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TIME SCALE MEASUREMENTS
BY THE ROSSI METHOD

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ABSTRACT

The mean life of a neutron in a chain reactor can be determined under suitable conditions by the Rossi method. This method makes use of the fact that the neutrons do not appear singly but in chains. Measurements of the decay period of these chains can be made by means of electronic gating circuits. These results are used to obtain the mean life of the neutron. Measurements have been made with the water boiler, a WC-tamped UH_{10} assembly and a beryllium-oxide-tamped UH_{10} assembly.

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TIME SCALE MEASUREMENTS

Introduction

An active assembly, especially when close to critical, does not have a simple dependence of neutron level with time. There are several groups of delayed neutrons emitted from the fission fragments after a time of some seconds. Their number is of the order of one percent of all neutrons emitted, but when close to critical these neutrons to a large extent determine the time behavior. An analysis shows that in a simple approximation the time behavior can be considered as a combination of a slow period, whose characteristics depend to a large extent on the delayed neutrons, and a fast period, which depends primarily on the time after fission for the prompt neutrons to be emitted, the fission spectrum and the scattering and absorption cross-sections of core and tamper. It is the prompt period which is of interest in this report. The time for a promptly emitted neutron to again cause fission is several orders of magnitude shorter than for a delayed neutron, so the two periods can be separated. The prompt period is very short - a few milliseconds at most - while the slow period is of the order of seconds or minutes, or with care in adjustment of criticality is even hours.

A measurement of the prompt period, in addition to checking the delay in emission of the prompt neutrons and certain features of the spectrum and scattering, is important in estimating the efficiency of an explosive reaction as the efficiency varies inversely as the square. No laboratory experiment has been made to measure the period in the highly supercritical condition which is of direct interest. A method has been suggested by Feynman (LA-29) to do this by suppressing the multiplication of a supercritical system with the introduction of a 1/v absorber. This experiment, even though done with Boron 10, would involve fairly large corrections for scattering and the fact that the boron cross-section is not strictly 1/v. It would also involve a certain amount of lost time in fabrication and subsequent purification. All measurements (except at the Trinity explosion) were, therefore, made in assemblies close to critical. These measurements, to be of direct interest, must be extrapolated to the supercritical condition, which is usually about three critical masses. In some cases the period as a function of mass has been calculated over a wide range of mass (LA-235), and a direct comparison with calculated values can be made. The theory also serves as a guide in the extrapolation.

Several methods have been used to measure the fast period. One is by a rapid change in criticality which was done with the water boiler (LA 183) by means of a motor-driven, cadmium control

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vane. This was also done with the hydride assembly in the so-called dragon experiment (LA-397). In this experiment the criticality was increased by dropping a slug of active material through the center of a nearly critical assembly. It was possible in this experiment to make the assembly supercritical for prompt neutrons for a short time. Measurements were made on metal assemblies by the introduction of a neutron pulse, and a study of the subsequent decay (LA-374).

Only one method was used satisfactorily on all three general types of critical assemblies: the water boiler, hydrides and metal. This is a method suggested by Rossi and is called the Rossi experiment. It makes use of the fact that an active assembly is in a sense self-modulated, if the mean time between the emission of source neutrons is of the order of or longer than the fast period. In these circumstances, the fluctuations in intensity due to the introduction of single neutrons are recognizable, and their time dependence can be studied. This method has no fundamental advantage over the straightforward modulation method. In fact, there are certain disadvantages. The intensity is fundamentally limited so that a comparatively sensitive detector is needed, and the experiment can only be done within a few percent of critical. Its advantage, on the other hand, lies in its technical simplicity. The presence of activity in the assembly is presumed whenever a neutron is counted in an appropriate detector. A time analyzing system then records the number of neutrons counted in short intervals of time immediately after the initiating neutron. This time dependence of the number of neutrons counted following each neutron is a direct measure of the prompt period.

The theory of the Rossi experiment has been developed by Feynman (LA-591). In the simple case where all neutrons are considered to be alike, he gives for the expected number of neutrons counted in an interval dt a time t after a neutron count at $t = 0$:

$$(1) \quad P(t)\,dt = \frac{ES\,dt}{\nu_{cr} - \nu} + \frac{E\nu}{\tau_f^2 \alpha}\left(\frac{X_2}{2\nu_{cr}} + \frac{\nu_{cr} - \nu}{\nu_{cr}}\right) e^{-\alpha t}\,dt$$

Where:

ν is the mean number of neutrons emitted per fission.

ν_{cr} is a measure of criticality. It is the value which ν would have to have to make the assembly just critical. Near critical at least $\frac{\nu_{cr}}{\nu} = K$, the usual measure of criticality. By critical is meant prompt critical. Delayed neutron effects are neglected.

E is the efficiency of the detector in counts per fission.

X_2 is a measure of the possible variation of ν from one fission to another. It is twice the number of pairs of neutrons liberated in each fission.

τ_f is the mean time between fissions in the same related chain, the mean time between parent and daughter fission.

S is the source strength in neutrons liberated per second. It includes spontaneous fission, α-neutron reactions, neutrons from fission fragments, as well as additional sources which may be purposely introduced.

α is the reciprocal of the prompt period.

Since the Rossi experiment has been done only within a few percent of critical, certain simplifications and alternative representations are possible. The mean life of a neutron $\tau = \frac{\tau_f}{\nu}$

$$\alpha = \frac{\nu - \nu_{cr}}{\tau_f} = \frac{\nu - \nu_{cr}}{\nu \tau} = \frac{1 - K_p}{\tau}$$

where the subscript on K refers to prompt criticality. $\nu_{cr} - \nu$, which is of the order of a few percent, can be neglected in comparison with X_2, which is of the order 4 or greater. $\frac{ES}{\nu_{cr} - \nu} = C$ the counting rate. It can also be expressed as $\frac{\epsilon S^1}{1 - K}$, where ϵ is the efficiency in counts per neutron born in the reactor, and S' is the source strength from all sources except from the fission fragments. The expression can now be written:

$$(2) \qquad P(t)\,dt = C\,dt + \frac{E X_2}{2\nu^2 \tau (1 - K_p)} e^{-\frac{1-K_p}{\tau} t}\,dt$$

The first term represents a background of unconnected counts, or counts from a different chain than the initiating count at $t = 0$. The second term represents the number of connected counts. The number of coincidences per second between an initiating count and a subsequent count are, of course, dependent of the total counting rate. It is not necessary that the initiating count come from the same neutron detector as the subsequent counts. In some experiments two separate channels were used. If the efficiency of this initiating channel is different, it will naturally have a different counting rate, C^1. The expression for the number of coincidences per second is then:

$$(3)\quad C^1 P(t)\,dt = C^1 C\,dt + \frac{C^1 E X_2}{2\nu^2 \tau (1-K_p)}\, e^{-\frac{1-K_p}{\tau} t}\, dt$$

Both C and C^1 (which are frequently equal) are proportional to source strength, so the first or background term is proportional to its square. The second term involves only the first power, so by proper choice of source a compromise between coincidence counting rate and low background can be made. Since both terms depend on the product (or square) of the detector efficiencies, a high efficiency detector is usually desirable.

