cross-component responses
10 are either from a longitudinally oriented receiver with a transverse transmitter, or vice versa. Another cross-component response is also zero between a mutually orthogonal transverse receiver and transverse transmitter.

The effect of the resistivity anomaly is seen in the
15 transient responses as time increases. In addition to the coaxial and the coplanar responses, the cross-component responses $V_{ij}(t)$ ($i \neq j$; $i, j = x, y, z$) become non-zero.

When the anomaly is large and distant compared to the transmitter-receiver spacing L , the effect of spacing can be
20 ignored and the transient responses can be approximated with those of the receivers near the transmitter.

Apparent Conductivity

Apparent conductivity, or its inherent inverse equivalent apparent resistivity, can be used to determine the
25 location of or distance to an anomaly in the wellbore. The time-dependent apparent conductivity can be defined at each point of a time series at each logging depth. The apparent conductivity at a logging depth z is defined as the conductivity of a homogeneous formation that would generate
30 the same tool response measured at the selected position.

In transient EM logging, transient data are collected at a logging depth or tool location z as a time series of induced voltages in a receiver loop. Accordingly, time

dependent apparent conductivity ($\sigma_{app}(z; t)$) may be defined at each point of the time series at each logging depth, for a proper range of time intervals depending on the formation conductivity and the tool specifications.

5 Coaxial Tools

FIG. 3 illustrates a coaxial tool in which both a transmitter coil (T) and a receiver coil (R) are wound around a common tool axis z. The receiver R is placed at a distance L from the transmitter T. The symbols σ_1 and σ_2 represent the conductivities of two formation layers.

Apparent Conductivity for a Coaxial Tool

The induced voltage of a coaxial tool with transmitter-receiver spacing L in the homogeneous formation of conductivity (σ) is given by,

$$15 \quad (2) \quad V_{zz}(t) = C \frac{(\mu_o \sigma)^{3/2}}{8 t^{5/2}} e^{-u^2}$$

wherein $u^2 = \frac{\mu_o \sigma L^2}{4 t}$ and C is a constant.

The coaxial tool as depicted in FIG. 3 is used to illustrate the voltage response for different values of t and L in FIGS. 4-6 below, where $\sigma_1 = \sigma_2$.

20 FIG. 4 shows the voltage response of the coaxial tool with L = 01 m in a homogeneous formation for various formation resistivities (R) from 1000 ohm-m to 0.1 ohm-m. The voltage is positive at all times t for t > 0. The slope of the

voltage is nearly constant $\frac{\partial \ln V_{zz}(t)}{\partial \ln t} \approx -\frac{5}{2}$ in the time interval
25 between 10^{-8} second and 1 second (and later) for any formation resistivity larger than 10 ohm-m. The slope changes sign at an earlier time around 10^{-6} second when the resistivity is low as 0.1 ohm-m.

FIG. 5 shows the voltage response as a function of formation resistivity at different times (t) for the same coaxial tool spacing ($L = 1\text{ m}$). For the resistivity range from 0.1 ohm-m to 100 ohm-m , the voltage response is single valued as a function of formation resistivity for the measurement time (t) later than 10^{-6} second . At smaller times (t), for instance at 10^{-7} second , the voltage is no longer single valued. The same voltage response is realized at two different formation resistivity values.

FIG. 6 shows the voltage response as a function of formation resistivity for a larger transmitter-receiver spacing of $L = 10\text{ m}$ on a coaxial tool. The time interval when the voltage response is single valued is shifted toward larger times (t). The voltage response is single valued for resistivity from 0.1 ohm-m to 100 ohm-m , for the measurement time (t) later than 10^{-4} second . At smaller values of t , for instance at $t = 10^{-5}\text{ second}$, the voltage is no longer single valued. The apparent conductivity from a single measurement (coaxial, single spacing) alone is not well defined.

For relatively compact transmitter-receiver spacing ($L = 1\text{ m}$ to 10 m), and for the time measurement interval where t is greater than 10^{-6} second , the transient EM voltage response is mostly single valued as a function of formation resistivity between 0.1 ohm-m and 100 ohm-m (and higher). This enables definition of the time-changing apparent conductivity from the voltage response ($V_{zz}(t)$) at each time of measurement as:

$$(3) \quad C \frac{(\mu_o \sigma_{app}(t))^{3/2}}{8 t^{5/2}} e^{-u_{app}(t)^2} = V_{zz}(t)$$

wherein $u_{app}(t)^2 = \frac{\mu_o \sigma_{app}(t) L^2}{4 t}$ and $V_{zz}(t)$ on the right hand side

is the measured voltage response of the coaxial tool. From a

single type of measurement (coaxial, single spacing), the greater the spacing L , the larger the measurement time (t) should be to apply the apparent conductivity concept. The $\sigma_{app}(t)$ should be constant and equal to the formation conductivity in a homogeneous formation: $\sigma_{app}(t) = \sigma$. The deviation from a constant (σ) at time (t) suggests a conductivity anomaly in the region specified by time (t).

Apparent Conductivity For a Pair of Coaxial Tools

When there are two coaxial receivers, the ratio between the pair of voltage measurements is given by,

$$(4) \quad \frac{V_{zZ}(L_1;t)}{V_{zZ}(L_2;t)} = e^{-\frac{\mu_o \sigma}{4t}(L_1^2 - L_2^2)}$$

wherein L_1 and L_2 are transmitter-receiver spacing of two coaxial tools.

Conversely, the time-changing apparent conductivity is defined for a pair of coaxial tools by,

$$(5) \quad \sigma_{app}(t) = \frac{-\ln\left(\frac{V_{zZ}(L_1;t)}{V_{zZ}(L_2;t)}\right) 4t}{(L_1^2 - L_2^2) \mu_o}$$

at each time of measurement. The $\sigma_{app}(t)$ should be constant and equal to the formation conductivity in a homogeneous formation: $\sigma_{app}(t) = \sigma$.

The apparent conductivity is similarly defined for a pair of coplanar tools or for a pair of coaxial and coplanar tools. The $\sigma_{app}(t)$ should be constant and equal to the formation conductivity in a homogeneous formation: $\sigma_{app}(t) = \sigma$. The deviation from a constant (σ) at time (t) suggests a conductivity anomaly in the region specified by time (t).

Look-Ahead Capabilities of EM Transient Method

To illustrate the usefulness of these concepts, the foregoing analysis may be used to detect an anomaly at a distance ahead of the drill bit, as will be elucidated in the remainder of this specification. Thus from here on σ_1 and σ_2 will have different values, one of which representing an anomaly.

Analysis of Coaxial Transient Responses in Two-Layer Models

FIG. 3 shows a coaxial tool with transmitter-receiver spacing L placed in, for example, a vertical well approaching an adjacent bed that is the resistivity anomaly. The tool includes both a transmitter coil T and a receiver coil R , which are wound around a common tool axis and are oriented in the tool axis direction. The symbols σ_1 and σ_2 represent the conductivities of two formation layers.

To show that the transient EM method can be used as a look-ahead resistivity logging method, the transient response of the tool in a two-layer earth model may be examined. The coaxial tool with transmitter to receiver spacing L may be placed in a wellbore, whereby the bed is ahead of the wellbore. There are three parameters that may be determined in the two-layer model using apparent conductivity ($\sigma_{app}(t)$). These are:

- (1) the conductivity (in the present example taken to be $\sigma_1 = 0.1 \text{ S/m}$) or resistivity (the corresponding resistivity of the example would be $R_1 = 10 \text{ ohm-m}$) of the local layer where the tool is placed;
- (2) the conductivity (in the present example taken to be $\sigma_2 = 1 \text{ S/m}$) or resistivity (the corresponding resistivity of the example would be $R_2 = 1 \text{ ohm-m}$) of an adjacent bed; and

(3) the distance d of the tool to the layer boundary. The example will be illustrated using several $d = 1, 5, 10, 25$, and 50 m.

The voltage response of the $L = 1$ m (transmitter-receiver offset) coaxial tool at different distances (d) as a function of t is shown in FIG. 7. Though the difference is observed among responses at different distances, it is not straightforward to identify the resistivity anomaly from these responses.

How information can be derived from these responses using apparent conductivity will be further explained with regard to FIG. 7.

The same voltage data of FIG. 7 is plotted in terms of the apparent conductivity ($\sigma_{app}(t)$) in FIG. 8. From this Table, it is clear that the coaxial response can identify an adjacent bed of higher conductivity at a distance ahead of the tool. Even a $L = 1$ m tool can detect the bed at 10, 25- and 50-m away if low voltage response can be measured for 0.1-1 second long.

The $\sigma_{app}(t)$ plot exhibits at least three parameters very distinctly in the figure: the early time conductivity; the later time conductivity; and the transition time that moves as the distance (d) changes.

As will be further explained below, in a two-layer resistivity profile, the apparent conductivity as t approaches zero can identify the layer conductivity around the tool, while the apparent conductivity as t approaches infinity can be used to determine the conductivity of the adjacent layer at a distance. The distance to a bed boundary from the tool can also be measured from the transition time observed in the apparent conductivity plot. The apparent conductivity plot for both time and tool location may be used as an image presentation of the transient data.

In FIG. 8, it should be noted that, at early time, the tool reads the apparent conductivity of 0.1 S/m corresponding to that of the layer just around the tool. At later time, the tool reads close to 0.55 S/m , an arithmetic average between the conductivities of the two layers. The change of distance (d) is reflected in the transition time.

FIG. 9 illustrates the $\sigma_{app}(t)$ plot of the coaxial transient response in the two-layer model of FIG. 3 for an $L = 1 \text{ m}$ tool at different distances (d), except that the conductivity of the local layer (σ_1) is 1 S/m ($R_1 = 1 \text{ ohm-m}$) and the conductivity of the target layer (σ_2) is 0.1 S/m ($R_2 = 10 \text{ ohm-m}$). Again, the tool reads at early time the apparent conductivity of 1.0 S/m that is of the layer just around the tool. At a later time, the tool reads about 0.55 S/m , the same average conductivity value as in FIG. 8. The change of distance (d) is reflected in the transition time.

Early time conductivity ($\sigma_{app}(t \rightarrow 0)$)

The early time conductivity, corresponding to small values of t , reflects the (apparent) conductivity of the local layer where the tool is located. At such an early time, the signal reaches the receiver directly from the transmitter without interfering with the bed boundary. Hence, it is affected only by the conductivity around the tool. Conversely, the layer conductivity can be measured easily by the apparent conductivity at an earlier time.

Late time conductivity ($\sigma_{app}(t \rightarrow \infty)$)

On the other hand, the late time conductivity, at relatively large values of t , reflects some average of conductivities of both layers. Nearly half of the signals come from the formation below the tool and the other half from above the tool, if the time to travel the distance (d) of the tool to the bed boundary is small.

FIG. 10 compares the $\sigma_{app}(t)$ plot of FIG. 8 and FIG. 9 for $L = 01\text{ m}$ and $d = 01\text{ m}$. The late time conductivity is determined solely by the conductivities of the two layers (σ_1 and σ_2) alone. It is not or at least not much affected by where the tool is located in the two layers in terms of distance d . However, because of the deep depth of investigation, the late time conductivity is not readily reached even at $t = 1\text{ second}$, as shown in FIG. 11 for the same tool. In practice, the late time conductivity may have to be approximated by $\sigma_{app}(t = 1\text{ second})$ which slightly depends on d as illustrated in FIG. 11.

FIG. 12 compares the $\sigma_{app}(t)$ plots for $d = 1\text{ m}$ but with different spacing L . The $\sigma_{app}(t)$ reaches a nearly constant late time conductivity at later times as L increases. The late time conductivity ($\sigma_{app}(t \rightarrow \infty)$) is nearly independent of L . However, the late time conductivity defined at $t = 1\text{ second}$, depends on the distance (d) as shown in FIG. 13.

FIG. 14 compares the $\sigma_{app}(t)$ plots for $d = 5\text{ m}$ and $L = 01\text{ m}$ but for different resistivity ratios. This table shows that the late time apparent conductivity is proportional to σ_1 for the same ratio (σ_1/σ_2). For instance:

$$\begin{aligned} (6) \quad \sigma_{app}(t \rightarrow \infty) (R_1 / R_2 = 10; R_1 = 10\text{ ohm-m}) \\ = \\ 2 * \sigma_{app}(t \rightarrow \infty) (R_1 / R_2 = 10; R_1 = 20\text{ ohm-m}) \end{aligned}$$

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FIG. 15 shows examples of the $\sigma_{app}(t)$ plots for $d = 5\text{ m}$ and $L = 01\text{ m}$ but for different resistivity ratios while the target resistivity is fixed at $R_2 = 1\text{ ohm-m}$. The late time apparent conductivity at $t = 1\text{ second}$ is determined by the local layer conductivity as shown in FIG. 16. Numerically, the late time conductivity may be approximated by the

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arithmetic average of two-layer conductivities as:

$$\sigma_{app}(t \rightarrow \infty; \sigma_1, \sigma_2) = \frac{\sigma_1 + \sigma_2}{2}. \text{ This is reasonable considering that,}$$

with the coaxial tool, the axial transmitter induces the eddy current parallel to the bed boundary. At later time, the axial receiver receives horizontal current nearly equally from both layers. As a result, the late time conductivity must see conductivity of both formations with nearly equal weight.

To summarize, the late time conductivity ($\sigma_{app}(t \rightarrow \infty)$) at $t = 1 \text{ second}$ can be used to estimate the conductivity of the adjacent layer (σ_2) when the local conductivity near the tool (σ_1) is known, for instance, from the early time conductivity ($\sigma_{app}(t \rightarrow 0) = \sigma_1$). This is illustrated in FIG. 17.

Estimation of the distance (d) to the adjacent bed

The transition time (t_c) at which the apparent conductivity starts deviating from the local conductivity (σ_1) toward the late time conductivity clearly depends on d , the distance of the tool to the bed boundary, as shown in FIG. 8 for a $L = 0.1 \text{ m}$ tool.

For convenience, the transition time (t_c) is defined by the time at which the $\sigma_{app}(t_c)$ takes the cutoff conductivity (σ_c), that is, in this example, the arithmetic average between the early time and the late time conductivities: $\sigma_c = \{\sigma_{app}(t \rightarrow 0) + \sigma_{app}(t \rightarrow \infty)\} / 2$. The transition time (t_c) is dictated by the ray-path (d) minus $L/2$ that is, half the distance for the EM signal to travel from the transmitter to the bed boundary to the receiver, independently on the resistivity of the two layers. Conversely, the distance (d) can be estimated from the transition time (t_c), as shown in FIG. 18 when $L = 0.1 \text{ m}$.

Image Presentation with the Apparent Conductivity

A plot of the apparent conductivity ($\sigma_{app}(z; t)$) in both z - and t -coordinates may serve as an image presentation of the transient data, which represents apparent conductivity plots for the same tool at different depths, as shown in FIG. 19. The z -coordinate represents the tool depth along the borehole. The $\sigma_{app}(z; t)$ plot clearly helps to visualize the approaching bed boundary as the tool moves along the borehole. A deviation from a constant conductivity value at time (t) suggests the presence of a conductivity anomaly in the region specified by time (t).

Coplanar Tools

While the coaxial transient data were examined above, coplanar transient data from a coplanar tool are equally useful as a look-ahead resistivity logging method. FIG. 20 shows such a coplanar tool with transmitter-receiver spacing L placed in a well approaching an adjacent bed that is the resistivity anomaly. On the coplanar tool, both a transmitter T and a receiver R are oriented perpendicularly to the tool axis and parallel to each other. The symbols σ_1 and σ_2 represent the conductivities of two formation layers, the boundary between which is located ahead on the tool axis.

