PARALLEL-PLATE COUNTERS
AND THE
MEASUREMENT OF VERY SHORT TIME INTERVALS

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Abstract

The counter characteristics of a discharge tube using plane-parallel electrodes have been investigated, particularly with regard to the short time lags inherent in the streamer type of spark which occur with such a geometry at near-atmospheric pressure. Construction details for parallel-plate counters with good counter characteristics are given. Spurious counts were minimized by an argon-xylene filling mixture and the use of a univibrator quench circuit. The uncertainty in the reaction time of the counters is $\pm 5 \times 10^{-9}$ sec. Also described is a timing circuit which, in conjunction with the new counters, makes possible the measurement of time intervals between ionizing events to a precision of $\pm 5 \times 10^{-9}$ sec.

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Contents

I. INTRODUCTION

There has been considerable interest lately in the measurement of very short time intervals between ionizing events. This problem arises, for example, in studying the various mesotron decay phenomena and the gamma-decay of metastable states of nuclei. At present, time measurements are limited by the variable lags of the conventional Geiger-Muller tube, which introduce an uncertainty of about 0.1 μsec.(1,2) This paper describes a new type of counter using plane-parallel electrodes, for which the uncertainty in the reaction time is about 5 x 10^{-9} sec. A timing circuit is also described which permits the measurement of time intervals commensurable with the fast reaction time of the parallel-plate counters.

The development of the timing system herewith presented took as its point of departure an investigation of the counter characteristics of a discharge tube using plane-parallel electrodes. It has been known for some time, thanks to the work of White,(3) Wilson,(4) and Newman,(5) that the time lag of breakdown of overvolted plane-parallel spark gaps was exceedingly short, and indeed Wilson found at 100% overvoltage, lags of the order of a few times 10^{-9} sec., with no apparent lower limit as the overvoltage was increased. The short lags of the streamer-type spark are due primarily to the important role played by photo-ionization,[6] but even apart from the spark lag studies, one would expect from elementary considerations a shorter lag with the plane-parallel geometry--where the field strength is everywhere sufficient to propagate a Townsend electron avalanche--than with the cylindrical shape, where the initiating electrons must first drift into the strong field near the wire.

Here, then, was a prospective fast mechanism. Could a parallel-plate spark gap be made to trigger if and only if an external agent produced an electron within the active volume? In the answer to this question, it was early realized, lay the key to the entire problem. An investigation of the possible origins of ions within the active volume was undertaken; and it turns out that primarily one has to deal with after-effects of previous discharges on the surfaces and in the gas of the tube. Such after-effects--which are similar, if not identical, to the spurious counts observed in conventional cylindrical counters--are discussed in Part III. Although the after-effects are very poorly understood, nevertheless it has been possible to minimize them to the point where the spurious counting rate is but a small fraction of the true counting rate, for a considerable range of over-voltages, and thus produce a workable counter.

II. CHARACTERISTICS OF PARALLEL-PLATE COUNTERS

A. General Description

The counters studied so far have consisted of parallel plates of molybdenum, copper, or copper-plated steel spaced 2.5 mm. and ranging from 3 to 35 cm.^{2} in area. Several fillings have been tried, one of the most satisfactory being $\frac{1}{2}$ atm. argon and 6 mm. xylene vapor.

An external electronic quench circuit is necessary with a parallel-plate counter for two reasons: first, unlike the cylindrical G-M tube, the space-charge geometry is not such that the discharge is self-quenching.* Second, the intensity of after-effect or spurious counts, especially at the large overvoltages required for a really fast breakdown, is such that a "cooling off" period has been found necessary. The details of the quench circuit are discussed in Part IV, and we shall mention only the resulting wave-form at this point. The firing of the counter triggers the quench circuit, and the counter is not recharged by the quench circuit (a more appropriate name might be recharging circuit) until a time T_Q has elapsed; at this point it is recharged as positively and rapidly as possible. The sequence of events is

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* The term "quenching", as applied to a counter, usually implies two conditions: (a) Although the initial electron avalanche triggers off many other avalanches (Townsend β-process) the discharge, after spreading the length of the wire, is quickly choked off by space charge, and (b) during the subsequent positive ion collection no further electrons are produced.

shown in Fig. II-1, case (a). It is evident that the quench time T_Q is a parameter which must be specified, in general, when discussing the behavior of a counter operated with such a circuit.

B. Characteristics as a Counter

We shall discuss here the more conventional counter characteristics, reserving for Part VI the discussion of the reaction time.

Some threshholds for several different filling mixtures are listed in Table II-1. They are for a counter with molybdenum plates spaced 3 mm. (as compared with the standard 2.5 mm. copper counters later used) and are intended primarily as orienting magnitudes. Mercury vapor was present.

Table II-1*

Counter Threshholds
(Total pressure in each case 38 cm. of Hg.)

Filling	Voltage
Argon	550
Argon + 3.4 mm. Air	1450
Argon + 6.2 mm. Air	1950
Air	4500
Argon + 6.0 mm. Xylene	1700

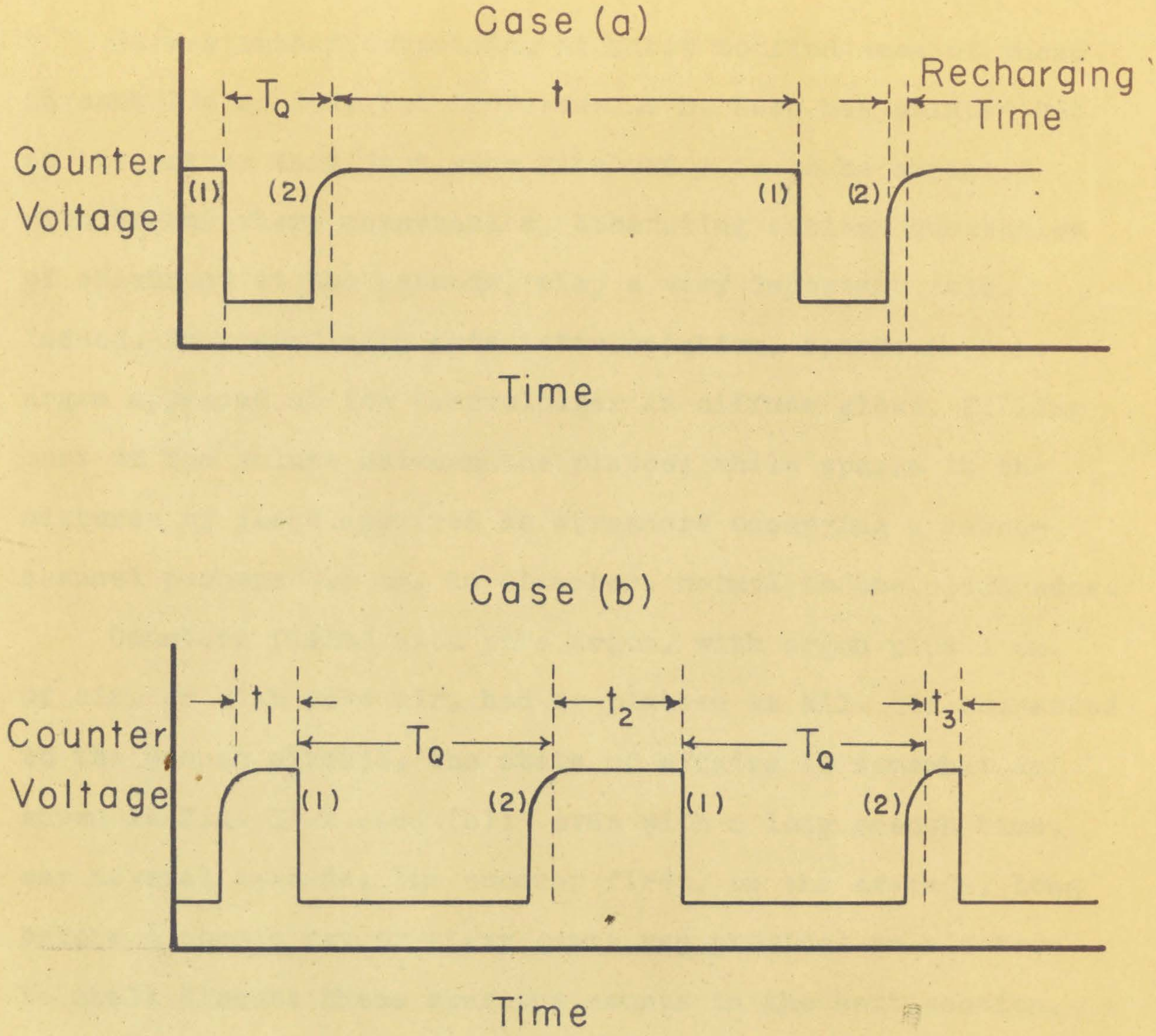

FIGURE II-1. Typical waveforms showing the potential across a counter vs. time.* Case (a) is the usual case: quench time $T_Q \ll$ mean interval between counts $\bar{t}$. Case (b) may occur if T_Q is made very long or spurious counts reduce $\bar{t}$. Typical value for T_Q is .05 sec.

* The counter fires at (1) and is recharged at (2).

It was rather surprising at first to find some of these threshholds so low, but Professor L. B. Loeb has pointed out to the writer that just such a behavior is to be expected with argon, where metastables, liberating copious quantities of electrons at the cathode, play a very important role. Indeed, in accord with this interpretation, sparks in pure argon appeared at low overvoltages as diffuse glows, filling most of the volume between the plates; while sparks in the mixtures of gases appeared as streamers occupying a narrow channel perhaps 0.5 mm. in diameter, normal to the electrodes.

Counters filled with pure argon, with argon plus 1 cm. of air, or with pure air, had no plateau at all. If connected to the quench circuit, the state of affairs is somewhat as shown in Fig. II-1 case (b): even with a long quench time, say several seconds, the counter fires, on the average, long before a cosmic ray or stray gamma ray provides an electron. We shall discuss these spurious counts in the next section. Counters filled with argon plus a very small trace of air, or better still, argon plus 6 mm. of xylene, exhibit, on the other hand, a plateau in the usual sense. Their background counting rate is, within experimental error, what it should be by comparison with conventional G-M counters, and the counting rate increases as it should when a radioactive source is brought up. An additional check on their operation is afforded by the coincidence experiments discussed in Part VI.

A typical plateau for an argon-xylene counter is shown in Fig. II-5, and for argon-air counters in Fig. II-6. Four counters have so far been constructed; a summary of their characteristics when filled with 38 cm. of argon and 6 mm. of xylene is given in Table II-2.

Table II-2

Counter Characteristics

Counter	Electrode Material	Spacing (mm.)	Area ($cm.^2$)	Profile*	Plat. slope %/100 v.	Backgnd (c/sec.)
1P1	Mb	3.0	3.1	bevelled	4.4	.17
2P1	Cu	2.5	35	flat	3.6	2.0
2P2	Cu	2.5	35	flat	3.7	2.0
3P1	Cu	2.5	35	bevelled	3.5	2.0

* See Fig. II-3

Counters 2P1 and 3P1 were both refilled two or three times during the past six months, exhibiting each time the same plateau slope within the experimental error of the slope determinations. However, counter 3P1 had a plateau which extended only up to 2500 volts after refilling. This limited the overvoltages which could be applied in the reaction-time measurements.

When a counter begins to go bad, the plateau slope starts to increase; for example, counter 2P2 after two months of intermittent operation had a plateau slope of 6.0% per

100 volts at 2500 volts. This change in slope, however, is not the principal characteristic of a bad counter; it is rather the instability and the occurrence of "spot-bursts" which limit the usefulness of a counter as it goes bad. These phenomena we discuss more fully in Part III.

As regards the actual useful lifetime of a parallel-plate counter, the data available at present are not complete enough to enable us to draw very definite conclusions. We may state however, that counter 2P2 was in use for two months, went bad, was refilled, and is still running now after another two months; and that 2P2 and 3P1 each ran for about a month; in each case the counters were running on the average a few hours each day, at various overvoltages and quench times. At any rate, the lifetime is long enough to make the counter a practical instrument.

The pressure and spacing were chosen so that the efficiency of the counter, for particles passing through normally with a velocity corresponding to the minimum of the ionization curve, was 98%.

The parallel-plate counter does not have a dead-time in the usual sense; the rapidity with which it can count is limited, however, by the requirement that the counter may not be recharged before (a) all the positive ions from the previous discharge have been collected, (b) the probability per unit time that a spurious count will occur has fallen well below the true counting rate. Although the quench time has been kept at .05 sec. during the present work, it was so adjusted mainly because the effect of a short quench time on the lifetime is not yet known. Counters have been operated for short periods of time with a quench time of a millisecond or less.

Finally, two more characteristics of parallel-plate counters should be mentioned. First, the discharge is localized, presumably, in the neighborhood of the initiating ion, with the streamer channel plainly visible. This has obvious possibilities as a means of determining the path of a particle, and it also makes the study of the spurious count phenomena considerably easier. Second, the amplitude of the pulse from a parallel-plate counter is tremendous, and is substantially independent of the circuit capacitance attached.

