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A STUDY OF THE FEASIBILITY OF INITIATING AN EXPLOSIVE PRIMER FROM A PIEZOELECTRIC IMPACT SYSTEM

T. R. Bates - 1453

ABSTRACT

A study was made of the general characteristics of a contact fuzing system consisting of a piezoelectric impacting network as the energy source for an explosive primer. Since the impedance match between a bridge wire and a crystal is very poor, it is necessary that an impedance-matching device be used between the crystal and primer.

An impedance-matching transformer is proposed from the standpoint of maximum circuit reliability and simplicity.

A parametric study of the crystal, transformer, primer system describes its general features including its response to various types of force imputs.

As in all contact fuzing studies the basic difficulty is in predicting the nature of the force inputs to the crystal units. The results of the parametric study are presented in such a way that one can determine the response of the system to various assumed ranges of force inputs or alternatively, if one has reason to believe that the force input to a crystal lies within a given range one can design the optimum system about this range.

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A STUDY OF THE FEASIBILITY OF INITIATING AN EXPLOSIVE PRIMER FROM A PIEZOELECTRIC IMPACT SYSTEM

INTRODUCTION

Division 1453 is doing research and development work on an explosive switch for firing set actuation. Such a switch would offer many advantages to X-unit designers such as (a) increase switch efficiency (lower inductance); (b) simplification of design and manufacture of an X-unit discharge plate; (c) shock, vibration, altitude, and humidity resistance superior to that of a gap switch; (e) sufficient miniaturizing of switch size to allow redundant switch installation with complete isolation between switch elements.

The above considerations indicate that the specific design of an explosive switch would be beneficial regardless of its activation time or required energy. However, if such a switch were to be used as a replacement for gaps in all X-unit designs, it would be required to be compatible with some sort of contact fuzing system. There are several contact fuzing systems which could be used; this report concerns itself mainly with the physics involved in initiating an electric primer from an impact-actuated piezoelectric crystal. Questions such as arming requirements and methods, redundant circuitry, crystal design and crystal mounting are deferred for later consideration.

The explosive primer under consideration is of the metal bridge-wire type, which when heated to a sufficient temperature will ignite a lead styphnate flash charge. The resistance of this wire approximates five ohms. Since a piezoelectric crystal is a high-impedance generator, direct connection to a bridge wire of low-impedance results in extremely poor circuit efficiency. Because a crystal of reasonable size is also a low energy source, such an impedance mismatch is intolerable; hence, an impedance-matching device between the crystal and the bridge wire is required.

A transformer seems an appropriate method of coupling these elements.

An impedance-matching transformer inserted between the crystal and primer can effectively transform the five-ohm primer resistance to any desired level for the crystal to work into.

Sandia Corporation's experience with the use of piezoelectric crystals as contact fuzing elements so far has been limited to their use as voltage generators to trigger thyratrons and spark gaps. There are several fundamental differences between crystal impacting systems used as voltage generators and as energy sources for explosive primers. These differences

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are in the concept of signal-to-noise ratio, optimum loading, build-up of delay time, optimum crystal, and circuit design.

THE CRYSTAL, RESISTOR, CAPACITOR SYSTEM

The first step in designing an efficient crystal transformer and bridge-wire system is to determine the resistive loading which will result in maximum energy transfer into the load and the various factors which affect this optimum loading and the degree of their effect. Once the desired value of crystal loading is established, the design of an impedance-matching transformer may be attacked as a separate problem. A shock-excited, resistively loaded crystal has been studied theoretically and experimentally. We will first consider the theoretical investigation as that has served as a guide to our experimental study.

The charge developed on the faces of a piezoelectric crystal is proportional to the extension or compression of the crystal. For a capacitively loaded crystal, this charge appears across the capacitive load of the crystal. In the equivalent circuit of a crystal, Fig. 1, the voltage developed is proportional to the force applied to the crystal. If one assumes that this force is balanced mainly by the spring reaction of the crystal, a capacitance, C_p, is drawn in series with the voltage generator which represents this blocking action, and this in turn is in series with another capacitance, C_c, representing the difference between the true electrostatic capacitance, C_x, and C_p.

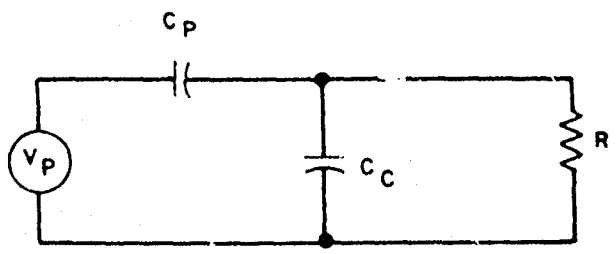

Fig. 1

$$V_p = \frac{F}{KD}$$

$$C_p = KD^2$$

$$C_c = C_x - C_p$$

where F = force applied to crystal,
K = spring constant of crystal,
D = piezoelectric constant,

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C_x = electrostatic capacitance of crystal plus external shunt capacitance.
R = external resistive load.

