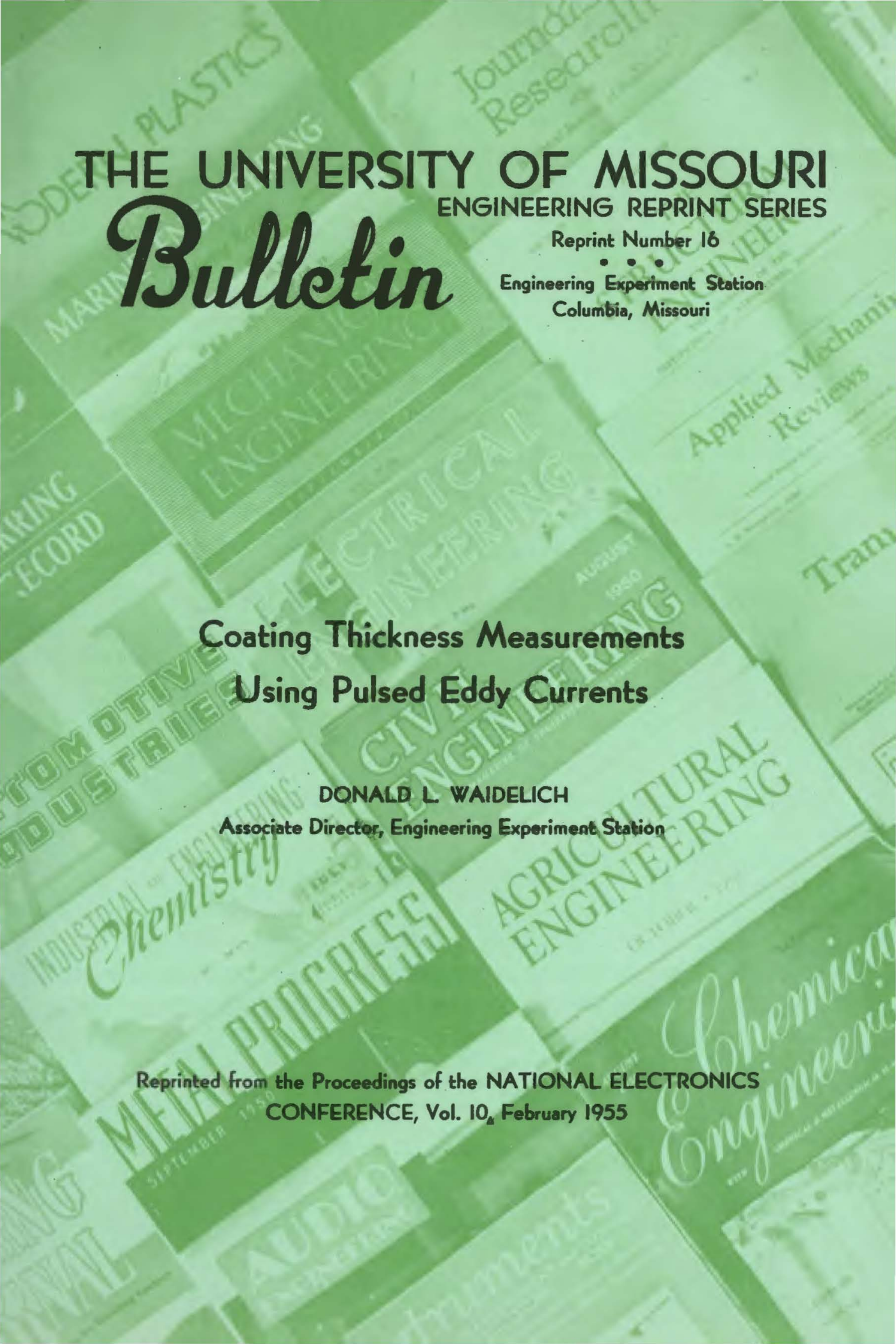

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Coating Thickness Measurements Using Pulsed Eddy Currents

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Associate Director, Engineering Experiment Station

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COATING THICKNESS MEASUREMENTS USING PULSED EDDY CURRENTS

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Abstract.—The nondestructive measurement of the thickness of one metal coated or clad upon another metal as a base has been studied for the past twenty years or more. If one of the metals is magnetic, the problem is relatively simple. If the clad and base metals are both nonmagnetic, the measurement problem is more difficult, particularly if both metals have nearly equal electrical conductivities. The phase measurement of sinusoidal eddy currents has been tried with some success although there is difficulty with low sensitivity and the presence of harmonic frequencies. The use of pulsed eddy currents in the manner of echo sounding appeared to have promise and was tried.