C. Construction

A counter construction which has been used for experimental work is illustrated in Figs. II-2, II-3, and II-4. The electrode assembly is mounted on a pinch seal somewhat in the manner of a radio tube, the main mechanical support being a frame made of 3/16" glass cane. The outer envelope is provided with a large ground joint ($1\frac{1}{2}$" clearance) making

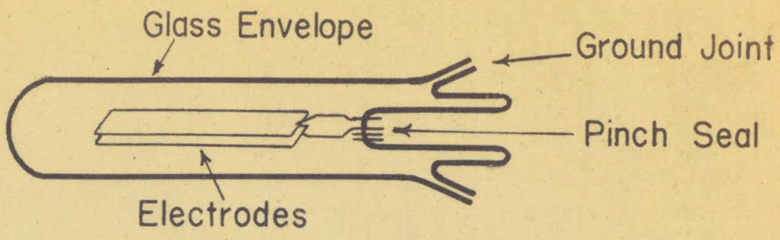

FIGURE II-2. Experimental Counter

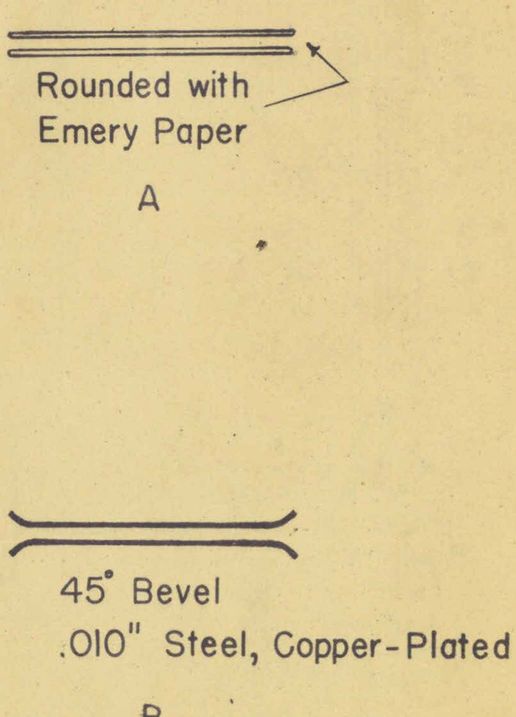

FIGURE II-3. Counter Profiles

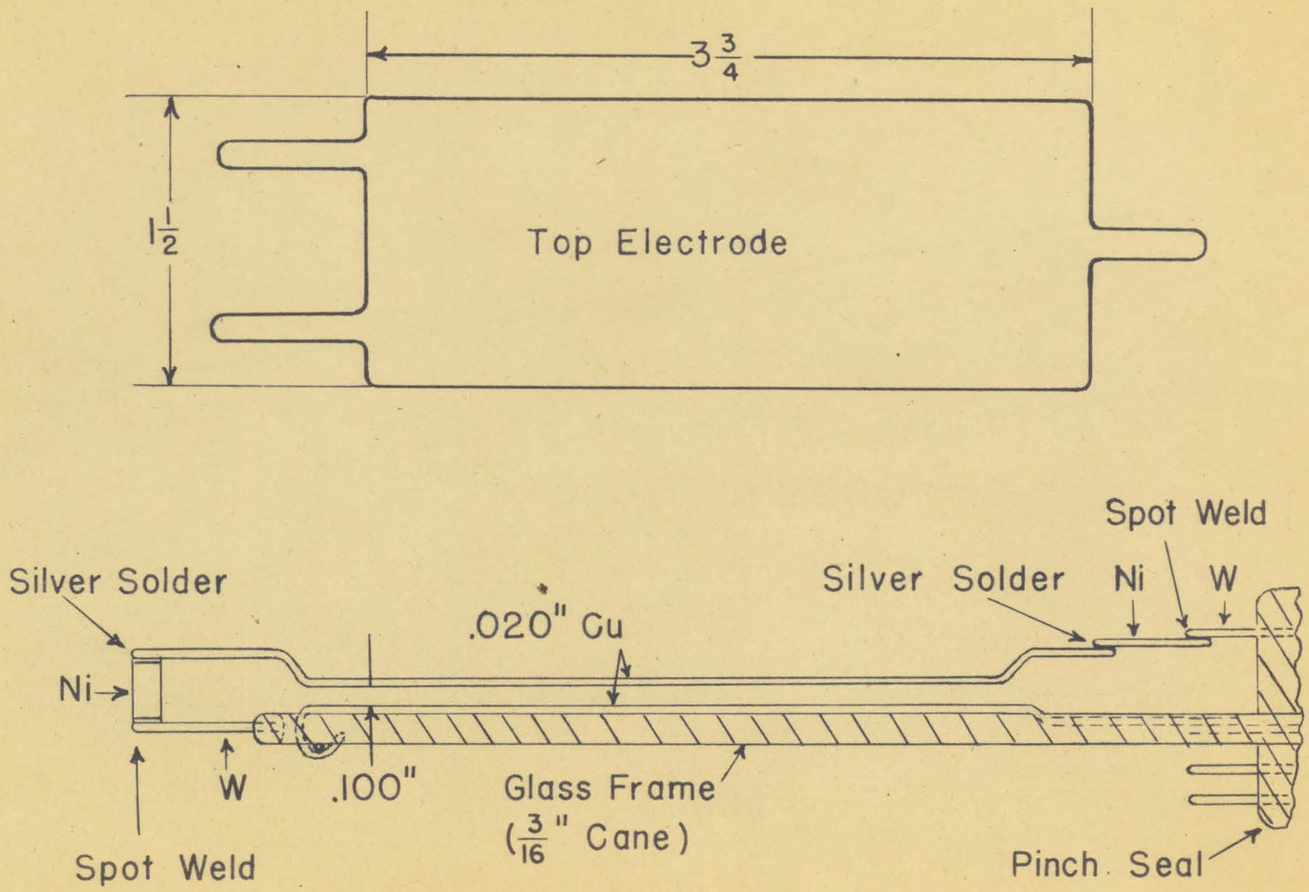

FIGURE II-4. Electrode Assembly.

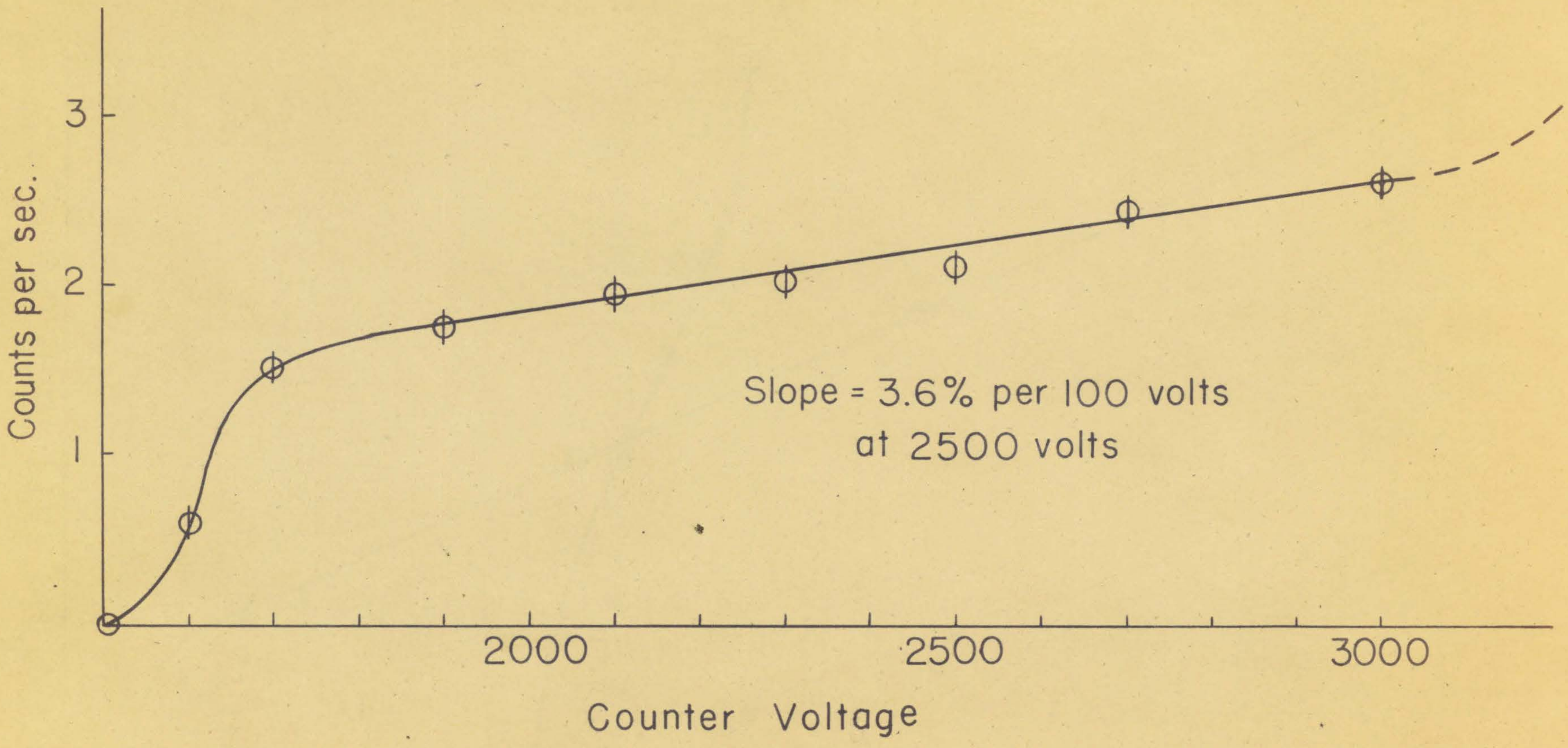

FIGURE II-5. Typical argon-xylene plateau. Quench time .05 sec.

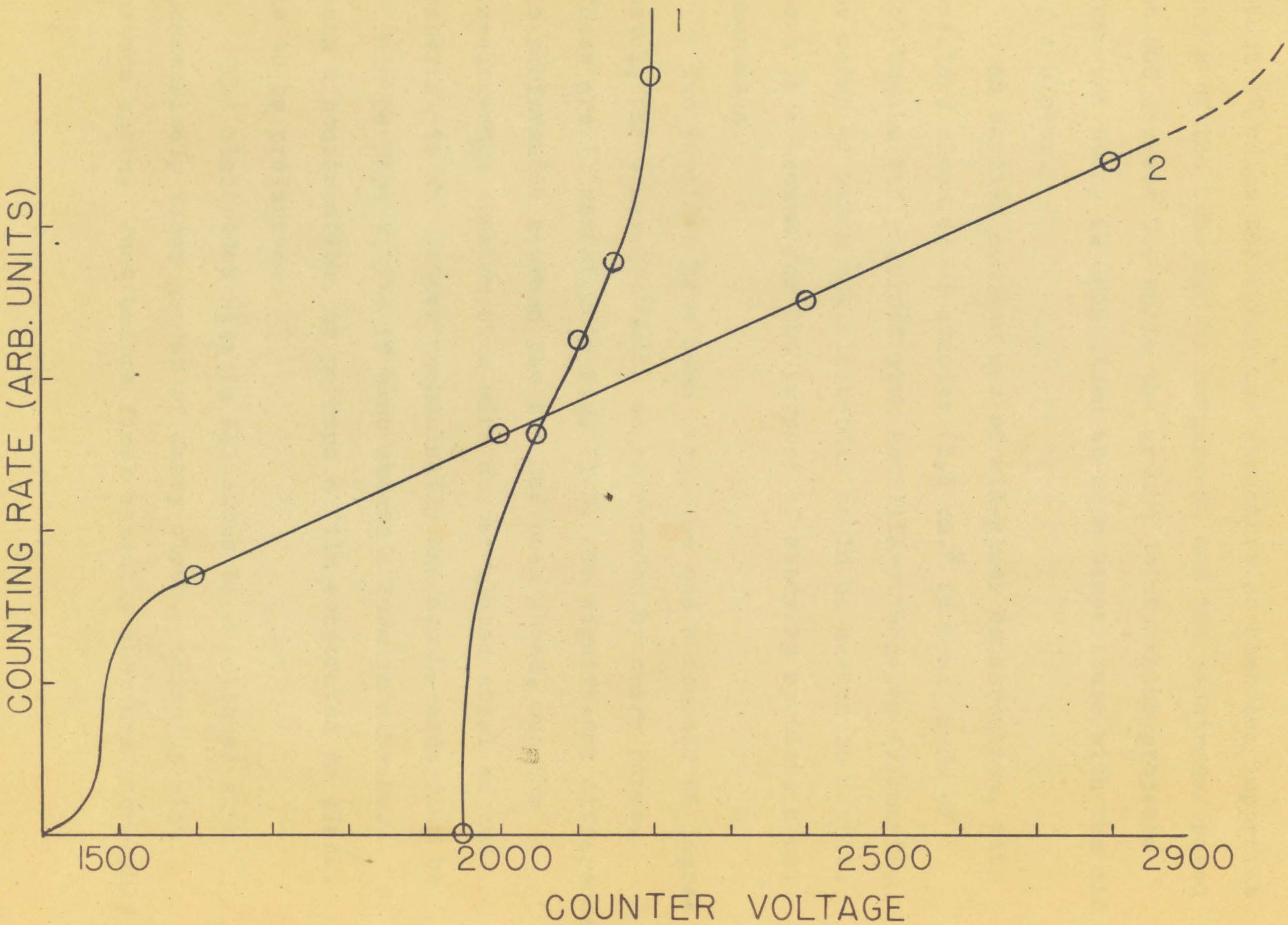

FIGURE II-6. Argon-air plateaus. (1)--6.0 mm. air. (2)-- 3.4 mm. air. Total pressure 38 cm. Quench time .05 sec.

it possible to take the tube apart without glassblowing. This joint is sealed with beeswax and rosin. It is located about 4" below the electrode structure so that the important parts of the tube may be outgassed, and the electrodes baked at 500 degrees C., while the ground joint, which projects from the oven, is maintained at room temperature with the aid of a blower.

An earlier counter was of all-glass construction, with smaller, circular electrodes (3.1 $cm.^2$ in area) made of molybdenum and provided with auxilliary tungsten filaments, by means of which the electrodes could be heated to a white heat in a vacuum for the purpose of studying spurious count phenomena.

Two profiles have been used, the one a rounded 45 degree bevel, the other flat with edges rounded by emery paper. These are illustrated in Fig. II-3. No significant difference in performance between the two has been noted, but the beveled-edge construction with copper-plated steel as the material is far better mechanically and can be made flat to within perhaps 2 mils if bent around a form in a brake. Such a construction, or perhaps a film evaporated on glass, is to be preferred.

The electrodes have in all cases been polished with successively finer grades of emery cloth, ending up with crocus cloth. Just before final assembly they are thoroughly swabbed with xylene, and after the tube has been assembled, rinsed with xylene, alcohol, distilled water, and alcohol. The tube is next evacuated to a high vacuum and baked at 500 degrees C. for two hours; in the case of the copper electrodes, hydrogen is admitted for 10 min. or so at this temperature to reduce off oxides. The tube is again evacuated to 10^{-5} mm. or better, cooled, and filled. Successful results have been obtained only when the xylene has been admitted first, followed by the argon; indeed, the best counters have resulted when the argon rushing into the tube has actually condensed droplets of xylene on the envelope, so that the tube has contained saturated xylene vapor. (The threshhold then becomes slightly temperature dependent, but with the parallel-plate counter operated far above threshhold, the change is not important in a normal laboratory room.) The importance of admitting xylene first is possibly due to the formation of a layer of xylene on the cathode.

The precision with which the plates must be held parallel depends on the precision with which it is desired to make time measurements. We shall discuss this in Section VI.

III. AFTER-EFFECT AND SPURIOUS COUNTS

It became apparent at the very outset of the present investigation that there were, in general, many more ions in a discharge tube than could be accounted for by the natural background radiation.

As a first step in studying the phenomenon, a quench circuit was constructed which permitted the electrodes to be recharged at a known time T_Q following the previous discharge. The state of affairs which results is shown in Fig. II-1 (b); T_Q was adjustable over a wide range, from milliseconds up to 60 seconds. In addition, an integrating circuit was so arranged that the intervals t between each charging of the electrodes and the subsequent discharge could be measured; in case the spurious counting rate is high, these intervals t may be tenths or hundredths of a second. During the "cooling off" period T_Q, a potential of a few hundred volts is left on the plates to clear away ions from the previous discharge, as well as any formed during this period.

An arrangement such as this permits a counter to be studied under conditions which would result otherwise in a so-called continuous discharge. The circuit is similar in principle to one used by Paetow[7] in a very interesting study of the after-effect. For preliminary investigations, a counter (number 1P1) consisting of parallel circular discs of molybdenum was used. The radii of the discs was about 1 cm. and their spacing 3.0 mm.; they were polished and cleaned before assembly.