<u>Water Boiler Measurements</u>

The first time scale measurements were made with the low-power water boiler described in LA-134. Two boron ionization chambers were used as detectors. They were placed in holes in the BeO tamper on opposite sides of the boiler, the faces in contact with the sphere containing the reacting solution. This arrangement not only provided good efficiency, but the close contact between the detector and solution decreased the time required for a neutron to travel from the reactor to the detector which, in a thermal reactor, is of importance. One of the chambers had an efficiency of about 2 x 10^{-3} counts per fission and the other about 10^{-4}. The presence of these two chambers and their holes in the tamper decreased the reactivity, and more 25 was added bringing the total amount to 625 grams from the usual 580.

A block diagram of the apparatus is shown in Fig. I. A neutron pulse received in the initiating channel was passed through the selector, which will be described below, and actuated the time analyzer. This circuit waited for a predetermined time T, and then opened a gate of determined width ΔT, through which neutron pulses from the counting channel were recorded in counter D. The time analyzer could not be reinitiated until after the gate had opened and shut. The number of times the analyzer was initiated was recorded in counter C. Thus, the ratio of the number of counts in D to the number of counts in C should give $P(T)\Delta T$. In actual experiments it seems to give $kP(T)\Delta T$, where k is an unknown factor less than one. In other words, the time dependence is properly measured, but the quantity $\frac{E X_2}{2 \nu^2 \tau (1-K_p)}$ is not determined. The reason for this seems to be that the circuit, as described, is not initiated by

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all neutrons nor by an average or random selection. The fact that the analyzer is dead to initiating neutrons for a time means that those pulses which closely follow other pulses are discriminated against. In other words, the initiating circuit discriminates against neutrons which are members of large chains, so the result is not surprising.

The purpose of the selector was to minimize this difficulaty. It consisted of a gate which was opened at random intervals with respect to the behavior of the boiler. Actually, since the boiler itself is more or less random, a regular opening was used. The time interval between openings was longer than any time delay studied. If this gate were made sufficiently narrow so that the probability that two pulses came through in one opening was sufficiently small, the pulses so passed would be randomly selected and each pulse would operate the time analyzer. One would then expect the factor of the exponential in (2) to be properly measured. It is not practical, for intensity reasons, to make the gate sufficiently narrow. Data were taken with different gate widths and different efficiencies in the initiating detector, and it was possible to extrapolate to effectively zero gate width. The number of pulses coming through the selector were counted in counter B. A comparison of the number of counts in B to the number in C gave a measure of the amount of discrimination in the time analyzer. The selector served another

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purpose. Without the selector the time analyzer could be reinitiated in a short time when the time delay was short, and only after a somewhat longer time when the time delay was long. With the selector in use, the time between possible reinitiations of the analyzer was independent of the time delay. Without this action the time dependence of the number of subsequent neutrons would not have been properly measured, as there would have been a different discriminating action of the analyzer at short times than long. Analytically, the factor k in what the apparatus measures, $kP(T)\Delta T$, is a function of T. With the selector, it is independent of T; and, as either the gate width or efficiency of the initiating detector are decreased, it approaches one.

The chamber efficiency was determined by a comparison of the counting rate with that of a small 25 chamber placed at an appropriate point in a re-entrant tube in the reactor. The efficiency of the 25 chamber was calculated from the mass of 25, the mass of 25 reacting in the boiler an estimation of its counting efficiency and a measurement of the neutron distribution in the boiler. The background was determined from the total counting rate in the counting channel as measured on counter E.

Measurements were made at three critical settings: One with the control rod set fairly close to critical, which, according to calibration measurements, was -2.9 grams: another with the control rod out and the safety rod in, which corresponded to -14.8 grams: and,

[redacted]

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finally, with both the control rod and safety rod in, which corresponded to -26.1 grams. These calibrations had been made with 580 grams in the reactor. For these measurements there were 625 grams present. The critical settings, therefore, were multiplied by 625/580 or 1.08 making more nearly correct values for the critical settings -3.1, -16.0, and -28.2 grams, respectively. In arriving at these figures it was assumed that the control and safety rods acted independently.

Fig. 2 shows the results for two measurements at the most critical setting, -3.1 grams. The number of connected counts per millisecond, per initiation of the time analyzer, is plotted against the mean time after the initiating count. The background, which was subtracted in each measurement, is indicated by the correspondingly labeled line on the vertical axis. In both cases, the gate width was one millisecond. The same channel was used for both initiation and subsequent counting. The efficiency of the detector was 2.3×10^{-3} counts per fission. The RMS error of several typical points is indicated. In both these curves, as well as in five others taken but not shown, a period of 10.9 milliseconds is indicated. All measurements were in excellent agreement.

The intercepts of the two curves at 0 time, which should be equal to $\frac{E X_2 dt}{2 \nu^2 \tau (1-K_p)} \doteq I$, are different. Curve A was taken with a gate width in the selector of 0.92 ms., while for curve B it was 0.33 ms. For curve A the ratio, R, of the number of times the

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analyzer was initiated to the number of pulses coming through the random selector, was 0.83; and for curve B it was 0.86. This general behavior was true for the five other curves which were taken with a wide variety of selector gate widths and chamber efficiencies. Fig. 3 shows a plot of the intercept I against R. The extrapolation to R = 1 or to the value which I would have if the circuit had been initiated for every pulse, is seen to be reliable and gives a value of .95 counts per initiation per millisecond.

Fig. 4 shows the results of three of the measurements at -16.0 grams. Curves A and B coincide and were taken under identical conditions, except that curve A was obtained with an additional source placed near the boiler. It is seen that the background is over three times as large, but that there is no other significant difference. The natural source present in the boiler due to spontaneous fission α-n reactions, etc., was of the order of 600 neutrons per second. All three curves were taken with a gate width of one ms. and a chamber efficiency of 2.3 x 10^{-3} counts per fission. A and B had a selector width of .92 ms., which gave values of R of 0.80 and 0.83, respectively. Curve C had a selector width of 2.8 ms.; R was 0.58. A total of six measurements were made, all of which gave a value of the period of 7.6 ms. Fig. 3 shows a plot of I against R which gives 0.58 as the extrapolated value of the intercept I.