One can apply Thevenin's theorem and redraw this circuit as a voltage generator in series with the capacitance C_x in series with the resistive load Fig. 2.

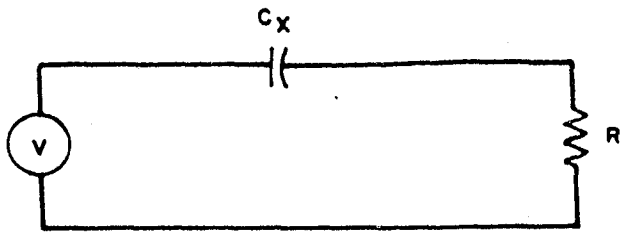

Fig. 2

$$V = V_p \frac{C_p}{C_x}$$

Let us assume that we have a normal slug-loaded piezoelectric crystal in its housing, bolted to the frame of the weapon. We will consider here only the effect of forces exerted axially along the crystal.

A force exerted on the crystal unit (through the mounting studs) will accelerate the CG of the crystal unit. If the housing, crystal, and slug are relatively rigid compared to the case structure, and the mass of the crystal is negligible compared to the mass of the slug, it would seem that our assumption that the force on the crystal faces is balanced by the spring reaction of the crystal is justified. It then follows that the voltage waveform, V, is directly proportional to the force waveform, F, applied to the crystal unit. In the more general equivalent circuit of a crystal unit, inductances representing masses and resistances representing mechanical and electrical losses are present. However, the simplified equivalent circuit of Fig. 2 will serve for the present as an adequate description of our piezoelectric crystals. This circuit may be used to study the effects of variations of the load resistor and various characteristics of the driving force.

One is now confronted with the question of what voltage or force input waveform to analyze. This, of course, is one of the basic problems associated with contact fuzing; the crystal waveforms obtained from telemetering data show that one can not expect any unique waveform to exist. We, therefore, will start by assuming that the input waveform is the first half-cycle of a sine wave.

It can be shown that unidirectional waveforms of quite different shape from a half sine wave, such as a square wave of the same area and duration, cause substantially the same resistive heating as the half sine wave. We then explore the effects of different time bases by varying the frequency of our half sine wave.

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THE PARAMETRIC STUDY OF THE CRYSTAL, RESISTOR, CAPACITOR SYSTEM

We assume the applied voltage, V, is zero before t = o in our equivalent circuit, Fig. 2, and after t = o, $V = V_o \sin \omega t$, then

$$V = iR + \frac{Q}{C_x} \tag{1}$$

which leads to the differential equation

$$V_o \, \omega \cos \omega t = R \frac{di}{dt} + \frac{i}{C_x} . \tag{2}$$

The solution of this differential equation is

$$i = \frac{V_o}{R} \frac{a}{1 + a^2} \left(\cos \omega t + a \sin \omega t - e^{-\omega t/a}\right), \tag{3}$$

where $a = R\omega C_x$.

We calculate the energy absorbed by the resistor by calculating the power from Equation 3 and integrating

$$W_r = \int_o^t P dt = \int_o^t i^2 \, R dt . \tag{4}$$

After performing the above integration, we find that the energy absorbed by the resistor from t = o to t = t is

$$W_r = \frac{C_x V_o^2}{2} \frac{a}{(1 + a^2)^2} \Big[\omega t \, (1 + a^2) - a e^{-2\omega t/a} + 4 a e^{-\omega t/a} \cos \omega t + \frac{(1 - a^2) \sin 2\omega t}{2} + 2 \sin^2 \omega t - 3a\Big] . \tag{5}$$

The quantity

$$\frac{C_x V_o^2}{2} = \frac{F_o^2 D^2}{2C_x} \tag{6}$$

should be maximized by maximizing F_o and D. The optimum value of C_x depends upon other considerations. If the system is limited by crystal breakage or high-voltage flashover, one should select C_x so as to make these two types of failure equally probable. If one is not limited by crystal failure but by the amplitude of the force, F_o, one should minimize C_x. For a given $\frac{1}{2} C_x V_o^2$, the

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quantity $W_r/\frac{1}{2}C_xV_o^2$ is a measure of the efficiency of the system. As shown by Equation 5, this quantity is a function only of a and ωt. If we assume the input signal, we have to work with is a half sine wave, i. e., $\omega t = \pi$, then $W_r/\frac{1}{2}C_xV_o^2$ is a function of a only.