Apparent Conductivity for a Coplanar Tool

The induced voltage of the coplanar tool with transmitter-receiver spacing L in the homogeneous formation of conductivity (σ) is given by,

$$(7) \quad V_{xx}(t) = C \frac{(\mu_0 \sigma)^{3/2}}{8t^{5/2}} (1 - u^2) e^{-u^2}$$

wherein $u^2 = \frac{\mu_0 \sigma}{4t} L^2$ and C is a constant. At small values of t ,

the coplanar voltage changes polarity depending on the spacing L and the formation conductivity.

FIG. 20 illustrates a coplanar tool in which the transmitter (T) and the receiver (R) are parallel to each other and oriented perpendicularly to the tool axis. The symbols σ_1 and σ_2 represent the conductivities of two formation layers. This tool is used to illustrate the voltage response for different values of t and L in FIGS. 21-22 below, where $\sigma_1 = \sigma_2$.

FIG. 21 shows the voltage response of a coplanar tool with a length $L = 1$ m as a function of formation resistivity at different times (t). For a resistivity range from 0.1 ohm-m to 100 ohm-m, the voltage response is single valued as a function of formation resistivity for values of t larger than 10^{-6} second. At smaller values of t , for instance at $t = 10^{-7}$ second, the voltage changes polarity and is no longer single valued.

FIG. 22 shows the voltage response as a function of formation resistivity at different times (t) for a longer coplanar tool with a length $L = 5$ m. The time interval when the voltage response is single valued is shifted towards larger values of t .

Similarly to the coaxial tool response, the time-changing apparent conductivity is defined from the coplanar tool response $V_{xx}(t)$ at each time of measurement as,

$$(8) \quad C \frac{(\mu_o \sigma_{app}(t))^{3/2}}{8t^{5/2}} (1 - u_{app}(t)^2) e^{-u_{app}(t)^2} = V_{xx}(t)$$

wherein $u_{app}(t)^2 = \frac{\mu_o \sigma_{app}(t) L^2}{4t}$ and $V_{xx}(t)$ on the right hand side is the measured voltage response of the coplanar tool. The longer the spacing, the larger the value t should be to apply the apparent conductivity concept from a single type of measurement (coplanar, single spacing). The $\sigma_{app}(t)$ should be

constant and equal to the formation conductivity in a homogeneous formation: $\sigma_{app}(t) = \sigma$.

Analysis of Coplanar Transient Responses in Two-Layer Models

Similar to FIG. 8 for coaxial tool responses where $L = 0.1$ m, the apparent conductivity ($\sigma_{app}(t)$) determined from voltage responses of a coplanar tool as shown in FIG. 20 is plotted in FIG. 23 for different tool distances from the bed boundary. It is clear that the coplanar response can also identify an adjacent bed of higher conductivity at a distance. Even a $L = 1$ m tool can detect the bed at 10-, 25- and 50-m away if low voltage responses can be measured for 0.1-1 second long. The $\sigma_{app}(t)$ plot for the coplanar responses exhibits three parameters equally as well as for the coaxial responses.

15 Early time conductivity ($\sigma_{app}(t \rightarrow 0)$)

It is also true for the coplanar responses that the early time conductivity ($\sigma_{app}(t \rightarrow 0)$) is the conductivity of the local layer (σ_1) where the tool is located. Conversely, the layer conductivity can be measured easily by the apparent conductivity at earlier times.

Late time conductivity ($\sigma_{app}(t \rightarrow \infty)$)

The late time conductivity ($\sigma_{app}(t \rightarrow \infty)$) is some average of conductivities of both layers. The conclusions derived for the coaxial responses apply equally well to the coplanar responses. However, the value of the late time conductivity for the coplanar responses is not the same as for the coaxial responses. For coaxial responses, the late time conductivity is close to the arithmetic average of two-layer conductivities in two-layer models. FIG. 24 shows the late time conductivity ($\sigma_{app}(t \rightarrow \infty)$) for coplanar responses where $d = 0.5$ m and $L = 0.1$ m but for different conductivities of the local layer while the target conductivity is fixed at 1 S/m. Late time conductivity is determined by the local layer

conductivity, and is numerically close to the square root average as, $\sqrt{\sigma_{app}(t \rightarrow \infty; \sigma_1, \sigma_2)} = \frac{\sqrt{\sigma_1} + \sqrt{\sigma_2}}{2}$.

To summarize, the late time conductivity ($\sigma_{app}(t \rightarrow \infty)$) can be used to estimate the conductivity of the adjacent layer (σ_2) when the local conductivity near the tool (σ_1) is known, for instance, from the early time conductivity ($\sigma_{app}(t \rightarrow 0) = \sigma_1$). This is illustrated in FIG. 25.

Estimation of the Distance (d) to the Adjacent Bed

The transition time at which the apparent conductivity starts deviating from the local conductivity (σ_1) toward the late time conductivity clearly depends on the distance (d) of the tool to the bed boundary, as shown in FIG. 20.

The transition time (t_c) may be defined by the time at which the $\sigma_{app}(t_c)$ takes the cutoff conductivity (σ_c) that is, in this example, the arithmetic average between the early time and the late time conductivities: $\sigma_c = \{\sigma_{app}(t \rightarrow 0) + \sigma_{app}(t \rightarrow \infty)\} / 2$. The transition time (t_c) is dictated by the ray-path (d) minus $L/2$ that is, half the distance for the EM signal to travel from the transmitter to the bed boundary to the receiver, independently of the resistivity of the two layers. Conversely, the distance (d) can be estimated from the transition time (t_c), as shown in FIG. 26 where $L = 1$ m.

The present invention has been described in relation to particular embodiments, which are intended in all respects to be illustrative rather than restrictive. Alternative embodiments will become apparent to those skilled in the art to which the present invention pertains without departing from its scope.

From the foregoing, it will be seen that this invention is one well adapted to attain all the ends and objects set forth above, together with other advantages, which are

obvious and inherent to the system and method. It will be understood that certain features and sub-combinations are of utility and may be employed without reference to other features and sub-combinations. This is contemplated and
5 within the scope of the claims.

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C L A I M S

1. A method for determining a distance to an anomaly in a formation ahead of a device comprising a transmitter for transmitting electromagnetic signals through the formation and a receiver for detecting responses, the method comprising:

bringing the device inside a wellbore;

transmitting an electromagnetic signal using the transmitter;

calculating one of apparent conductivity and apparent resistivity based on a receiver-detected response;

monitoring the one of apparent conductivity and apparent resistivity over time; and

determining the distance to the anomaly based on an observed change of the one of apparent conductivity and apparent resistivity.

2. The method of claim 1, wherein transmitting the electromagnetic signal includes inducing a transient change in the transmitted electromagnetic signal and wherein monitoring the one of apparent conductivity and apparent resistivity over time comprises monitoring the apparent conductivity during a time range following the transient change.

3. The method of claim 2, wherein the transient change comprises terminating the transmission of the electromagnetic signal, and wherein the receiver-detected response comprises a time-resolved decay of a signal during the time range following the transient change.

4. The method of claim 2 or 3, wherein the time range is selected based on a separation distance between the transmitter and the receiver.

5. The method of claim 2, 3, or 4, wherein the time range runs from at least 10^{-8} seconds to at least 0.1 seconds, preferably to at least 1 seconds.
6. The method of any one of claims 2 to 5, wherein the time range is selected sufficiently long to have the one of apparent conductivity and apparent resistivity reach an asymptotic value, whereby the distance to the anomaly is determined when the one of apparent conductivity and apparent resistivity reaches an asymptotic value.
7. The method of any one of the preceding claims, wherein the receiver-detected response comprises a voltage response.
8. The method of any one of the preceding claims, wherein calculating the one of apparent conductivity and apparent resistivity includes converting an induced voltage signal to an average conductivity of the formation.
9. The method of any one of the preceding claims, wherein calculating the one of apparent conductivity and apparent resistivity comprises evaluating one of a corresponding apparent conductivity and apparent resistivity of the formation in which the device is located.
10. The method of any one of the preceding claims, wherein calculating the one of apparent conductivity and apparent resistivity comprises evaluating the corresponding one of apparent conductivity and apparent resistivity of the formation ahead of the device.
11. The method of any one of the preceding claims, wherein determining the distance to the anomaly comprises determining a time in which the one of apparent conductivity and apparent resistivity begins to deviate from the corresponding one of apparent conductivity and apparent resistivity of the formation in which the device is located.

12. The method of any one of the preceding claims, wherein the electromagnetic signal is transmitted in the direction of the anomaly.

13. The method of any one of the preceding claims, wherein the device comprises a logging tool.

14. The method of any one of the preceding claims, wherein the device is provided in a measurement-while-drilling or logging-while-drilling section of a drill string located uphole relative to a drill bit.

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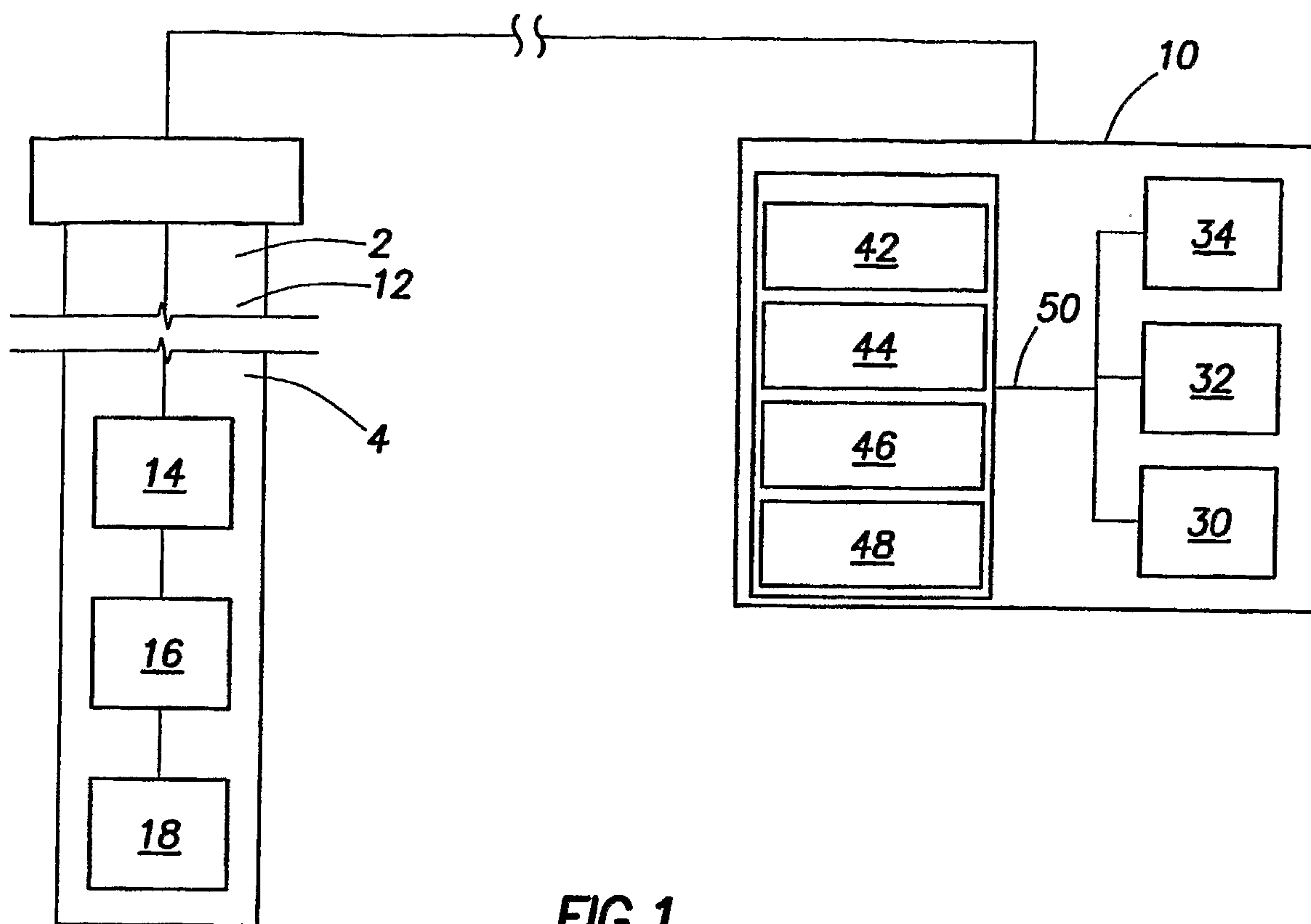