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Only one measurement was made at the least critical setting of -28.2 grams. The results are shown in Fig. 5. The gate width was as before, one ms.; the selector width 0.92 ms.; R was .95; the chamber efficiency 2.2 x 10^{-3} counts per fission. The slope indicates a decay period of 4.8 ms. Since only one measurement was made, it was not possible to extrapolate the I versus R plot. Since R was already close to one, however, the slope was guessed and an intercept of 0.36 was obtained.

Since both the period and intercept vary inversely as $1-K_p$, a plot of their reciprocals against criticality should be a straight line; and since the point where K = 1 is well determined, the difference between K and K_p in terms of grams should be determined. Fig. 6 shows such a plot. Unfortunately, neither the three points for the inverse period nor inverse intercept lie on straight lines. This probably means that the scale of criticality is not well determined. A possible reason is that safey rod and control rod do not act independently, which was assumed in setting up the criticality scale. Unfortunately, no recalibration was made at the time, or no other checks on criticality were made. The setting of -3.1 grams does not suffer from the difficulties of interaction between the control and safety rod and, since it is not far from critical, can not be far wrong in any case. According to LA-[illegible]83 one gram is equivalent to 5 x 10^{-4} in K, and the difference between K and K_p is 7.9 x 10^{-3}. For the -3.1 grams setting

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$1-K_p$ is, therefore, 9.5×10^{-3}, and τ the mean life of a neutron in the boiler is 104 microseconds. If one takes these values of τ and $1-K_p$ and assumes for X_2 its minimum possible value of 4 (obtained by assuming that either 2 or 3 neutrons are emitted per fission with equal probability) and calculates the value of the intercept, one obtains 0.74 as compared with the measured value of 0.95. The difference of 26 °/o is not disturbing in view of the several sources of error. This measurement, however, does establish the fact that X_2 is not much greater than its minimum possible value, and the even division between 2 and 3 neutrons per fission is not far from the truth. The value of X_2 is of interest in the calculation of predetonation probabilities.

Fluctuations

A series of experiments were performed on the water boiler which are related to the Rossi experiments, namely, a study of fluctuations. These are not written up or elsewhere reported. A gate was opened at regular intervals (which amounts to a random opening with respect to the conditions in the water boiler) and coincidences of neutron pulses through this gate were recorded; that is, the number of times two pulses, and so on up to 15 fold coincidences. Information above 15 fold coincidences was obtained by the use of scalers which effectively recorded, for instance, the number of times 200, 201, 202 . . . . . . 215 fold coincidences occured in a single counter. Data were taken with gate widths between one millisecond

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and a quarter of a second, at the same critical settings used in the Rossi experiment.

Unfortunately, the gating circuit was faulty, and the circuit tended to discriminate against many-fold coincidences. The results are, therefore, only a sort of lower limit to the magnitude of the fluctuations. Time was not available to repeat this work with proper equipment; and as there was no theoretical interest in the imperfect results, they have not been properly analyzed nor properly reported. Inspection and cursory examination show that the statistics bear little resemblance to a Poisson distribution. These results are available in LA notebook 276. This experiment is mentioned here, however, as a suggestion that a proper investigation might be interesting, in which case the preliminary results might be useful.

UH_{10} Assemblies

Two sets of time-scale measurements were made as part of the hydride program. One in a beryllium oxide tamper, representing a non-absorbing thermalizing tamper, and the other in WC, representing a non-thermalizing absorbing tamper. The hydride assemblies are described in LA-618. A flat fission chamber was used as a detector which contained 0.497 grams of 63 °/o oxide or 0.260 grams of 25. It was placed approximately in the center of the assembly of active material.

An estimate of the efficiency of the chamber was made by assuming that the 25 in the chamber underwent fission at the same rate as the 25 in the surrounding assembly, and that the counting efficiency of the chamber was one. Since the BeO assembly contained 4.3 Kg. of 25 the efficiency was 6.0×10^{-5} counts per fission and for WC 2.1×10^{-5} counts per fission, since the latter assembly contained 12.5 Kg. of 25. This estimate is only rough but serves to give the proper order of magnitude. The same chamber was used for both initiating and subsequent counting. The time analyzing circuit contained nine channels. It received an initiating count and opened each of the channels in order for a predetermined length of time, and then reset itself. The efficiency of the detector was sufficiently low so that no selector, such as was used with the water boiler, was necessary. The channel width was in all cases 40μs. It would have been desirable to have used wider channels in some cases, but the hydride assemblies were slower than anticipated and 40μs was the maximum range of the instrument.

The BeO measurements were made with the detector, active material and part of the tamper stacked in a steel tray, which could be moved in and out of the main body of tamper. The position of the tray could be accurately set and was used to adjust the criticality. This assembly is described in detail in LA-618. Measurements were made at approximately 1 °/o, 1 1/2 °/o and 2 °/o from prompt critical.

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The results are shown in Fig. 7 The expected number of counts per 40μs interval following a count at $t=0$ is plotted as a function of the time after the initiating count. Curve A is for 1 °/o off and indicates a value of 550μs for $\frac{1}{a}$ with an initial value or intercept of 2.3 x 10^{-3} counts per 40μs . Curve B is for 1.5 °/o off with a slope of 400μs and an intercept of 1.6 x 10^{-3}. These measurements are quite rough and the values above only approximate. The orders of magnitude are, however, established. The mean life of a neutron in such an assembly is about 5.5μs .

The results for WC tamper are shown in Fig. 8. As before, curve A is for about 1 °/o off prompt critical with a slope of 126μs and an intercept of 1.06 x 10^{-2} counts per 40μs . Curve B is for 1.5 °/o off with a slope of 75μs and an intercept of 6.5 x 10^{-3}, and curve C is for 2 °/o off with a slope of 67μs and an intercept of 3.2 x 10^{-3}. The mean life of a neutron in the assembly is about 1.3μs .

In both this case and for the BeO assembly, the measured value of the intercept is close to the value calculated from τ, the chamber efficiency, and a low value assumed for X_2.

The difference between the 5.5μs mean life with BeO tamper and 1.3μs with WC tamper is striking and is an illustration of the extent to which the properties of active assemblies depend on the tamper.

