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CONTROLLED PRODUCTION OF AN EXPLOSIVE NUCLEAR CHAIN REACTION

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ABSTRACT [redacted]

A chain reactor (the "dragon") was constructed so that by dropping a slug through an assembly (both of active material), a divergent chain reaction supported by prompt neutrons alone was achieved for about 1/100 second. In this short time neutron multiplications up to 10^{12} were obtained. Various measurements were made which permitted calculation of the generation time in two independent ways: from the shape, and from the size of the neutron burst which occurred when the system became prompt-neutron supercritical; these calculations agreed reasonably well with each other, and also with the time obtained from a Rossi time-scale experiment. The neutron bursts produced by the reactor were used in other experiments on delayed neutrons, gamma rays, the effect of intense radiation on coaxial cable, and on living animals.

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CONTROLLED PRODUCTION OF AN EXPLOSIVE NUCLEAR CHAIN REACTION

INTRODUCTION

The neutrons emitted in fission are of two kinds: "prompt", i.e. emitted by the fission fragments presumably within less than 10^{-12} seconds, and "delayed", i.e. emitted after times of the order of seconds.

Chain reactors constructed so far (graphite piles, water boilers) always depend partly on the delayed neutrons; this makes them easy to control since even in a slightly supercritical state the neutron population grows at a moderate speed, doubling in a time of minutes or perhaps seconds. If the multiplication were to be increased so much that the prompt neutrons alone can support a divergent chain, the neutron population would grow very rapidly, doubling in a small fraction of a second. Such a "prompt" chain reaction has therefore an explosive character and therein lies its military value.

In the experiments described here a chain reactor was arranged so that for a short time of about 1/100 second the conditions for a prompt chain reaction could be realized. This was done by dropping a slug of active material through a vertical hole in an active assembly.* By adjusting the conditions properly, very large neutron bursts could be obtained, indicating a multiplication of the original neutron population by up to twelve powers of ten within this short time. In one particular burst a temperature rise of the active material by over $6^{\circ}C$ was recorded, corresponding to the liberation of 12000 calories, and over 10^{15} neutrons. Since most of this energy is liberated within about 3 milliseconds, the heating rate was about $2000^{\circ}C$ per sec, corresponding to a peak power of 20,000 KW.

* Because of the similarity of this procedure with that of tickling the tail of a dragon (pointed out by R. Feynman) the experiment has been sometimes called "the dragon experiment."

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Measurements were made of the way in which the fission rate varied with time during the burst, of the slug position at the maximum of the burst, and of the dependence of the burst intensity on the adjustment of the multiplication. In conjunction with static calibrations, carried out with the slug in a fixed position, these measurements are in good agreement with what was expected. It is for instance possible to calculate from them the generation time, i.e. the mean time τ_0 between a fission and its daughter fission in two independent ways, and the results agree well with each other and with a third determination of τ_0 by a Rossi time-scale experiment.*

The intensity varied considerably from one burst to another, even if the conditions were not changed; these fluctuations are to be expected because each burst is the result of an enormous multiplication of very few primary neutrons. A crude measurement of the size of these fluctuations again showed agreement with theory.

Some additional experiments were carried out in which the neutron bursts were used as a tool to study the delayed neutrons (see LA-252) and gamma rays, and also to investigate the effect of intense radiation on coaxial cable and on rats. An unsuccessful attempt was made to thermalize the neutrons and to use them in conjunction with a cloud chamber.

MECHANICAL STRUCTURE AND SAFETY DEVICES

The falling slug of active material was contained in a steel box, 14" long and with a 2-1/8" x 2-1/8" cross section. Its path was defined by 4 Dural guides, with a slack of about 1/8" so that even a considerable warping of the guides would not interfere with its drop. The guides were kept at the correct relative

* Report Forthcoming.

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position by brass clamps every 2 feet or so, and held straight and vertical by guy wires attached to a steel derrick, about 12 feet high. They passed through a hole in a heavy (3/8") steel table on which the active material and tamper could be assembled around them, and led at the bottom into a catcher box into which the slug fitted with a few mils clearance; this close-fitting catcher box served as a pneumatic brake.

Part of the reacting assembly was contained in a pivoted steel box which could be raised into position by compressed air acting on a piston. This "safety box" could be raised and lowered by throwing a switch operating an electromagnetic air valve; during static calibration this valve was connected to a neutron monitor* so that it would drop automatically whenever the neutron level increased over a preset value. When the safety box was down, the reactivity of the system was decreased so that even with the slug at the center no reaction could occur.

To control the multiplication, a flat brass box ("control vane") filled with a suitable absorber could be inserted between the safety box and the rest of the system, its position being adjustable by a screw drive.

Fig. 1 shows a view of the whole setup, without active material.

Before each drop the slug was picked up by an electromagnet hanging on a rope and hoisted to a suitable point near the top of the guides. To do this safely one had to lower the "safety box" first, and, lest one should forget it, the magnet was wired in series with a microswitch which was closed only when the safety box was down. On arrival the slug was secured by pushing a "latch" through the guides below it (this was done by a pair of Selsyn motors). The purpose of the latch was to prevent the slug from being dropped unintentionally, e.g. because of a power failure.

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* R.J. Watts, LAMS-161. [redacted]

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By pushing in the latch another microswitch was closed which provided an alternative path for the magnet current so that now the safety box could be lifted without dropping the slug on the latch. When the operator was sure that everything was ready for a drop (controls properly adjusted, no people near the system, etc.) he pressed the HWG ("Here We Go") button, establishing a third path for the magnet current and enabling him to remove the latch and subsequently, by releasing the HWG button, to drop the slug.

This whole somewhat complicated arrangement was designed to relieve the operator from any responsibility until he pressed the HWG button. If, for instance, he tried to raise the safety box before the slug was up on top and secured by the latch, the magnet would at once release the slug, which would fall into the catch box well within the time required for the compressed air to raise the safety box (about 10 sec). Again, if he tries to pull out the latch without pressing the HWG button, the slug falls on the latch which then can no longer be moved. (The latch was moved through a slow gear so that one could not pull it out in less than about 5 sec). Colored lights were arranged to keep the operator informed about the position of the safety box, latch, and magnet.

The velocity of the slug was checked in each single drop (see below under "timing system") and found to be constant well within 1%. At the beginning of each series of drops several dummy drops (with the safety box down) were made in order to make sure that the slug was falling freely and with the correct velocity.

All the operating and recording equipment was placed in a room about 40 ft away from the assembly and behind a 5-ft wall of concrete and earth. If (to assume the worst) the slug had got stuck at the center of the assembly, there would have been a rather inefficient explosion, probably equivalent to a few ounces of H.E. In this case the control room would have afforded sufficient protection against the radiation, although it would have been advisable to leave it quickly before the active fumes had time to spread. [redacted]

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ACTIVE ASSEMBLIES

Three different active assemblies were used; we shall call them assemblies 1, 2, 3 in what follows.

Assembly 1 consisted of about 10 kg of UH_{10} surrounded by about 6" of BeO. The UH_{10} was made by the CM division by pressing UH_3 with Styrex into cubes, some of $\frac{1}{2}$", some of 1" side. The symbol U stands for the beta-stage material of 71 to 75% 25 content. The UH_{10} also contains about 4 atoms of carbon for each atom of U.

The reactivity was controlled by means of the control vane which contained 5/16" of pyrex sheet. The safety box was filled with BeO. The UH_{10} did not extend beyond the control vane, but was built up in roughly spherical shape with its center outside the guides for the slug. It was found that moving the slug sideways inside the guides changed the multiplication constant K by about 0.1%, a change which would alter the size of burst by a large factor. We therefore tilted the whole arrangement by about 1.5° and straightened the guides carefully in order to make sure that the slug would always slide down on one side of the guides. Tests with electric contacts showed that it always followed the same path to within 0.005" and the corresponding uncertainty of about 0.01% in K was considered tolerable.

This assembly gave the first evidence that a prompt-neutron reaction could be produced, and served to get some qualitative information. The control vane was pushed in far enough so that no prompt reaction could occur (see later under "static calibration"). The slug was then repeatedly dropped and the control vane was pulled out in small steps. The first bursts were obtained in the small hours of January 20. Some more active material was added and the pyrex in the control vane was replaced by a mixture of B_4C and paraffin wax, to give stronger control. The following night bursts were increased until a temperature rise of $0.01^{\circ}C$

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was observed due to the strongest burst. After that the whole assembly was dismantled and the UH_{10} was used for various critical-mass determinations.

Assembly 2

On January 28, the UH_{10}, together with amounts which had arrived in the meantime, was reassembled, making about 15.4 kg in all. In order to make the best use of the material, the control vane was removed and control was effected by moving a tray containing a part of the core and tamper. The tray was moved by a screw and its position was read by a micrometer to the nearest mil; this arrangement was meant to eliminate slack but didn't completely. We tried to use tungsten carbide as a tamper in order to avoid the large contribution of thermal neutrons which results from the use of a BeO tamper. However, the system would not go critical because of the gaps due to the guides, tray walls, etc., and we had to come back to BeO. But we found it possible to cut the contribution of thermal neutrons by placing a layer of cadmium between the UH_{10} and the tamper, without reducing the multiplication too much.