FIG. 1

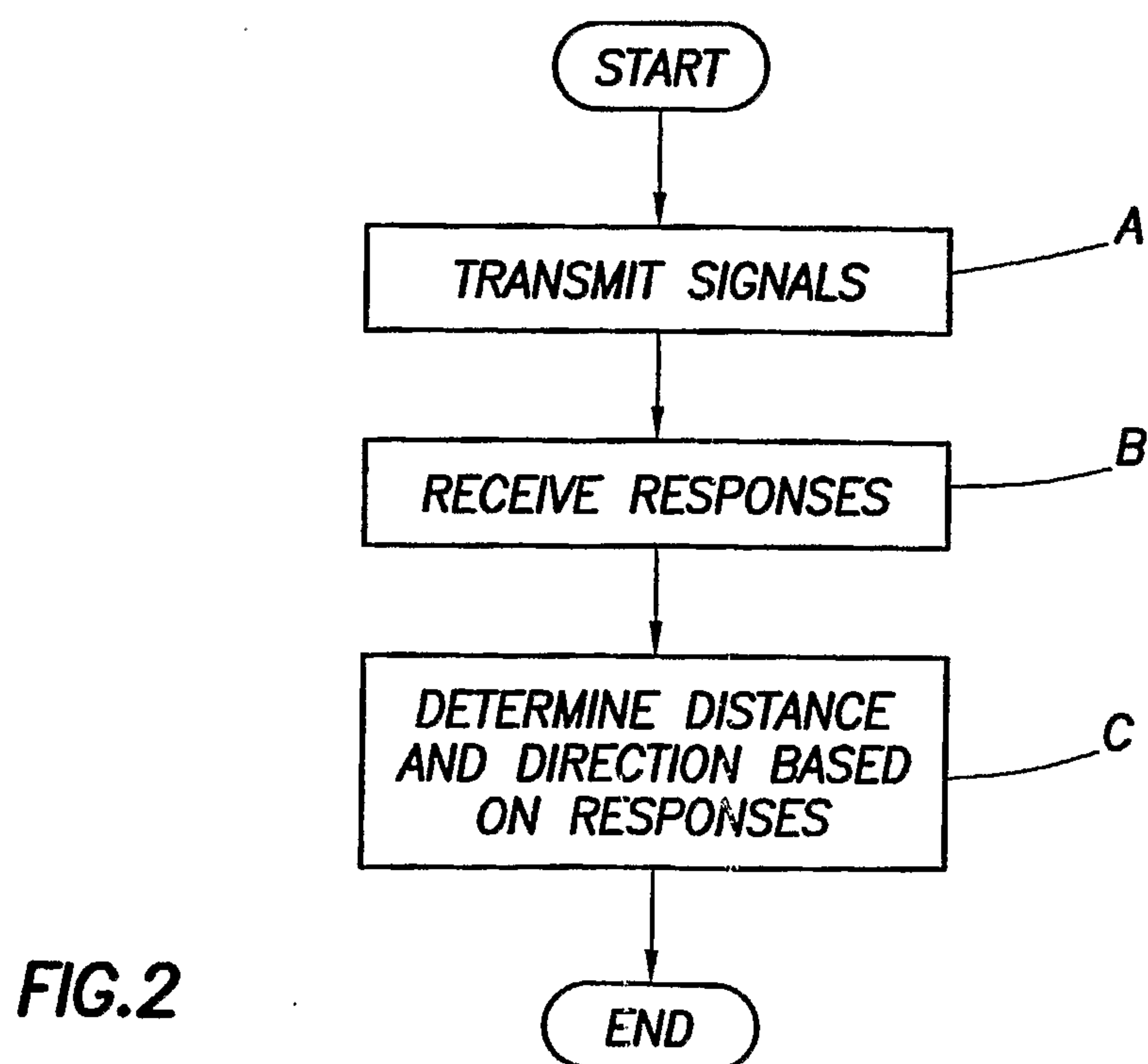


FIG. 2

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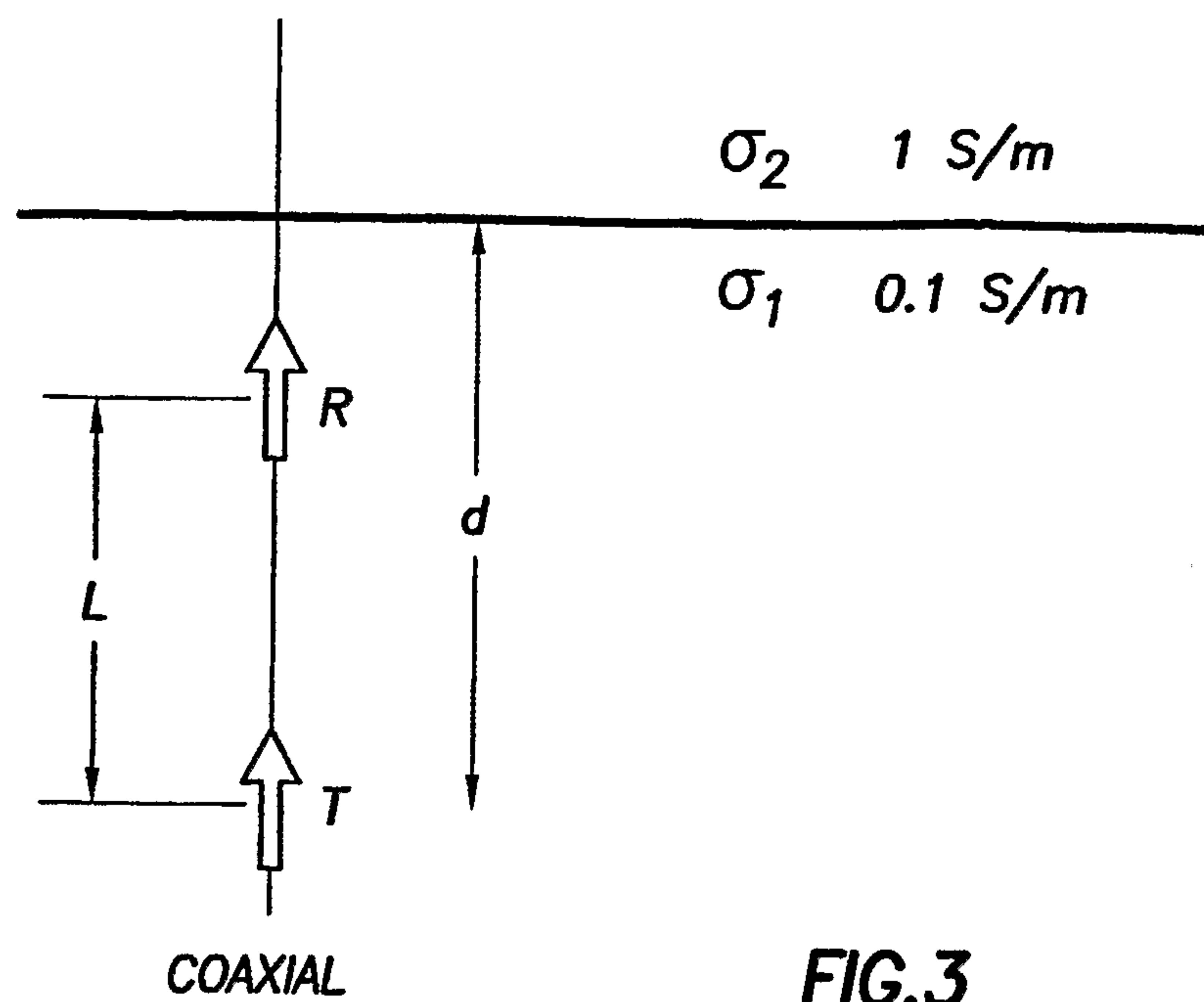


FIG.3

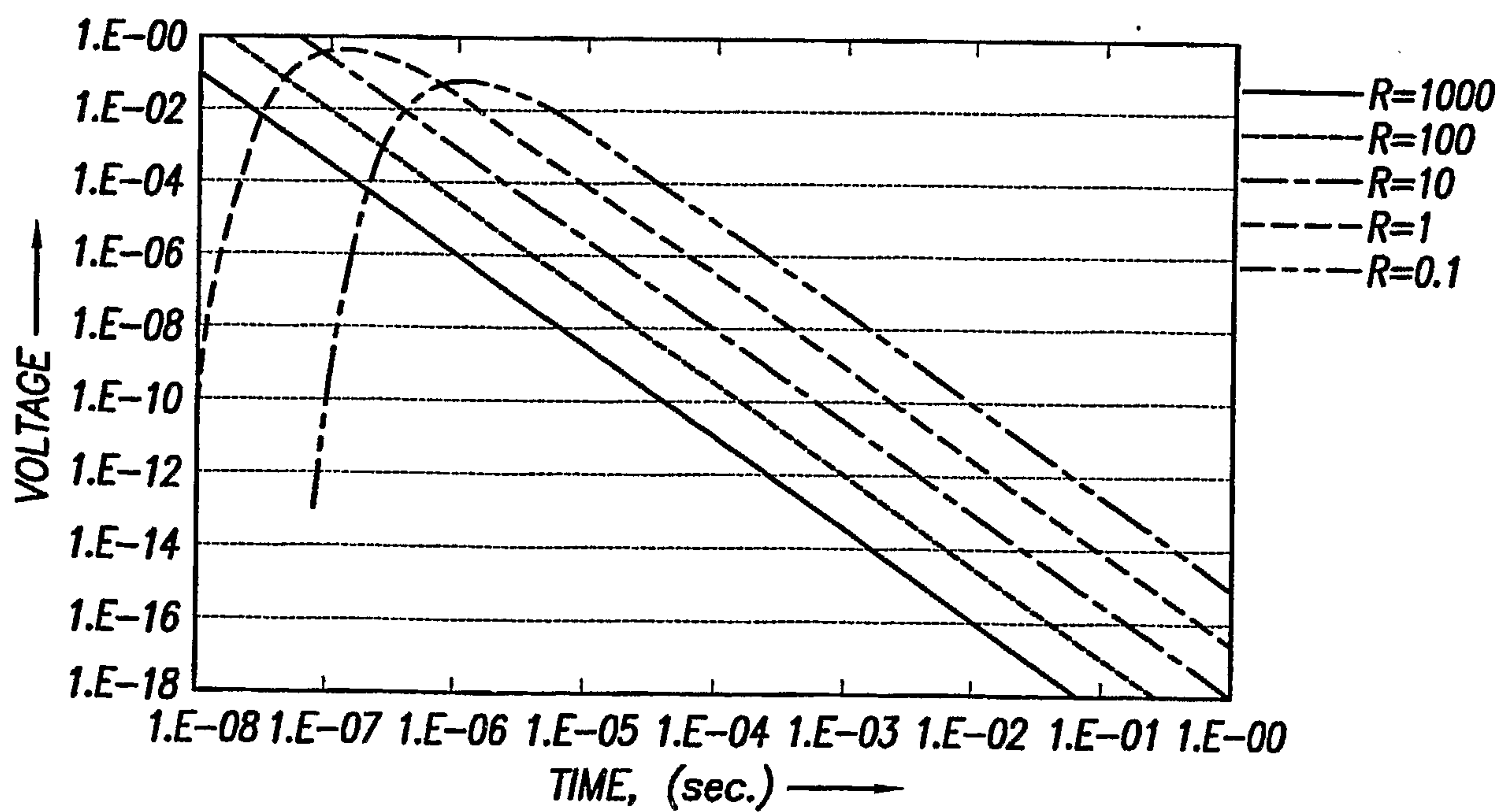


FIG.4

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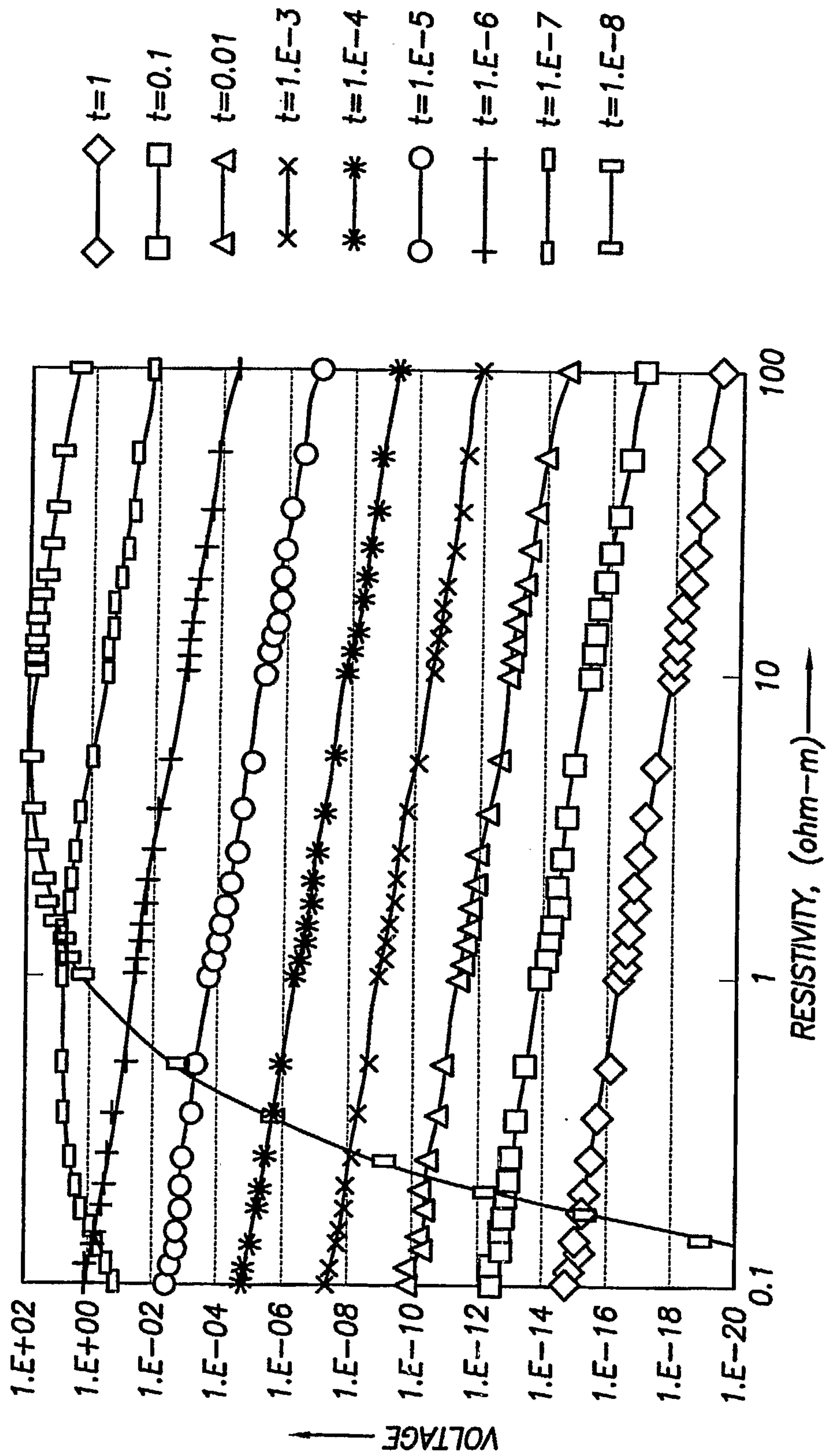


FIG.5

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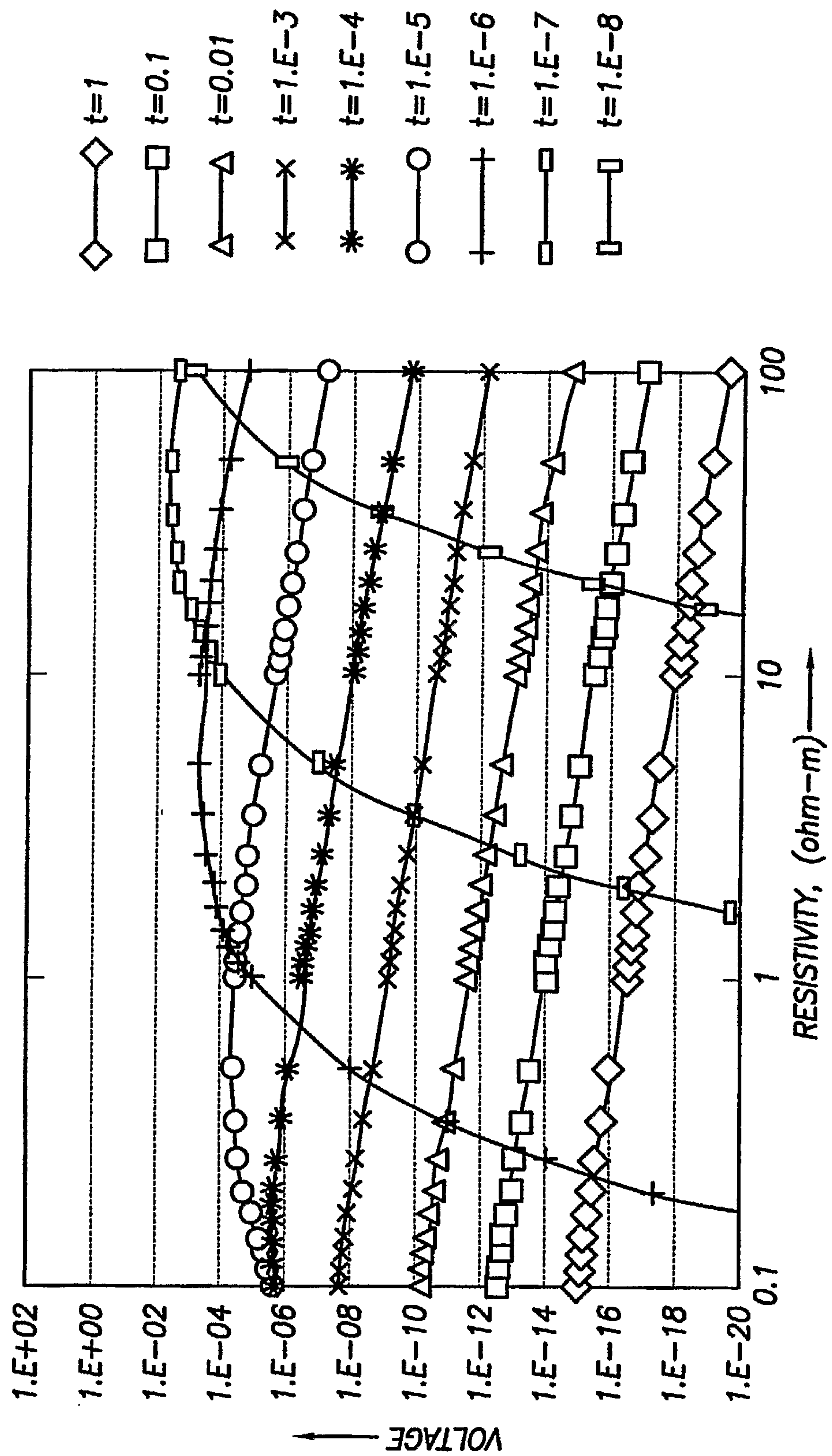