We have already mentioned in Part II that counters filled with pure argon, or with argon plus more than a few millimeters of air, or with air alone, have no plateau. To amplify this statement, some tests made with a "bad" argon-air counter will be discussed. The counter was connected to the quench circuit mentioned above, and spurious counting rates were measured by means of the integrating circuit: the reciprocal of the mean interval t between the charging of the counter and the subsequent discharge is equal to the rate of production ofspurious plus natural background counts.

Typical behavior of a bad counter under such conditions is shown in Fig. III-1. If we take a counter which has not been used for 24 hours and start "counting", using a quench time of 0.53 sec., the intervals t gradually get shorter as the spurious activity builds up, and the upper curve is obtained. The points represent the reciprocal of the mean interval for a 100-sec. period of counting. If after the curve has levelled off, the quench time is shortened to .16 sec., the spurious counting rate increases once more and then levels off again.

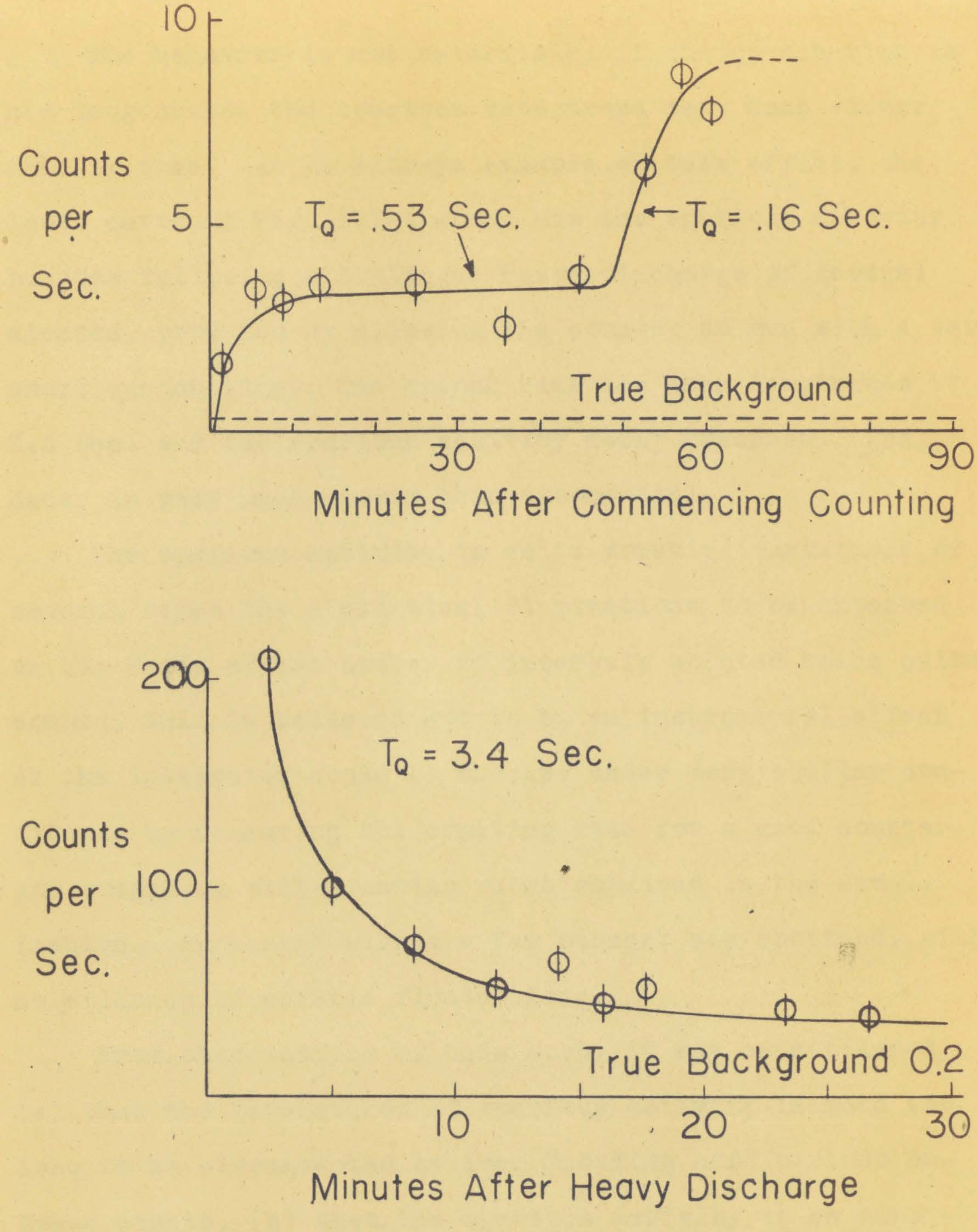

FIGURE III-1. Build-up and Decay of Spurious Activity. Counting rates obtained from reciprocal of mean interval between charge and discharge of counter.

The behavior is not reversible; if the quench time is now lengthened, the spurious rate drops very much slower than it rose. As an extreme example of this effect, the lower curve of Fig. III-1 shows how the spurious activity behaves following a prolonged heavy discharge of several minutes, produced by allowing the counter to run with a very short quench time. The quench time was then lengthened to 3.4 sec. and the spurious activity decay observed. The decay is very much slower than exponential.

The spurious activity is quite erratic, variations of several times the statistical fluctuations to be expected on the basis of the number of intervals counted being quite common; this is believed not to be an instrumental effect as the integrator could be checked under very similar conditions by measuring the counting rate for a good counter and comparing with counting rates obtained in the usual fashion. Agreement within a few percent was obtained, with no evidence of erratic fluctuations.

From observations of this sort, it may be concluded (a) that the persistence of spurious activity is much too long to be circumvented by long "cooling off" periods between counts, (b) that the spurious activity <u>is</u> an after-effect of previous counts.

On the other hand, the production of spurious counts is very much lessened by the addition of an organic vapor such as xylene. Now it is well-known that the addition of one of the so-called "self-quenching" vapors to the conventional G-M counter enables it to be used with a very low value of resistance, so that it may be very rapidly recharged--say in the order of 100 μsec. This is generally interpreted as being due to the reduction of secondary electron production at the cathode during the arrival of the positive-ion sheath, and it is quite certain that the vapor does do this. On the other hand, the importance of the self-quenching constituent in suppressing spurious counts arising from origins other than the positive ion bombardment does not seem to be so widely recognized. It is not the purpose of this paper to discuss cylindrical counters, but it seems well to point out there are at least two kinds of spurious counts. Secondary electrons from the positive-ion bombardment are avoided in the present set-up by always using a quench-time greater than the positive-ion collection time.

A typical plateau for argon-xylene counters is shown in Fig. II-5. From the tests described in Part II it is known that most of these counts are true counts. To investigate whether the slope to the plateau is due primarily to additional spurious counts as the overvoltage is raised, or to some other effect, the counting rate was measured as a function of voltage, at two quench times, using the integrator circuit and the "mean interval" method of measurement described above. The results are shown in Fig. III-2; curve 2 is for a quench time of .05 sec., and has a slope of 4.4% per 100 volts at 2500 volts while curve 3 is for a quench time of 3.4 sec. and has a slope of 2.9% per 100 volts. Curve 1 is a plateau taken after the electrodes had been outgassed at white heat for ten minutes and the counter refilled; the lower threshhold is due to a slightly lower filling pressure.

Some, at least, of the plateau slope is due to spurious counts according to the above curves. However, the coincidence rate for two counters in close proximity was measured in connection with the uncertainty-time measurements, and found to vary with the overvoltage in the manner shown in Fig. III-3. This behavior indicates that the active area of the counters must increase with voltage, which is not surprising. (It should be remembered that the coincidence rate goes up approximately as the square of the active area, changes in angular distribution being neglected.) The remainder of the plateau slope is thus attributable to a geometrical effect. Since the parallel-plate counters are designed for time measurements, spurious counts are not particularly objectionable until they become so frequent that the counter spends most of its timing counting them to the exclusion (because of the finite quench time) of the true counts

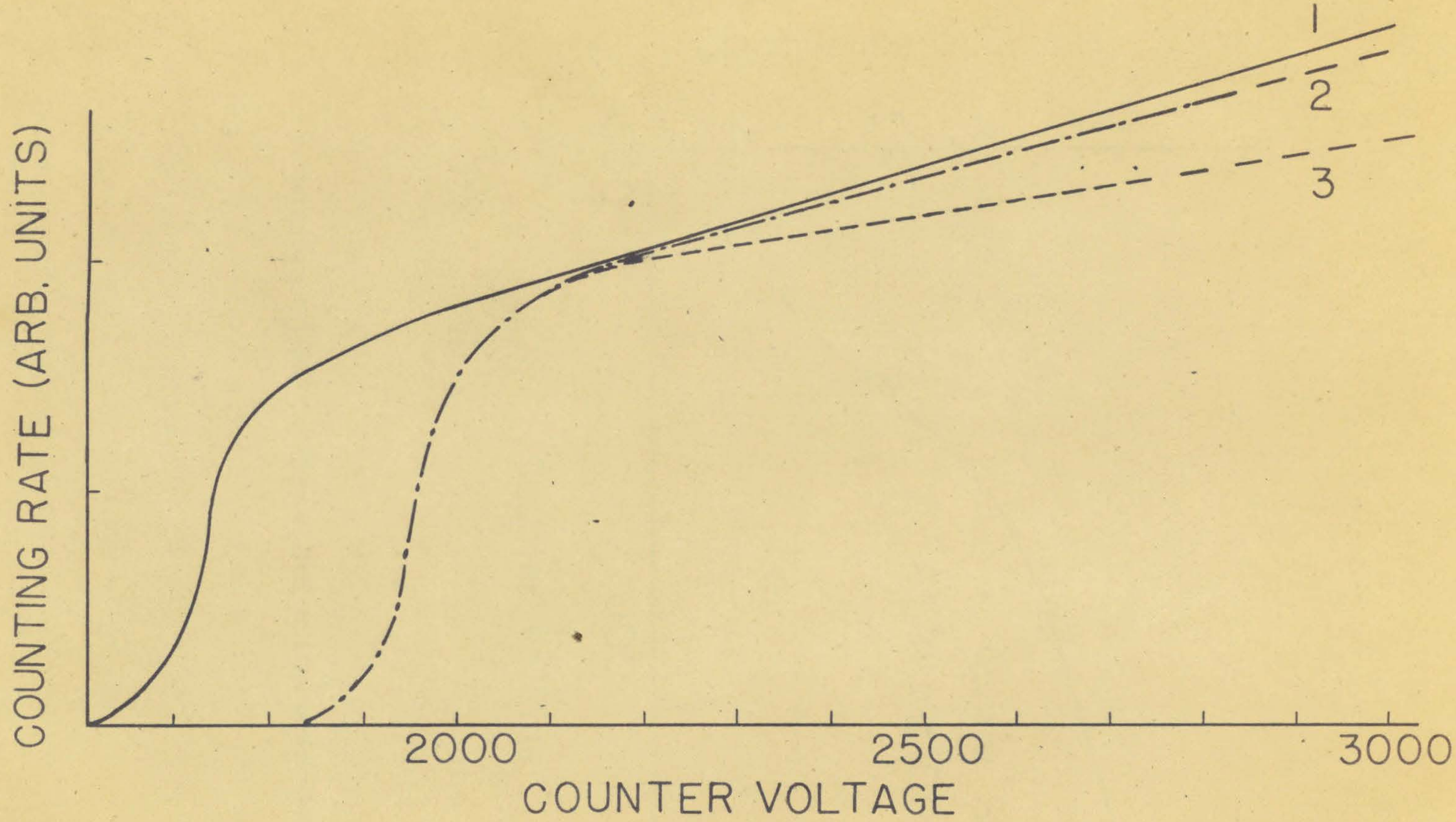

FIGURE III-2. Effect of quench time on plateau. (1),(2)--.05 sec, (3)--3.4 sec.

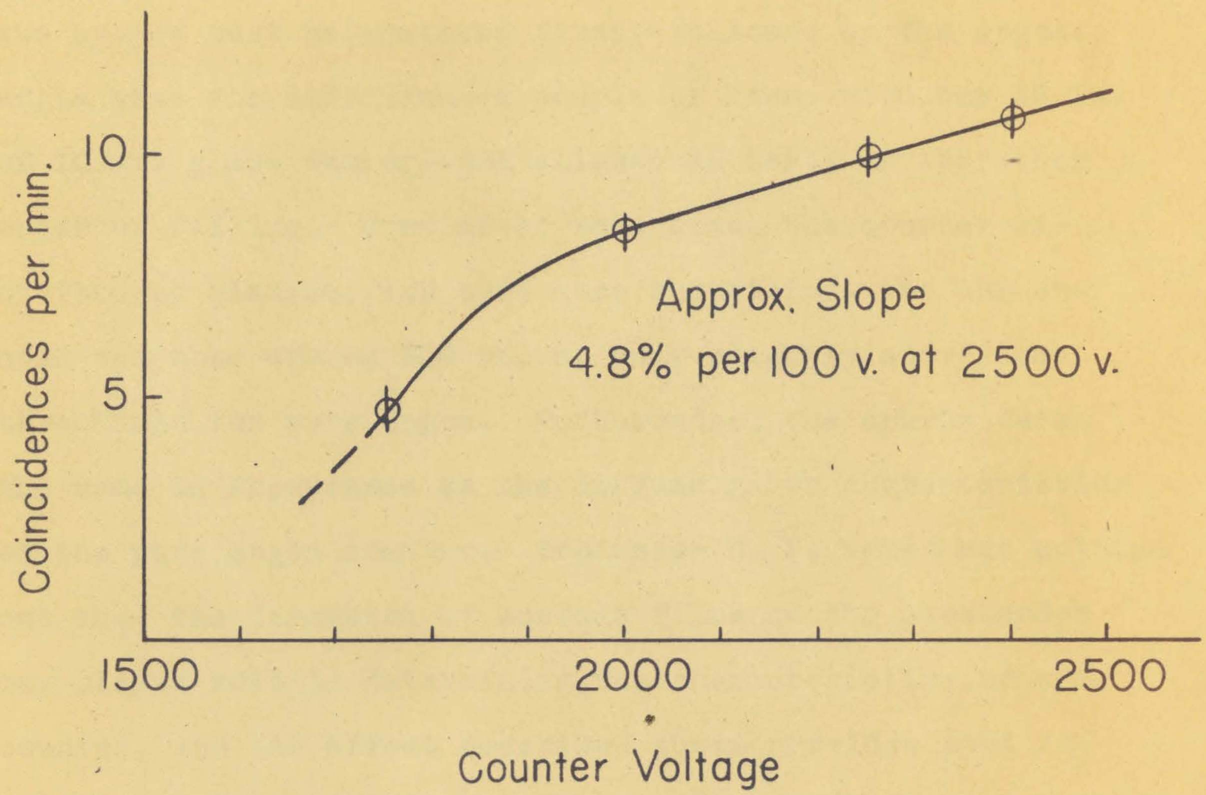

FIGURE III-3. True Coincidences Vs. Voltage.

The investigation of the plateau slope was not, therefore, carried any further.