A brief theoretical treatment indicated that the necessary pulse length depended upon the thickness of the coating. For thickness of the order of ten mils of coating, pulse lengths of approximately one microsecond were found satisfactory. A thyratron was used to pulse the magnetic probe, while a balancing circuit was employed almost to eliminate the echo from the air-to-metal surface so the echo from the metal-to-metal boundary could be detected. Several different forms of the balancing circuit were tested. Comparison of thicknesses measured using the pulsed probe is made with those measured optically.

I. INTRODUCTION

One of the problems that arises in many applications at the present time is that of measuring in a nondestructive manner the thickness of one metal coated or clad upon a base metal. If one of the metals is ferromagnetic, the problem is relatively simple.[1,2] For two nonmagnetic metals the problem is more difficult but a number of methods can be used such as ultrasonic, back-scattering of beta or gamma rays, and eddy currents. The eddy-current method appeared to offer the best promise of success and therefore was used in this investigation. Methods using sinusoidal eddy currents of a single frequency have been employed by a number of investigators.[3-6] This method of using sinusoidal eddy currents presents difficulties such as low sensitivity and high harmonic content. The use of pulsed eddy currents in the manner of echo sounding offered considerable promise and was selected for application. This paper presents some of the theoretical considerations and a brief summary of the experimental work.

II. THEORETICAL CONSIDERATIONS

Some work has been done on pulsed high frequency currents in conductors.[7,8] In the present application, an intense localized electromagnetic field is applied to the surface of the clad metal and echoes from the metallic layers are received. These echoes result when the electrical properties of the metals have a sudden discontinuity such as that caused by a metal-to-metal interface.

A small single-layer probe coil with its axis perpendicular to the surface of the metal is used to set up the electromagnetic field and to receive the echoes. This allows the investigation of a small area and facilitates point-by-point measurements. Since the exact solution of the field of such a coil is difficult,

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[a] The work reported in this paper was done while the author was either a resident research associate or consultant to Argonne National Laboratory, Lemont, Illinois.

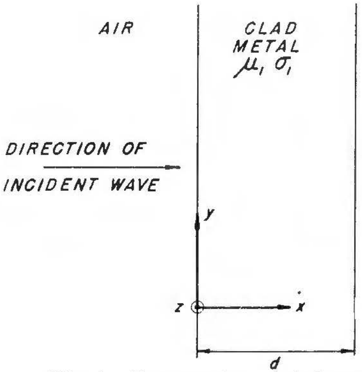

Fig. 1—Cross section of clad metal.

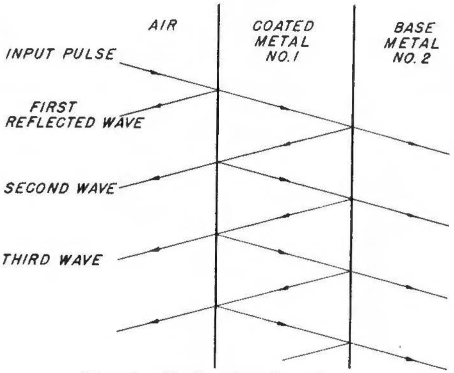

Fig. 2—Paths of reflected waves.

the problem is simplified by assuming that a plane wave with its front parallel to the metal surface was established. This would indicate the kind of echo which might result but would ignore the spreading of the waves from the source, which is almost a point source. Another approximation used is the assumption that the input pulse is square and of length T seconds when actually it has more the shape of a sinusoidal half-period wave.

The clad metal is assumed to have a thickness d as shown in Fig. 1. Some details of the analysis are given in the Appendix. Equation (7) indicates that the reflection from the metal is composed of a series of waves. The paths of these waves are shown in Fig. 2. The first term in the series represents the reflection of the wave from the surface of the clad metal and consists of a sharp rise at the head of the wave and a tail which is quite long compared to the reflection time of the wave. This reflection time T' is of the order of 10^{-18} second for most air-to-metal boundaries. The characteristics of this first wave depend upon the permeability μ_1 and the conductivity σ_1 of the clad metal, and hence the length or amplitude of the tail would be useful in determining these electrical constants of the clad metal. If, on the other hand, the primary object is to measure the thickness of the cladding, then the first reflected wave will not be useful and should be balanced out by means of a bridge circuit.