FIG.6

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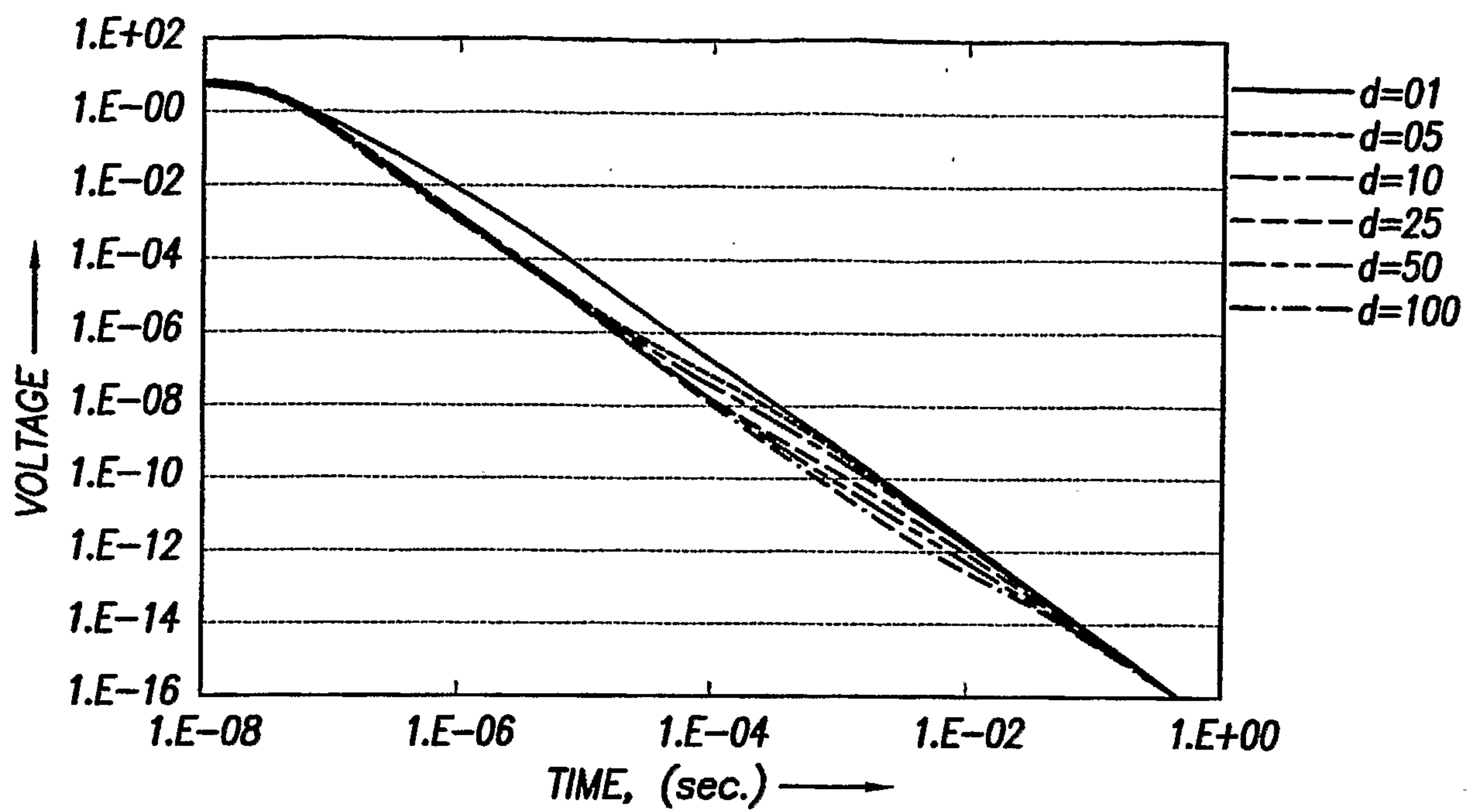


FIG.7

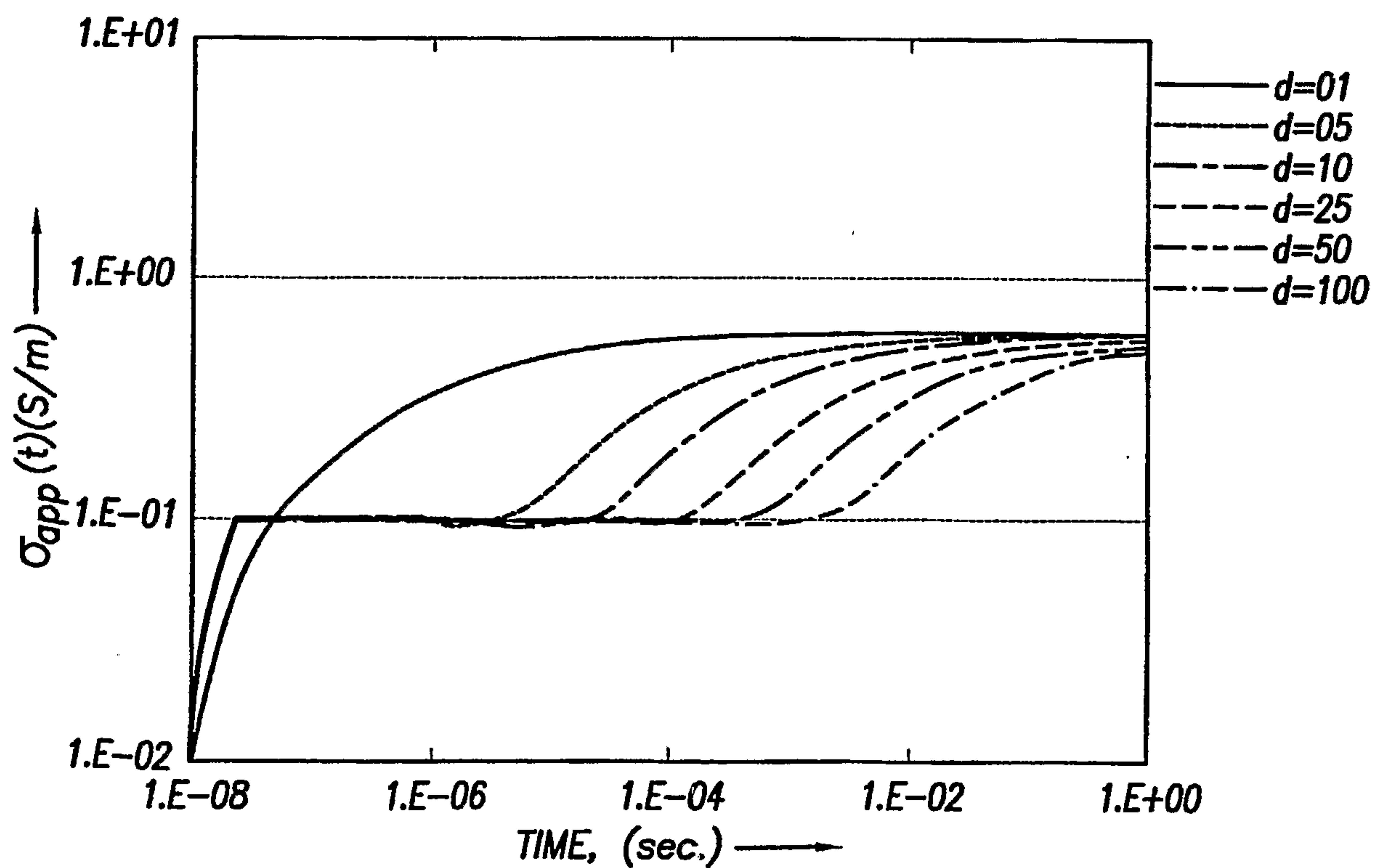
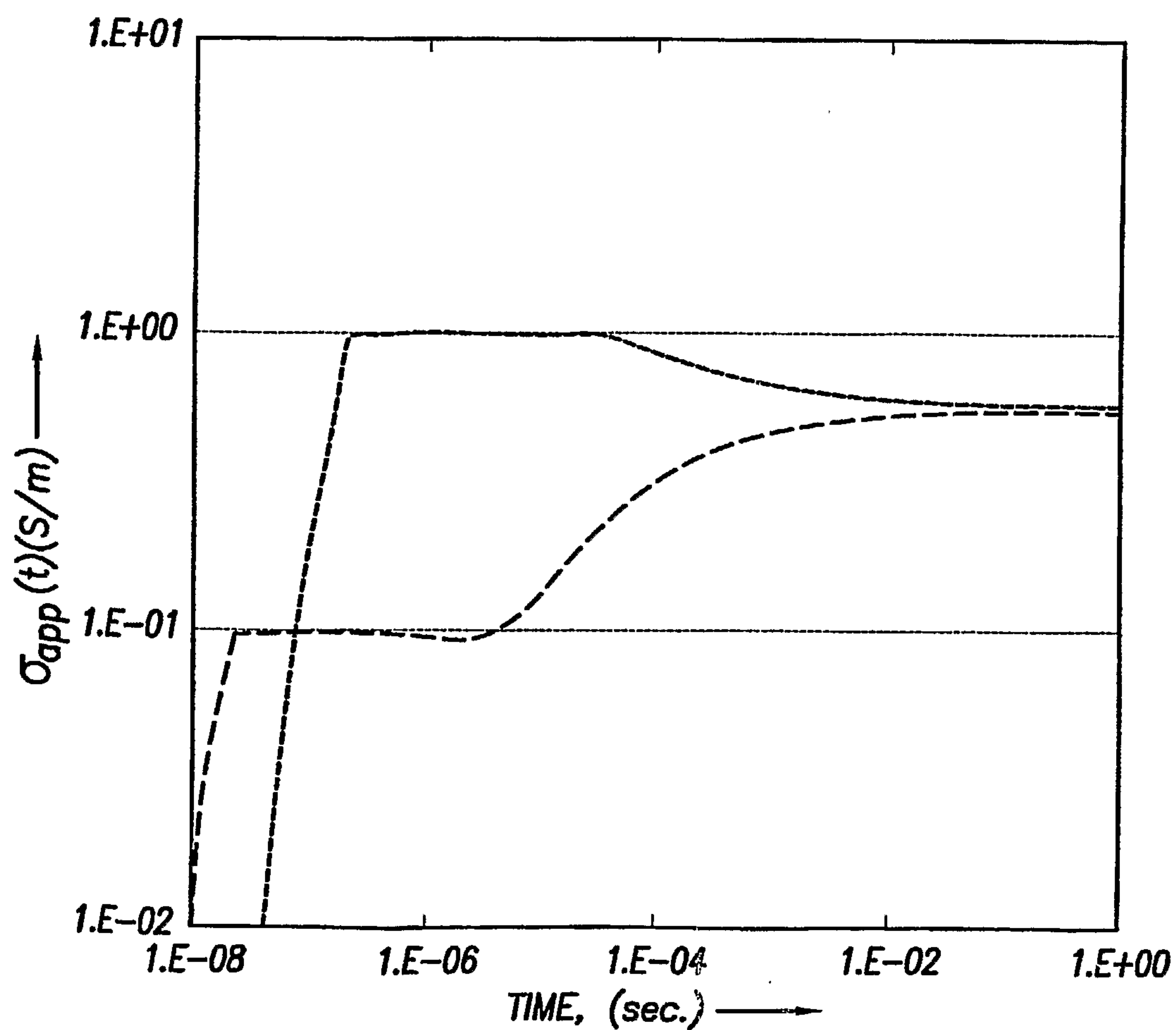
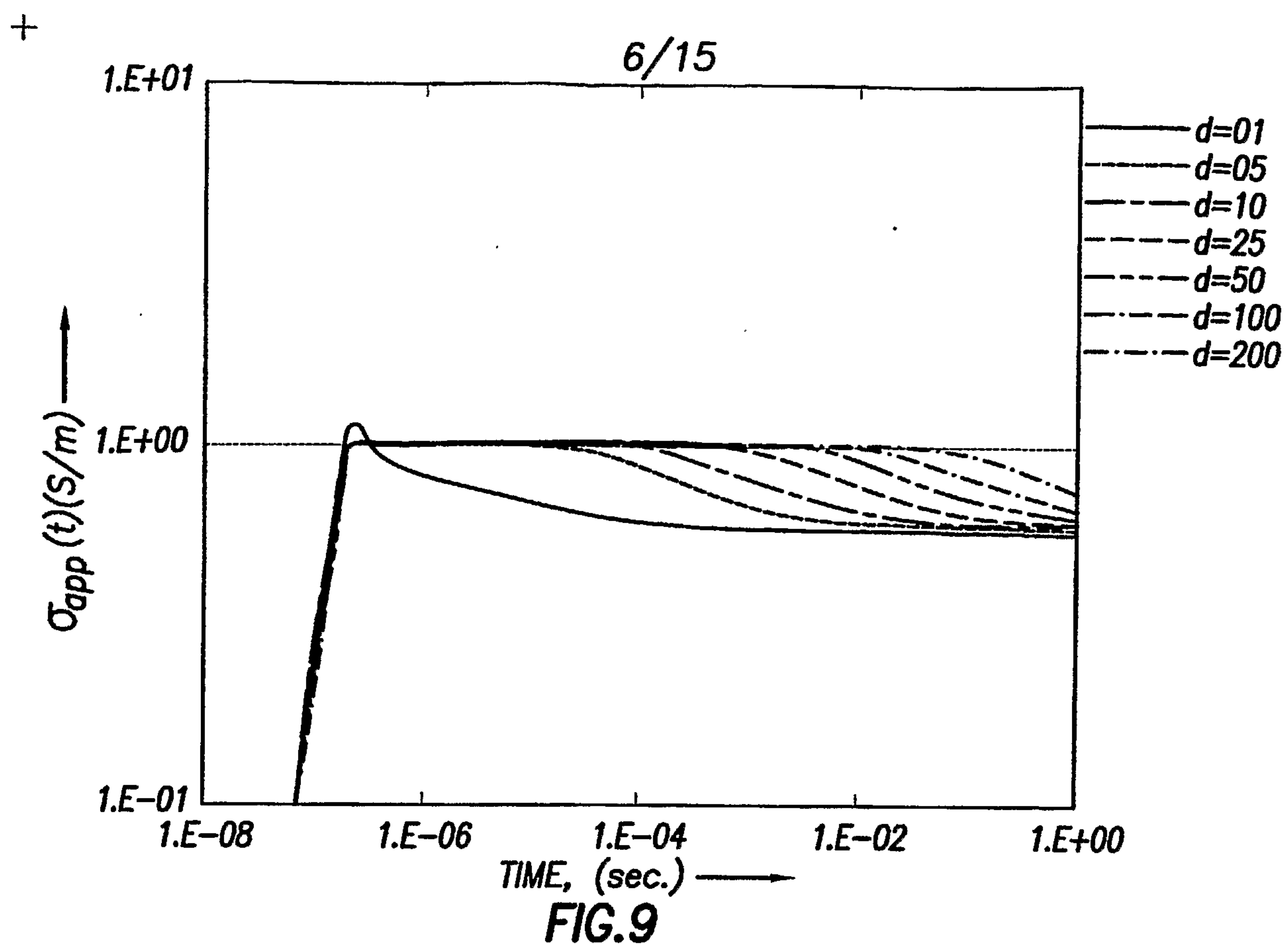