This function of a will be maximum when a is about .7. Therefore, the optimum value of R for a given frequency is:

$$R_{opt} = \frac{.7}{C_x\omega}. \tag{7}$$

A plot $W_r/\frac{1}{2}C_xV_o^2$ versus a is given in Curve I.

CONSIDERATIONS OF THE CASE INPUT TO THE CRYSTAL UNIT

If we knew nothing at all about the probable values of ω, we would have no way of selecting R_{opt}. However, we should be able to put limits on a and therefore bracket R_{opt} from the following considerations. The speed of the weapon and the tolerable amount of case damage determine the lowest value of ω which could be effective in initiating the explosive switch (by means of half sine-wave actuation) before vital parts of the weapon are destroyed. The upper limit of ω is more difficult to define.

One might try to define ω_{max} as the frequency the crystal would resonate at if it received a true impulse which, of course, would represent the fastest unidirectional force function with which the case could drive a crystal. Under these conditions, one may excite standing waves in the crystal, backup slug, and housing structure, in which case our simplified equivalent circuit would lose its validity. However, if this should be the sole mode of crystal excitation, the frequency would be so high that there could be many half cycles from which the primer could extract energy before the weapon components were damaged.

Let us consider Curve I and continue with our assumptions that the equivalent circuit holds and that we must initiate the primer during the first half cycle. We also assume that the amplitude of the force function is constant, no matter what the frequency. From Curve I we may draw another Curve, II, of operable bandwidth $\omega_{max}/\omega_{min}$ versus $W_{r\,max}/W_{r\,min}$ where $W_{r\,max}/W_{r\,min}$ is the ratio of the energy absorbed by the primer if a = .7 to the energy required for primer initiation.

From this, it is seen that the bandwidth increases very rapidly for small increases in crystal sensitivity. In particular if $W_{r\,max}/W_{r\,min}$ is 3, then $\omega_{max}/\omega_{min}$ is 100.

Curves III and IV show $W_r/\frac{1}{2}C_xV_o^2$ versus a for various numbers of successive half cycles. The label N indicates the number of half cycles. Any curve for which N is greater than one applies, of course, only to crystal units capable of full-wave output. These all have a

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constant peak amplitude except the curve labeled N = 1/16. For the N = 1/16 curve, the peak amplitude was adjusted so that at the point $\omega t = \pi/16$ the amplitude is the same as the other curves. The N = 1/16 curve can be used for investigating a linearly rising force. These curves may be used for testing the effects of various hypotheses concerning the impact waveforms.

EXPERIMENTAL WORK ON THE CRYSTAL, RESISTANCE COMBINATION

Division 1453 has conducted laboratory work to determine the validity of the equivalent circuit shown in Fig. 2. The crystal used for these tests was the XMC-565 direct-fire crystal under development by Division 1464.

Comparisons were made of experimental waveforms of resistively loaded crystals to theoretical waveforms. The correlation was generally good.

Oscillographic waveforms of the voltage across various resistors at different driving frequencies were analyzed by Data Reduction in the following manner. From the voltage-time relationships given by the oscillographs, calculations were made of the energy absorbed by the resistors versus time. From this data, curves were plotted of the relative energies absorbed during the first positive half cycle versus $R\omega C_x$. These were compared to Curve I and the correlation was quite good. The two frequencies used in these tests were $f = 2.86\ 10^3$ cps with a half period of 175 microseconds obtained by the quarter-inch drop tester and f = 330 cps with a half period of 1.5 milliseconds obtained by increasing the drop height on the quarter-inch drop tester and absorbing the impact in a piece of 1/8-inch-thick rubber sheeting. The results are indicated in Curve I.

The computation of an energy input versus time curve from the voltage-time pictures was quite lengthy and time-consuming. An attempt was made in our laboratory to construct a computing circuit which would display the energy versus time curves directly on an oscilloscope. This involved taking the voltage signal (across the resistor) and feeding it through a squaring circuit then, through a dividing circuit to obtain the power, and then into an integrating circuit whose output would be connected to the oscilloscope. One would then have a direct display of energy absorbed versus time. When difficulty was encountered in designing a satisfactory squaring circuit, the computer idea was dropped since we had a limited amount of work we wished to do. However, this type of thing might well be worth the effort in a more extensive program.

Attempts were made to excite the crystals at higher frequencies than obtainable from the quarter-inch drop tester. In one such test, case-hardened steel BB's and steel darts were fired at a case-hardened steel end cap on the crystal mounting stud. Though it was possible to excite higher frequencies in this way, the data were not suitable as a check on the equivalent

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circuit. The basic or lowest frequency in these traces was the same as obtained from the quarter-inch drop test. In another attempt to generate higher frequencies, the crystal was shocked with an explosive primer. The frequency was the same as that obtained from the quarter-inch drop tester. However sled test telemetering data indicate that higher frequencies do exist during weapon impact conditions.