Most of our information was obtained with this assembly. It was used until February 1 when we had to return about two thirds of our UH_{10} to the CM Division for conversion into metal.

Assembly 3

The remaining 5.4 kg of UH_{10} were "diluted" with polyethylene ("Polythene") bricks in the volume ratio 1 UH_{10} to 5 Polythene. As a tamper we used 3" of graphite backed by 1" Polythene. (This was about as effective as 6" of graphite, and better than any thickness of Polythene alone). The safety box contained 5" Polythene. The slug contained 6 1" cubes of UH_{10} in an unbroken row, surrounded by ½" Polythene and backed above and below by about 4" Polythene. The rest of the assembly was approximately a cube of 8"

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sides, the center of the guides being $1\frac{1}{4}$" off the center of the cube. The multiplication was varied by removing pieces of the outer 1" Polythene layer.

Because of the presence of large amounts of hydrogen and carbon, with no Cd present, the τ_0 of this assembly was expected to be quite large (we found it about 20 μsec). Although this makes the experiment less "interesting" it has the advantage that the fluctuations are much smaller and that bursts can be made to order. This assembly was used to measure delayed neutrons and gamma rays and to make a rough test of the size of fluctuations. In the course of these experiments the size of bursts was gradually increased until in one burst the cubes became so hot that swelling and blistering occurred. The whole system expanded by about 1/8" and its multiplication became reduced so much that no more bursts could be obtained from it.

TIMING SYSTEM

Two narrow light beams were arranged to cross the path of the falling slug, 92.3 cm apart, one above and one below the active assembly, and then to fall on two photocells of the multiplier type. The slug carried a small knife edge on top so that the instant when the light beam is re-established after interruption is sharply defined. The photocells operate a gate circuit, opening it when the knife edge passes the first light beam and closing it when the knife edge passes the second beam. The gate allows the signal from a 100-Kc crystal oscillator to pass into a large scaling system (three standard scales of 64 in series). Thus the scaler counts at a rate of 100,000 counts/second during the time it takes the knife edge on the falling slug to cover the distance between the light beams, and by reading the interpolator lights one obtains this time in units of 10 microseconds. The light beams were nearly a millimeter wide and hence the opening and shutting times are determined not better than to about 100 microseconds. The

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electronic equipment was built by W. C. Elmore of G-4.

The drop velocity calculated from this was found to be reproducible to $\pm\frac{1}{4}\%$, and about 1% less than the value calculated from Galileo's law. This deficiency is probably due to friction. In calculating the position of the slug at any given time it is assumed that the slug falls with a constant acceleration of 965 cm sec^{-2} so as to get agreement with the observed average velocity.

STATIC CALIBRATION

It is obviously impossible to carry out static measurements in those configurations of the system in which a prompt-neutron chain can develop because the assembly would blow up in a small fraction of a second. We therefore had to be satisfied with measurements in a state of reduced reactivity, extrapolating to the region in which we are really interested. These extrapolations were based on the hypothesis that the different means by which we can change the reactivity have additive effects. This hypothesis was checked in a rough way in the region accessible to static measurements and found to be tolerably correct.

To obtain K for any particular position of slug and control, the exponential growth rate of the reaction was measured with an outside BF_3 chamber and DC amplifier. No great precision was aimed at. Doubling times down to about 2 sec were used; shorter times were too hard to measure, and also increasingly dangerous.

To convert doubling times into K values, the inhour formula for the water boiler* was used. This would be correct only if the contribution of delayed neutrons in our assembly was the same fraction of the prompt neutron effect as in the water boiler, namely, 0.008. This assumption is probably not far from correct but we shall point out in the discussion how it affects the results.

* LA-394.

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Fig. 2 indicates the dependence of K on the position of the slug and of the control vane filled with B_4C and paraffin in assembly 1. The curves corresponding to different slug positions can be made to coincide approximately with the dotted extrapolated curve, by moving them up by a suitable amount, which means that our additivity hypothesis is approximately correct.

It is seen that for vane position 8" $K-1$ becomes 0.008 if the slug is at the center, and hence if the vane is pulled out further a prompt reaction becomes possible for an increasing range of slug positions.

Fig. 3 shows the calibration of assembly 2. The change of K with the control tray position is fairly linear and is believed to continue linearly into the prompt critical region. The effect of slug position was measured over a small range only, unfortunately, and the curve shown indicates what we believe is the best extrapolation.

Fig. 4 shows the effect of slug position on K in assembly 3.

RECORDING OF BURSTS

1) A boron-lined ion chamber (converted RaLa chamber filled with pure argon*) was placed close to the active assembly, so that the average time of flight of thermal neutrons from the assembly to the chamber was only about 0.1 millisecond. While the electrons produced in such a chamber are swept to the wire in about 1 to 2 microseconds, the positive ions will take several milliseconds to move to the outer electrode and will therefore be almost stationary during the burst. With strong bursts these ions would form a very substantial space charge and may slow down the collection of the electrons and distort the pulse shape. We therefore prepared, in addition, a chamber which contained only a small amount of boron, painted on the inside wall in the shape of a thin spiral line. Most records were obtained with the latter chamber. We found no evidence for distortion due to space charge.

* Mr. Nicodemus kindly filled the chambers for us. [redacted]

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The collecting electrode (central wire) of the chamber was directly connected to the grid of a cathode follower tube, using a high grid leak ($10^{10}\Omega$). The cathode follower fed the pulse through a concentric cable to the input amplifier of a DuMond oscilloscope. The sweep of the scope was triggered from a suitable stage of the timing scaler (see section on timing system) and signals from another stage were fed to the intensifier so that the sweep took the form of a dotted line, the dots serving as time marks. Fig. 5 shows a typical record.

2) Copper rings (about 1" high and 1" OD) were placed on the assembly in a standard position and after the drop the activity of the ring was measured on a G-M counter. This gave the integrated intensity of the neutron burst and by waiting or by using an absorber one could cover the very large range of actual burst sizes.

3) For absolute calibration of the bursts, a platinum resistance thermometer was stacked into the UH_{10} and connected to a potentiometer circuit and galvanometer. It was possible to observe a rise of 0.001°C of the UH_{10} due to a drop. The suddenness of the actual temperature rise did not show up since it took about a minute for the resistance element to follow a sudden change in temperature of the UH_{10}. Many of the pulses were too weak to be measured in this way. In assembly 3 no temperature measurements were made because it was felt that they would be too difficult to interpret, in view of the inhomogeneous structure of the system.

4) To record the delayed neutrons emitted after the burst, a flat fission chamber containing a thin layer of 25 and filled with argon was used. In the assemblies 1 and 2 the chamber was stacked in with the UH_{10} close to its surface; in assembly 3 it was placed on top of the graphite tamper and covered by 1" of Polythene. The chamber was connected to a fast amplifier, scaler, and photographic recorder. The whole arrangement and the results obtained with it are

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described in detail in LA-252.

In addition to the photographic recorder, an ordinary mechanical counter (Chicago type) was connected to the scaler and in some runs an Esterline-Angus recording milliammeter was connected in parallel with the counter. A recording obtained in this way is shown in Fig. 6 and while at low counting rates the individual counts (each corresponding to 2048 particles) can be distinguished, at high counting rates the average current becomes large enough to shift the mean position of the pen. It would not be difficult to calibrate this shift in terms of counting rate and this arrangement is then a simple means of recording intensities varying over about 3 powers of 10.

THEORY

In order to calculate the expected neutron burst from the dragon we make the following assumptions:

1) S source fissions per second occur in the system, i.e. fissions that are not produced by prompt neutrons. S includes spontaneous fissions, and those produced by delayed neutrons and by neutrons from an external source (eg. Po-Be).

2) Only prompt neutrons are assumed to contribute to the multiplication process; this is justified since the whole process takes only a few milliseconds.

3) The average time between a fission and its daughter fission is τ_o.

4) The prompt multiplication constant K_p varies in a smooth fashion with time. At the instant t_1 when it first exceeds unity its time derivative is $1/T_1$ and at t_2 when it goes below unity again, $1/T_2$. We write α for $(K_p-1)/\tau_o$.

Consider the $S\, dt_o$ source fissions which occur between t_o and t_o+dt_o. At a later time t the number of their offspring which occur between t and $t+dt$ will be $(S/\tau_o)\, dt_o\, e^{\int_{t_o}^{t} \alpha dt}\, dt$.