FIG.8



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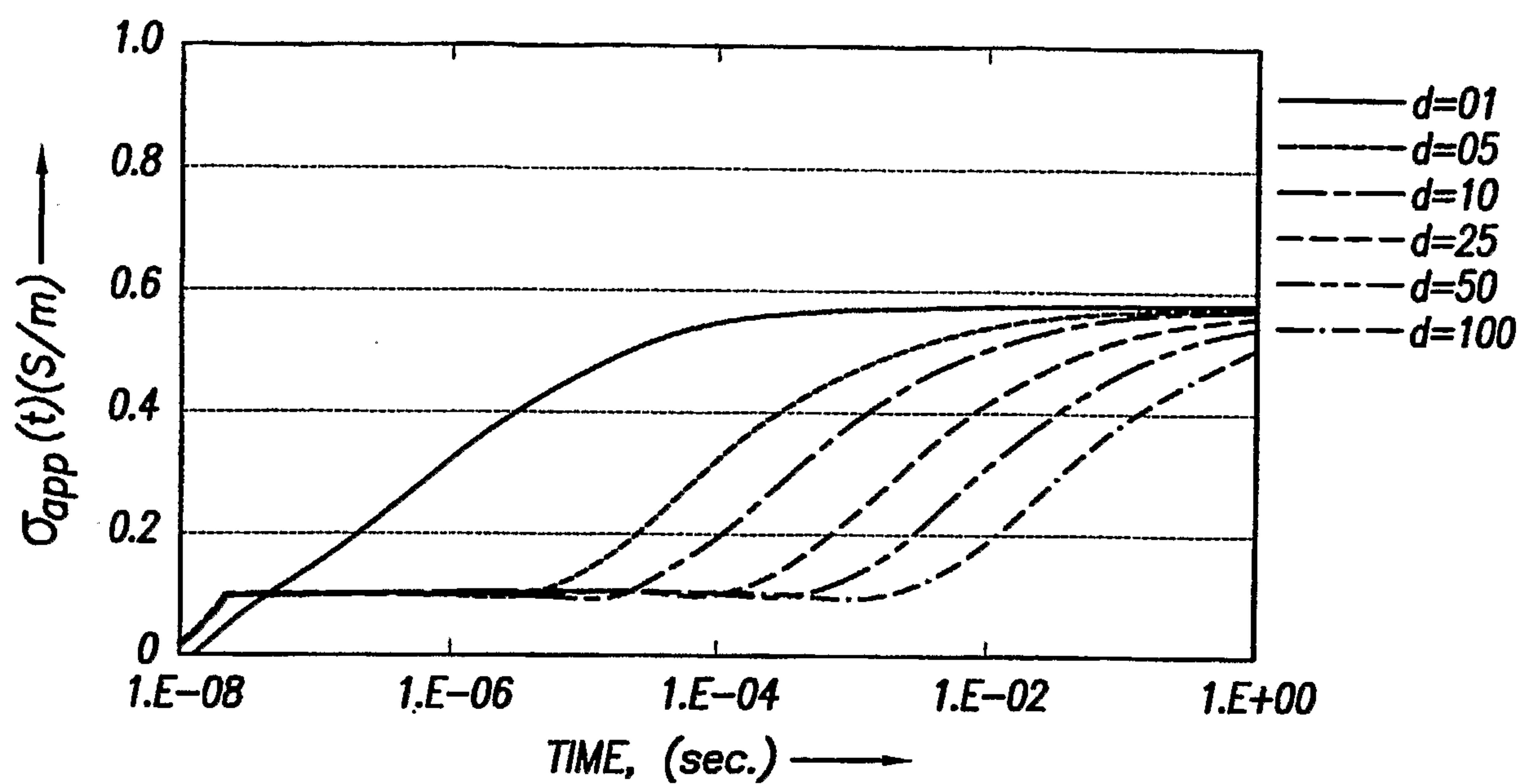


FIG. 11

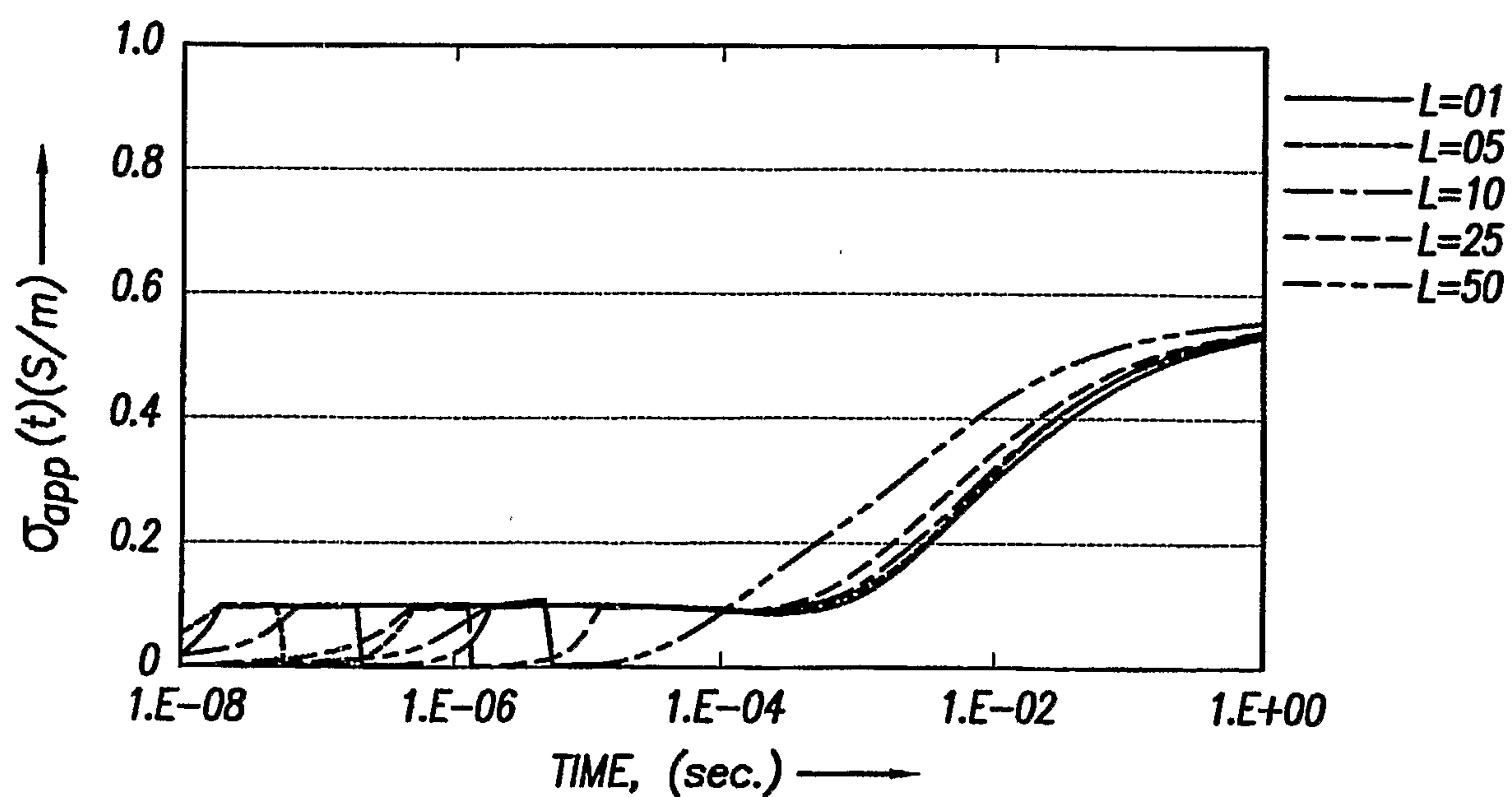


FIG. 12

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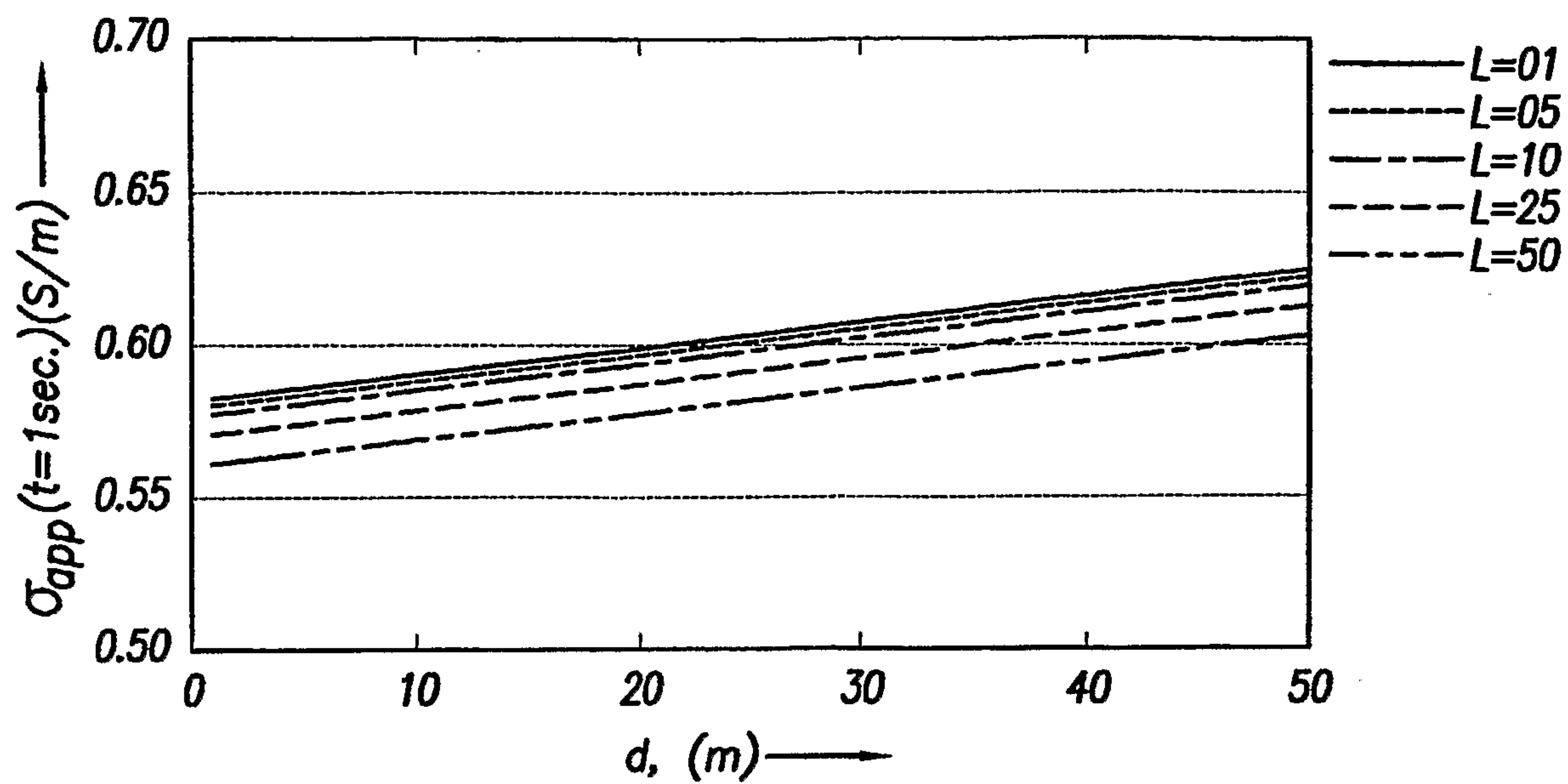