Another test was performed to test the basic feasibility of using an impedance-matching transformer with the crystal. An EX1544-Y (28-volt gap-fire transformer) with a turns ratio of 400-1 was placed between the crystal and a 1-ohm resistor. Its reflected impedance to the crystal was therefore 160 K ohms. The crystal was shocked in the quarter-inch drop tester. The energy dissipated in this resistor was compared to the energy dissipated in a 160 K ohm resistor. The efficiency of the transformer, resistor combination was found to be about 50 per cent. This would seem to demonstrate that an efficient impedance-matching transformer could be developed.

SIGNAL-TO-NOISE RATIO

In discussing contact fuzing systems, the concept of signal-to-noise ratio is a useful figure of merit for comparing various systems. We would like to compare the signal-to-noise ratio of our explosive primer system to that of a thyratron system. A rigorous comparison of the two would be very difficult since the thyratron is voltage sensitive and the primer is temperature sensitive. To grossly simplify the problem let us assume that the noise is a DC voltage V_n across the primer and that the signal is a higher DC step function V_s, applied to the primer upon impact.

If one assumes that all heat losses are through the ends of the wire and the bridge-wire leads act as heat sinks and one neglects the effect of transient temperature variations along the wire, then we can calculate the ratio of the temperature rise $T_s - T_o$ caused by the signal voltage V_s to the temperature rise $T_n - T_o$ caused by the noise voltage V_n. The differential equation describing the bridge-wire temperature versus time is obtained by a power balance equation. The power input to the bridge wire is equated to the rate of increase of internal energy plus the power dissipation by conduction.

$$\frac{HV^2}{R} = Sm\frac{dT_B}{dt} + (T_B - T_o)k \tag{8}$$

where $H = \frac{1 \text{ Calorie}}{4.18 \text{ Joule}}$

S = specific heat of bridge wire

m = mass of bridge wire

T_B = instantaneous temperature of bridge wire

T_o = ambient temperature

k = power dissipation by conduction per ^oC

If we take V to be constant then the solution of this equation is:

$$\left(T_B k - T_o k - \frac{HV^2}{R}\right) = \left(T_B k - T_o k - \frac{HV^2}{R}\right)_o e^{-kt/sm} \tag{9}$$

We will first apply this to the steady-state noise condition.

at t = o $T_B = T_o$ and

$$\left(T_B k - T_o k - \frac{HV_n^2}{R}\right) = \frac{HV_n^2}{R} e^{-kt/sm}$$

at t = infinity $T_B = T_n$

$$(T_n - T_o) = \frac{HV_n^2}{kR} \tag{10}$$

Now let us apply the solution to the signal condition. We now let t = o be the moment of application of the step function signal V_s, at t = o $T_B = T_n$

$$\left(T_B k - T_o k - \frac{HV_s^2}{R}\right) = \left(T_n k - T_o k - \frac{HV_s^2}{R}\right) e^{-kt/sm}$$

At any later time t, T_B can be regarded as the instantaneous signal temperature T_s.

$$T_s - T_o = \frac{HV_s^2}{kR} + \left(\frac{HV_n^2}{kR} - \frac{HV_s^2}{kR}\right) e^{-kt/sm} \tag{11}$$

The signal-to-noise ratio is then

$$\frac{T_s - T_o}{T_n - T_o} = \left(\frac{V_s}{V_n}\right)^2 \left(1 - e^{-kt/sm}\right) + e^{-kt/sm} \tag{12}$$

if kt/sm = 0 then $\frac{T_s - T_o}{T_n - T_o} = 1$

if kt/sm = ∞ then $\frac{T_s - T_o}{T_n - T_o} = \left(\frac{V_s}{V_n}\right)^2$

It appears then that the larger the quantity kt/sm is the better the signal-to-noise ratio is. If t is the time available for ignition, there is not much we can do to extend it. The specific heat of all metals fall within a fairly narrow range; in addition, the type of metal is dictated by other considerations. We also see that variations of either the radius or length of the bridge wire tends to produce the same effect on k and m so that the ratio of k/m tends to remain constant. Some increase in k could be obtained by decreasing the resistivity of the bridge-wire material

but other than this it would seem rather difficult to make any spectacular improvement in the quantity kt/sm by juggling parameters. It would be interesting, though, to know about what kt/sm is for present types of primers.