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Sufficient time of both personnel and active material was not available to pursue these experiments further or to improve the precision. The experiments served, however, to establish that the reaction time of the hydride assemblies was too long to be of military interest, and to give valuable experience which was applied to the metal assemblies (LA-374).

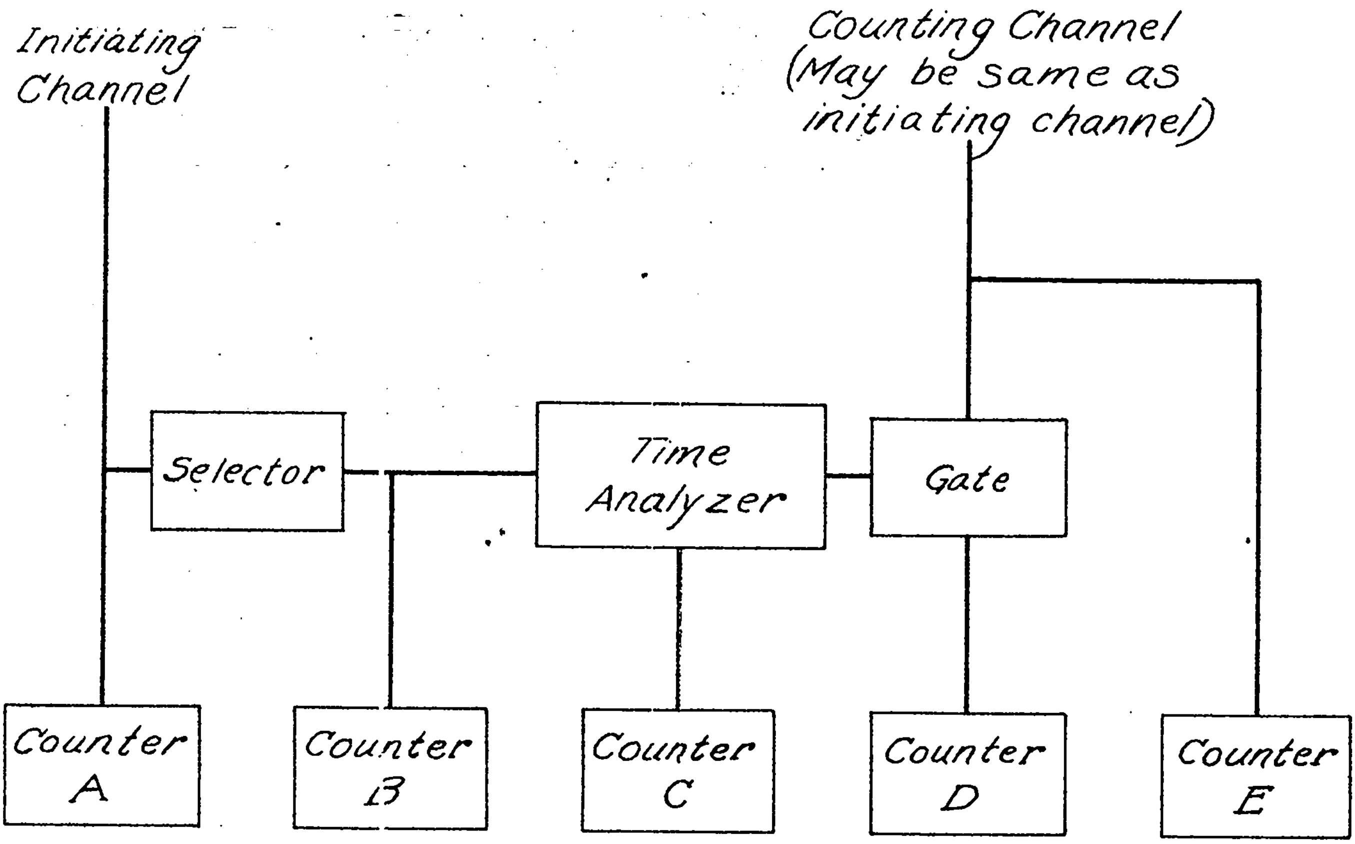

FIG. 1
Block Diagram of Water Boiler Rossi Experimental Apparatus

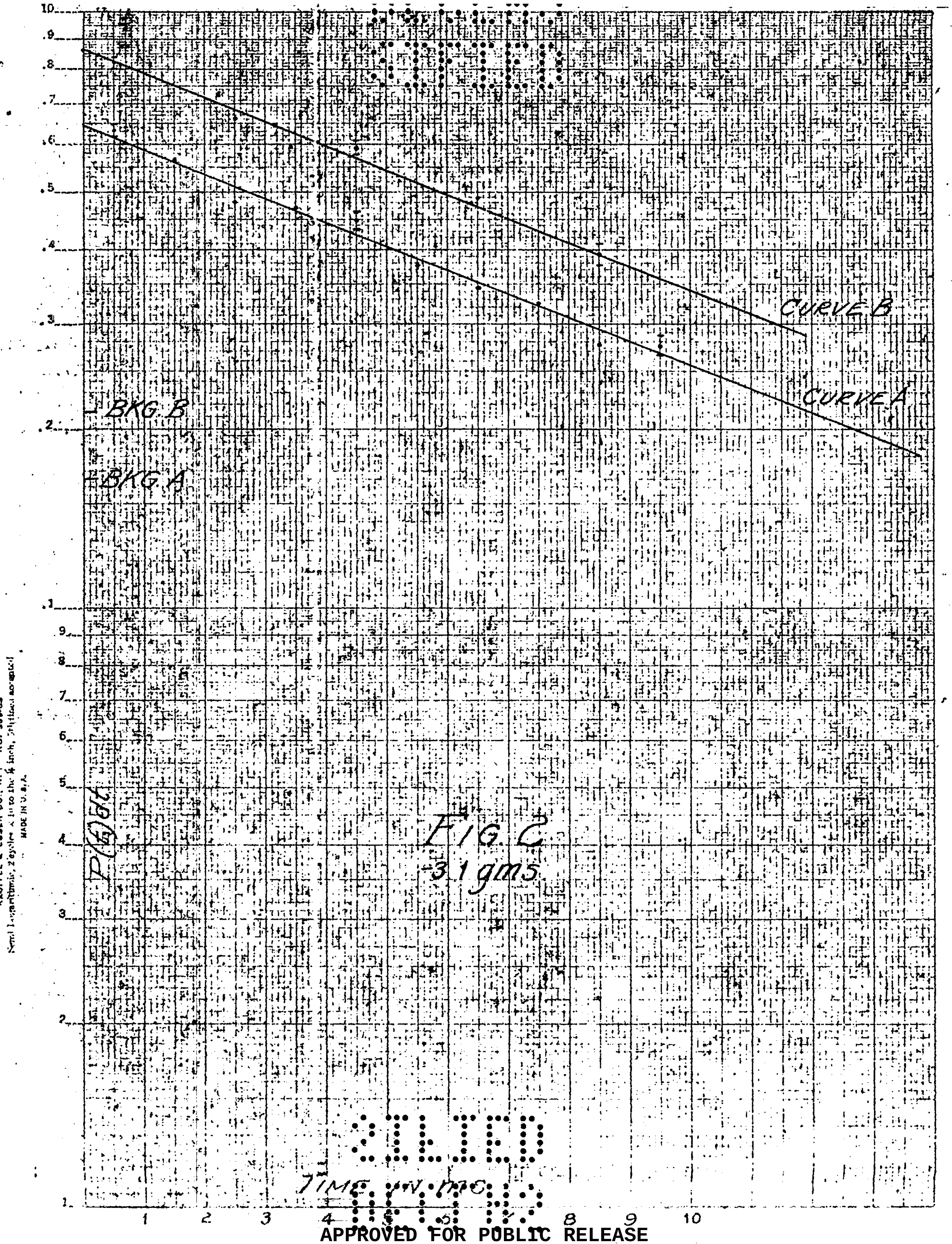
CURVE B
CURVE A
BKG B
BKG A
P(t)dt
TIME IN MC
1
2
3
4
5
6
7
8
9
10
KEUFFEL & ESSER CO., N.Y. NO. 359-83
MADE IN U.S.A.