FIG. 13

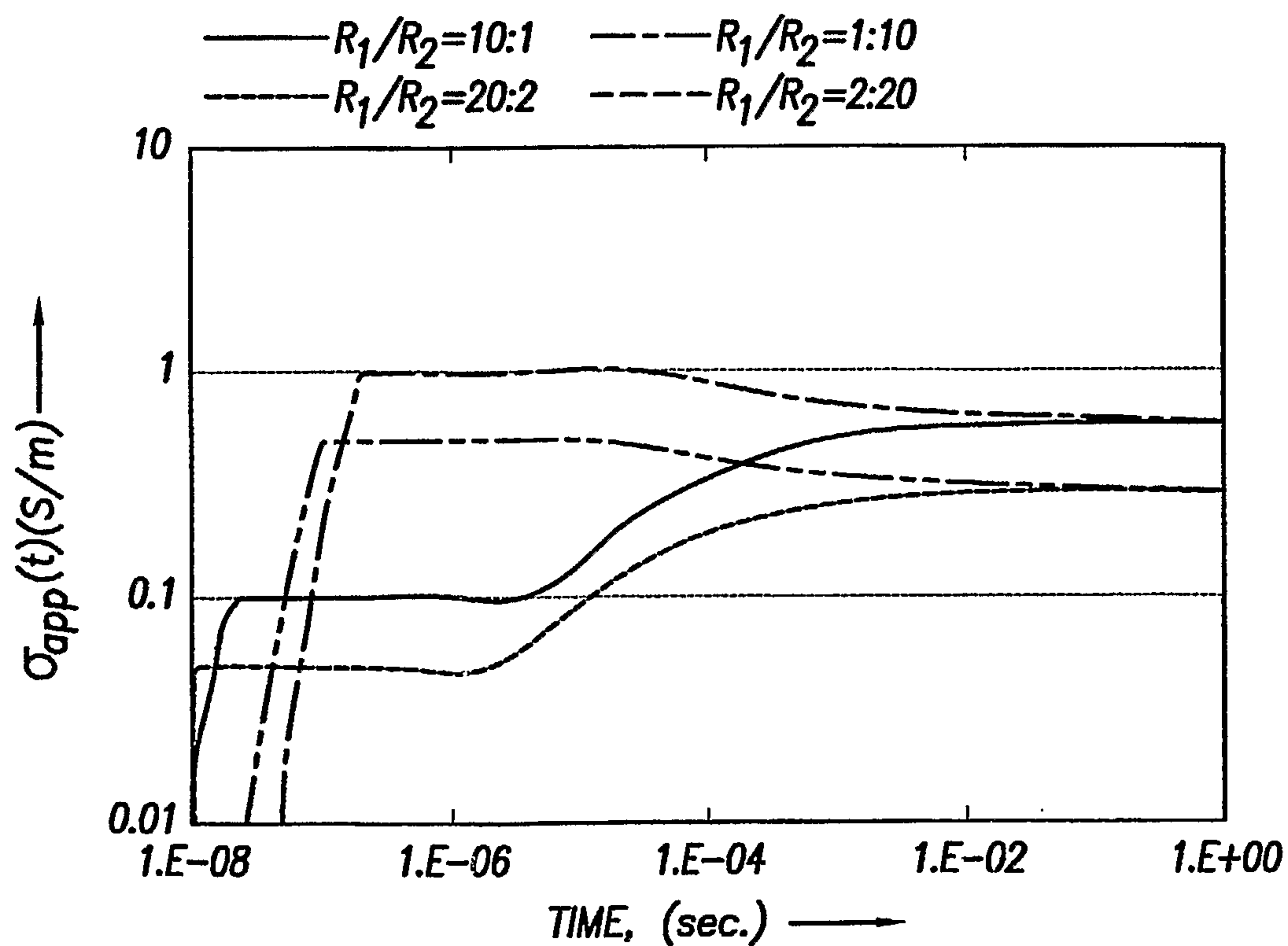


FIG. 14

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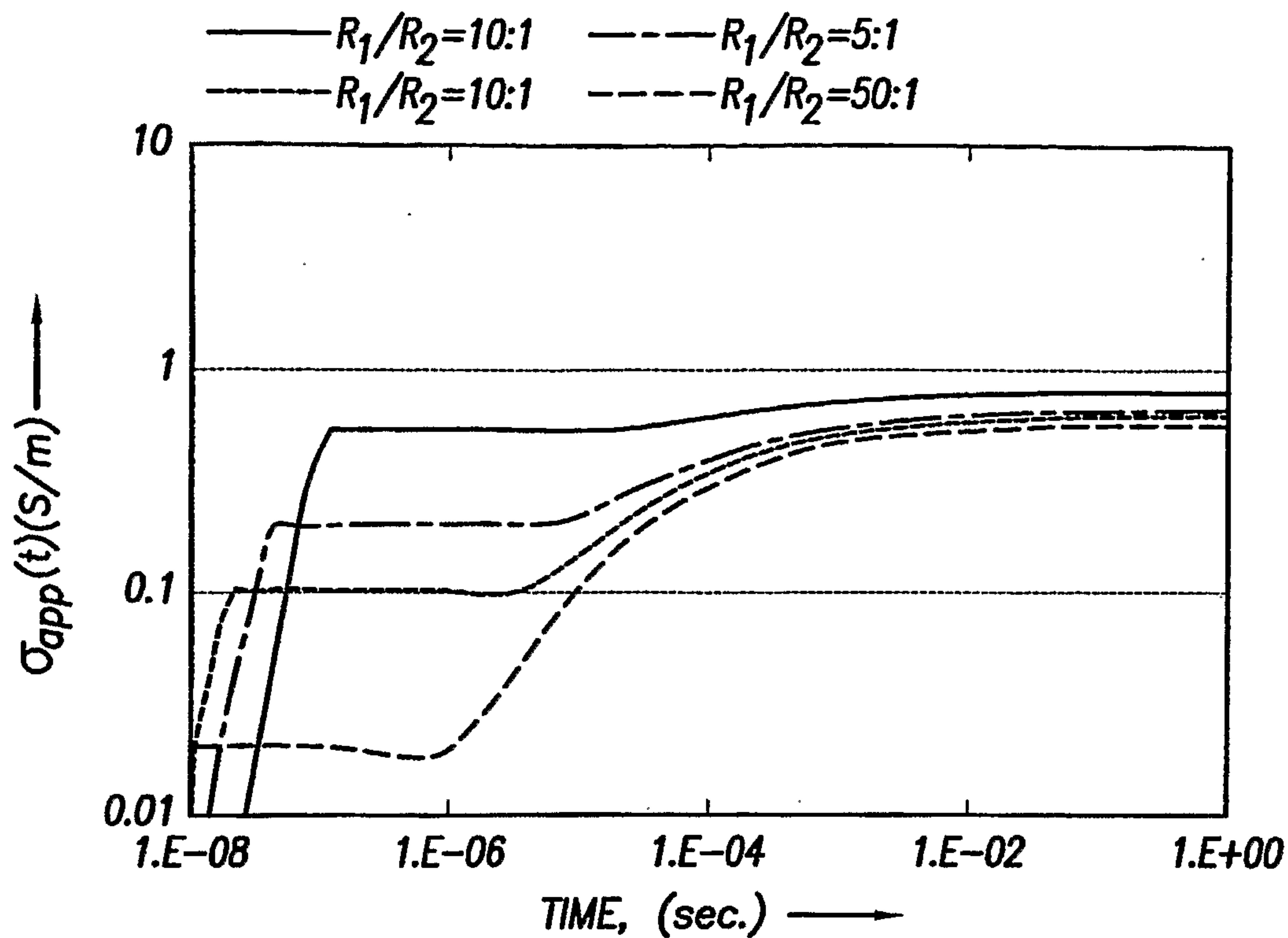


FIG. 15

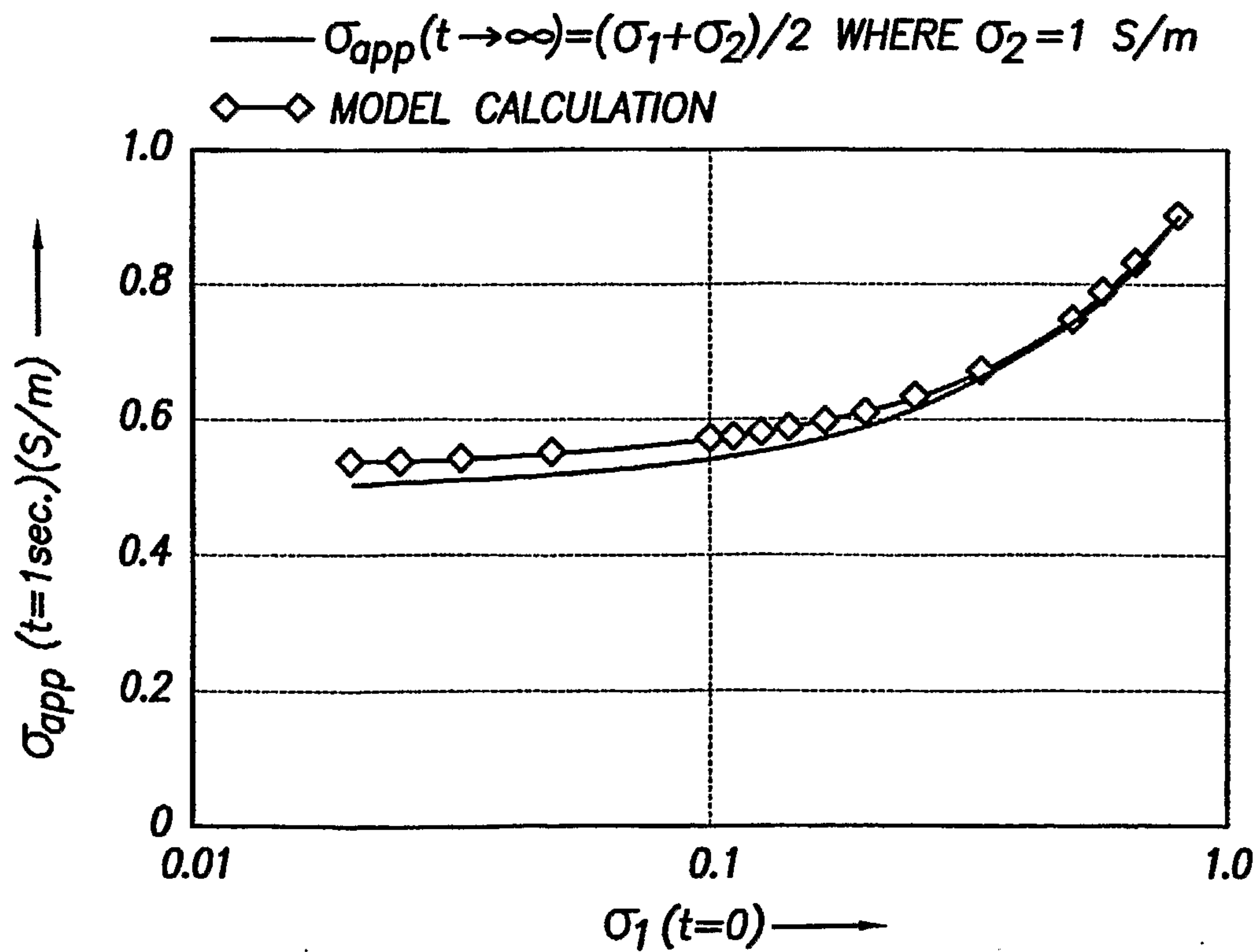


FIG. 16

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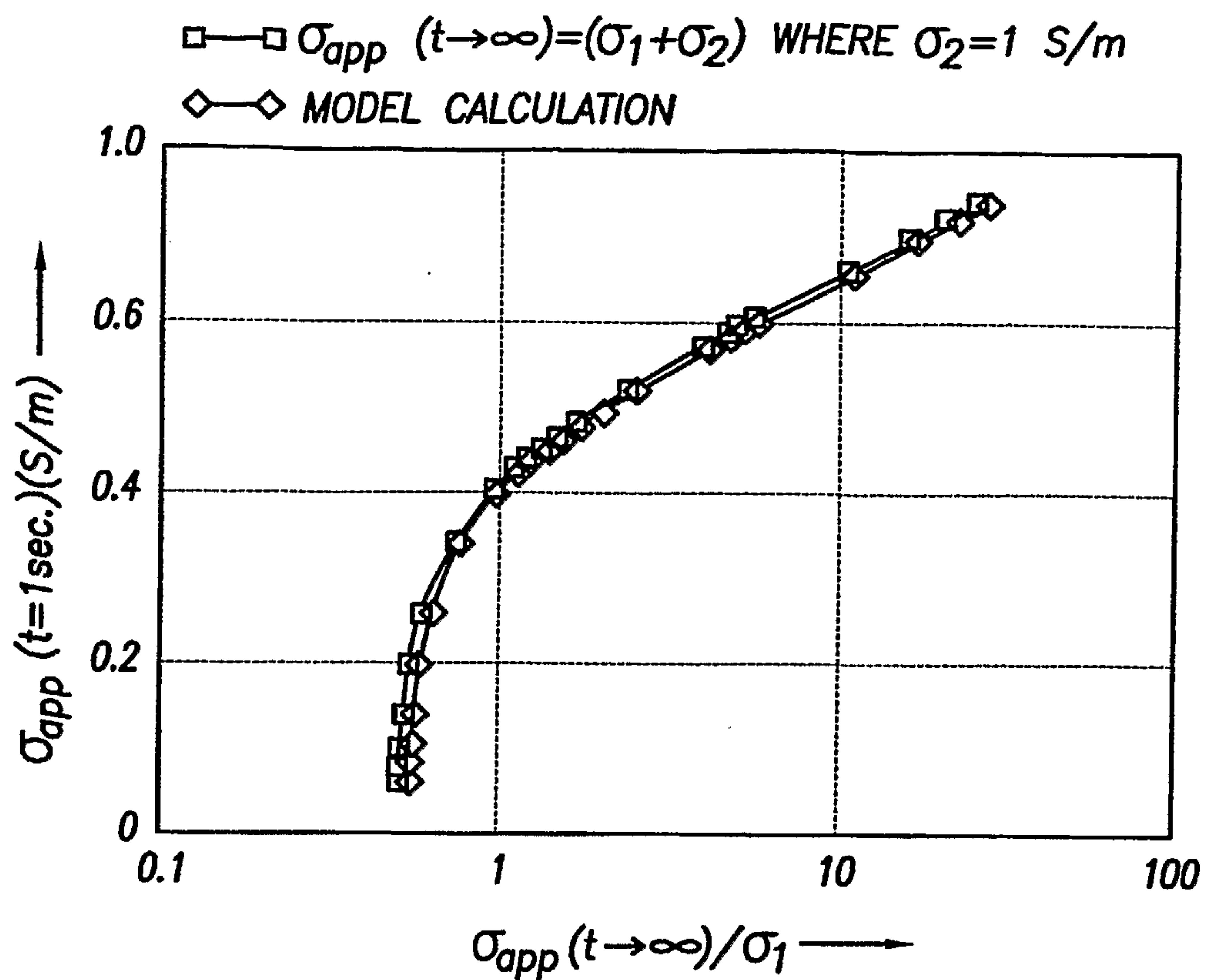