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The total number of fissions occurring between t and $t+dt$ is found by integrating over t_o

$$F(t)dt = dt(S/\tau_o)\int_{-\infty}^{t} dt_o\, e^{\int_{t_o}^{t}\alpha dt} = dt(S/\tau_o)e^{\int_{t_1}^{t}\alpha dt}\int_{-\infty}^{t} e^{\int_{t_o}^{t_1}\alpha dt}\, dt_o$$

The exponential under the second integral is appreciable only in the neighborhood of t_1 and by replacing α with $(t - t_1)/T_1\tau_o$ (see assumption 4) is found to be $e^{-(t_o - t_1)^2/2T_1\tau_o}$. If we furthermore replace the upper limit of the second integral by $+\infty$ this integral becomes $\sqrt{2\pi T_1\tau_o}$ and hence the fission rate at the time t is

$$F(t)dt = (S/\tau_o)\,dt\,\sqrt{2\pi T_1\tau_o}\; e^{\int_{t_1}^{t}\alpha dt}$$

The integral in the exponent keeps growing as long as α is positive and hence the maximum intensity occurs when K_p passes unity on its way down. Around the maximum the intensity can be written

$$(S/\tau_o)\,dt\,\sqrt{2\pi T_1\tau_o}\; e^{\int_{t_1}^{t_2}\alpha dt}\, e^{\int_{t_2}^{t}\alpha dt}$$

where the second exponential again may be approximated by $e^{-(t - t_2)^2/2T_2\tau_o}$. Hence the shape of the burst is Gaussian around t_2, with an equivalent width of $\sqrt{2\pi T_2\tau_o}$ and the total number of fissions in the burst is

$$2\pi S\sqrt{T_1T_2}\; e^{\int_{t_1}^{t_2}\alpha dt}$$

Actually the variation of α with time is nearly symmetrical, and we can therefore assume $T_1 = T_2 = \sqrt{T_1T_2} = T$. The total number of fissions in the burst is then simply

$$2\pi S\,T\, e^{\int_{t_1}^{t_2}\alpha dt}$$

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RESULTS AND DISCUSSION [redacted]

Before presenting any results we should like to emphasize that the experiments were done not so much in order to measure any definite quantity, but rather with the idea of demonstrating the existence of divergent chains supported by prompt neutrons only, and of keeping an eye open for any unexpected phenomena. We attempted to keep track of all quantities which could easily be measured and interpreted, but because of the shortness of time we could not interpret some of our data until after the active material had been returned to the chemists and then we found that some data were not accurate enough for reliable interpretation.

Perhaps the best way of demonstrating the internal consistency of the various measurements is to show how the generation time τ_0 can be calculated both from the shape and from the size of the bursts, both results being in reasonable agreement with the figure obtained from a Rossi time-scale experiment.

A. Burst Shape

Fig. 5 shows the record for drop No. 73, obtained with assembly 2. Each dot represents a time interval of 0.64 msec. The ordinates of the center of each dot were measured and replotted on an extended scale in Fig. 7. They can be fitted very well by a Gauss integral, the curve shown. The deviation is probably due to the non-linear behavior of the cathode follower. The equivalent width is seen to be 2.8 milliseconds. From the number of dots preceding the pulse we see that the maximum of the burst occurred $42.9 \times 0.64 = 27.4$ msec after the beginning of the sweep, which in turn was triggered 40.96 msec ($= 2^{12} \times 10\ \mu sec$, see under "timing") after the knife edge had passed the top light beam. The slug dropped 224.6 cm from its starting position to where it passed the top light beam and hence we can calculate that the slug (or, to be precise, the knife edge on it)

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was $y = 47.5$ cm below the top light beam at the instant of the maximum of the burst. Since the static calibration showed the maximum multiplication at $y = 43.6$ cm and since the maximum of the burst must occur at the instant when the system, on its way down, again becomes just critical for prompt neutrons, we conclude that the two points where the slug passed criticality were $2 \times (47.5 - 43.6) = 7.8$ cm apart.

Fig. 8 shows the variation of K_p with slug position (and hence with time). The solid curve is taken from Fig. 3 and shifted upward so that the two intercepts with the line $K_p - 1$ are 7.8 cm apart. From the slope at the intercept and the average speed of 722 cm/sec of the slug we can get T which is found to be about 1.0 sec. From this and the pulse width we can calculate τ_0: $W = 2.8 \times 10^{-3} \text{ sec} = \sqrt{2\pi \tau_0 T}$, hence $\tau_0 = (2.8 \times 10^{-3})^2/2\pi = 1.3\ \mu$sec.

B. Burst Size

Fig. 9 shows the initial counting rate of the Cu detectors plotted against the temperature rise of the system. The specific heat of UH_{10} was measured* as 0.14 cal/gm degree; hence the heat capacity of the whole active material (15.4 kg) is $0.14 \times 15400 = 2160$ cal/degree or $2160 \times 4.19 = 9000$ joule/degree. Since about 3×10^{10} fissions are needed to produce one joule of heat, 1° temperature rise corresponded to about $9000 \times 3 \times 10^{10} = 2.7 \times 10^{14}$ fissions. From Fig. 9 we see this gives an initial counting rate of 1.15×10^{5} counts/minute, hence 1 count/min means a burst of 2.4×10^{9} fissions.

The counting rate shown by the Cu detector exposed at drop 73 was

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80 counts/min, hence the burst contained $80 \times 2.4 \times 10^9 = 2 \times 10^{11}$ fissions. According to theory this must be equal to $2\pi S\ T \exp(\int_{t_1}^{t_2} \alpha dt)$. S was due to a Po-Be source emitting about 5.10^5 n/sec and placed in a hole in the tamper; we estimate that this source caused 10^5 fissions per sec, hence S is 10^5. $T = 1$ (see preceding section); hence the exponential is found to be 3×10^5, and $\int_{t_1}^{t_2} \alpha dt = \text{lognat}\ (3 \times 10^5) = 12.6$.

This value must be equal to the shaded area in Fig. 8 if the time is measured in units of τ_0. Actually the area is 20 μsec and hence we find $\tau_0 = 20/12.6 = 1.6\ \mu$sec. The agreement of the value with that of 1.3 μsec obtained from the pulse shape is not unsatisfactory.

We tried to calculate τ_0 from the way in which the size of burst varied with the adjustment of the multiplication. However the statistical fluctuations were very large and furthermore the adjustment showed some slack; as a result, while the variation of burst size comes out roughly as expected it is not possible to calculate any relevant figure for τ_0 from it.

A third and independent value for τ_0 was however obtained by performing a Rossi time-scale experiment* on the assembly. Nine gates of 40-μsec width were opened successively upon arrival of a fission pulse in the built-in fission chamber, and any pulse following the trigger pulse within 360 μsec was recorded in the appropriate channel. Fig. 10 shows the distribution of counting rates over the nine channels (after subtracting accidental coincidences, calculated from the counting rate) and indicates an exponential decay with a time constant of 120 μsec. The multiplication constant K was determined as 0.995_5 by extrapolating the calibration curve; hence (0.008 being the effective fraction of

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* The electronic arrangement for this was built and operated [redacted]ereson.

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delayed neutrons) $1 - K_p = 1 - (0.995_5 - 0.008) = 0.0125$, and hence $\tau_o = 120\,\mu\text{sec} \times 0.0125 = 1.5\,\mu\text{sec}$.

It was pointed out earlier that the static calibrations were based on the assumption that the delayed neutrons caused 0.008 times as many fissions as the prompts. If the true figure were higher by a factor g then all values of $K - 1$ should be multiplied by g. The value $K_p - 1$ in the Rossi experiment would also be g times larger, and so would the value of τ_o resulting from it. The same is true of the value of τ_o calculated from the absolute size of the burst, and from the shape of the burst. The reasonable agreement between the various determinations of τ_o does not therefore constitute evidence for the correctness of our static calibration.

It is difficult to set any definite upper limit to the presence of neutrons delayed by times greater than a few microseconds. In assembly 2 $K_p - 1$ never became more than 0.01 and hence the e-folding time was never shorter than 150 μsec. Neutrons with delays up to say 50 μsec may well have been present if they were offset by short-lived neutrons of sufficient number to give the correct value (about 1.5 μsec) for the average time between a fission and its daughter fissions (excluding daughter fissions with a delay of more than 150 μsec). On the other hand, neutrons with much more than 150 μsec and less than a few milliseconds delay would not have contributed to the bursts. Their number could not have exceeded about 0.005 per fission since bursts were observed at positions of the control tray which were about as predicted from the static calibration under the assumption that there were no delayed neutrons of very short period. Neutrons with a delay of more than a few milliseconds were detectable as such and a period of about 6 msec was indeed found (see LA-252) containing about 10^{-4} neutrons per fission.

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Fluctuations.

Calculation indicates that if the size of a burst be N (in arbitrary units) then the relative mean square fluctuation $(\overline{N^2} - \overline{N}^2)/\overline{N}^2$ should be $(1/S\tau_0) \cdot \overline{\nu(\nu - 1)}/2\overline{\nu}$. The term $\overline{\nu(\nu - 1)}/2\overline{\nu}$ is 0.8 if we assume that $\overline{\nu} = 2.5$ and that the fission can result in the emission of 2 or 3 neutrons but neither more nor fewer. If we assume a Poisson distribution for the number of neutrons per fission, the term becomes 1.25. The true value probably lies between these limits.

The observed fluctuations are illustrated by Table 1. Each column contains the intensities of a number of subsequent bursts obtained under identical conditions. Column A shows the large fluctuations of bursts obtained with assembly 2 where τ_0 is small. Column B was taken with assembly 3 where τ_0 was more than 10 times larger, and despite the use of a weaker source the relative fluctuations are seen to be smaller. Column C was obtained with the same adjustment of assembly 3 as column B, but the source used was about 9 times stronger. The relative mean square fluctuation should have been 9 times smaller; actually it only dropped by a factor 4, which probably indicates the presence of another source of fluctuations, perhaps slight variations in the path of the slug. Column D differs from C by the fact that the multiplication was slightly reduced; this reduced the average burst size by about a factor 3 but did not alter the relative fluctuations. This is not surprising since the fluctuations arise mainly in the beginning of the burst and are not much affected by the later stages of multiplication when the number of fissions has become large.