An interesting effect in connection with the filling of the counters has already been mentioned, namely that the xylene must be admitted first, followed by the argon. Ample time for diffusion--a couple of hours with but 18 in. of 10 mm. glass tubing--was allowed in tests of the other order of filling. Even after this time, the counter exhibited no plateau, and even more surprising, the threshhold was down around 600 volts, only slightly above the threshhold for pure argon. Furthermore, the sparks were the same in appearance as the diffuse glows characteristic of the pure argon counter. Professor H. V. Neher has pointed out that the formation of surface films on the electrodes may play a role in determining the characteristics of a counter, and the effect described above provides good evidence in support of this hypothesis, at least in the case of parallel-plate counters. According to this picture, the change in threshhold is due to the fact that in the xylene-first case a surface film of xylene prevents the metastable argon atoms* from liberating copious secondary electrons at the cathode and thus reducing the sparking potential. Evidently the argon prevents this film from forming if it

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* The xylene molecules reduce the lifetime of the argon metastables but evidently not enough to suppress their role here.

is admitted first. The film of xylene on the cathode is also responsible for minimizing the spurious counts, if we accept this hypothesis.

When an argon-xylene counter "goes bad", the spurious counts are observed to originate from one or two very definite spots on the cathode, the counts occurring in bursts which are easily distinguishable from the normal background counts which are scattered in a random fashion over the surfaces of the plates. At first these bursts choke themselves off, presumably when, by chance, genuine counts occurring elsewhere in the counter give the spot a chance to "cool off". Once such a spot starts, it gets worse, bursts occurring more frequently. Lengthening the quench time helps somewhat, as does also reducing the overvoltage but in all cases the spot eventually develops, and even at the longest quench times, the counter counts at the spot almost as fast as the quench circuit recharges the electrodes. The situation is thus unstable, each spurious count making the spot more or less permanently worse and increasing the chance for a subsequent spurious discharge at that spot. Deposits of what appears to be carbon from the breaking down of the organic vapor may be seen at either plate where the bursts occur.

Once such a spot has developed, the counter must be re-baked and re-filled, and in the worst cases, taken apart and the spot swabbed with xylene.

Because of their localization, the spots must have something to do with the state of the electrodes. It is not a matter of a sharp point forming, as the spots do not alter the threshhold, nor do sparks favor the spots at low voltages--indeed, until the spot is very bad, the counter may be continued in operation at a very low overvoltage. The phenomenon does seem to fit in with the hypothesis that a film of xylene on the cathode prevents the occurrence of spurious counts, but without further study one cannot be sure.

As to the origin of the spurious counts themselves, Paetow(7) has suggested that they arise when bits of insulating materials are charged up by photons from the sparks. High fields are formed because of the small size of the particles, and electrons are produced either by breakdown of the insulating matter or field emmission. The present investigation does not yield any information on this question.

IV. QUENCH CIRCUIT AND AUXILIARY ELECTRONICS

A. Quench Circuit

In order to realize the count and recharging cycle discussed in Part II, the quench circuit shown in Fig. IV-1 was developed. In addition to producing at the plate of T_3 the waveform of Fig. II-1, this circuit should have certain other characteristics. It should be isolated from the counter and timing circuit during the first 0.1 µsec., but must still trigger fairly rapidly thereafter. The recharging time should be short compared with the mean interval between counts, to minimize the possibility of a count occurring at less than the full counter voltage and hence giving a long time lag. The current drain from the high-voltage supply should be low, to simplify the design of the latter. And finally, it is desireable that the quench time T_Q be adjustable over a wide range, especially when investigating the spurious count phenomena.

It was found necessary to use three tubes if the rapid recharging as well as the low drain from the high-voltage supply were to be realized; since a double triode may be used, this is not particularly objectionable. In Fig. IV-1, T_1 and T_2 form a simple cathode-coupled univibrator,[8] and the cathode of T_3 is connected directly to the common cathodes of the univibrator. It should be noted that there is only

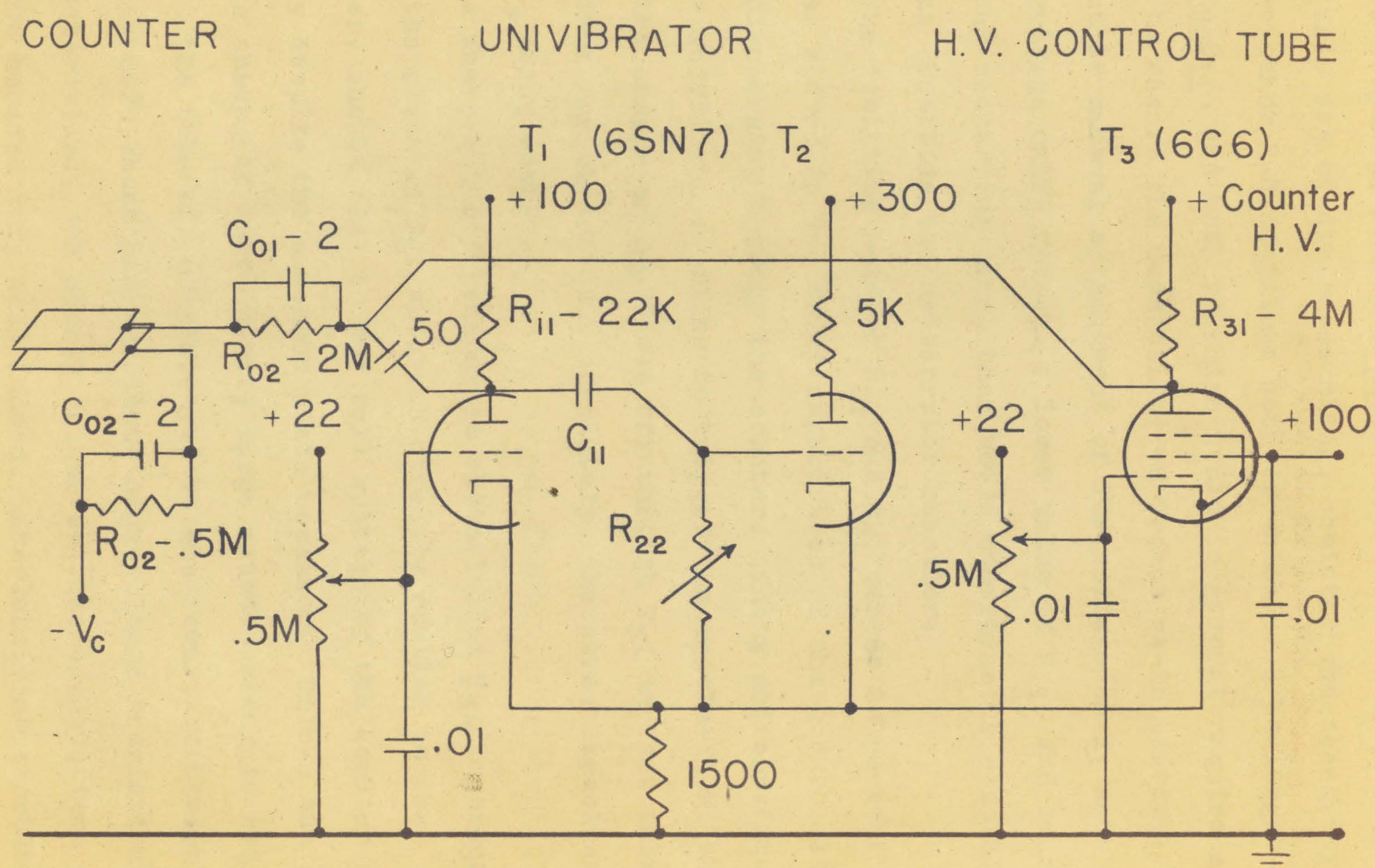

FIGURE IV-1. Quench Circuit. For .05 sec. quench time, R_{22} is 20 megohms, C_{11} .02 uf.

one R-C coupling, namely $C_{11}R_{22}$, which determines the quench time; this use of direct couplings obviates the necessity for two other R-C couplings both of which must be larger than $R_{22}C_{11}$, and both of which would in general require a diode to assure the possibility of prompt re-initiation. The rather unusual arrangement of low voltage on T_1 and high voltage on T_2 permits a lower value of R_{11}, and hence a faster recharging time, than would otherwise be possible without upsetting the univibrator behavior.

The isolating network R_{01} and C_{01} serves to prevent the charges stored in the stray capacitance of the quench circuit from discharging through the counter. The 2 μμf. capacitor C_{01} is sufficient coupling to trigger the univibrator, whereupon the charge on C_{02} flows off through T_3; in fact this capacitor may be left out completely, the stray capacitance of R_{01} being enough.

A sharp cut-off pentode is essential at T_3, in order that the plate of T_3, which is directly coupled to the counter, should rise to the full voltage of the counter H.V. supply despite the 4 megohm plate resistor. Unless the cut-off is sharp, an inordinately large cathode swing is required to cut the tube off completely. It was found, for example, that an 807, which has excellent high-voltage insulation characteristics, was poorly suited to this application, while the 6C6 behaved very well indeed. Absolutely no trouble has been experienced with voltage breakdown with up to 4000 volts on the plate; for those Tories among us who believe in manufacturer's ratings (250 volts in this case!) the bakelite base can be removed from the tube and the leads dipped in ceresin wax; or one of the loktal series tubes could be dipped and used.

B. <u>Auxilliary Electronics</u>

Fig. IV-2 shows how two counters may be connected simultaneously to a common quench circuit as well as to a simple coincidence circuit without appreciably disturbing the initial UVF pulse which each counter sends down the timing line. The time-constants are such that the counters are left alone, so to speak, until the UVF pulse is over; the 0.5 $\mu\mu$f. stray shunt capacitances of the various resistors attached to the counter plates merely increase slightly the capacitance of each plate to ground during the initial fast transient. The above-mentioned time constants are also so large that only the charge actually stored on a counter flows off during breakdown, thus minimizing the energy in the spark.

On the other hand, no difficulty is encountered in triggering the univibrator of the quench circuit through the 2-megohm resistor. This is due in part to the stray capacitance across this resistor, in part to the tremendous voltage swing from the parallel plate counter; even if the over-

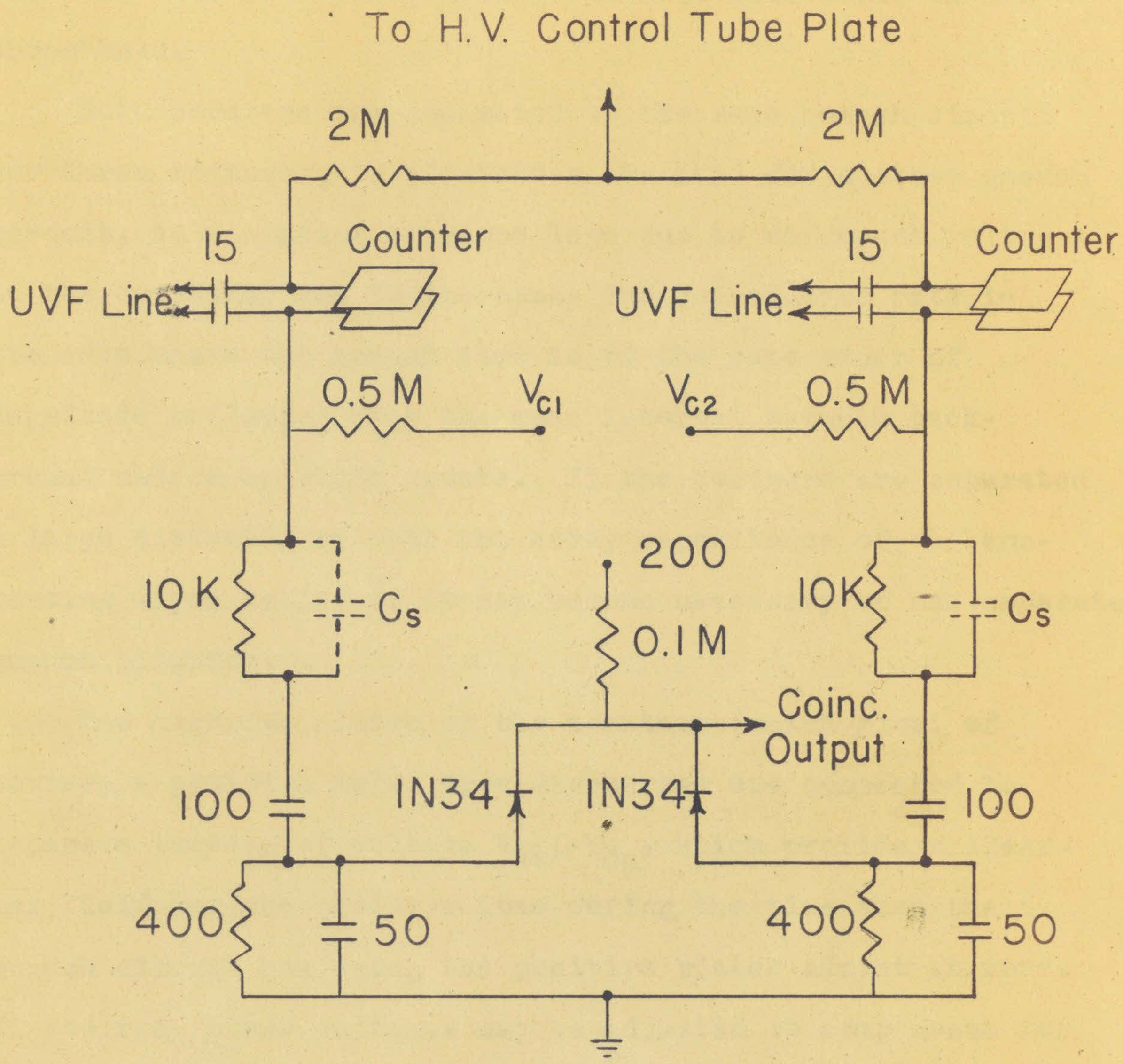

FIGURE IV-2 Two counters on single quench circuit and coupled to a simple coincidence circuit. Stray capacitance of each resistor 0.5 $\mu\mu f$.

voltage is very small, the characteristics of the counter are such that the voltage swings down to well below the threshhold.

Both counters are connected to the same quench circuit for three reasons: it eliminates the need for another quench circuit, it minimizes spurious lags due to different voltages on the counters, and it increases the coincidence rate in the case where the quench time is of the same order of magnitude or larger than the mean interval between background and/or spurious counts. If the counters are separated a large distance, so that the stray capacitance of the connecting wires is large, it may become necessary to use separate quench circuits.

The negative plates of the counters (which give, of course, a positive pulse upon discharge) are connected to separate sources of voltage V_{C1}, V_{C2}, which provide a clearing field for the positive ions during the time that the quench circuit has swung the positive plates almost to zero. If desired, these voltages may be adjusted to compensate for different threshholds of the individual counters; they must not, however, be more negative than about -600 v. in order that the discharge shall not continue even after the quench circuit has fired and the positive plate swung down to zero.