Let us consider the MC-748 actuator, an approximately 30,000-erg primer with a lead-styphnate flash charge and a "Tophet C" bridge wire (similar to nichrome). The quantities m, s and t are available from specifications, tables and speculation, respectively, and it remains to find k.

If the current through an electric primer were slowly increased so that the "net" power input to the bridge wire was negligible, then by means of a simple power balance we may say

$$(T_B - T_o)k = iV$$

If a primer is instrumented for power input, iV, and the power input is slowly increased until initiation occurs, then

$$(T_i - T_o)k = iV$$

where T_i is the ignition temperature. This experiment was performed on four MC-748's in Division 1463's laboratory. The threshold power input was about .2 watt, room temperature was about 25°C. A quantity defined as the "instantaneous ignition temperature" of lead styphnate is about 320°C. The ignition temperature in the above experiment should be somewhat lower than this; let us arbitrarily choose 300°C.

We can then calculate k

$$k = \frac{.2 \text{ watt}}{275^\circ\text{C}} = .000174 \text{ calorie/sec } ^\circ\text{C}$$

$$m = 3.75\ 10^{-6} \text{ grams}$$

$$s = .12 \text{ calorie/gram } ^\circ\text{C}$$

or $$\frac{k}{sm} = 390/\text{sec}$$

if t = 10 microseconds

$$\frac{T_s - T_o}{T_n - T_o} = .004\left(\frac{V_s}{V_n}\right)^2 + 1$$

if t = 100 microseconds

$$\frac{T_s - T_o}{T_n - T_o} = .04\left(\frac{V_s}{V_n}\right)^2 + .96$$

[redacted]

if t = 1 millisecond

$$\frac{T_s - T_o}{T_n - T_o} = .3\left(\frac{V_s}{V_n}\right)^2 + .7$$

if V_s/V_n is taken as 10

t (in microseconds)	$T_s - T_o/T_n - T_o$
10	1.4
100	5.0
1000	31.0

These figures indicate the advantage to be gained by a weapon which can tolerate a longer ignition time.

The reader is reminded that the signal-to-noise ratio, Equation 12, was based on many simplifying assumptions.

The above discussion indicates however that the signal-to-noise ratio problem must be kept in mind if this type of contact fuzing system is developed. The signal-to-noise ratio might be a strong factor when considering the type of arming system necessary.

CONCLUSION

It is the author's opinion that a contact fuzing system utilizing a piezoelectric impacting device to trigger a fast-acting explosive switch is capable of development, provided an impact crystal of sufficient sensitivity can be developed.

To get some idea of where we stand here, the MC-565 crystal used with its optimum load, about 75 K, under quarter-inch drop test conditions, will supply about 3000 ergs to the resistor. The primer used may require approximately 5000-30,000 ergs for initiation.

It might be well to look at full-wave crystals in order to take advantage of the successive half-cycle heating described by Curves III and IV.

There are other possible systems such as crush switches and magnetic transducers which are worthy of consideration before a decision is made to follow a piezoelectric system.