If one wants to produce a large burst, it is clearly better to increase S rather than the multiplication, in order to reduce the uncertainty in burst

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TABLE I

A	B	C	D
650	17	80	28
1690	13	106	30
470	7	97	36
610	9	91	32
360	8	91	22
1180	8	113	28
1190	9	94	32
1050	10	70	22
1410	9	111	27
1700	7	89	34
1500	7	69	30
830	21	70	34
690	6	58	21
	2	81	39
$\bar{N} = 1010$	11	99	30
$(\overline{N^2} - \bar{N}^2)/\bar{N}^2 = 0.20$	7	89	27
	2	68	33
	8	73	26
	10	75	24
	10	86	32
	8	80	37
	14	76	21

[redacted]

[redacted]

TABLE I CONT.

A	B	C	D
	9	106	31
	8	83	34
	5	$\bar{N} = 85.5$	22
	$\bar{N} = 9.4$	$(\overline{N^2} - \bar{N}^2)/\bar{N}^2 = 0.036$	26
	$(\overline{N^2} - \bar{N}^2)/\bar{N}^2 = 0.148$		20
			34
			31
			39
			38
			30
			22
			$\bar{N} = 29.5$
			$(\overline{N^2} - \bar{N}^2)/\bar{N}^2 = 0.033$

[redacted]

[redacted]

size. This can be done by dropping the slug twice within a short interval (2 to 3 minutes) so that the delayed neutrons from the first burst serve as a source for the second. By making the second drop when the delayed neutron intensity has fallen to the desired level the intensity of the second burst can be adjusted fairly closely. It may even pay to make three successive drops and thus build up the necessary delayed neutron intensity in two steps. We always used this technique of making one or two "leader" drops when we wanted to obtain very strong bursts close to what the assembly could tolerate.

ADDITIONAL EXPERIMENTS

The decay of the delayed neutrons was studied with considerable accuracy by F. de Hoffman et al, using the scaling and recording equipment briefly described on page 13 . The work has been reported in LA-252.

The decay of gamma rays during the first few seconds was studied by P.B. Moon (LA-253).

Also the effect of the intense burst of radiation on the insulation of coaxial cable was observed in a preliminary way by Moon.

H. Richards set up a cloud chamber and synchronized it with the falling slug so that the bursts would occur during the sensitive time of the chamber. It was planned to expose the chamber to thermal neutrons only and then to observe recoil tracks from fission neutrons emitted by a piece of 25 placed in or near the chamber. However, in the short time available we did not succeed in eliminating the background of fast neutrons getting through or around the graphite moderator, and the attempt was abandoned.

Four rats were placed by R. Steinhardt at various distances close to the assembly. They all survived the exposure to a single drop in which about 10^{15}

[redacted]

fissions were produced. Unless the high instantaneous intensity of the irradiation had greatly increased its detrimental effects this result was to be expected since the dose was only a few hundred R units.

[redacted]

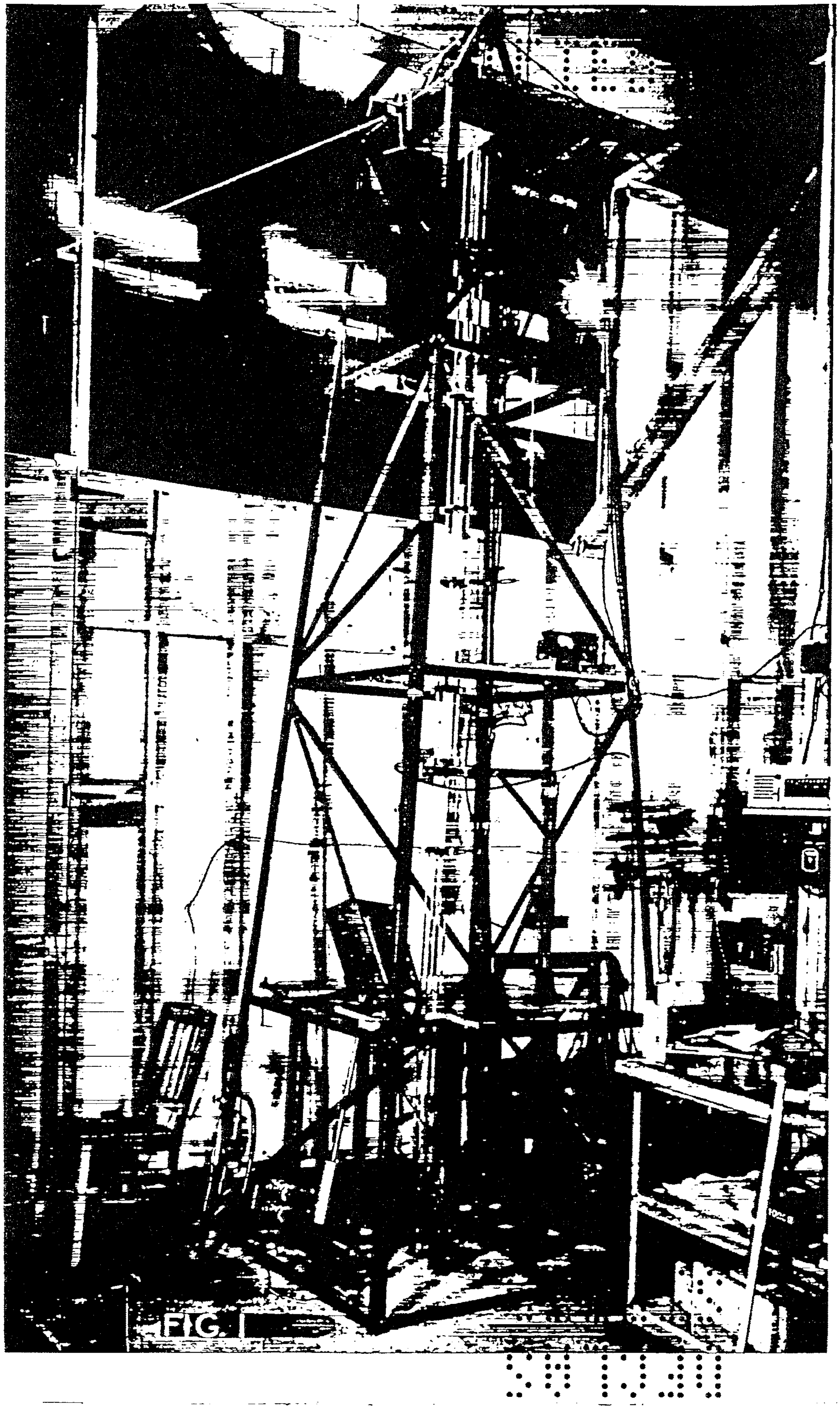
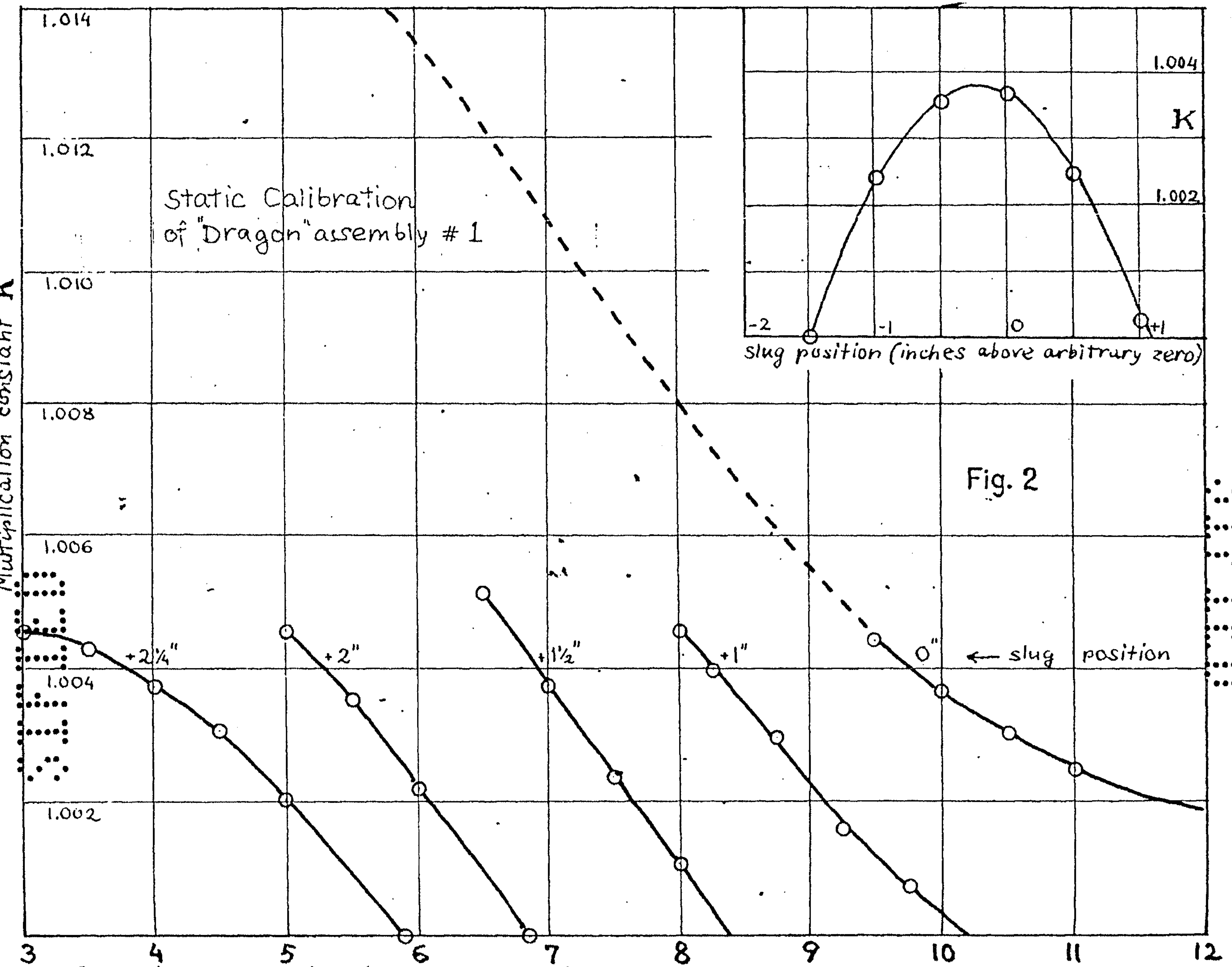