The negative plate of each counter is connected through a resistance-capacitance divider to the cathode of a 1N34 crystal diode as shown in Fig. IV-2. These diodes are the heart of a very simple coincidence circuit of the type discussed by Howland, Schroeder, and Shipman.[9] It is interesting to note that the large voltage swing of the parallel-plate counter makes it possible to use the voltage divider instead of the conventional amplifier tube required with cylindrical counters. The coincidence output is fed to a cathode follower (stray capacitances must be kept small at this point) and thence to the trigger input of the synchroscope. The performance of this simple little circuit has been most gratifying; it operates positively over a range of counter voltages from threshhold to 1500 volts overvoltage without adjustment. The resolving time of the circuit is around 1 to 2 µsec.

Originally, the resistance-capacitance divider had a 2 µµf. capacitor across the 10K resistor, but it works just as well without this on the stray shunt capacitance C_S alone.

V. TIMING CIRCUIT

A. Introduction

The measurement of time intervals of the order of 10^{-9} sec. is not altogether new. The Kerr-cell electro-optical shutter was used for this purpose around 1935 by White[3] and by Wilson.[4] So far as the author knows, Newman[5] was the first to apply the method of pulses travelling along an electrical transmission line, which is fundamentally the same as the method to be described in this paper. A more refined instrument using this principle has been described by Neddermeyer, Althaus, Allison, and Schatz.[10] Besides the Kerr-cell optical method and the electrical transmission line scheme, two other methods were considered by the author before adopting the present approach. One of these is the direct oscilloscope method, the other a method suggested by Alvarez[11] and independently conceived by the author, in which the Fourier components of two pulses are analysed by a series of tuned circuits.

Two strong objections to any method using the Kerr-cell shutter are (a) the need for a very large voltage pulse to actuate the shutter and (b) the difficulty of recording the time interval measurement, since the light intensity from the small sparks available does not seem sufficient for photography, while a photo-multiplier involves a complicated high-gain amplifier. The direct oscilloscope method requires writing speeds which, while not unattainable, require special high-voltage cathode-ray tubes; in addition, the deflection sensitivity at such writing speeds is very low, and the problem of providing a precision time base is a formidable one. As for the method of Alvarez, it seems less direct and less certain than the method of intersecting pulses.

The basic principle of the chronotron is most easily presented with the aid of an analogy from schoolboy algebra: train A leaves Chicago for New York; at some later time, train B leaves New York for Chicago. Both travel with the uniform speed c, and they are observed to pass each other at a distance x from the midpoint of the tracks. Train B therefore left New York at a time $2x/c$ later than the departure time of train A. In the case of the chronotron, the trains are extremely short electromagnetic pulses, of the order of 5×10^{-9} sec. in duration, or--since light travels one foot in 10^{-9} sec. very nearly--about 5 feet long. The track on which the pulses travel is a parallel-wire line, and the velocity is precisely the velocity of light if the line has an air dielectric. The position at which the pulses meet is determined by a series of detectors, which function at least approximately as peak voltmeters. If the peak voltages recorded at each detector are plotted against the detector positions, a curve is obtained which is called the <u>superposition locus</u>; if the pulses have the same polarity, the superposition locus has a peak at the point of intersection, while if the polarity of the pulses is opposed, the meeting point is revealed by a dip. Evidently the detector spacing must be less than the width of the pulses, the two pulses must be approximately the same length (in the case of the polarity-opposed pulses) and the detector must be, if not a true peak voltmeter, at least non-linear (if the superposition locus is to show a peak in the reinforcing-polarity case).

A block diagram of the chronotron timing circuit is shown in Fig. V-1. In order to facilitate the discussion of this circuit, we shall introduce the term "ultra-video-frequency" (UVF) to describe wide-band circuits for the range of approximately 50 to 1000 megacycles per second, and pulses of the order of 5×10^{-9} sec. in duration. The term "video-frequency" will as usual refer to pulses of the order of one μsec. long.

The wave-form of the counter discharge is a step-function with a rise time of a few billionths of a second. It is differentiated and passed on to the UVF line as a pulse a few feet long. The detectors D record the superposition locus of these pulses and the remainder of the circuit merely serves to present a trace of the <u>superposition locus</u> (not the UVF pulses themselves) on the synchroscope. We shall now take up in some detail the design and performance

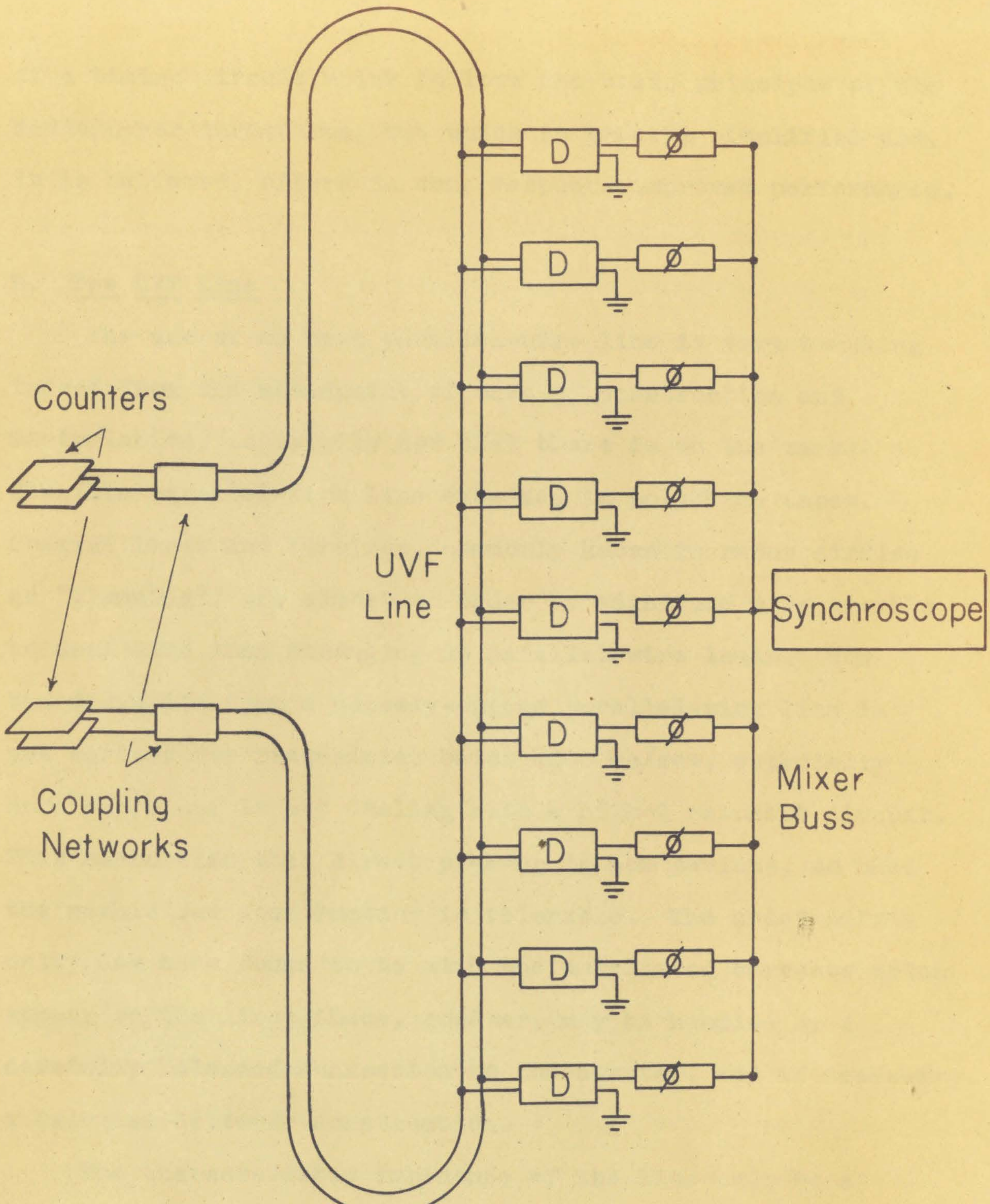

FIGURE V-1. Chronotron Timing Circuit.

of a timing circuit which follows the basic principle of the Neddermeyer chronotron, but which is greatly simplified and, it is believed, offers in some respects improved performance.

B. The UVF Line

The use of an open parallel-wire line is very tempting indeed from the standpoint of ease of construction and manipulation, especially now that there is on the market a flexible parallel-wire line embedded in polythene tape*. Coaxial lines and fittings, commonly known in radar circles as "plumbing", are almost an order of magnitude more trouble to deal with than stringing up parallel-wire leads. Now the radiation from a closely-spaced parallel-wire line is not serious for frequencies below 1000 mc/s**, especially here where one is not dealing with a high-Q resonant circuit. This means also that direct pick-up is not serious, so that the unshielded construction is tolerable. The chief difficulty has been found to be with the unbalanced currents which appear on the line; these, however, may be handled by a carefully balanced connection to the counter, and if necessary, a balanced detector construction.

The characteristic impedance of the line must be a compromise between the demands of matching the line to the

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* Amphenol "Twin Lead" designed for television and FM lead-ins.
** See, for example, Terman, Radio Engineer's Handbook, McGraw-Hill (1943) page 193.

counter (which requires a high impedance) and the demands of low loading of the line by the detectors. These factors are considered in more detail later; it is fortunate that the convenient 300-ohm Amphenol Twin-Lead is almost the optimum compromise. The characteristic impedance of the usual co-ax is 70 ohms, inconveniently low from the counter matching standpoint.

A 300-ohm parallel-wire line was therefore adopted. The section along which the detectors are mounted is an air dielectric line, made of #14 copper wire spaced 3/8" center to center. Connections are made with the flexible polythene tape, as are also fixed delay sections which may be introduced to shift the detector section about with respect to the midpoint. In this connection it should be noted that, although the velocity of light on the polythene tape line is slower by about 10% than in air,* the velocity is independent of frequency, and hence the line is non-dispersive, provided only that the dielectric constant of the polythene is independent of frequency over the UVF band.

Finally, it may be remarked that no difficulty has been encountered with reflections on the line from supports and from soldered joints between sections of line. The supports have been of polystyrene 1/16" thick except for small ceramic buttons to bear the strain of supporting the air line. Coupling between adjacent sections of line has likewise not been troublesome; a spacing of a few inches has been easily adequate.

C. Counter-to-Line Coupling

The counters are coupled to the UVF line through small capacitors (10 to 15 μμf.) for two reasons: (a) The effective capacitance in shunt with a counter must be kept low to minimize the charge, and hence the total energy, which flows through the counter per discharge; (b) the step-function waveform of the counter proper must be converted to a short pulse. Since the line looks like a pure resistance if it is either matched or long compared to the pulse length*, we have here the usual differentiating circuit which will give us just the waveform desired, if the time constant is properly chosen.

The coupling network is shown in Fig. V-2a. The exponential taper section** converts the 300-ohm line to a 600-ohm impedance; it was made simply by splitting the last 30 cm. of the polythene tape line and supporting the wires on appropriate lucite spacers. This arrangement transforms the line without reflection or loss for all frequencies above a certain critical frequency, which in this case is about 100 mc/s.

The coupling network also matches the counter impedance to the line, so that pulses travelling back along the line

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* There may, of course, be reflected pulses in the case of the unterminated line, but the pulse which starts down the line is still the same as in the terminated case.

** See, for example, Terman, Radio Engineer's Handbook, McGraw-Hill (1943) page 196.

towards the counter are absorbed. The elimination of unwanted reflected pulses in the timing circuit is, of course, essential. The coupling network shown here was tested for reflections by connecting the counter and coupling network directly to the end of the timing line. A pulse from another counter was then sent down the line towards the network to be tested, and the superposition locus of the incident pulse plus its reflections, if any, was observed. It was found that the reflected pulse was less than 1/10 the amplitude of the incident pulse and of the opposite polarity. On the other hand, the counter itself, if connected to the test line through C_D, behaves almost as an open circuit, with a large positive reflection. In accord with this observation, it was found that the resistors R_1 could be left out without seriously impairing the line-to-counter match. They may be given any value up to a few hundred ohms if a longer RC constant is desired. A remark on the high-frequency characteristics of 1/3-watt midget resistors may well be made at this point, as they are used extensively in the coupling sections and detectors of the chronotron. The shunt capacitance of several such resistors, all less than 1000 ohms, were measured and found to be about 0.5 μμf. In addition, a better test was provided in the case of the 300-ohm value by terminating the UVF line with such a resistor and looking for reflections on the timing line. So far, the performance of the resistors in the UVF band has been consistent with the assumption that they look like approximately their nominal resistance in parallel with 0.5 $\mu\mu f$.

D. Detectors

The ideal detector would behave as a peak voltmeter even for transient pulses a few feet long. In addition, the ideal detector would present to the line such a high impedance that the loading would be negligeable even for 20 or 50 detectors; and the detector impedance would be very nearly a pure resistance, so that what loading remained would be non-dispersive in the sense discussed below. This ideal can, in fact, be very closely realized with a detector built around the new 1N34 germanium crystal diode*. Such a detector can be made compact, simple, and satisfactorily stable.

Figure V-3 shows the circuit diagram of a detector, together with the video pulse-forming network. A small fraction of the voltage pulse appearing along the UVF line at the location shown is impressed across the crystal and C_2 by means of the voltage divider R_3R_4. If the pulse is positive the capacitor C_2 then charges up to the peak voltage across R_4, provided that the time constant $(R_4 + R_x)C_2$ is

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* Manufactured by Sylvania.

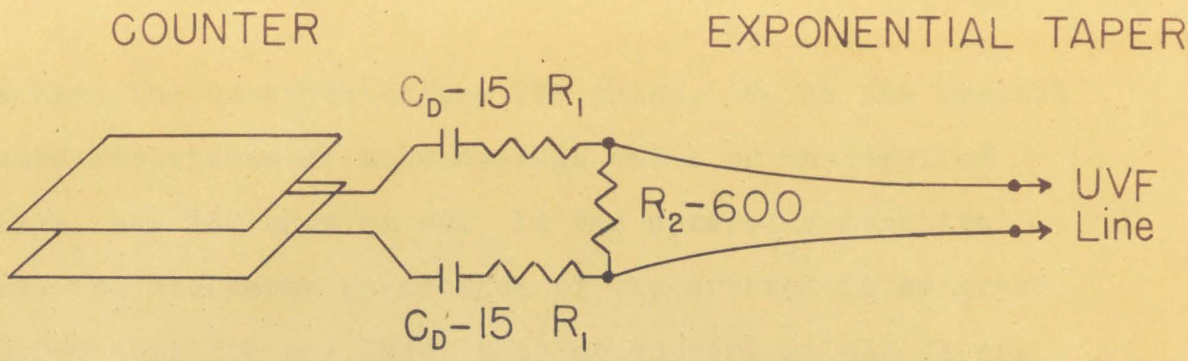

FIGURE V-2. Differentiating and Matching Network.