The second reflected wave (second term) does contain information about the depth d of the clad metal, and it should be the one used for this purpose because it will be the strongest of all the remaining waves. The greater the electrical difference that exists between the clad and the base metals, the larger is the metal-to-metal reflection factor R_{12} and the greater is the ease of determining the clad depth. The basic constant having to do with the depth of the clad metal is the time, $T_2 = d^2 \mu_1, \sigma_1$. Representitative values are given in Table I. The output pulse for a step input magnetic field is given by (13) and is shown in Fig. 3. This pulse has a large positive peak followed by a very small negative peak. If a rectangular input pulse were used, the output would be a large positive pulse followed by a large negative pulse. Any characteristic such as the amplitude or length of this output pulse would be sufficient to determine the depth d, but the most useful characteristic was found to be the crossing point between the positive and negative pulses. This crossing point depends directly on T_2 which in turn depends upon d. This crossing point also depends upon

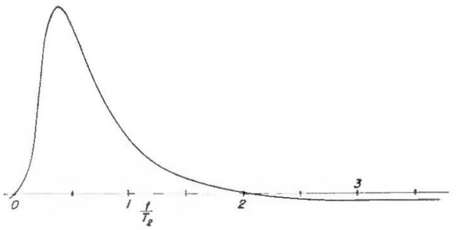

Fig. 3—Output pulse wave.

μ_1 and σ_1 hence for good measurements of d, the electrical constants of the cladding should remain nearly constant. Since the third and higher order reflected waves will be present to a lesser degree, the electrical properties of the base metal should also remain fairly constant. From Fig. 3 for best sensitivity the input pulse if rectangular should have a length of about $T = 2T_2$. For input pulses with less abrupt rises, such as half-sinusoidal-loop and triangular pulses, T should probably be more of the order of five or six T_2. From Table I this would necessitate an extreme range of length of pulses, and hence it is better to select the pulse length or lengths to fit the most difficult case. This case in Table I would be that of zirconium on uranium, and thus a pulse length of approximately three microseconds was selected. This means a decreased sensitivity in the other cases. The repetition rate appeared to have no influence except to cause the duty cycle to become too long or the oscilloscope image to become too dim.

TABLE I

VALUES OF TIME T_2 IN MICROSECONDS

	Distance d *5 mils*	*15 mils*	*25 mils*
Aluminum	0.7520	6.770	18.830
Zirconium	0.0449	0.404	1.123
347 Stainless Steel	28.1000	252.000	702.000

III. EXPERIMENTAL WORK

The basic block diagram of the experimental set-up is shown in Fig. 4. The rate generator of the oscilloscope is used to trigger a thyratron which sends identical pulses through the standard and the test probes. The responses of these probes are balanced against each other and the difference voltage is amplified and reproduced by the oscilloscope. Proper interpretation of the oscilloscope trace will yield the depth of the coating thickness.

A simplified schematic diagram of the thyratron pulser and bridge circuit is shown in Fig. 5. The capacitor C_1 is charged through the resistor R_1 and then discharged through the primary of the air core transformer T. Since the secondary of the transformer is rather loosely coupled to the primary, the duration and shape of the pulses are primarily determined by the shunt circuit composed of the capacitor C, the resistor R, and the primary inductance L along with the capacitor C_1. The shape of the pulses is further modified by the action of the transformer and the bridge circuit containing the probes. Auxiliary variable resistors and capacitors are inserted in the bridge circuit to make the balance

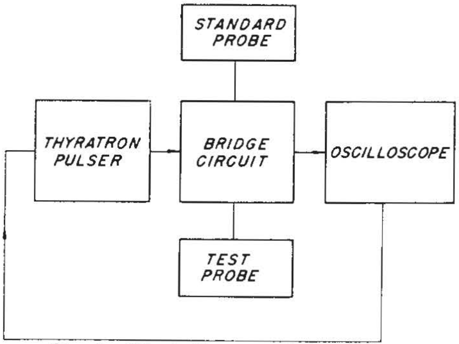

Fig. 4—Block diagram of the circit.