T. R. BATES - 1453

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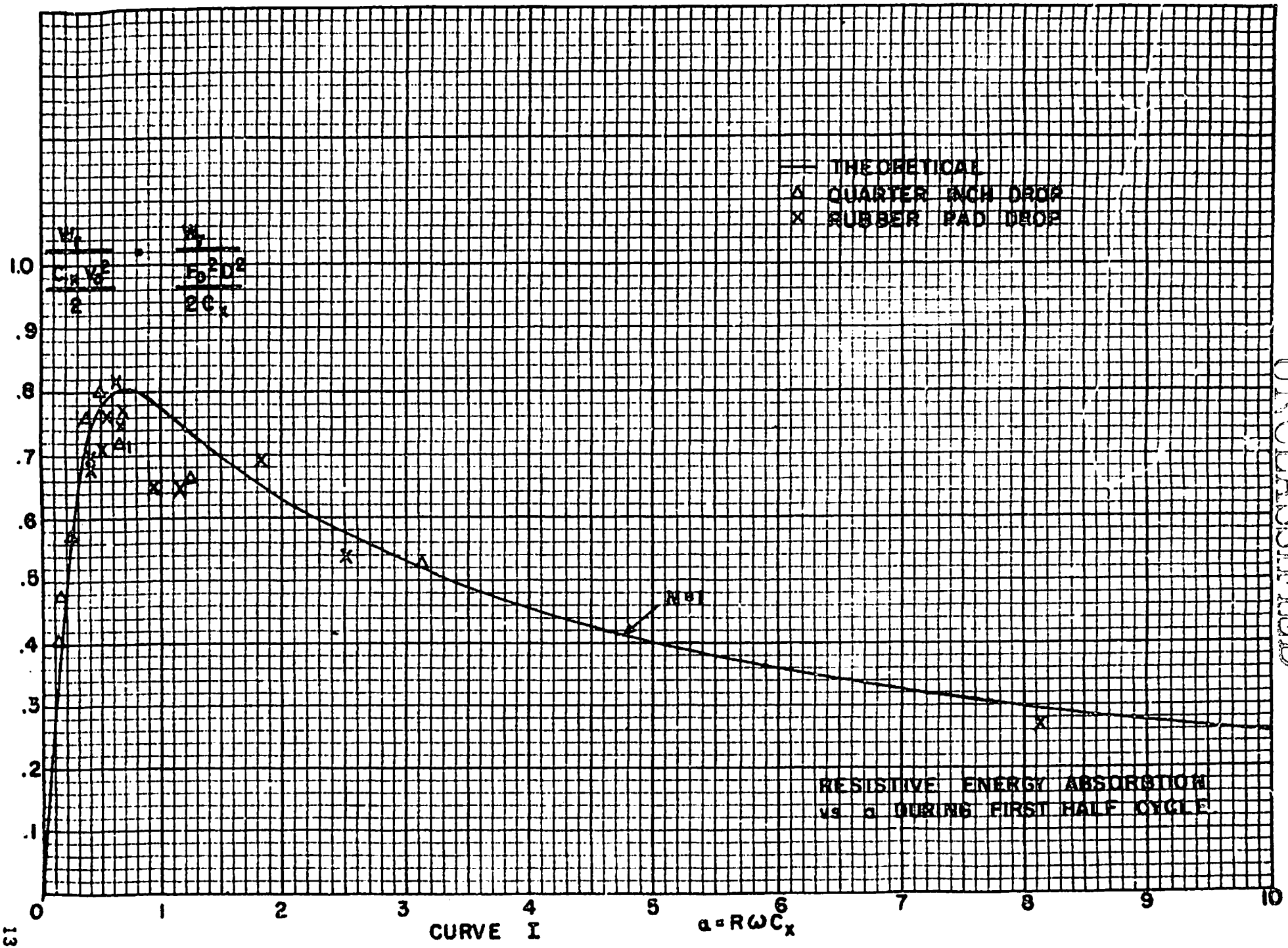

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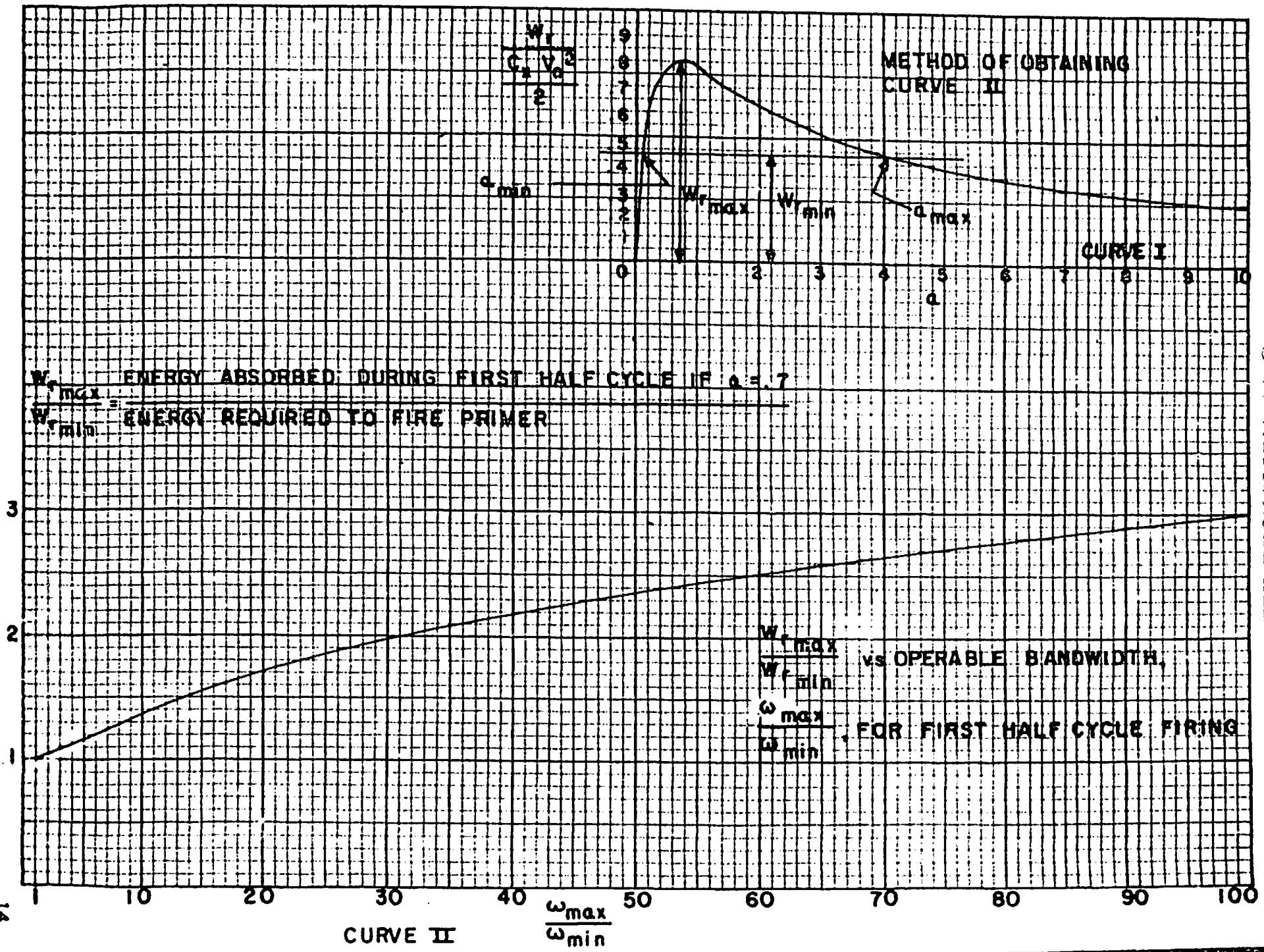