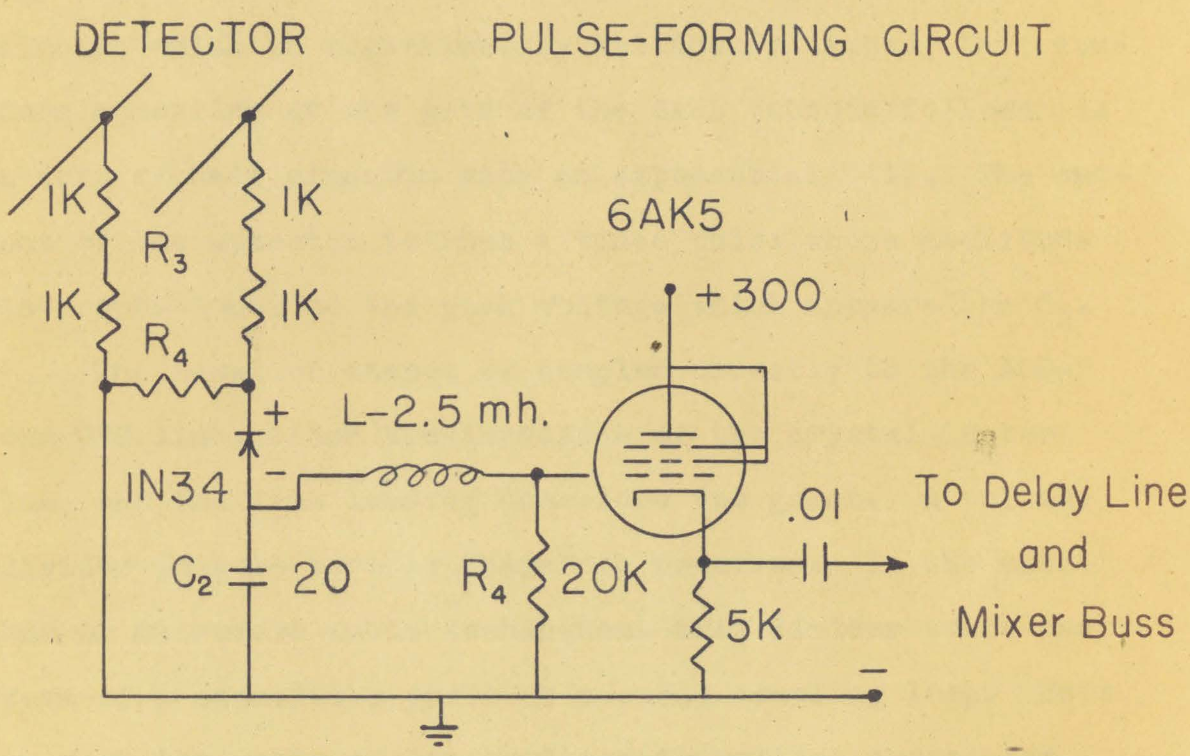

FIGURE V-3. Detector and Pulse-Forming Circuit.

less than the duration of the UVF pulse. R_X is the crystal forward resistance at some average value of the applied voltage, say 100 ohms or so. In the case of a negative pulse, the backwards resistance of the crystal is so great (150,000 ohms for the 1N34) that no current at all flows.

The high backwards resistance of the crystal prevents the charge on C_2 from flowing off, at least for a relatively long time (in terms of UVF phenomena) of a couple of microseconds. Instead, this charge now flows off through L and R_5; since these elements, together with C_2, form a resonant circuit which is approximately critically damped, the waveform appearing at the grid of the 6AK5 cathode follower is a sort of half sinusoid with an exponential tail. The output of the detector is thus a video pulse whose amplitude is proportional to the peak voltage which appeared on C_2.

The detector cannot be coupled directly to the 300-ohm UVF line, since the impedance of the crystal is too low, and the line loading therefore too great. A voltage divider of some sort is therefore required. In the usual UHF or microwave radio techinques, this divider takes the form of a capacitive probe or a small coupling loop. Here we wish the ratio of line voltage to voltage across the crystal to be independent of frequency over an extremely wide band, and since the loop is particularly poor in this respect, only capacitance and resistance dividers were considered. The resistive coupling was adopted for two reasons: (a) The attenuation of the UVF pulse produced per detector connected across the line is less than for the capacitive coupling, the latter being serious at the higher frequencies. (b) The dispersion of the pulse produced by the presence of the detectors is to the first approximation zero in the case of the resistive coupling only.

The loading effects of detectors on the line are discussed further in the Appendix. We may summarize the results obtained there as follows. With the resistive detector shown in Fig. V-3, the attenuation per pulse is .30 db per detector over the central portion of the UVF band (b) the frequency at which the attenuation caused by stray shunt capacitance in the midget resistors is equal to the attenuation produced by the pure resistance alone is about 1500 mc/s. Since it is voltage and not power which is our primary concern, it is thus possible to use about 20 detectors for a maximum voltage ratio from one end of the detector line to the other of two-to-one. If a four-to-one ratio may be tolerated, or if the detector impedance can be approximately doubled, then forty detectors become possible.

It is not essential that the detector operate strictly as a peak voltmeter, but only that it should discriminate between two pulses arriving at different times and two pulses arriving simultaneously. If the crystal is operated along a portion of its characteristic which follows approximately a square law, such discrimination is provided. However, the crystal characteristics are not exactly identical, and may change with use; these disadvantages are minimized if the charging time constant is made so small that the detector behaves as a peak voltmeter. In practice, a value of 300 ohms for R_4 has been found to give a satisfactory compromise, even though this resistance, plus the estimated 100 ohm forward resistance of the crystal, gives a time constant of 8×10^{-9} sec. while the pulse lengths used are of the order of 5×10^{-9} sec. It is to be noted that C_2 may not be reduced, in order to reduce this time constant, below 10 $\mu\mu$f. or so, because the charge stored on it would then leak off through the backward resistance of the crystal.

E. Presentation Circuit

By "presentation circuit" we shall mean the circuit which takes the information contained in the series of charges stored on the detector condensers and transforms them into laboratory data--for example, pulses on a synchroscope screen. There are, no doubt, many ways to do this; the present system is quite simple and in addition, has the major advantage that all the pulses pass through the same amplifier. The shape of the superposition locus therefore depends only on passive, relatively stable circuit elements and cathode followers.

As already mentioned in the preceeding section, the charge stored on a particular detector condenser (C_2 in Fig. V-3) flows off through L and R_4, forming a rounded pulse roughly 0.3 μsec. wide at the grid of the 6AK5 cathode follower. The inductance L is a standard National 2.5 mh. r.f. choke, which probably behaves as a capacitance over most of the UVF band; thus charge is stored not only in C_2 but in the stray capacitances of the circuit. However, this does not seem to prevent the circuit from performing substantially as indicated. The value 20K for R_4 was chosen by trial and error as a reasonable compromise between the demands of pulse height, pulse width, and freedom from "wiggles". It is somewhat less than critical damping.

The pulses from the pulse-forming circuits are next passed through delay lines (ø in Figs. V-1 and V-4) whose function is to sort them out so that they appear in order upon the trace of the synchroscope. These delay lines are of the continuously-loaded coaxial-line type* developed by General Electric during the war; high inductance and capacitance per unit length are achieved by winding the center conductor in a tight spiral in close proximity to the outer braid. In this way a characteristic impedance of 1000 ohms and a delay of 0.6 μsec./foot are obtained. In so doing, the line becomes a low-pass filter, and a sharp pulse is

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* Now manufactured by James Millen Mfg. Co., Malden, Mass.

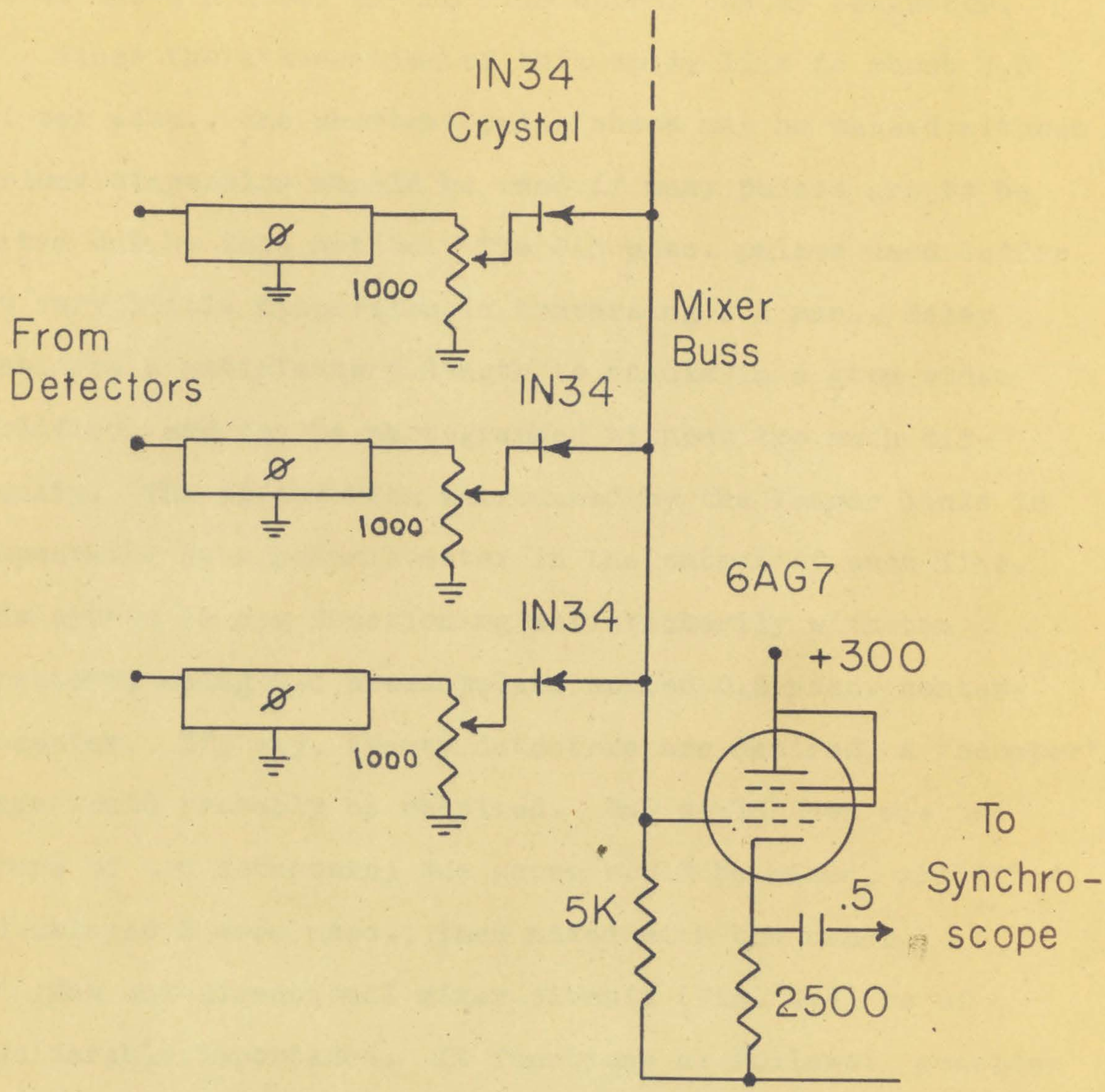

FIGURE V-4. Video delay lines and mixer.

therefore dispersed in transmission, besides being attenuated due to the I^2R loses in the fine spiral center conductor.

Since the attenuation of this delay line is about 2.5 db. per μsec., the shortest pulse which may be passed without serious dispersion should be used if many pulses are to be sorted out by this method. The 0.3 μsec. pulses used suffer but very little dispersion in traversing a 5 μsec. delay line, are a satisfactory length to handle in a good video amplifier, and may be photographed without too much difficulty. The attenuation introduced by the longer lines is compensated by a potentiometer in the output of each line. This system is now functioning satisfactorily with ten detectors, using 0.3 μsec. pulses spaced 0.5 μsec. center-to-center. If, say, twenty detectors are desired, a "booster" stage would probably be required. One would then use two groups of ten detectors; one group would be mixed, amplified, and delayed 5 more μsec., then mixed with the other.

The uni-directional mixer circuit (Fig. V-4) is of considerable importance. It functions as follows: consider a pulse coming from one of the delay lines, and further, suppose that the amplitude of this pulse is larger than any of the voltages at the other potentiometer outputs at this instant. Only the crystal at the output of the line we are considering will conduct, provided that the response of the cathode-follower grid circuit is fast enough. The pulse emerging from this line therefore sees an impedance which is approximately the 1000-ohm resistance of the output trimmer potentiometer; this match is adequate to prevent troubles from reflected pulses. Furthermore, the voltage at the cathode-follower grid is the voltage of the pulse of interest only; the voltages at the other outputs produce no flow of current in the grid resistor since the other crystals are nonconducting. The delay line whose output voltage is, at any given instant, the highest thus dominates the others.

This has a two-fold effect: first, the "tails" of neighboring pulses do not contribute underneath the dominating pulse, making possible the small pulse separation cited above; second; the video lines can all be connected to the cathode-follower grid without the large voltage losses which a passive matching network would entail.

Since the detectors are spaced out physically over a distance of several feet, the mixer buss which connects the various crystals to the cathode-follower grid must be made of fine wire and shielded by a large pipe (one or two inches in diameter) to keep stray capacitance to a minimum.

The output of the final cathode follower is fed directly to the 50-ohm input of a synchroscope whose amplifier has a gain of several thousand and a rise-time of 0.1 μsec. The 3BP1 cathode-ray tube of this synchroscope was replaced by a 3FP7 tube, with 4000 volts on the post-deflection accelerator electrode. The long persistence of this screen aids visual observation of single transients, such as we deal with here, and at the same time the screen photographs quite well with the yellow filter removed. With an f/4.5 lens, it was necessary to reduce the 10-pulse picture to about 2x5 mm. on the film to obtain sufficient intensity; a better lens, say around f/2, would permit larger images, or a special photographic phosphor could be used. The present image, viewed through a small magnifier, was large enough to determine with ease which pulse of the superposition locus was highest.

F. Performance

The instrument was set up for tests as follows. One end of the UVF line was connected to a counter, while the other end was connected to 15' of 300-ohm Twin-Lead, which was in turn terminated with a 300 ohm resistor. The synchroscope sweep was triggered by the counter pulses. The detector outputs were then roughly equalized by means of the potentiometers at the delay-line outputs. The final adjustment was made by alternately reversing the direction of travel of the pulse on the line, and leveling the video pulses on the synchroscope screen as well as possible considering the attenuation the UVF pulse suffers in travelling past the detectors.

The following qualitative tests were then made:

(a) Negative UVF pulse, terminated line. Result: superposition locus everywhere zero.

(b) Positive pulse, open-ended line: hump in superposition locus at open end of line.

(c) Positive pulse, shorted line: dip in s.l. at end of line.

(d) Negative pulse, shorted line: same as (c) but somewhat lower due to attenuation.

(e) Positive pulse, 15' of line shorted at end: s.l. substantially same as with 300-ohm terminating resistor.

(f) Counter connected to 3-way matching section[10] so that equal pulses were simultaneously applied to both ends of line: s.l. has hump or dip in center according as polarity of pulses applied reinforce or cancel.

Examples of the superposition loci which appear on the synchroscope are shown in Part VI, Fig. VI-3.