FIG.



Static Calibration of "Dragon" assembly # 1
Multiplication constant K
1.014
1.012
1.010
1.008
1.006
1.004
1.002
3
4
5
6
7
8
9
10
11
12
+2¼"
+2"
+1½"
+1"
0"
← slug position
K
1.004
1.002
-2
-1
0
+1
slug position (inches above arbitrary zero)

Fig. 2

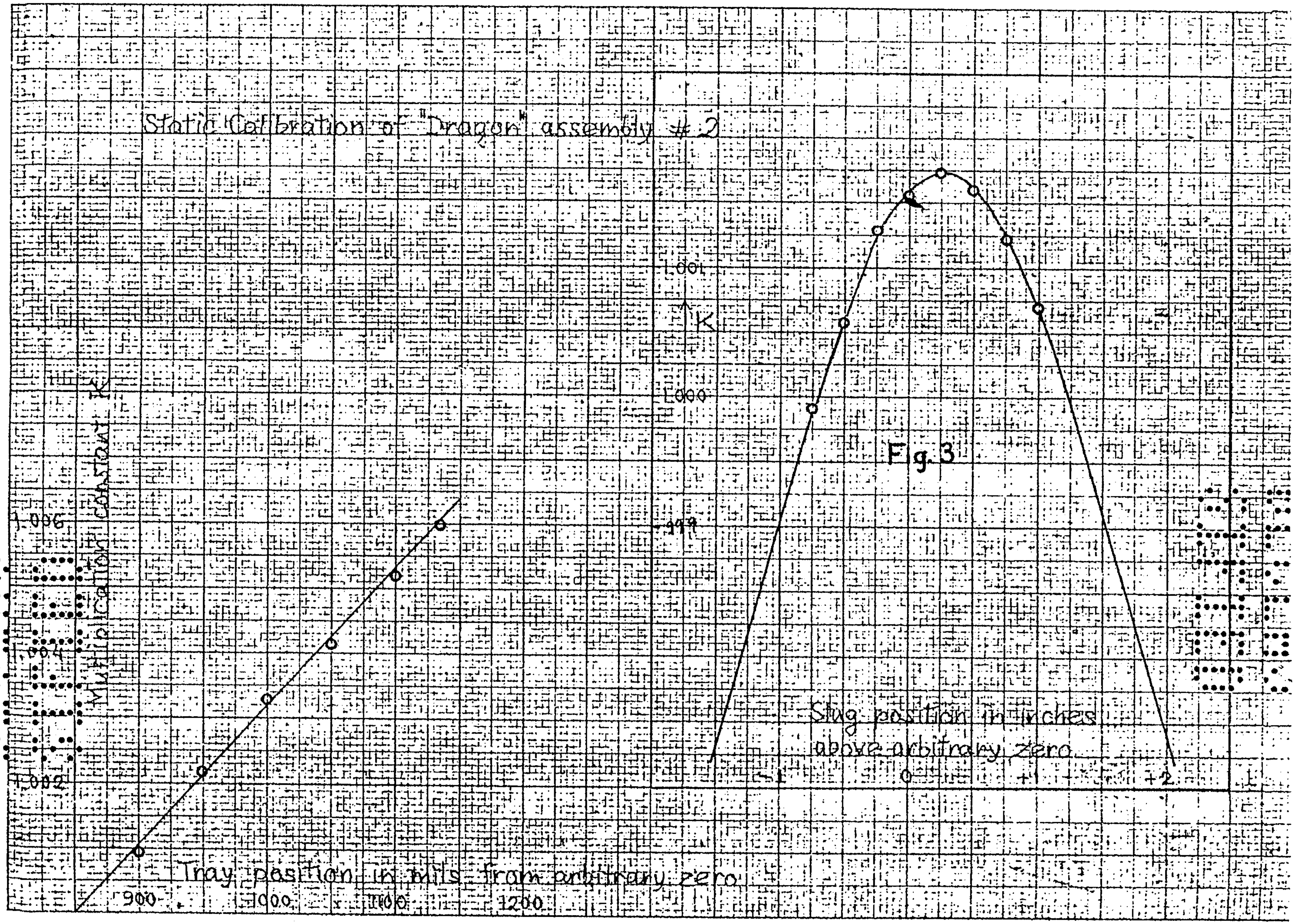


Fig. 3

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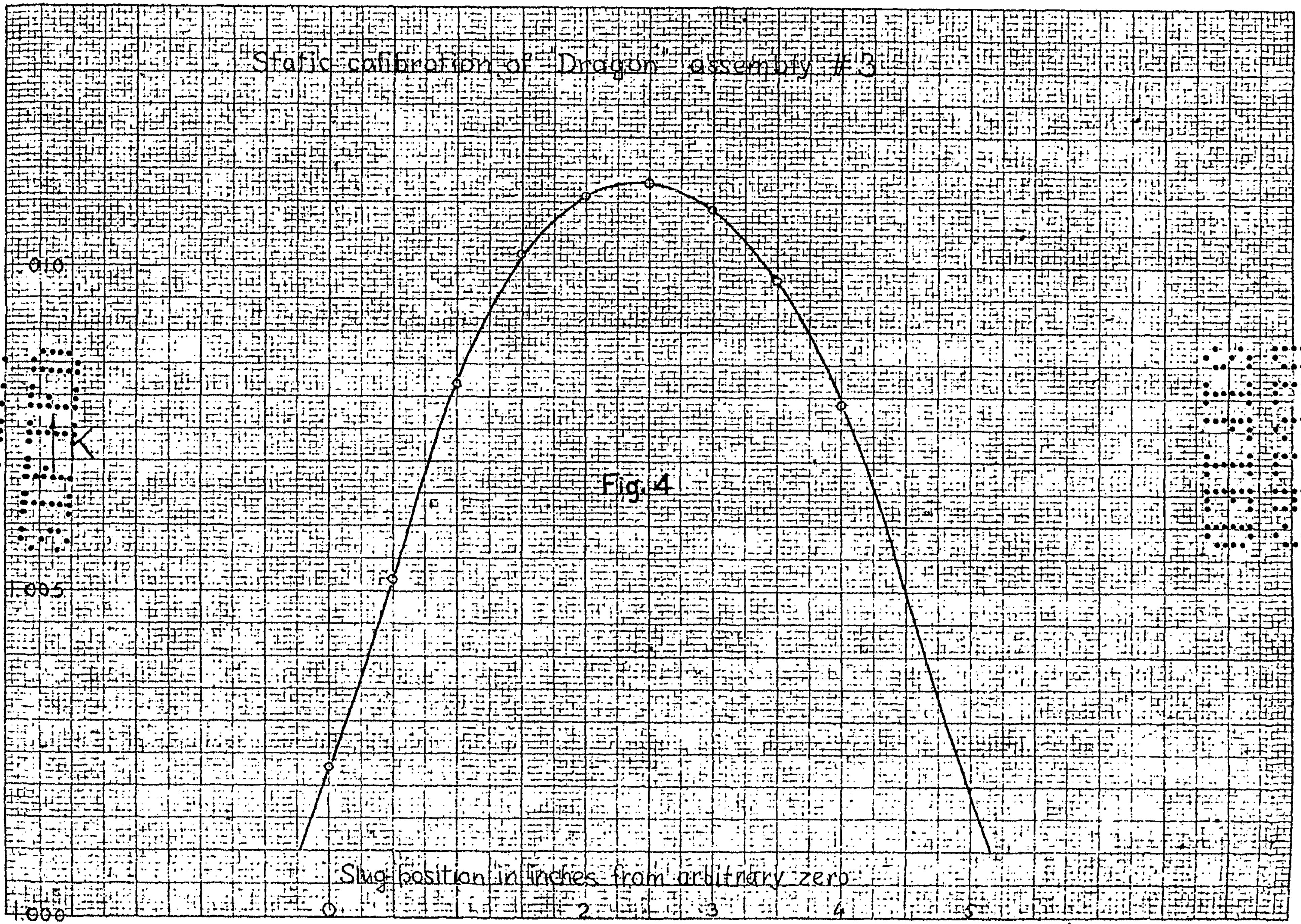
Static calibration of "Dragon" assembly # 3
K
1.005
1.000
Slug position in inches from arbitrary zero
0
1
2
3
4
5