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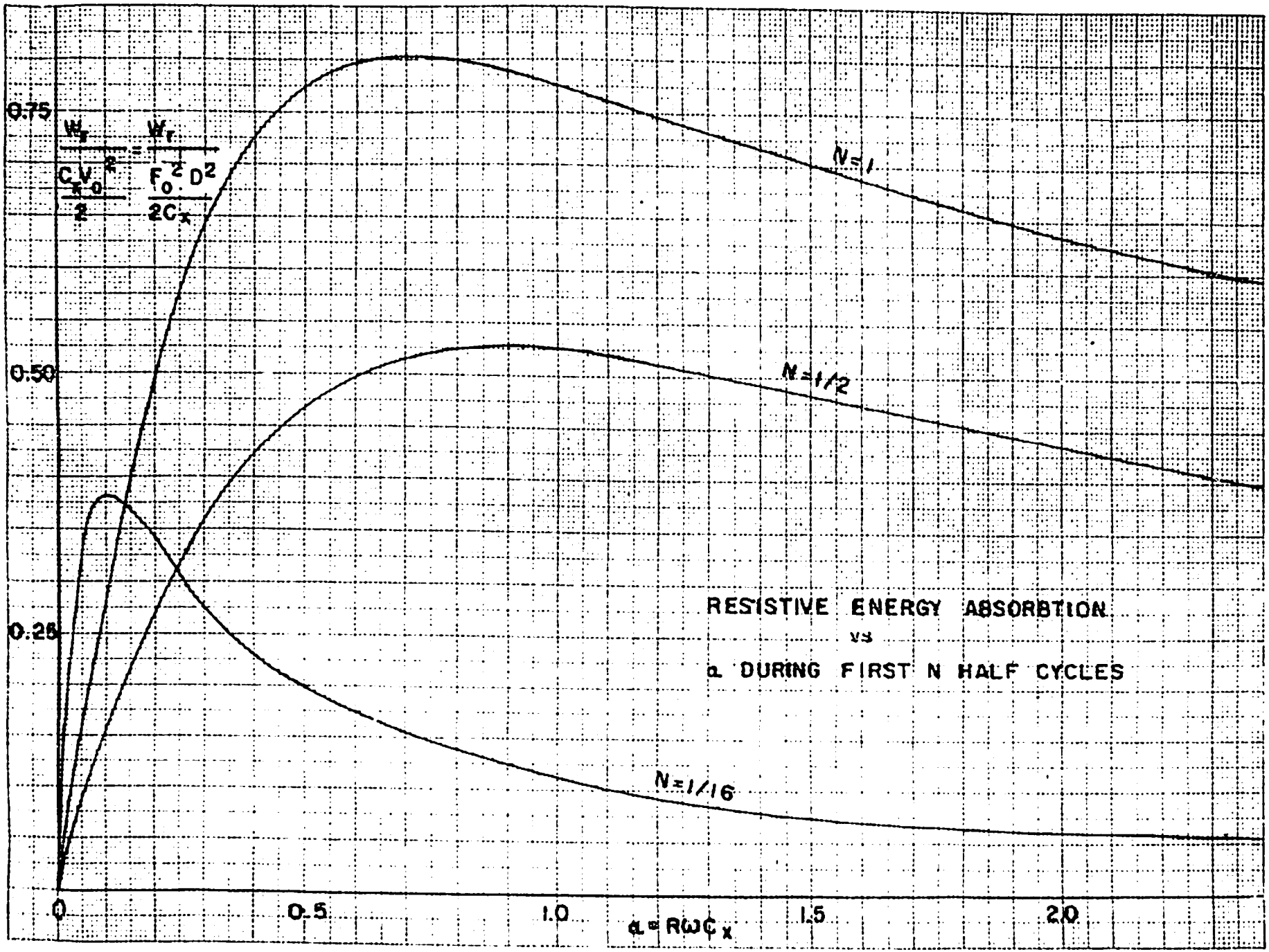