FIG. C
3.1 gms

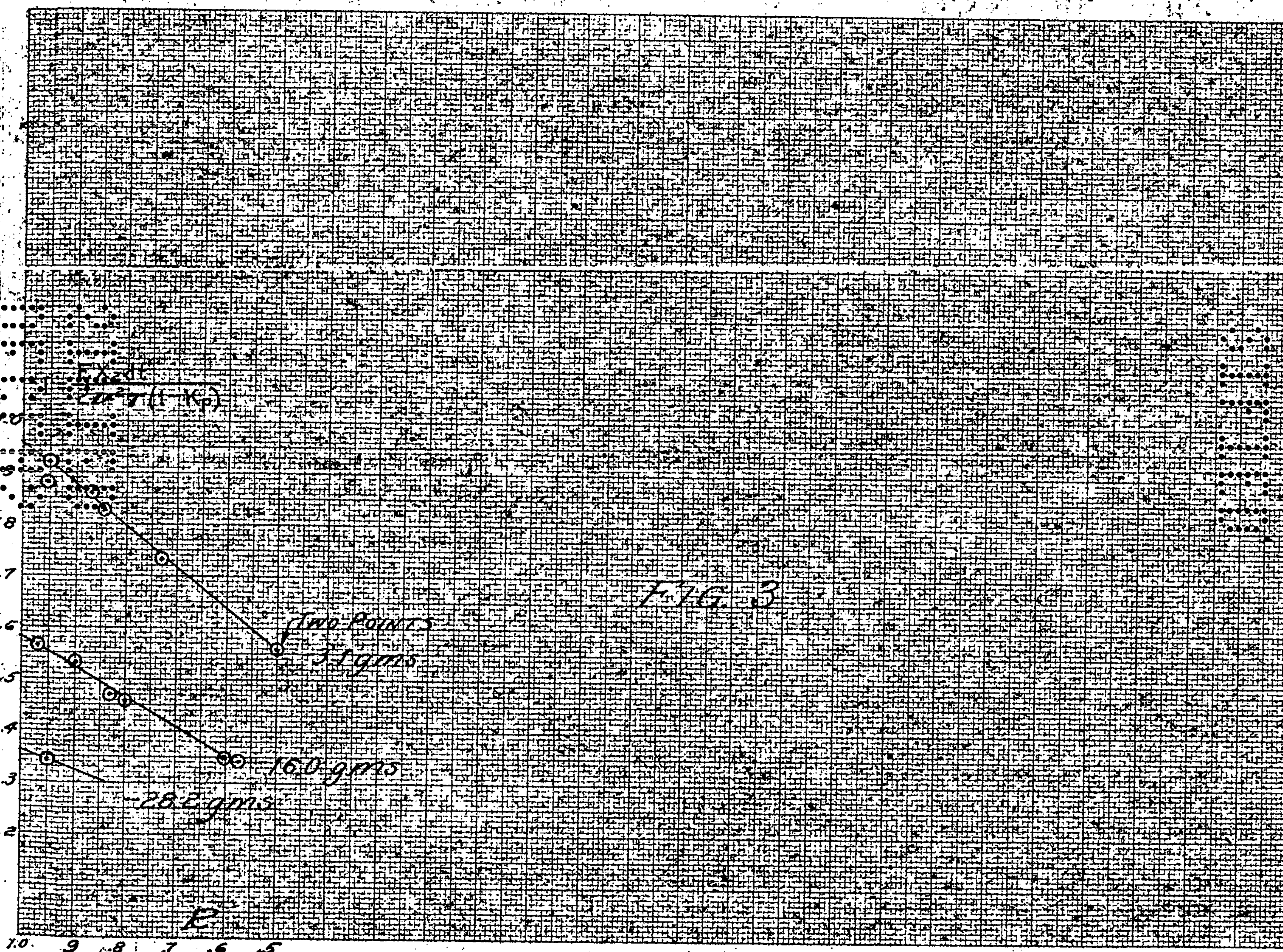

FIG. 3

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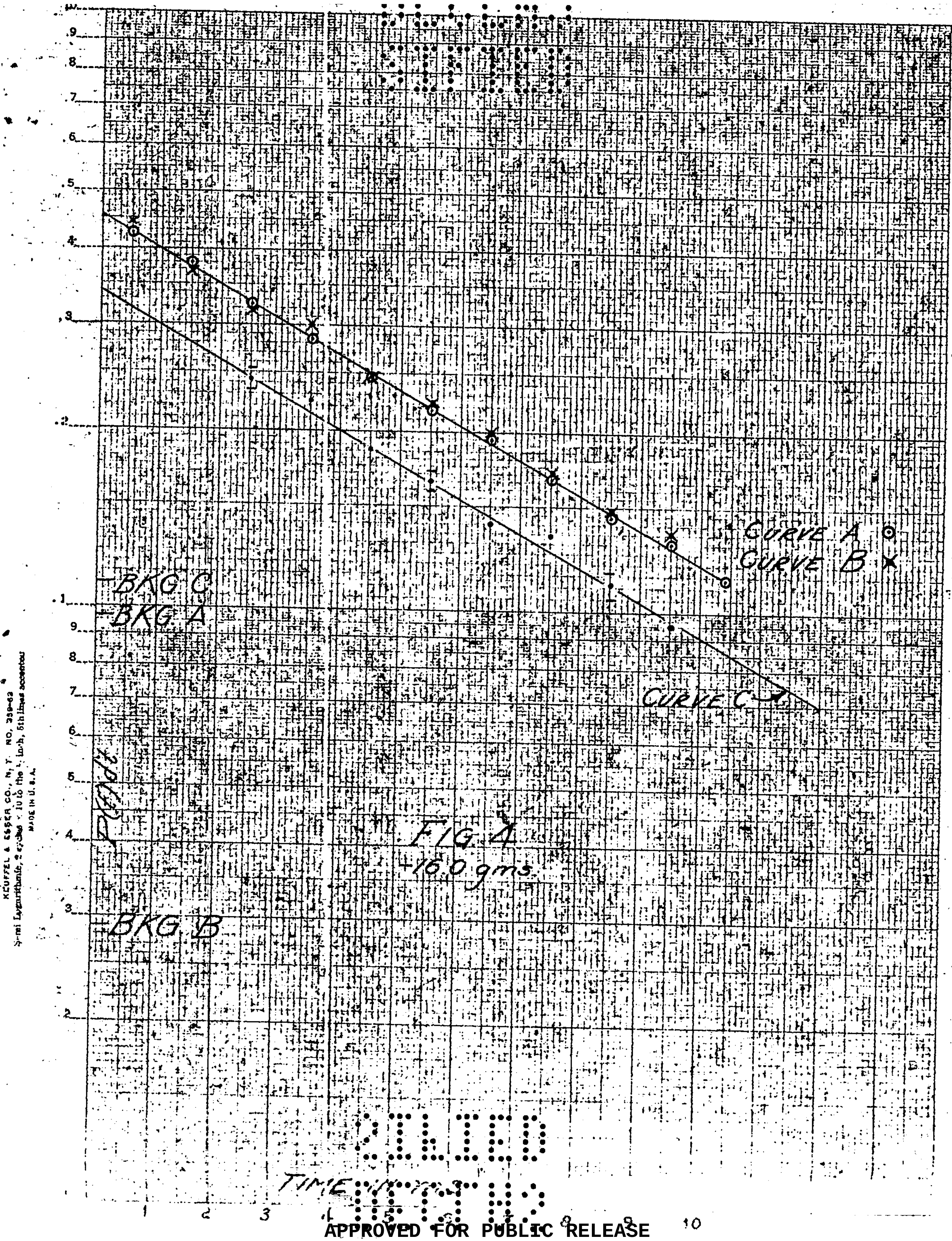
CURVE A
CURVE B
CURVE C
BKG C
BKG A
BKG B
TIME
KEUFFEL & ESSER CO., N.Y. NO. 359-62