Fig. 4

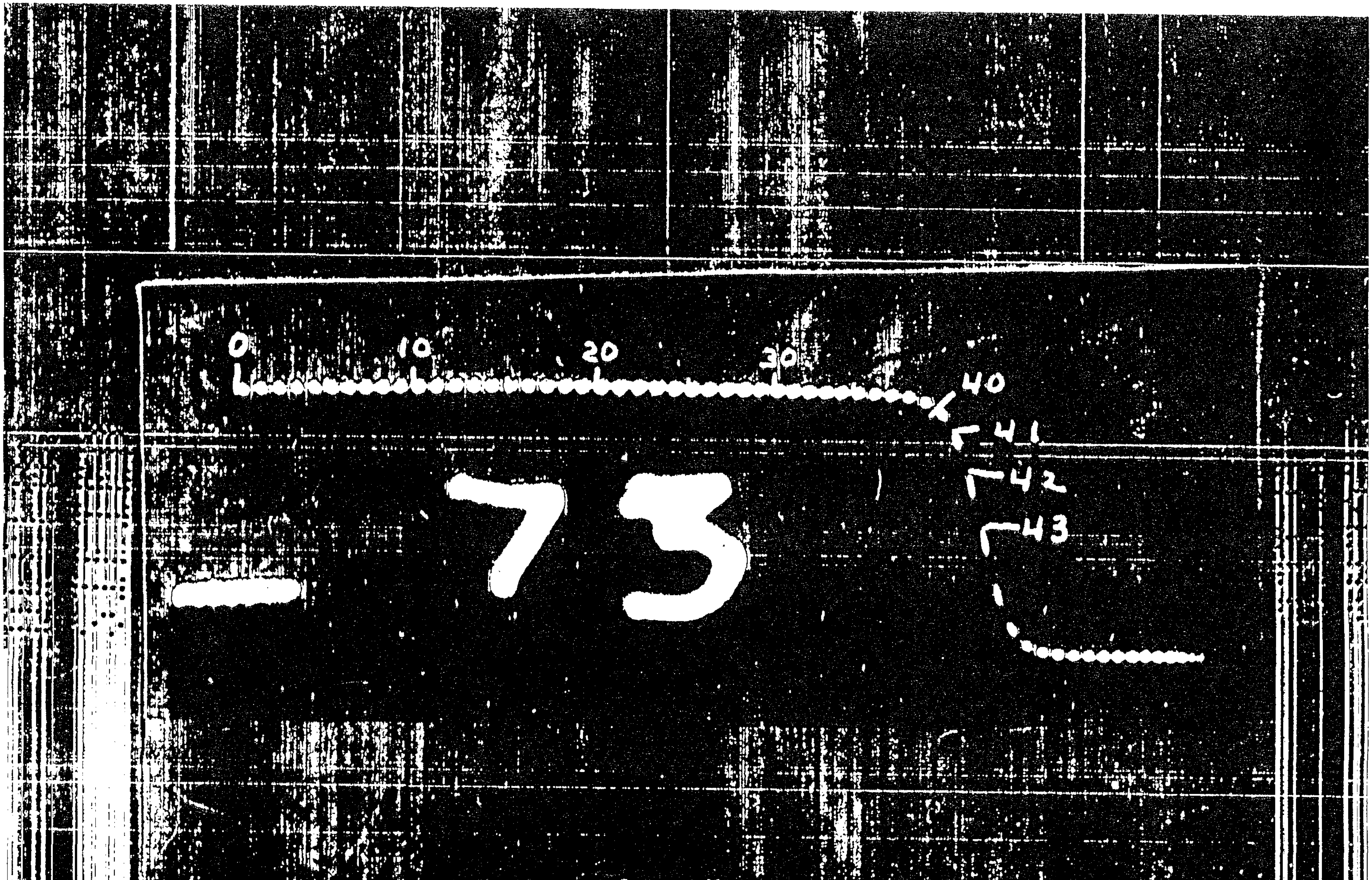

Fig. 5

ES

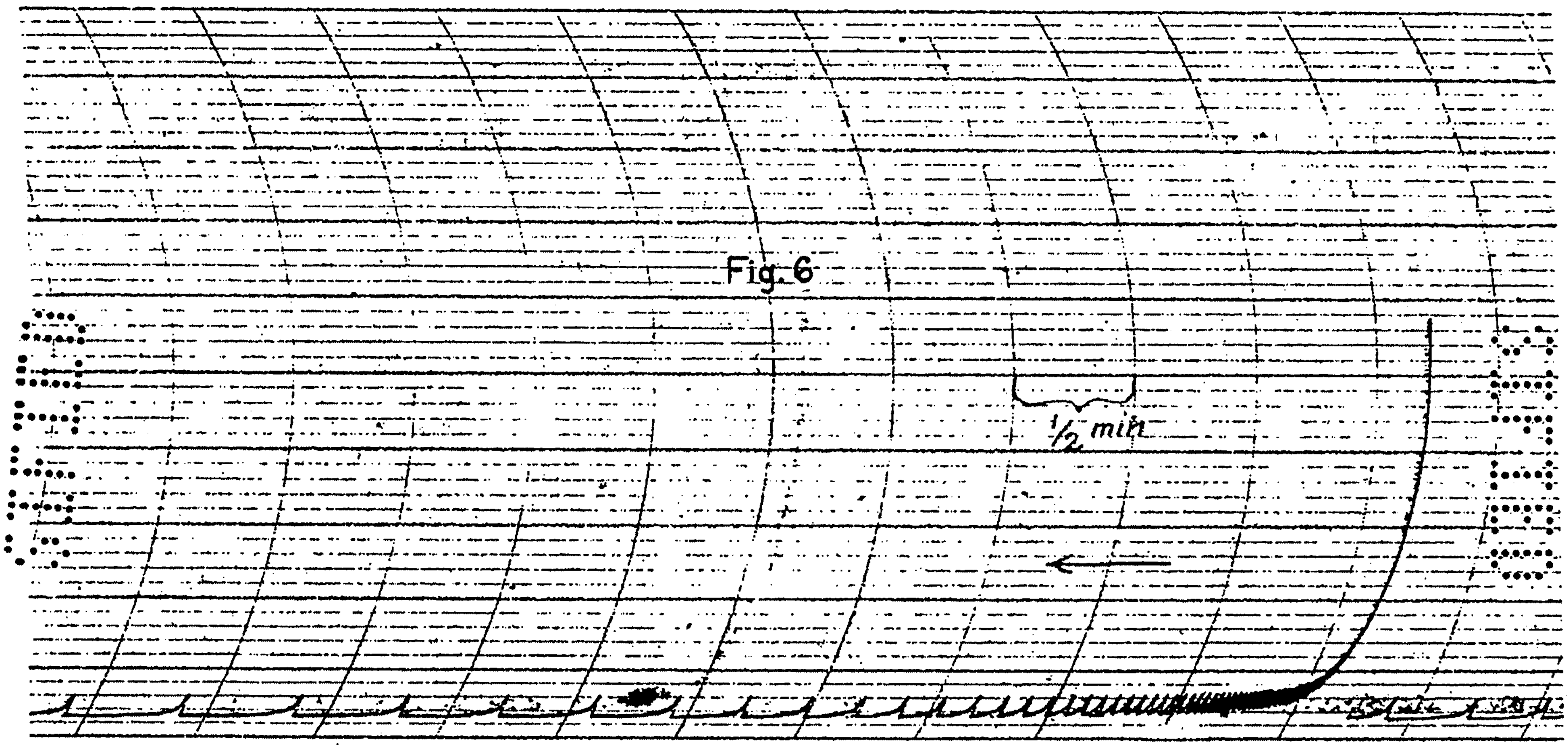

Fig. 6

APPROVED FOR PUBLIC RELEASE

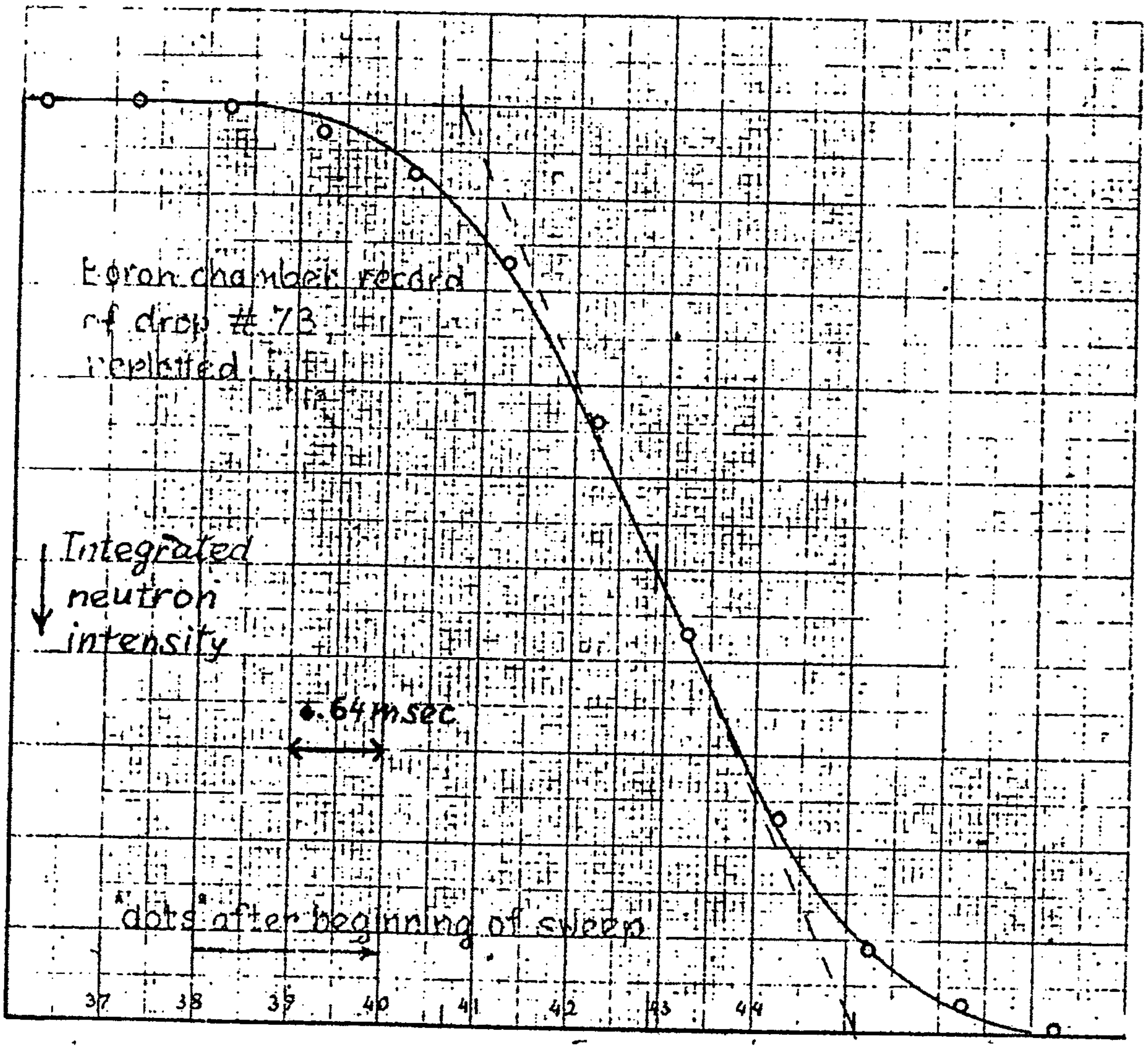