In addition, a quantitative test was made by using the arrangement in (f) but inserting several different lengths of Twin-Lead in either side. The displacement of the superposition locus as a function of the length of lead added to one side is shown in Fig. V-5. The velocity of propagation of the Twin-Lead as measured by the slope of this graph is 0.90c, while from measurements of the resonant frequency of a length of Twin-Lead it is 0.87c.

These checks, together with the general consistency of the results of Part VI on the counter reaction times, provide a very satisfactory verification of the chronotron performance. As regards stability, it has not been found necessary to change the trimmer settings over a period of a couple of weeks. The crystals have behaved remarkably well, with no evidence of changing characteristics and no cases of burnout, accidental or otherwise, over a period of nine months.

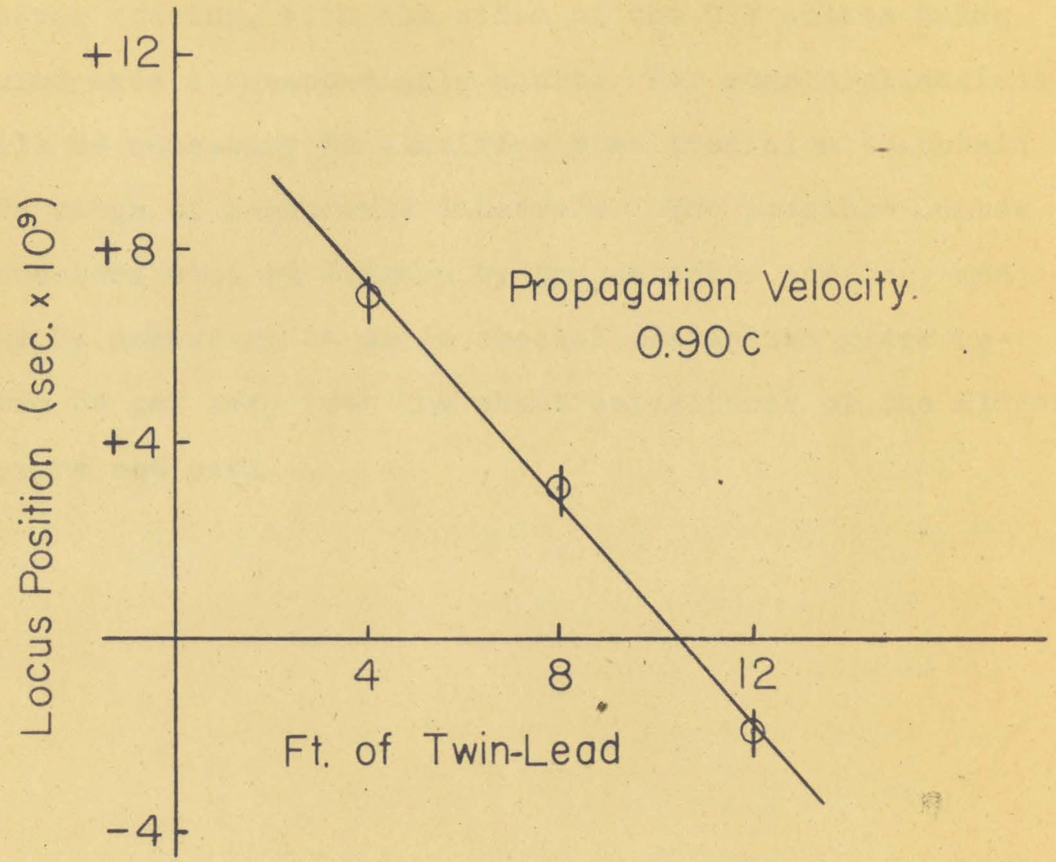

FIGURE V-5. Chronotron Test.

In any case, it is a very simple matter to take an occasional calibration picture as a routine check while taking data.

The overall precision of the instrument is evidently a function of the detector spacing: precise measurements call for close spacing, with the width of the UVF pulses being measured made correspondingly short. For some applications it will be necessary to sacrifice some precision to obtain a wide range of measurable intervals. The possible number of detectors will be limited by the detector loading, and it may be necessary to go to special platinized glass resistors to get away from the shunt capacitance of the midget resistors now used.

VI. THE REACTION TIME

A. Experimental Set-Up

In order to ascertain the precision with which a time interval between two ionizing events may be measured, one needs to know the uncertainty in the reaction time of the parallel-plate counters. The reaction time itself--the time between the appearance of an ionizing event in the counter and the maximum of the short electromagnetic pulse sent down the timing line by the counter--is fortunately of less interest, since it would be much more difficult, if not impossible, to measure.

The reaction-time uncertainty was measured as follows. Two counters were placed directly one above the other, and connected one to each end of the chronotron timing line. They were, in addition, connected to a common quench circuit and a coincidence circuit as shown in Fig. IV-2. This coincidence circuit triggered the synchroscope baseline whenever there occurred what we shall call a gross coincidence between the two counters (i.e. within 1 or 2 μsec.) caused for the most part by mesotrons or high-energy electrons in the cosmic radiation; accidentals could be completely neglected, since with such a resolving time and individual counting rates of at most 4 per sec. the accidental rate is only a few per day.

A continuous record of the synchroscope screen was kept by means of a camera with a slowly-moving film. A picture of the chronotron superposition locus thus appeared for each gross coincidence, and from the position of the maximum (or minimum, in case the counters were connected with polarity opposed) the precise interval ΔT between the two counter pulses could be determined.

For the purpose of studying the present counters, it sufficed merely to record, for each picture, which of the detector pulses forming the superposition locus was the highest. Occasionally there is no peak in the superposition locus; such cases are recorded as "off-scale". Since the detectors were spaced at two-foot intervals, a shift in the locus maximum from one detector to the next corresponded to a time interval of 4×10^{-9} sec. very nearly, and this interval is about right for plotting the distribution curves obtained with the present counters.

As a by-product of the reaction-time measurements, one obtains from the width of the peaks of the superposition loci the rise-time of the counter pulses. It should be noted, however, that if x_R denotes the full width at half maximum of the locus peak, the rise time is given by $T_R = x_R/c$; the factor 2 which enters in the expression for the time interval causing a given locus shift is no longer present. If the differentiating circuit between the counter and the UVF line really gave the true mathematical derivative of the counter pulse, the rise-time defined as above would be the time required for the counter pulse <u>slope</u> to pass through its maximum, starting and ending at half that maximum value. Definitions of pulse rise-times are in any case arbitrary and this one should serve our purposes.

It is also possible to obtain a measurement of the rise-time from a single counter, using any one of a number of methods for causing a given pulse to, so to speak, meet itself. This may be accomplished by reflecting a pulse at the open or shorted end of a line or the pulse may be split by means of a 3-way matching section as discussed already in Part V. However, rise-time measurements by the first method have the added significance that they correspond to a known type of initiating ionizing event, namely a fast lightly-ionizing particle traversing the counter in a nearly-normal direction. One might expect some difference in the rise time depending on the number and location of ion-pairs formed in the initiating event.

The rise-times defined above tell us very little, of course, about the reaction time itself; it may be some time between the formation of the initiating ion-pair and the first observable voltage surge.

B. Results

In Fig. VI-1 we present distribution curves of the relative lags between counters 2P1 and 3P1. (Data on these

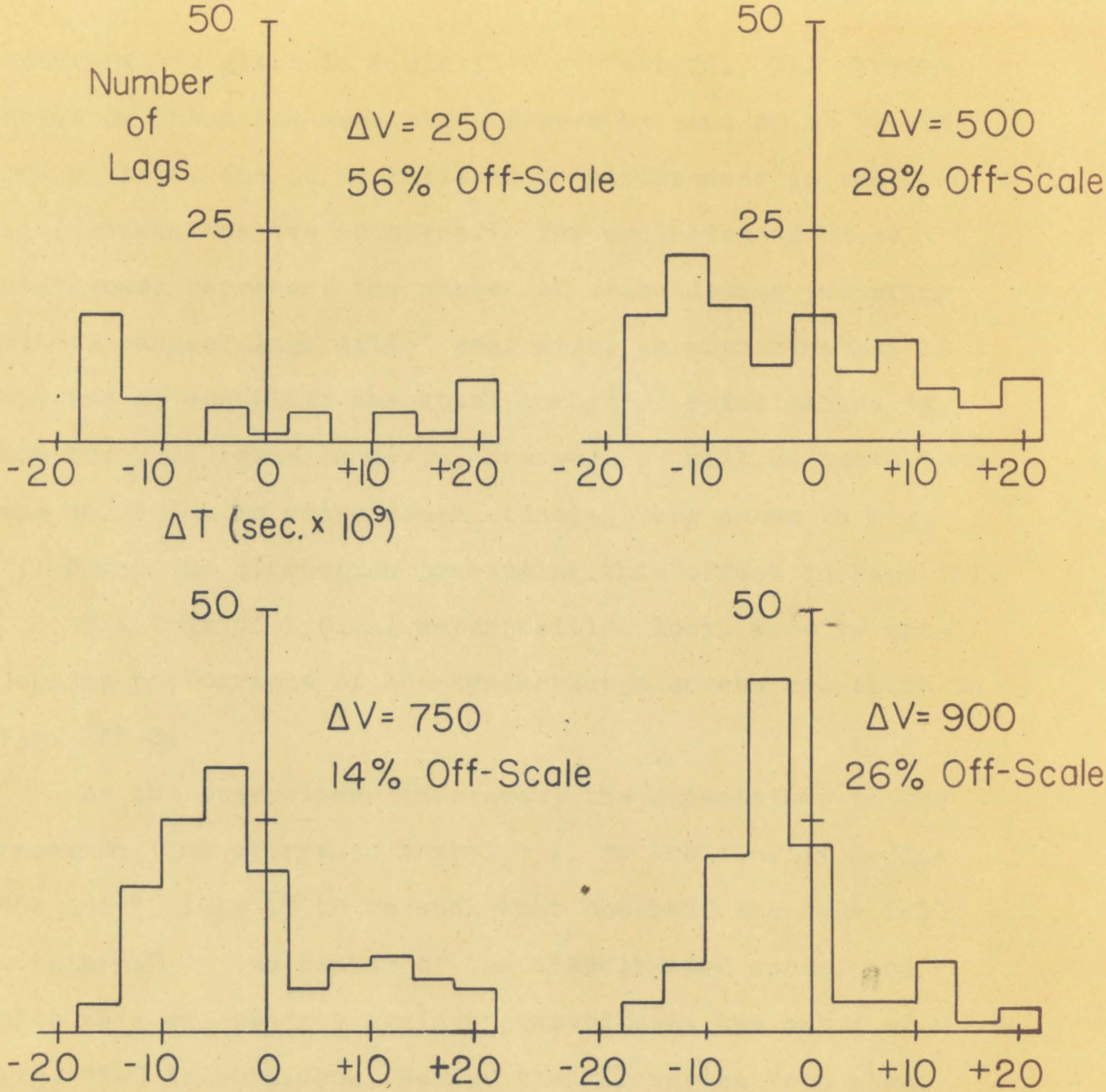

FIGURE VI-1. Distribution of relative lags between two counters in close proximity. Chronotron range here was -16×10^{-9} to $+20 \times 10^{-9}$ sec.

counters are given in Table II-2 of Part II. The thresh-holds on these two counters differed by some 50 to 75 volts out of 1450, due it is believed to differences in the spacings within the two counters.) The ordinates of these histograms represent the number of coincidences occurring with a rangeof lags 4×10^{-9} sec. wide, in approximately 18 minutes of counting; the total number of coincidences is not the same for each graph, however, as will be noted from the variation in coincidence counting rate shown in Fig. III-3 and the discussion concerning this effect in Part III.

Tracings of typical superposition loci, made by projecting photographs of the synchroscope screen, are shown in Fig. VI-3.

As the overvoltage increases, the uncertainty in the reaction time decreases sharply; if we arbitrarily define the uncertainty $\overline{\Delta T}$ to be such that one-half the lags fall within $\pm\overline{\Delta T}$ of the center of the distribution curve, and plot this uncertainty against overvoltage, the curve of Fig. VI-2 is obtained. We see that $\overline{\Delta T}$ varies from about 17×10^{-9} sec. at 250 volts to about 5×10^{-9} at 900. In evaluating $\overline{\Delta T}$ from the histograms of Fig. VI-1, the method used was to plot an integral of the distribution curve, and take the 50% point from this. The uncertainties so calculated are those which bracket one-half of <u>all</u> the coincidences, whether on or off of the chronotron scale.

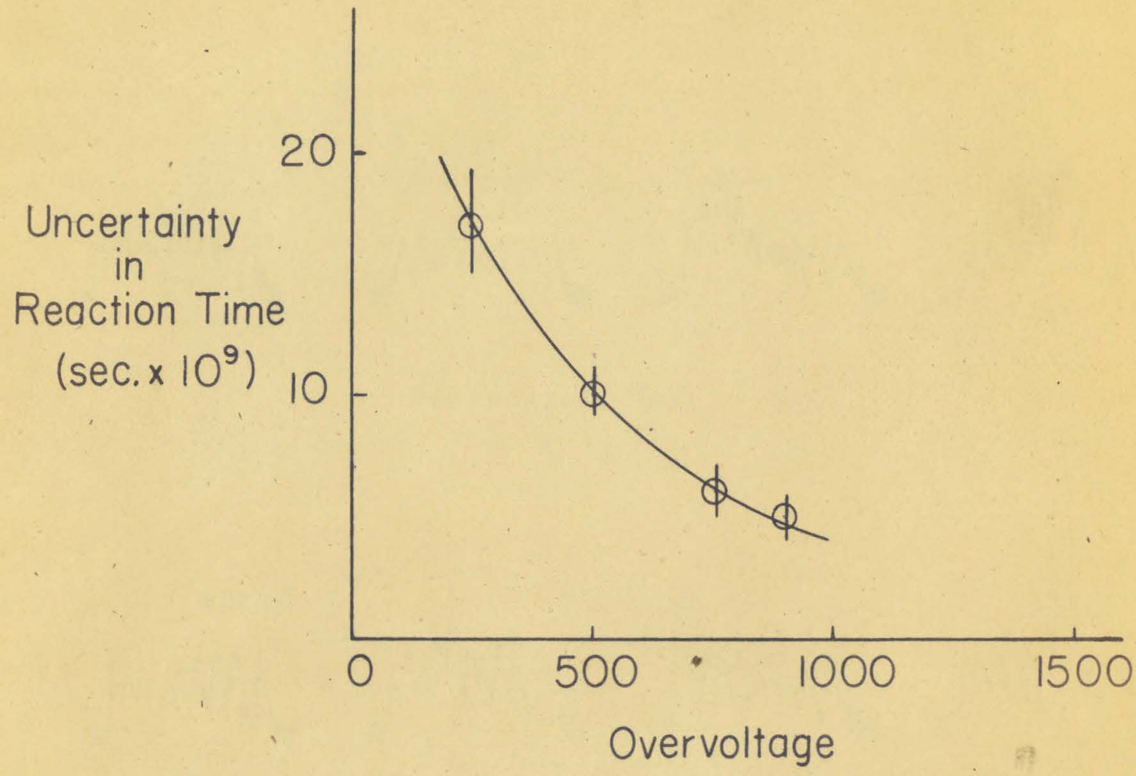

FIGURE VI-2. Uncertainty in reaction time vs. overvoltage.