Semi-Logarithmic, 2 cycles × 10 to the ½ inch, 5th lines accented
MADE IN U.S.A.

FIG 4
16.0 gms

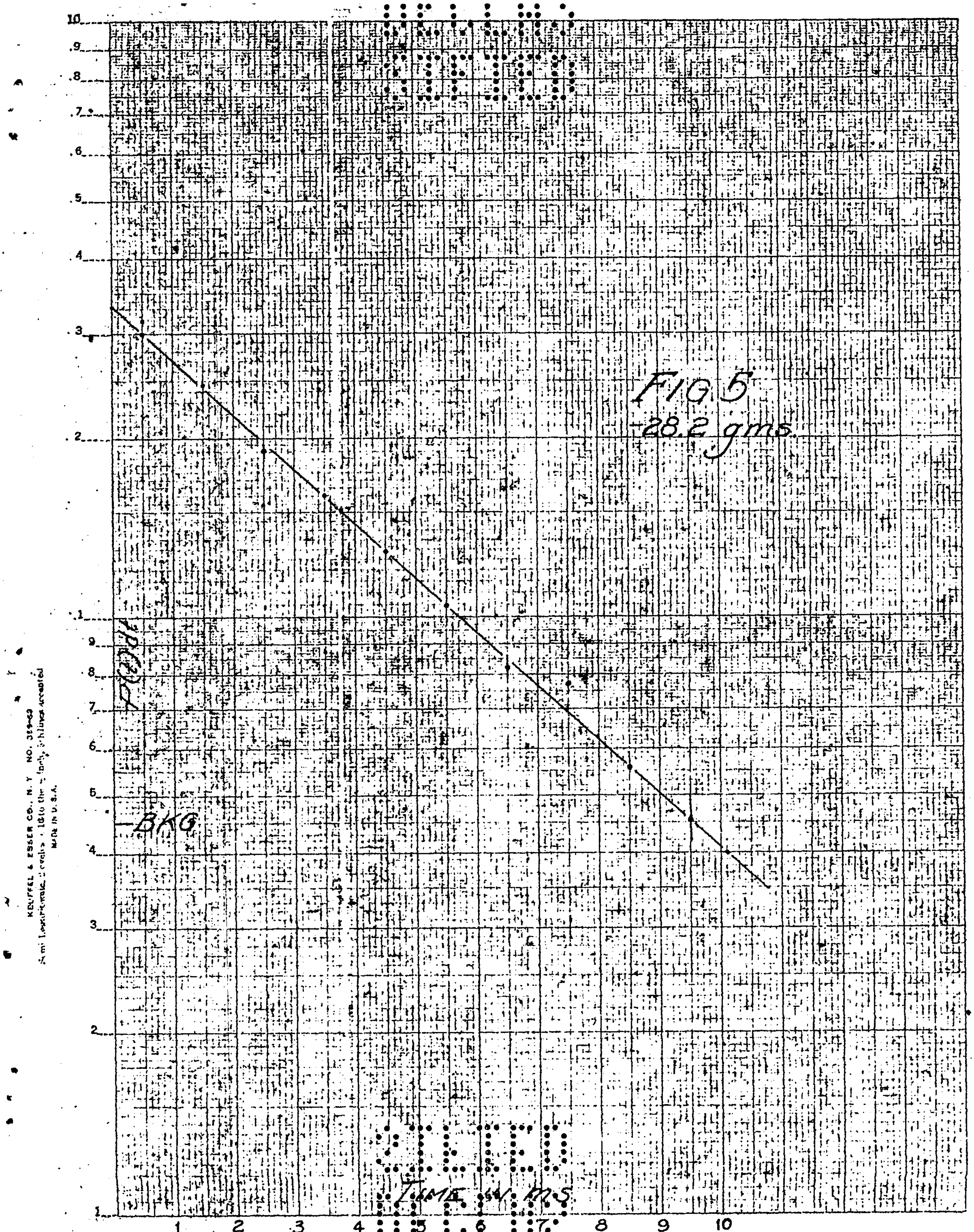
FIG. 5
28.2 gms.
BKG
Time in ms
KEUFFEL & ESSER CO., N.Y. NO. 359-62
MADE IN U.S.A.