Fig. 7

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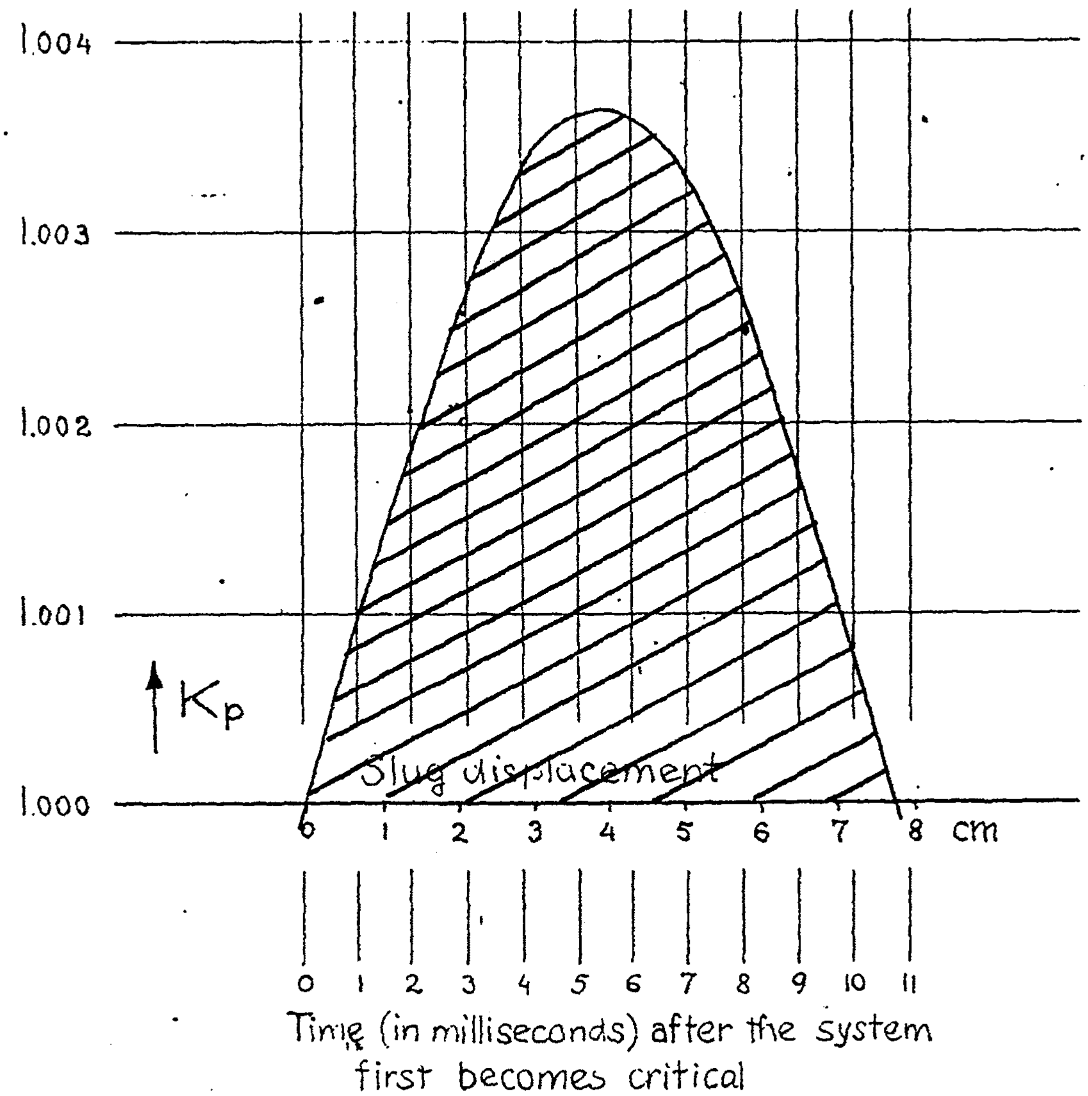
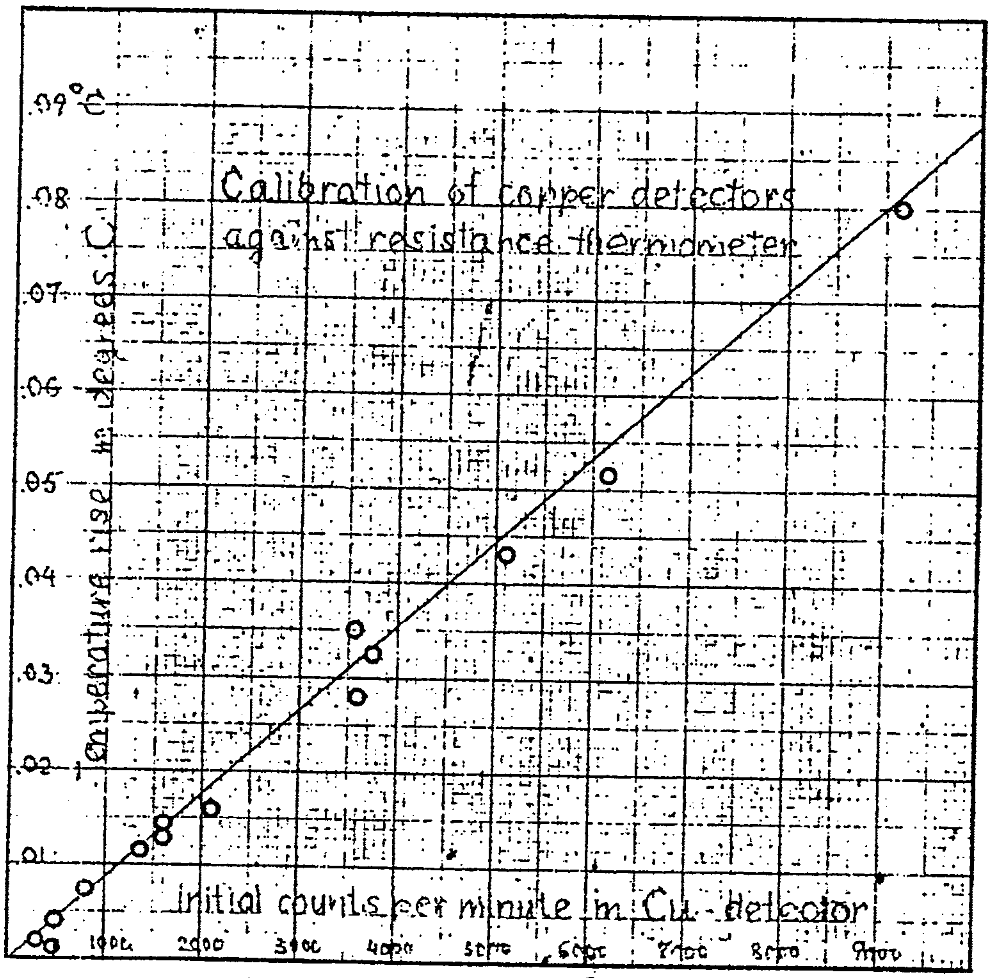