FIG. 17

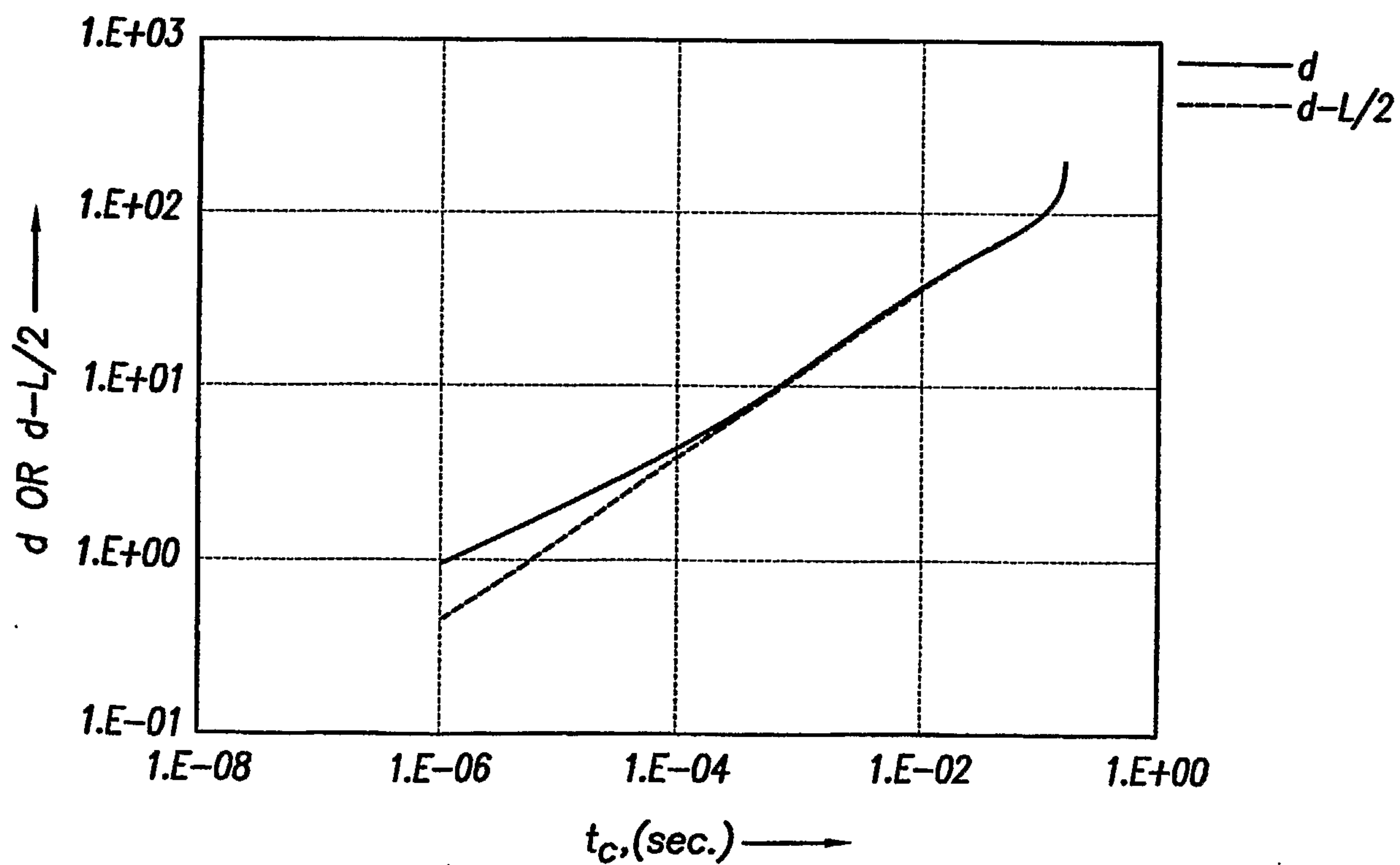


FIG. 18

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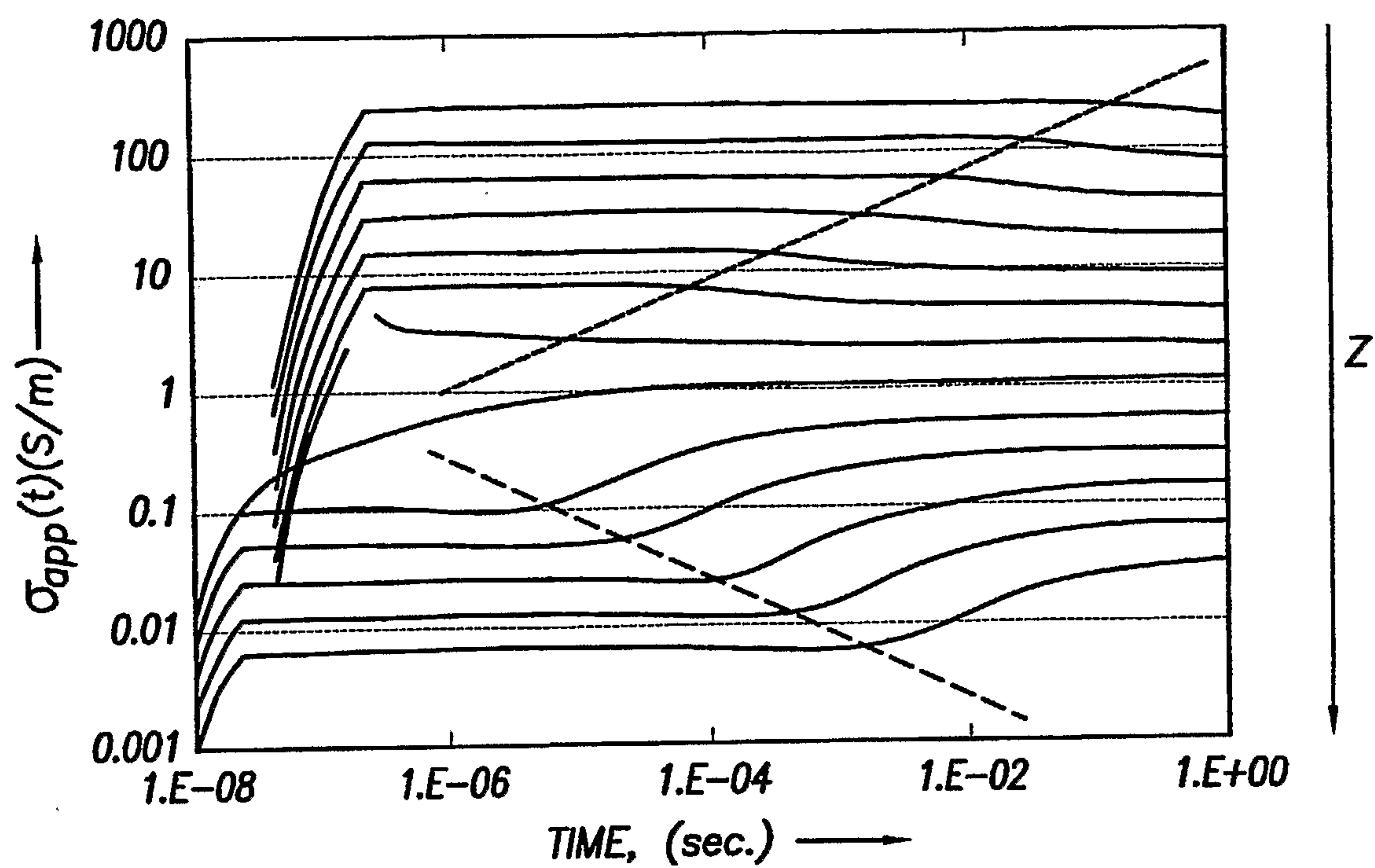


FIG. 19

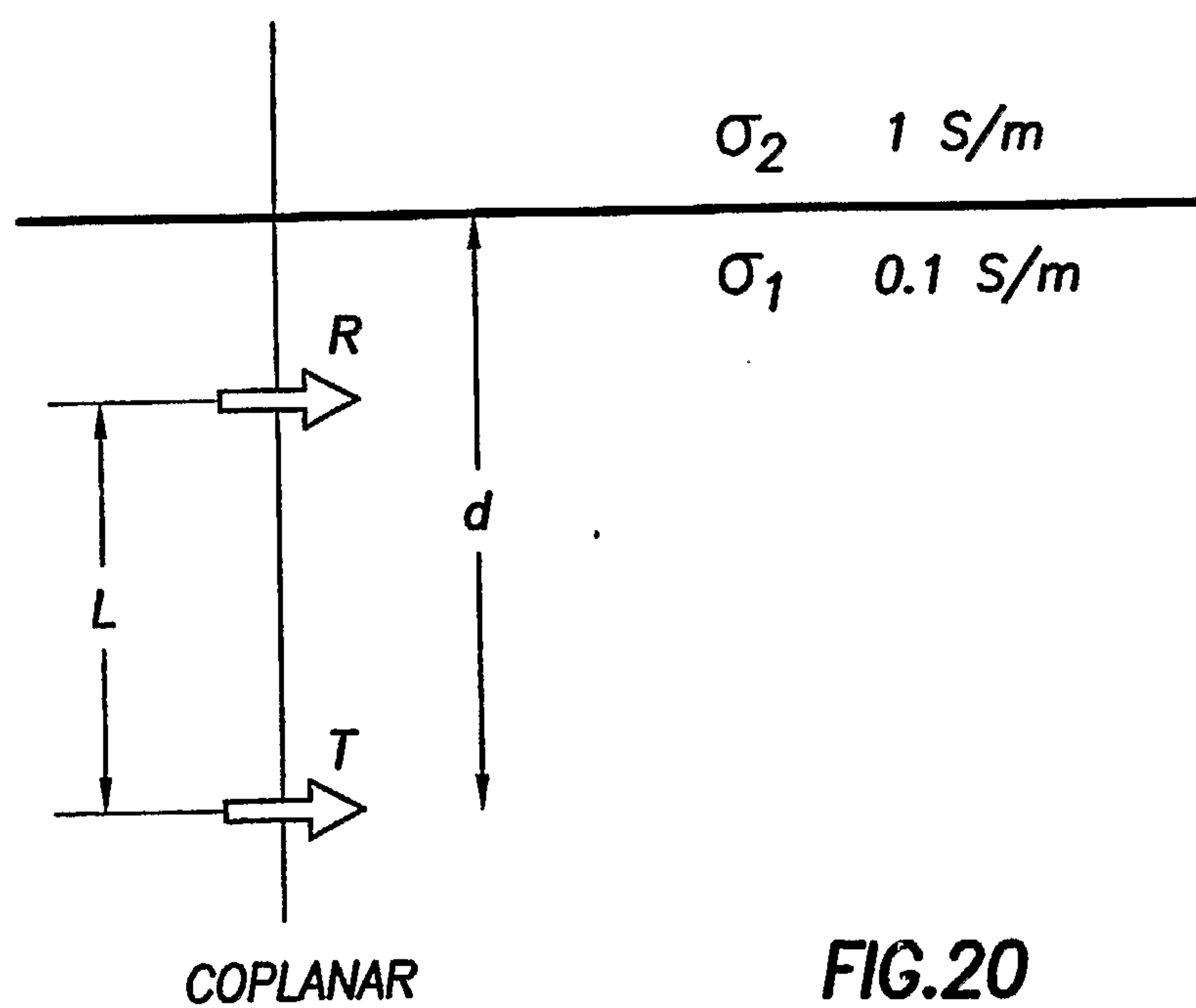


FIG. 20

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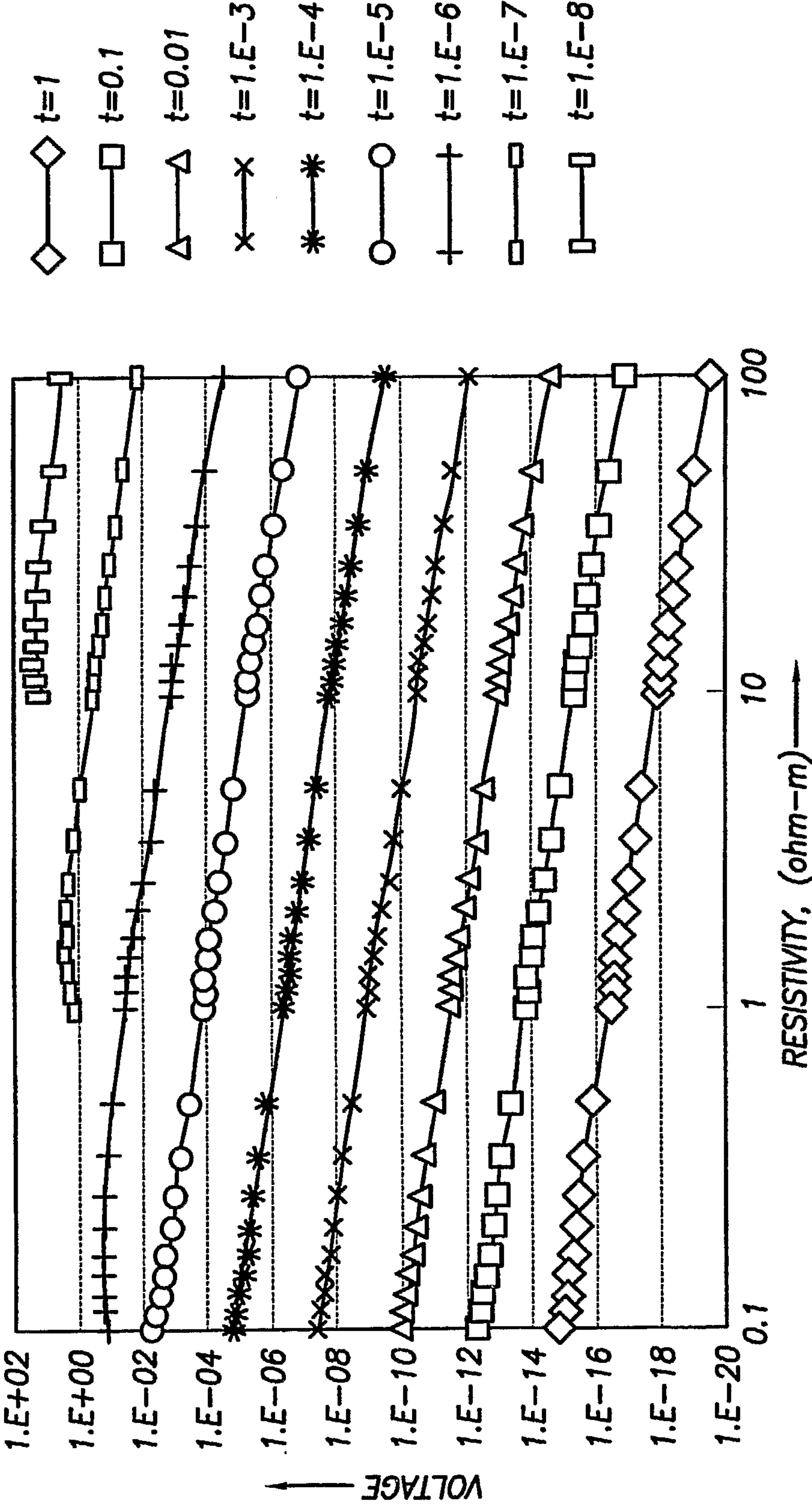