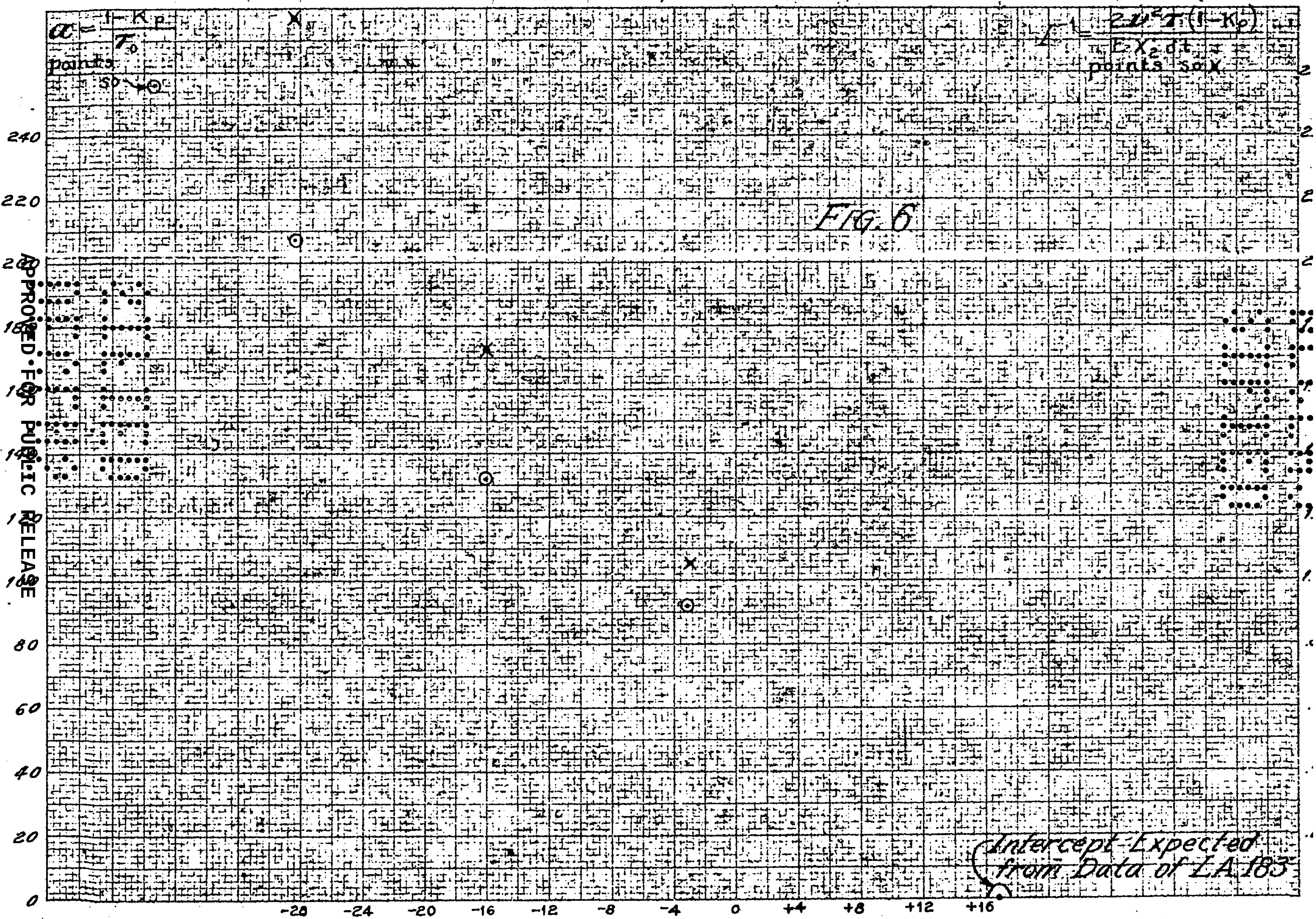
points so ⊙
points so X
Intercept Expected from Data of LA 183
240
220
80
60
40
20
0
-28
-24
-20
-16
-12
-8
-4
0
+4
+8
+12
+16