1.004
1.003
1.002
1.001
1.000
Kp
Slug displacement
0 1 2 3 4 5 6 7 8 cm
0 1 2 3 4 5 6 7 8 9 10 11
Time (in milliseconds) after the system first becomes critical

Fig. 8



.09°C
.08
.07
.06
.05
.04
.03
.02
.01
Calibration of copper detectors
against resistance thermometer
Temperature rise in degrees C
Initial counts per minute in Cu-detector
1000
2000
3000
4000
5000
6000
7000
8000
9000

Fig. 9

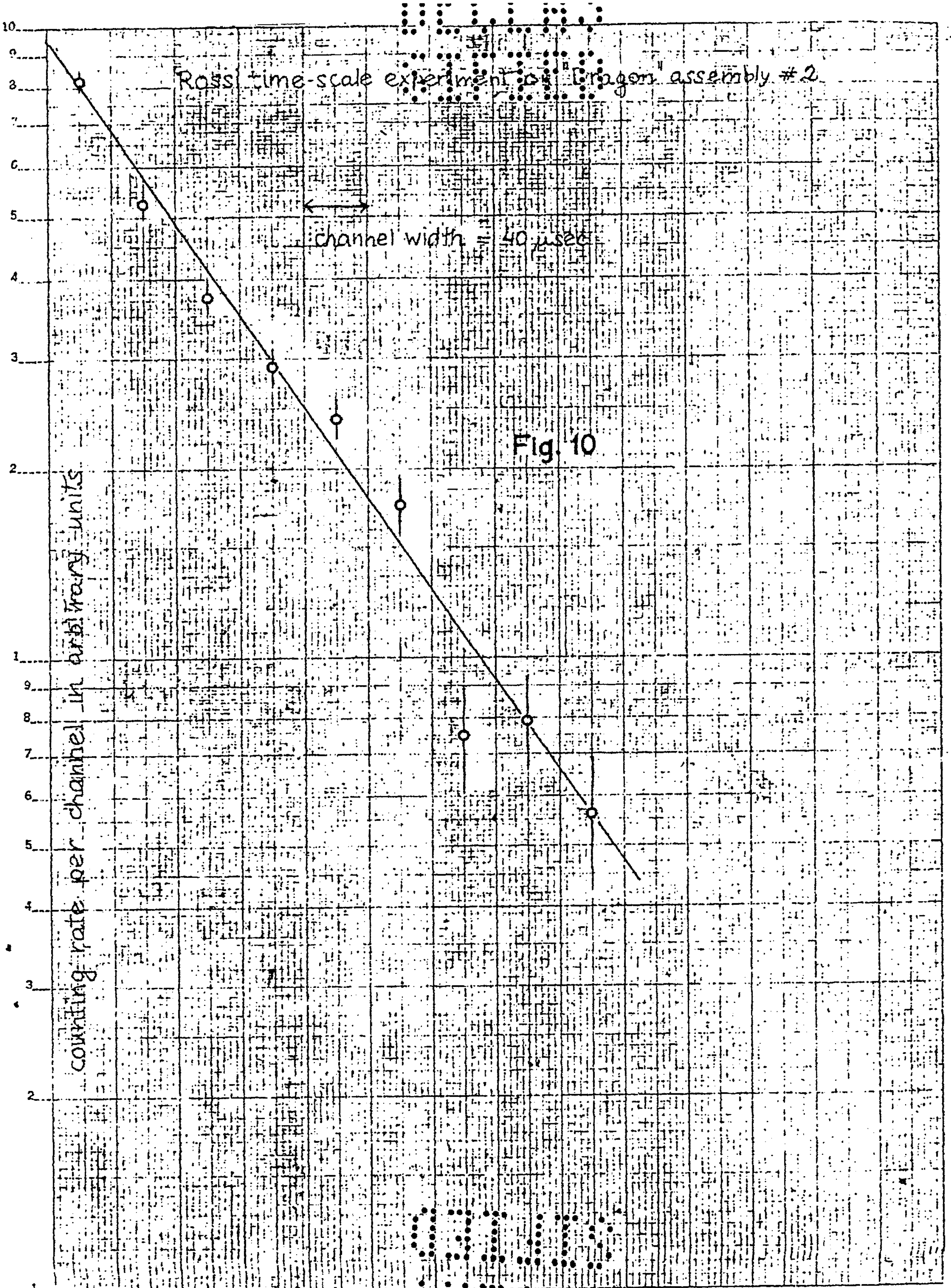

Ross time-scale experiment
assembly #2
channel width = 40 μsec
counting rate per channel in arbitrary units
10
8
6
5
4
3
2
1
9
8
7
6
5
4
3
2
1

Fig. 10

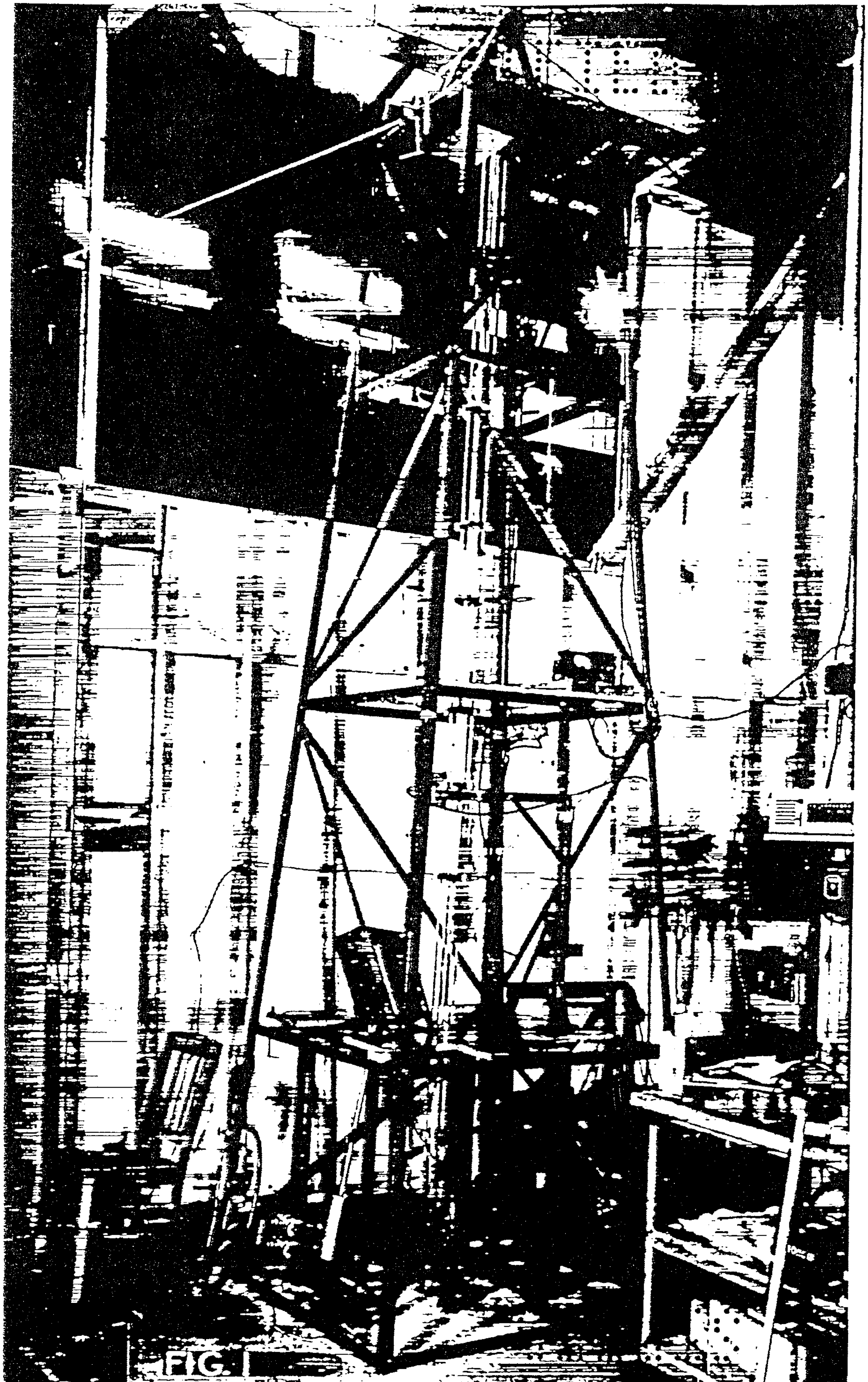


FIG. 1

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