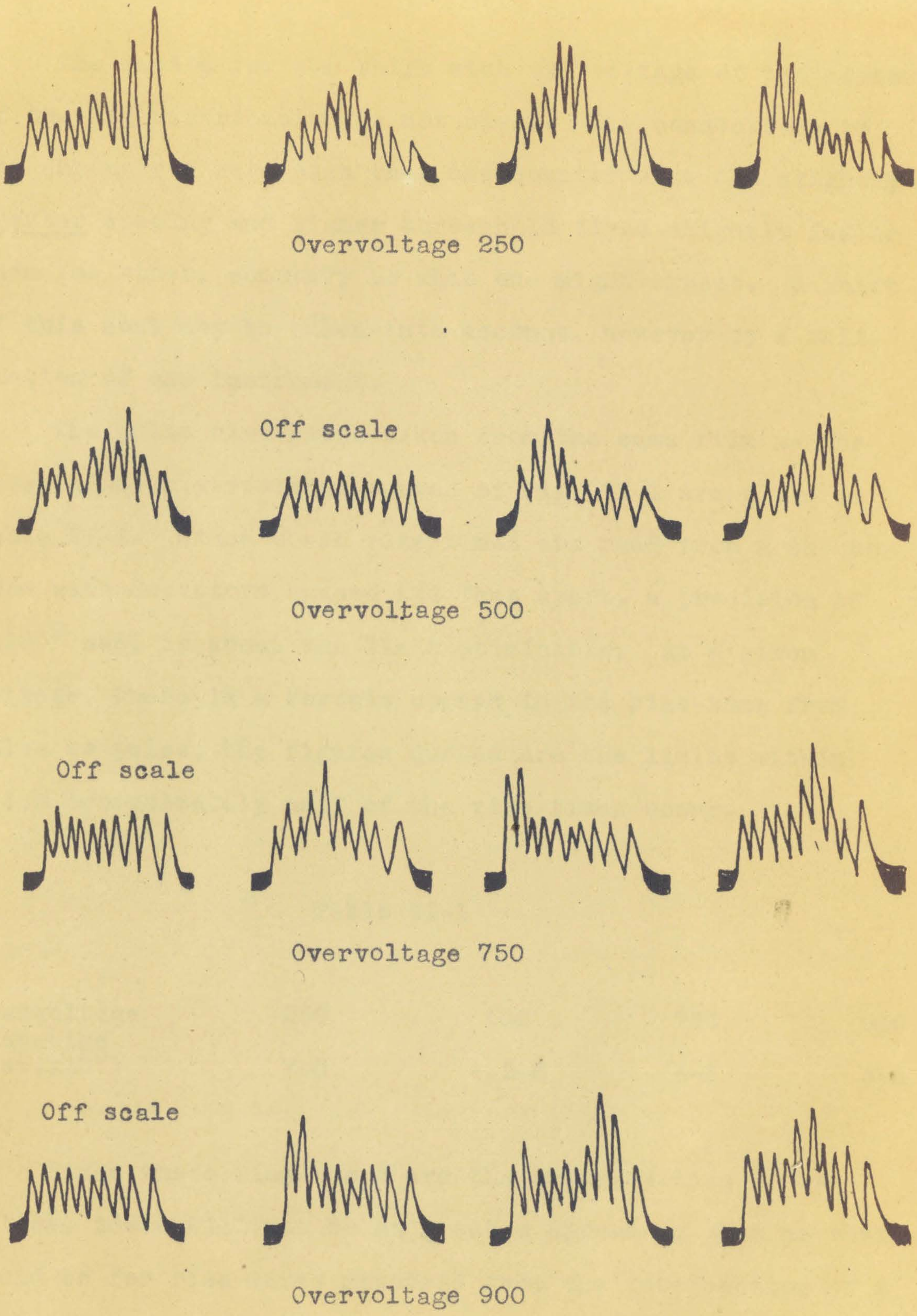

FIGURE VI-3. Tracings of representative chronotron superposition loci. Note that spacings between pulses are important only insofar as they permit identification of pulses.

The reason for the shift with overvoltage of the center of the lag distribution is not clear. The connections to the chronotron were such that the counter with the slightly greater spacing and higher threshhold fired slightly faster than the other, contrary to what one might expect. A shift of this sort may be taken into account, however by a calibration of the instrument.

The pulse rise-times taken from the same film as the uncertainty distribution curves of Fig. VI-1 are given in Table VI-1. Since these rise times are read from a chronotron with detectors spaced two feet apart, a precision of $1x10^{-9}$ sec. is about the limit attainable. At a given voltage, there is a certain spread in the rise-time from pulse to pulse; the figures quoted are the limits within which approximately half of the rise-times occur.

Table VI-1

Overvoltage	250	500	750	900
Rise-time (sec.x10^{9})	7-8	4.5-6	4-5	3-4

Since these rise-times are the superposition of two pulses, there will not be as great a spread in them as there would be for rise-times measured from the intersection of a single pulse with itself. Observations show, however, that the latter method of measurement does not give significantly different results.

The effect of varying the total voltage on one counter, while holding the voltage of the other fixed, has also been investigated. The results presented in Fig. VI-4 indicate that a change of 100 volts out of a total voltage of 2250 shifts the curve about 4×10^{-9} sec.

C. Discussion of Results

We conclude from the foregoing that time measurements to a precision of $\pm 5 \times 10^{-9}$ sec. are now possible--an improvement of almost two orders of magnitude over the precision heretofore obtainable.

It is to be noted that the percentage of lags which lie off scale (i.e. outside of about $\pm 20 \times 10^{-9}$ sec.) does not continue to decrease in going from an overvoltage of 750 to 900, and in fact rises by a significant amount. Long lags such as this may be a detriment in some applications, particularly where rare events in the cosmic radiation are being studied.

The cause of the "off-scale" readings at the higher overvoltages is not certain. Time has not permitted a complete investigation of the effect, but we give what evidence is already at hand. In the first place no superposition peak would be recorded if for some reason one of the pulses on the timing line were very much smaller than the other,

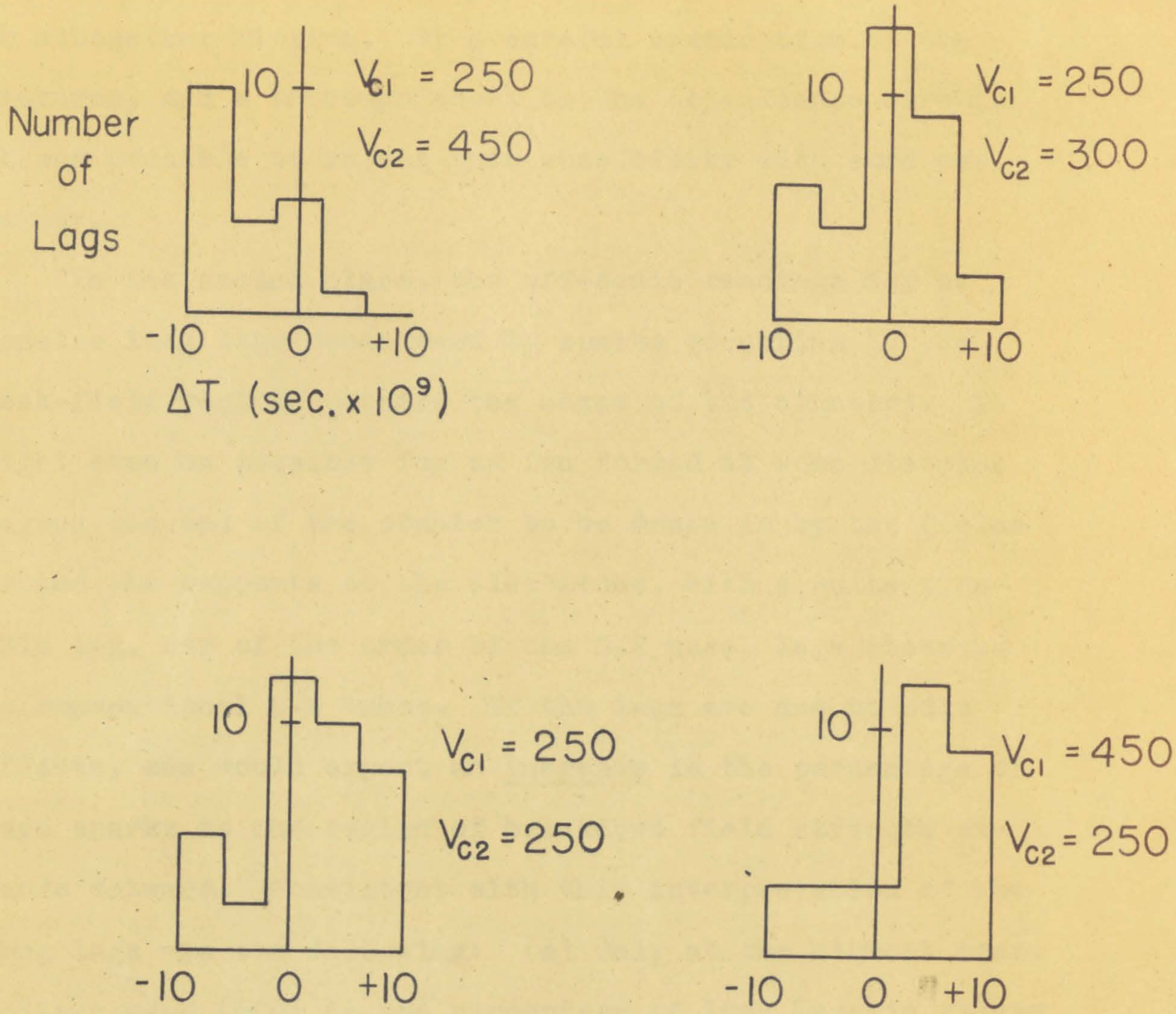

FIGURE VI-4. Lag distributions vs. variation in voltage of one counter. Total voltage on counter 1, 2000 plus V_{c1}; on counter 2, 2000 plus V_{c2}.

or altogether missing. By a careful examination of the pictures, and a thorough check on the coincidence circuit, it was possible to reject this possibility with some certainty.

In the second place, the off-scale readings may be genuine long lags occasioned by sparks occurring in the weak-field regions outside the edges of the counters. It might even be possible for an ion formed at some distance beyond the end of the counter to be drawn in by the fields around the supports to the electrodes, with a quite sizeable lag, say of the order of the 0.2 μsec. lags observed in conventional G-M tubes. If the lags are due to edge effects, one would expect an <u>increase</u> in the percentage of edge sparks as the region of breakdown field strength expands outward. Consistent with this interpretation of the long lags are the following: (a) Only at the highest overvoltage used (900) is the percentage of long lags in excess of what one might expect from the trend of the distribution curve "wings"; (b) the coincidence rate increases with the counter voltage (see Fig. III-3, which was plotted from the same data as the distribution histograms) an effect which is difficult to explain except as an increase in the active volume of the counters: (c) an increase in the number of sparks visually observed to go at the edges has been noted as the overvoltage is raised--which is, after all, what one would expect.

It does not seem likely that the long lags are a result of statistical variations in the reaction time proper. In fact, it is entirely possible, if not indeed probable, that not even the shorter lags, which give the spread in the reaction times near the center portion of the distribution curves, are due primarily to the intrinsic statistical fluctuations in the rise times. Instead, the shorter lags may be largely geometrical in origin; a 5% change in total voltage of one counter at an overvoltage of 900 volts produces, according to Fig. VI-4, a shift of about 5×10^{-9} sec. in the position of the distribution maximum, and since the counters are hardly parallel to better than 5%, the variations in field strength arising from this source could account for most of the shorter lags. In any case, tests with precisely plane-parallel counters, constructed perhaps by sputtering copper on glass plates, should affirm or deny the above interpretation.

If and when the limit to the uncertainty in reaction times due to statistical fluctuations in the build-up of the streamer is reached, there are still two fairly promising avenues for improvement remaining open: one may, by studying the origin of the spurious counts, produce a counter which may be operated at still higher overvoltages; and one may improve the statistics by using greater spacings or higher pressure, thus smoothing out fluctuations in the number of ions produced by the initial ionizing event. On the basis of the work done thus far, it is not possible to predict the lower limit of the uncertainty which may be attainable, but it seems likely that even greater precision will be possible.

Appendix

LOADING OF UVF LINE BY DETECTORS

The line loading--by which is meant the effect of the detectors on a pulse travelling along the UVF line--is most easily discussed from the transient point of view. Consider, therefore, such a pulse as it strikes the discontinuity caused by a detector. A reflected wave is set up, and at the same time the amplitude of the transmitted pulse is diminished. If the detector impedance is a pure resistance, (a good approximation in our case) the shapes of the transmitted and reflected pulses are identical with that of the incident pulse (although the latter is inverted); the proof of this statement follows immediately from the fact that in the resistive case, the reflection coefficient* is independent of the frequency, and hence the Fourier coefficient of each frequency is reduced by the same factor.

The reflected pulses travel back along the line, spaced out a distance equal to twice the detector spacing. As the reflection per detector in any practical case will be small, secondary reflections may be completely neglected; and as the primary reflections are now moving in the same direction

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* See, for example, ref. (8) page 8-28.

as the main pulse from the other end of the line, it is evident that they will not affect the superposition locus.

Since the reflection coefficient is independent of frequency, the attenuation produced per detector may be calculated from the reflection coefficient for a single frequency. Consider a transmission line of characteristic impedance Z_0 terminated by an impedance Z_R consisting of the detector resistance R in parallel with a resistance Z_0. We know from the usual transmission-line theory* that the line equations for such a set-up are satisfied by a sine wave travelling toward the termination with amplitude E^+ and a reflected wave travelling away from the termination with amplitude E^-; if $K = (Z_R - Z_0)/(Z_R + Z_0)$ is the reflection coefficient, then $E^- = KE^+$ and the voltage across the termination is $E_T = E^+ + E^- = (1 + K)E^+$. (Note that in our case K is real and negative.)

Introducing for Z_R the parallel impedance of Z_0 and R we have $1 + K = (1 + Z_0/2R)^{-1}$.

But the voltage E_T is just the voltage of the transmitted wave in case the resistance Z_0 is replaced by the continuation of the line to the right of the detector, which we consider for the moment to be infinite in extent.

A transient pulse is therefore reduced in amplitude by the factor $(1 + Z_0/2R)^{-1}$ in passing across a detector of

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* See, for example, ref (8) page 8-15.

resistance R in the middle of an infinite line. But this obviously holds also, now that we regard the pulse as a transient of finite short duration, in case the line has other detectors on it and is not infinite or terminated in Z_0; though now we must of course consider the reflected and transmitted waves at these further discontinuties.

In the present case secondary and higher reflections may be neglected and the transmitted pulse is reduced by the factor $(1 + Z_0/2R)^{-1}$ each time it passes a detector.

Inserting $Z_0 = 300$, $R = 4300$ we obtain $(1 + Z_0/2R)^{-1} = .967$, a loss of about 3% (in voltage) or .30 db. per detector for the present set-up.

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