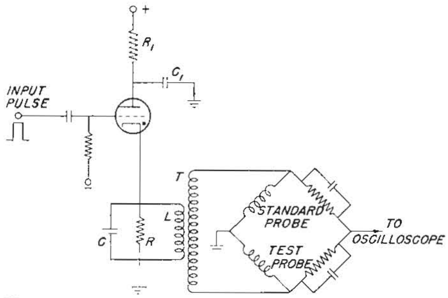

Fig. 5—Simplified schematic diagram of the circuit.

as nearly perfect as possible. The secondary winding of the transformer is isolated and shielded sufficiently from the primary winding so that both ends of the secondary are nearly symmetrical with respect to ground potential. Various other bridge circuits were tried, some with a fair amount of success. The circuit of Fig. 5, however, appeared to have the most promise and was adopted for that reason.

Two probes are used and are made as nearly identical as possible. The simplified cross section through the axis of one type of cylindrical probe is shown in Fig. 6. The cross-hatched material is one of the ferromagnetic ceramic materials, and the single layer coil is wound on the axial rod. This rod has two separate parts mounted within an insulating tube with an air gap between the two parts. The left hand part of the axial rod is movable so that a better balance is obtainable between the standard and the test probes. These probes were about one-half inch in diameter. If sufficient sensitivity were available, the outer shell of the probe could be dispensed with, and only the inner axial rod used. This would materially reduce the effective area of the probe.

The oscilloscope amplifier should have a band width sufficiently wide so that the details of the pulse are faithfully reproduced. Sufficient gain is needed to bring the pulse response up to a readable level and auxiliary wide-band amplifiers are useful in this regard. It is convenient but not necessary to have the rate generator contained within the oscilloscope itself. A variable delay is needed so that portions of the pulse response may be selected and examined.

The standard sample of metal is placed on the standard probe and another

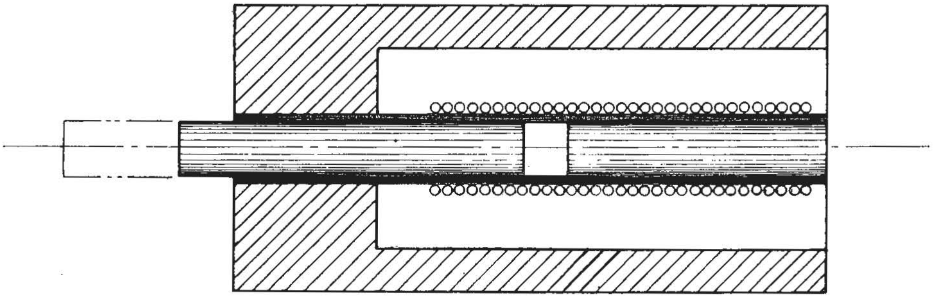

Fig. 6—Cross section of probe.

sample of metal is placed on the test probe. The various balancing adjustments, such as those of the bridge and those on the probe, are then made so the pulse output is as nearly zero as is possible. Then a slight unbalance is added by changing the test probe adjustment a small amount. The crossing point of the resulting pulse is singled out and the time axis about this point is expanded considerably. As the thickness of the cladding of the sample changes, the position of the crossing point on the zero axis also changes and thus the position of the crossing point may be calibrated in terms of thickness of cladding.

One of the early difficulties with this method was the variation of the crossing point with the probe spacing, i.e., the distance between the probe and the metal plate. It was found experimentally that the slope of the oscilloscope trace varied with this probe spacing also. If the distance between the probe and the plate were varied until the slope of the trace had some fixed value, then the probe spacing would always be the same and the crossing point would be a measurement of the clad thickness.

This method was followed with good results. The appearance of the oscilloscope trace is shown as A in Fig. 7. The position A, for example, might correspond to a clad thickness of 25 mils, that of B to a clad thickness of 15 mils, and *C* to a clad thickness of 5 mils. Sloping lines ruled on the bezel of the oscilloscope aid in maintaining the slopes of the traces of Fig. 7 constant.