FIG. 6

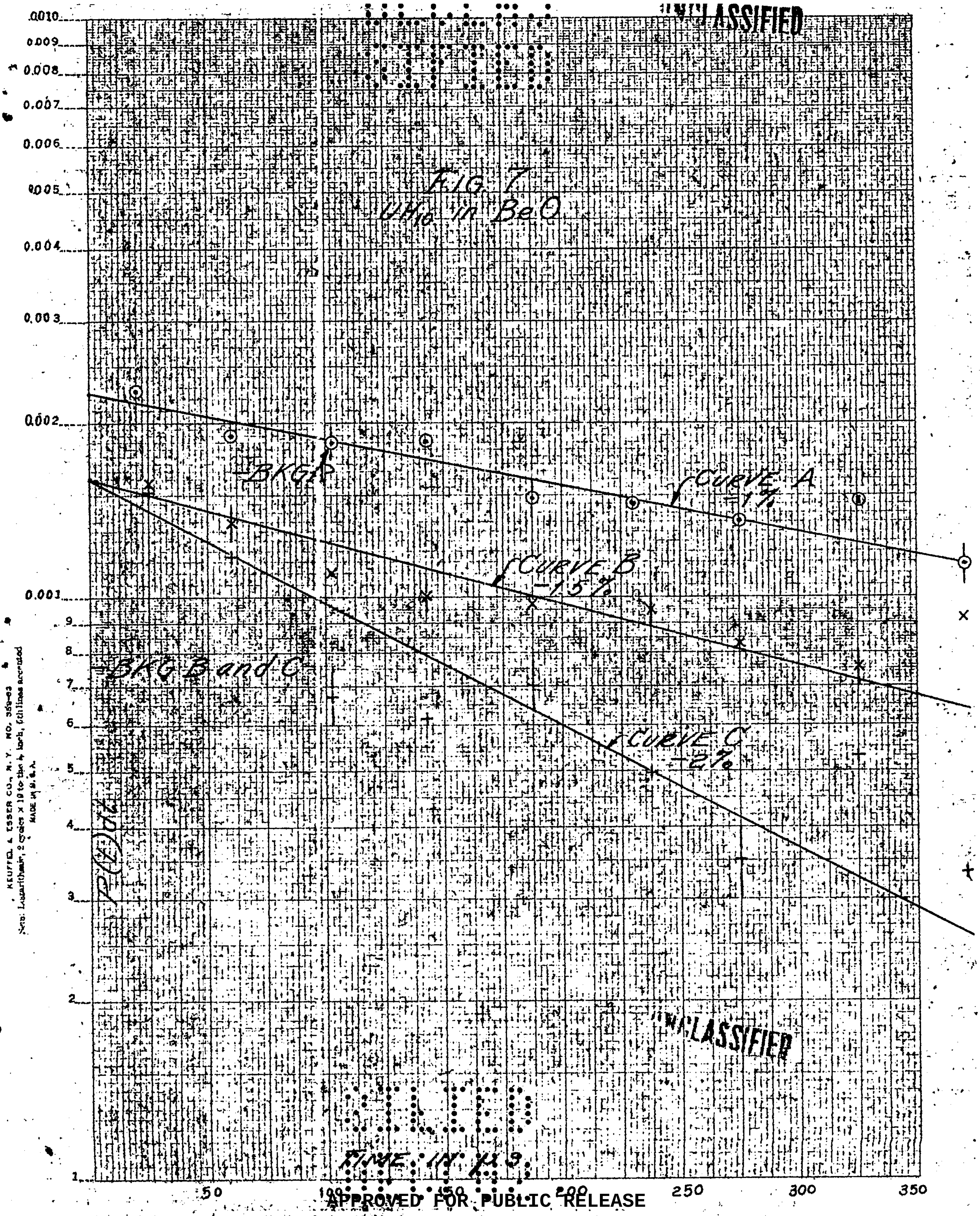

FIG. 7
UH10 in BeO
BKG A
CURVE A
-1%
CURVE B
-1.5%
BKG B and C
CURVE C
-2%
P(t)dt
TIME IN μs
0.010
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
50
100
150
200
250
300
350
KEUFFEL & ESSER CO., N. Y. NO. 359-63
Semi-Logarithmic, 2 cycles × 10 to the ½ inch, 5th lines accented
MADE IN U.S.A.

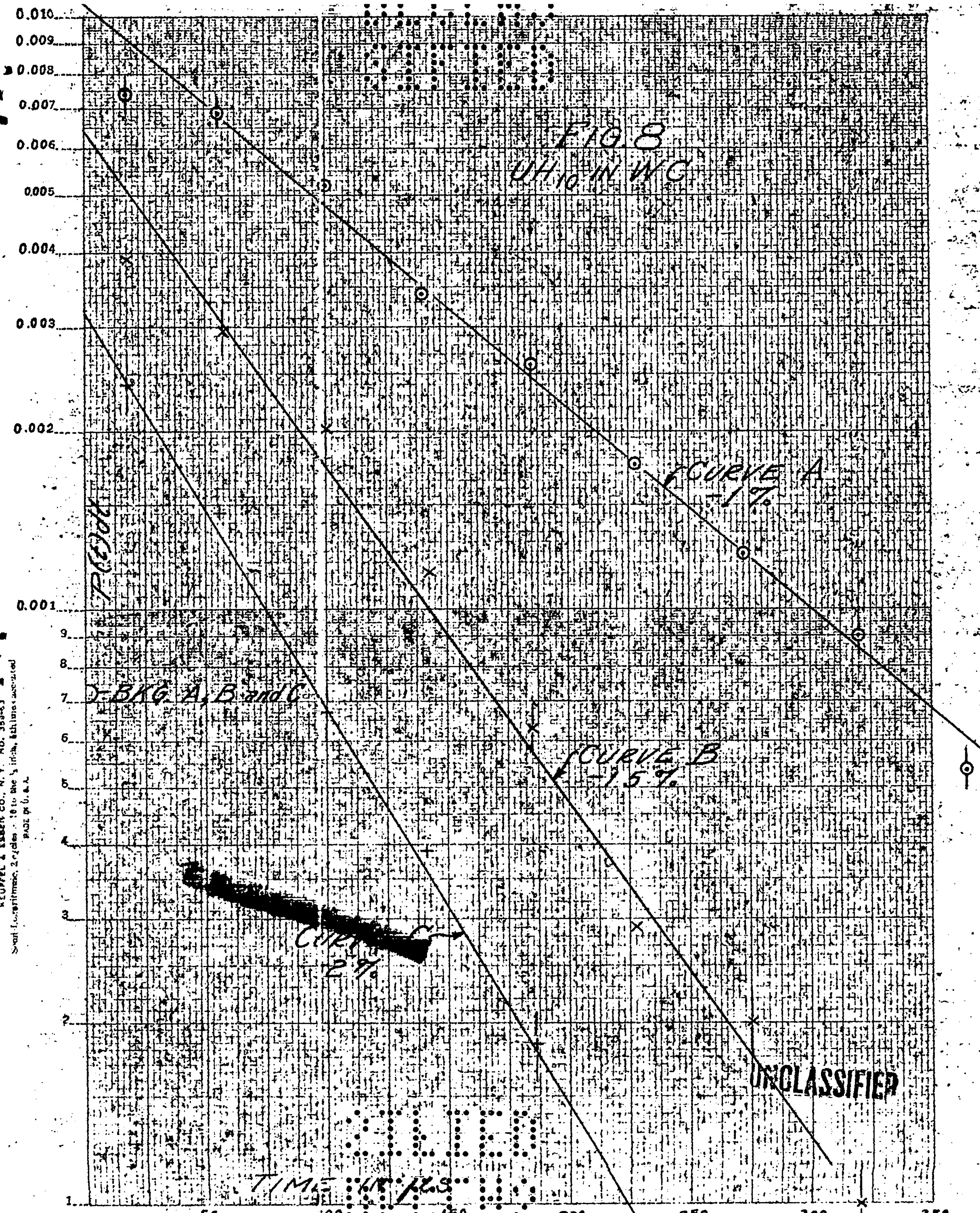
FIG 8
UH10 IN WC
CURVE A
-1%
CURVE B
-15%
CURVE C
2%
BKG. A, B and C
P(t)dt
TIME IN μs
0.010
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
50
250
300
350

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