FIG.21

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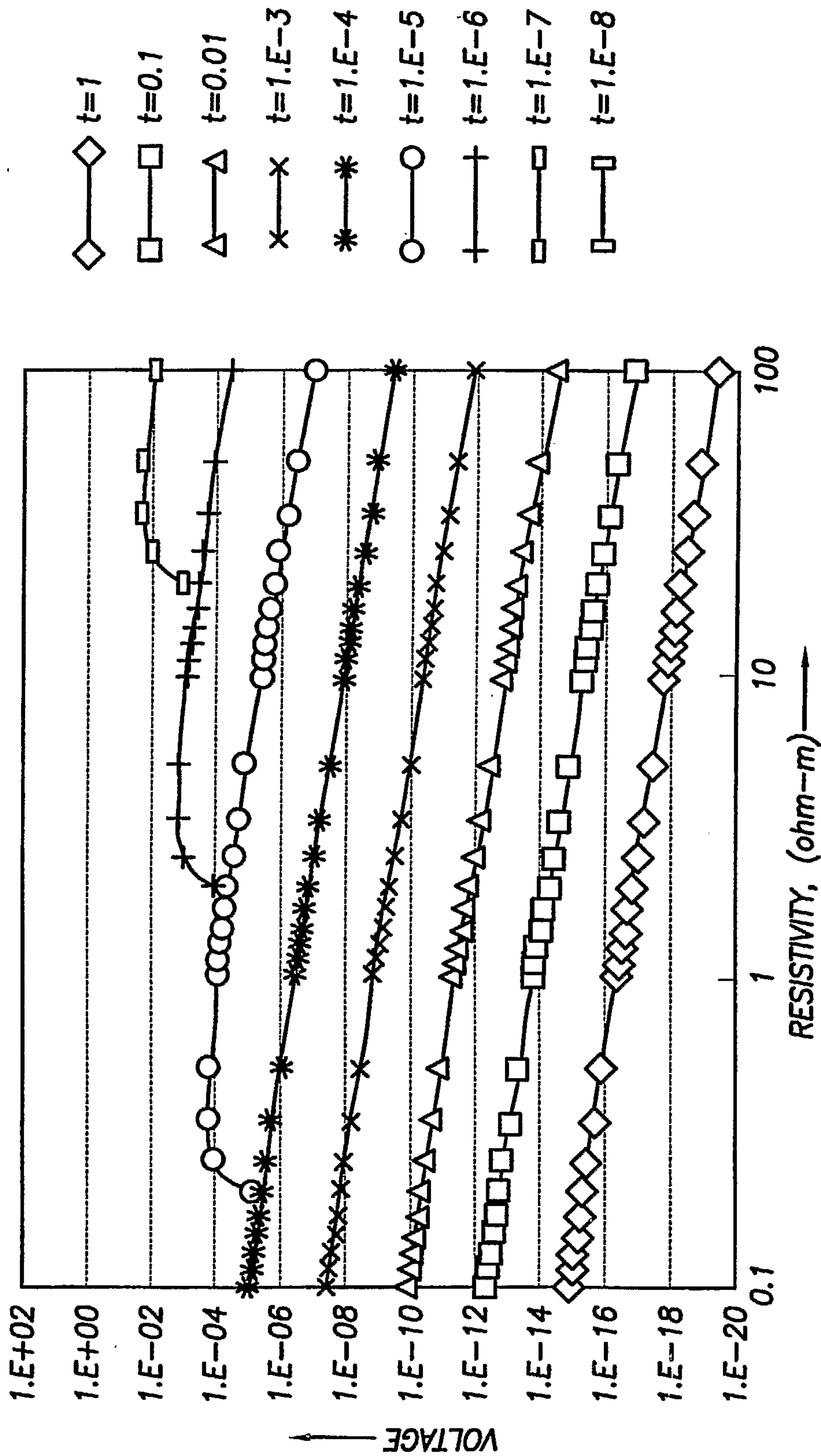
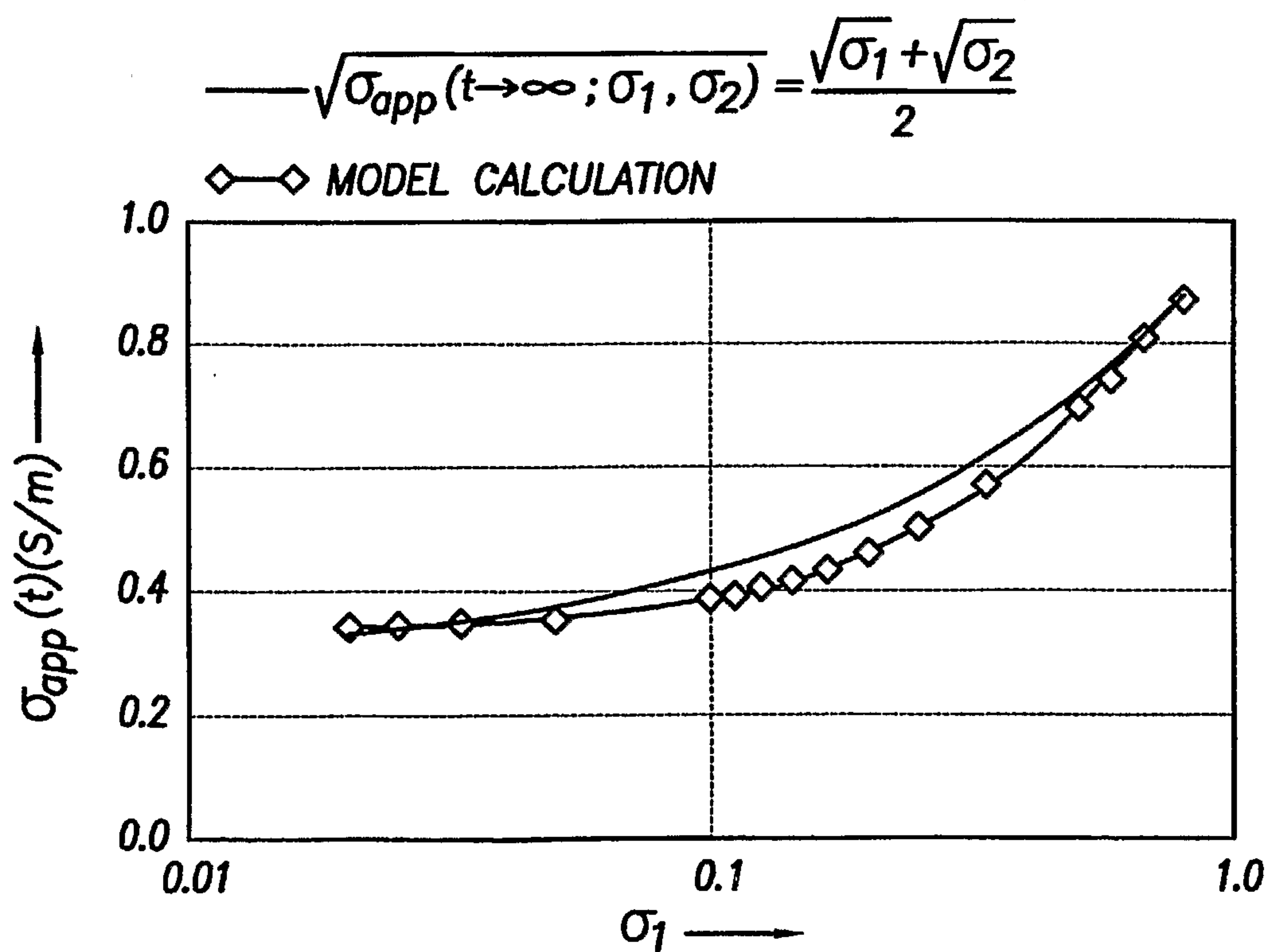
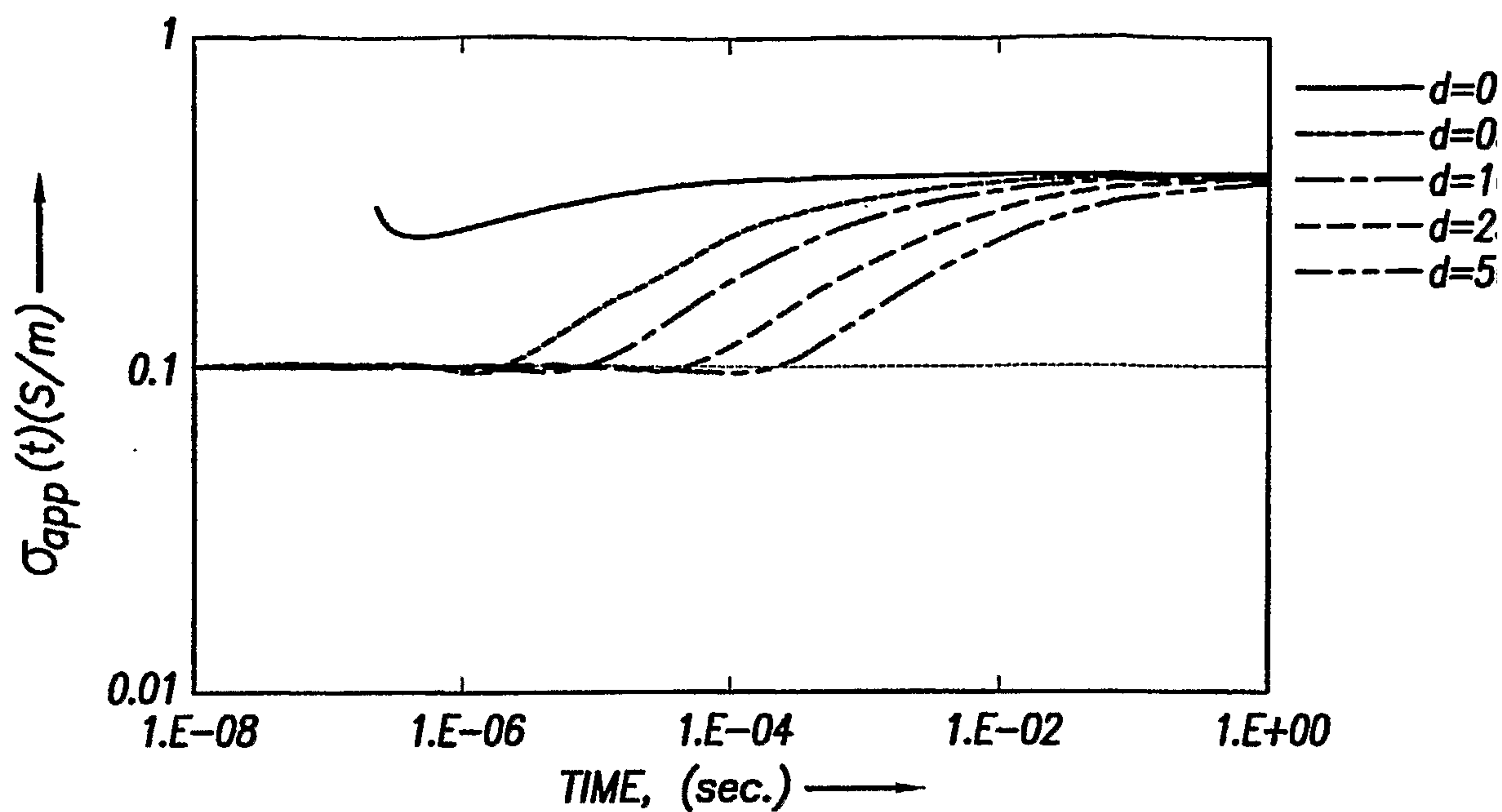


FIG.22

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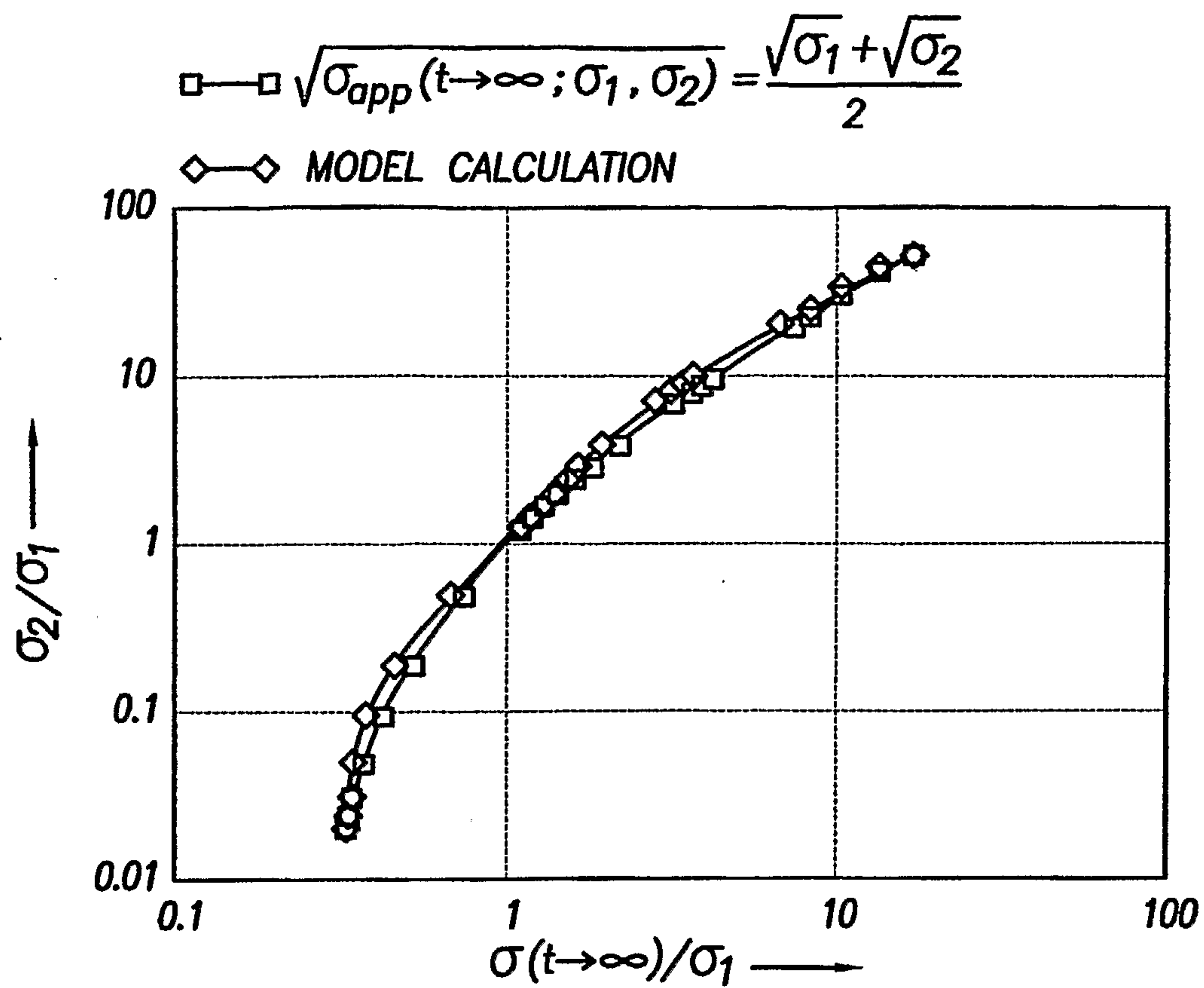


FIG.25

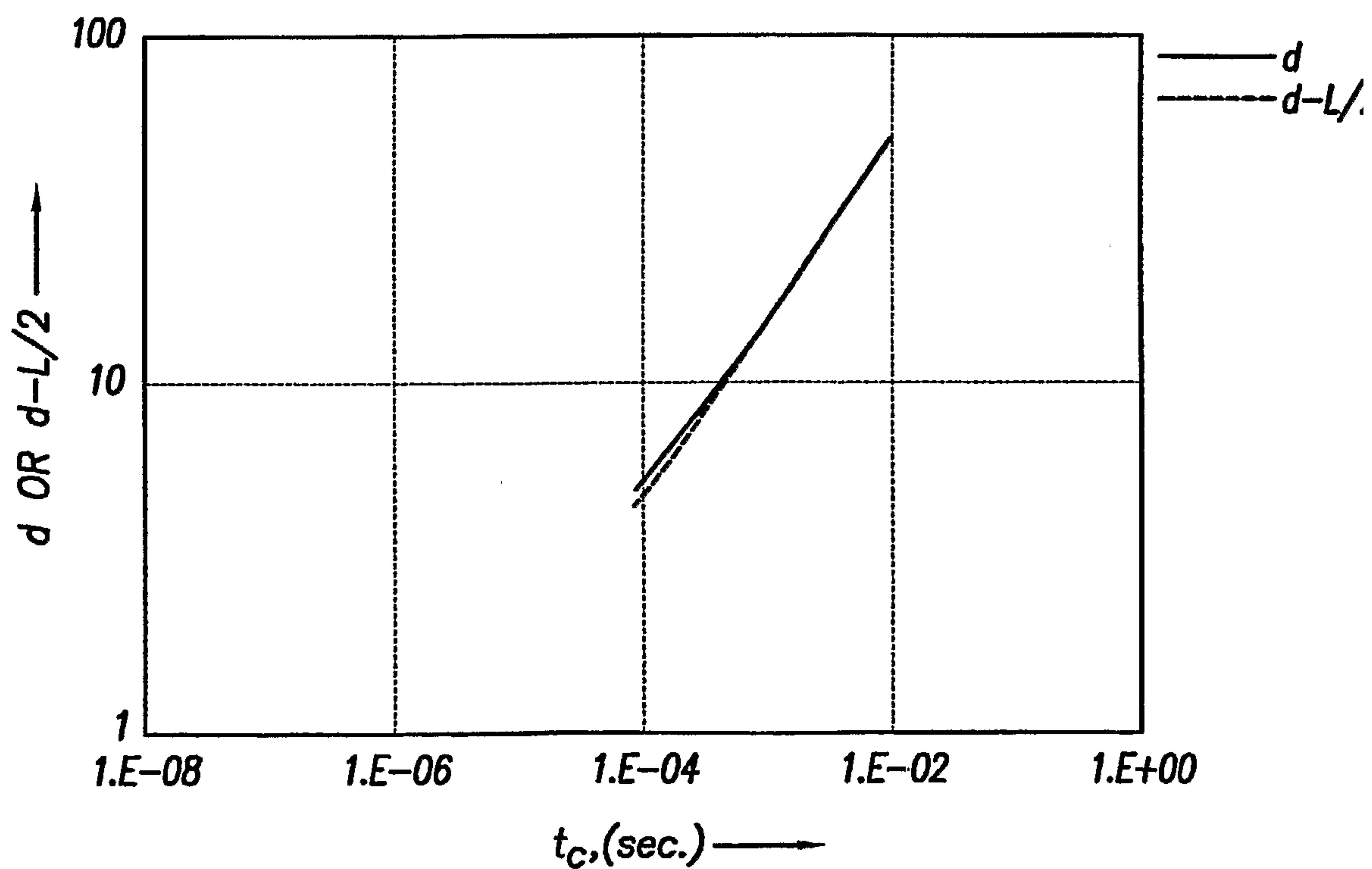


FIG.26