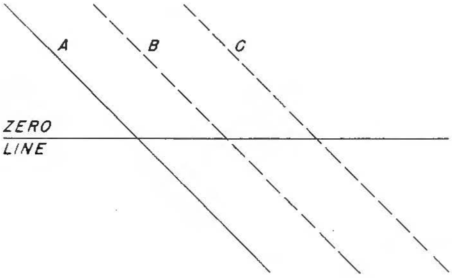

Fig. 7—Appearance of the oscilloscope trace.

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APPENDIX

Equations of Reflected Waves

In a metal [9, 10] if **H** is the Laplacian transform of the magnetic field intensity, σ_1 and μ_1 are the conductivity and the permeabiilty respectively of the metal and *S* is a complex variable

$$\nabla^2 \mathbf{H} = \sigma_1 \mu_1 S\mathbf{H} \tag{4}$$

Assume now that the plane wave is traveling in the + (x) direction and that the electric field **E** and the magnetic field **H** are in the *y* and *z* directions respectively. If H_z is the *z* component of **H** and E_y the *y* component of **E**, then

$$H_z = A \exp(-\tau_1 x) + B \exp(\tau_1 x) \tag{2}$$

$$E_y = \eta_1 [A \exp(-\tau_1 x) - B \exp(\tau_1 x)] \tag{3}$$

where $\tau_1 = \sqrt{S \mu_1 \sigma_1}$ and $\eta_1 = \sqrt{S \mu_1 / \sigma_1}$

Similarly in the air, if μ and ε are the permeability and the permittivity respectively of the air

$$\nabla \mathbf{H} = \mu\varepsilon S^2 \mathbf{H} \tag{4}$$

$$H_z = C \exp(-Sx/V) + D \exp(Sx/V) \tag{5}$$

$$E_y = \eta[C \exp(-Sx/V) - D \exp(Sx/V)] \tag{6}$$

where $V = (1/\sqrt{\mu\varepsilon})$ and $\eta = \sqrt{\mu/\varepsilon}$

For the base metal let μ_2 and σ_2 be the permeability and conductivity respectively, and μ_1 and σ_1 be the corresponding quantities for the clad metal. Assume that the depth of the base metal is infinite and thus there is no return wave. In the air let the incident magnetic field intensity wave be a step wave of height H_o traveling in the plus x direction. Then in the air the reflected wave from the surface of the metal is

$$\begin{aligned} D &= \frac{H_0}{S}\left[\frac{R_{01} + R_{12}\exp(-2\tau_1 d)}{1 + R_{01} R_{12} \exp(-2\tau_1 d)}\right] \\ D &= \frac{H^0}{S}\Big[R_{01} + R_{12}(1 - R^2_{01}) \exp(-2\tau_1 d) \\ &\qquad - R_{01} R_{12}^2 (1 - R^2_{01}) \exp(-4\tau_1 d) + \ldots \Big] \end{aligned} \tag{7}$$

where

$R_{01} = \dfrac{\eta_0 - \eta_1}{\eta_0 + \eta_1}$ = operational reflection factor at the air-to-metal boundary

$R_{12} = \dfrac{\eta_1 - \eta_2}{\eta_1 + \eta_2}$ = operational reflection factor at the metal-to-metal boundary

The first term of (7) represents the wave reflected from the air-to-metal boundary as shown in Fig. 2, while the second term represents the wave reflected once from the metal-to-metal boundary. The third term of (7) represents the wave reflected twice from the metal-to-metal boundary and so on. Since the reflection factor R_{12} will be less than one, each term of (7) will be smaller than the preceding terms. Thus only the first two terms need be considered.

The first term is

$$\left[\frac{H_o}{S}\right] R_{01} = \frac{H_o}{S}\left[\frac{1 - \sqrt{ST_1}}{1 + \sqrt{ST_1}}\right] \tag{8}$$

where $T_1 = \left[\dfrac{\varepsilon \mu_1}{\mu_1 \sigma_1}\right]$

To the reflected wave of (8) must be added the initial field (H_0/S) to obtain the total field in the air outside the metal. This is supposing at first that there are no layers of other metals beneath the surface. The voltage from the probe coil observed by means of the oscilloscope may be taken as the time derivative of the magnetic field. Hence if V_1 is this voltage

$$L\,(V_1) = 2H_0/[1 + \sqrt{ST_1}] \tag{9}$$

Using a transform table,[10] the voltage V_1 is

$$V_1 = \frac{2H_0}{\sqrt{T_1}}\left[\frac{1}{\sqrt{\pi t}} - \frac{1}{\sqrt{T_1}}\exp\left(\frac{t}{t_1}\right)\operatorname{erfc}\sqrt{t/T_1}\right] \tag{10}$$

$$\text{where } \operatorname{erfc} x = \frac{2}{\sqrt{\pi}}\int_X^{\infty} \varepsilon^{-u^2}\,du$$