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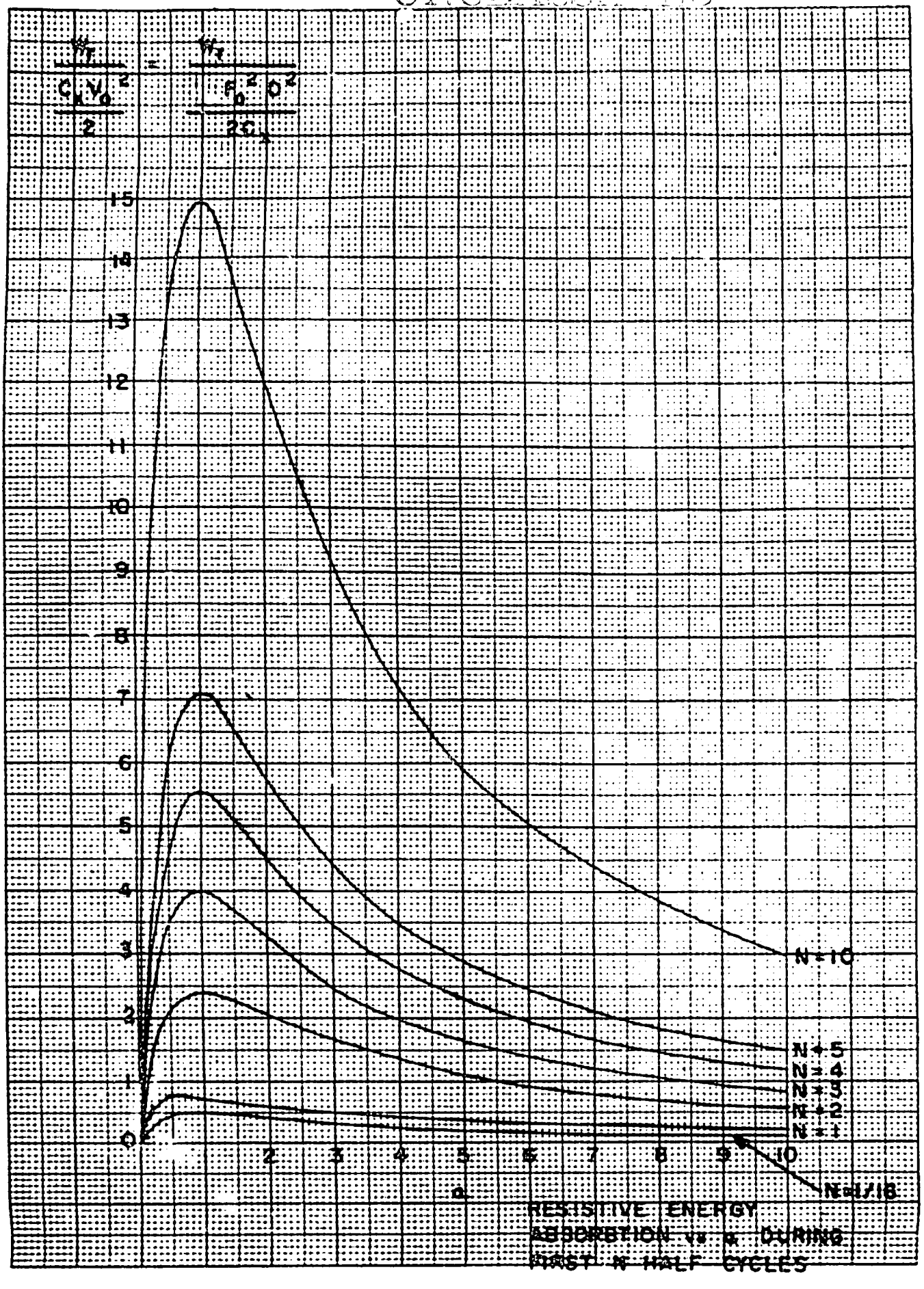

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