The voltage wave of (10) has an initial impulse (caused by application of the step magnetic field) and a long tail which gradually approaches zero. The length of the tail depends upon the time T_1, which might be called the reflection time for the air-to-metal boundary. This time is extremely short for metals, and as an example, it is 2.39×10^{-19} second for aluminum, 3.97×10^{-18} for zirconium and 6.38×10^{-15} for 347 stainless steel. The tail of the wave, however, has sizable values even for times of the order of one microsecond, and it is this tail that must be nearly balanced out by a bridge circuit.

The second term is

$$F(S) = \frac{H_0}{S} R_{12}\left[1 - R_{01}^2\right]\exp\,(-\,2\tau_1 d)$$

$$= 4H_0\,R_{12}\,\sqrt{T_1}\,\frac{\exp\,(\,-2\sqrt{ST_2}}{\sqrt{S}\,(1+\sqrt{ST_1})^2} \tag{11}$$

where

$$R_{12} = \frac{\sqrt{\dfrac{\mu_1}{\sigma_1}} - \sqrt{\dfrac{\mu_2}{\sigma_2}}}{\sqrt{\dfrac{\mu_1}{\sigma_1}} + \sqrt{\dfrac{\mu_2}{\sigma_2}}}$$

$$T_2 = d^2\,\mu_1\,\sigma_1$$

The reflection factor R_{12} at the metal-to-metal boundary is thus a constant. The probe voltage again is assumed to be the derivative of the magnetic field. Hence, if V_2 is this voltage

$$L(V_2) = 4H_o\,R_{12}\,\sqrt{T_1}\,\frac{\sqrt{S}\exp\,(-2\sqrt{ST_2})}{(1 + \sqrt{ST_1})^2} \tag{12}$$

Again using the transform table[10], (12) becomes

$$V_2 = 8\,H_o\,R_{12}\Biggl\{\biggl[\frac{(\tfrac{1}{2}) + (\varepsilon/T_1)}{\sqrt{\pi T_1\,t}}\biggr]\exp(-t/T_2) - (1/T_1)\biggl[1 + \sqrt{T_2/T_1} + (t/T_1)\exp/2\sqrt{T_2/T_1}\biggr] - \left(\frac{1}{T_1}\right)\biggl[1 + \sqrt{T_2/T_1} + (t/T_1)\biggr]\exp\biggl[2\sqrt{T_2/T_1} + (t/T_1)\biggr]\operatorname{erfc}\biggl(\sqrt{T_2/t} - \sqrt{t/T_1}\biggr)\Biggr\} \tag{13}$$

It is possible to show that the wave of (13) has the slope shown in the solid curve of Fig. 3. Notice particularly the large initial peak. If the incident magnetic field were applied in the form of a rectangular pulse and the system were linear, the output probe voltage would be a positive pulse followed by a similar negative pulse. If the length T of the rectangular pulse were approximately equal to 2 T_2, the crossing point on the zero axis between the positive and negative pulses of the probe voltage would depend upon the value of $T_2 = d^2\mu_1\sigma_1$ and hence upon the depth of the clad material as well as its permeability μ_1 and conductivity σ_1. If μ_1 and σ_1 are reasonably constant, the position of the crossing point will vary with the cladding depth and can be used as a measure of this quantity. Any other characteristic of the voltage pulse, such as the amplitude or the position of the maximum, could be employed in the same fashion as a measure of the cladding depth. The actual incident pulses employed were not rectangular in shape but had shapes closer to a half senusoidal loop. A similar analysis for this type of pulse would probably show that the length T of the pulse should be somewhat longer than 2 T_2, say 5 or 6 T_2 in length. This was subsequently borne out in the experimental work.

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