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by Michael D. Williams

Langley Research Center
Langley Station, Hampton, Va.

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SUMMARY

This report describes a technique and apparatus for spark gap research and presents the results of an investigation performed with that apparatus. The investigation was conducted primarily to determine how the variation of each of several spark gap parameters affects the firing-time differences (switch jitter) of simultaneously triggered trigatron spark gap switches. These parameters were switch voltage (15 to 20 kV), peak trigger voltage (14 to 20 kV), and the curvature of the edge of the trigger electrode hole. The firing times were measured by using the light emitted from the switches.

The more significant conclusions drawn from experimental results are (1) By inference, the physical differences in the members of a switch group create firing-time differences like a component of true switch jitter and only higher switch voltages (of the parameters investigated) significantly diminish their magnitude; (2) true switch jitter is more sensitive to changes in switch voltage than to changes in peak trigger voltage; (3) increased peak trigger voltage is not very effective in reducing switch jitter; (4) the curvature of electrode hole edges does not significantly affect switch jitter in the "fast" mode of switch operation; and (5) the curves of the firing distributions are not Gaussian integrals as previously believed.

A theory involving a probability surface in three dimensions is presented in explanation of the asymmetric firing distributions.

INTRODUCTION

The increased interest in the trigatron spark gap switch (two hemispherical electrodes with a trigger electrode in one hemisphere) is due mainly to the increased use of large energy storage capacitor banks as a scientific tool. Banks are used with pulsed

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plasma generators, exploding wire devices, electromagnetic and electrohydraulic metal-forming machines, high-magnetic-field apparatus, and hypervelocity wind tunnels. They are used chiefly in association with plasma and thermonuclear research.

A typical capacitor bank is composed of several hundred high-capacity high-voltage capacitor units connected in parallel through load cables and switches to the apparatus of interest. The capacitor units are charged to a high voltage (typically 20 kV), then the stored energy is switched into the load. The chief asset of this type of energy storage system is the speed with which the energy can be released.

The switch is a very important factor in determining how well the system performs. The perfect switch will switch unlimited energy in zero time. The practical switch is limited in both respects. In practice, the higher the energy of the bank, the larger the number of switches required to handle the energy and the more acute the problem of switch synchronization. It is well known that spark gap switches, although triggered simultaneously, nevertheless conduct at different times. This phenomenon gives rise to the term "switch jitter." Switch jitter is comparable to transit times of electrical pulses on cables $\left(10^{-8}\text{ sec}\right)$ and affects system performance several ways – among them: (1) It causes circulating currents (currents which do not pass through the load), (2) it limits the voltage and its rate of rise at the load, (3) it is a determining factor in the current stresses on load cables, and (4) it determines the voltage reflected from the load.

These phenomena motivated the present study of the trigatron switch. In this experiment three of the more readily controllable variables of the switches were investigated in order to determine the nature of variations in switch firing time and the existence or nonexistence of optimum conditions for switch firing. Firing times were measured by using the light emitted from the switches.

SYMBOLS

A, A_o	constants
a	rate of voltage rise
M	constant
N	number of firings
P	probability
P_V	probability associated with voltage

T,t	time
T_1	minimum formative time lag
V	voltage
$\bar{V}$	average voltage
V_1	quasi-static breakdown voltage
x	dummy variable for time
y	dummy variable for voltage
Δ	change or increment
σ_V	standard deviation of voltage

APPARATUS

The experimental system was engineered to measure the switching times of trigatron spark gap switches by using the light emitted from them. Therefore, the spark gap assembly (figs. 1 and 2) was the central part of the system and several requirements were imposed upon its design. Briefly, the assembly was designed to gather and conserve as much light from as many switches as was practicable. The other members of the system shown in figure 3 served to make the system work automatically and to record data. The sequence of events was initiated by the clocked pulse source and terminated with the photographic recording of light from the spark gaps by the ICT (image converter tube) camera. The camera recorded the firing times of all switches relative to the camera shutter opening time, and the gigacycle oscilloscope was used to record the shutter opening and closing time relative to the arrival of trigger pulses at the switches.

The switch apparatus consisted of three apparently identical pairs of assemblies, the only difference being the curvature of the edge of the trigger electrode holes. The multiplicity of switches was required to make comparisons between switches and to reduce the number of measurements needed. The assemblies were arranged in a hexagonal configuration for compactness. The compactness conserved light by reducing the length of light pipe needed to transmit light to the camera. Each assembly consisted of two polished-brass hemispherical electrodes 3.81×10^{-2} meter in diameter. The gap of the electrodes was located at one focus of a concave ellipsoidal reflector. The reflector was a plexiglass shell with a vacuum-deposited-aluminum surface coating which reflected the light rays from the switch to the other focal point of the ellipsoidal surface. The reflected light rays converged at the other focal point at an angle equal to the acceptance angle of a light pipe placed there. (Actually, the rays did not focus to a point because the switch discharge was not a point but focused to a somewhat magnified and distorted image of the discharge. See fig. 1.) The reflectors served two important purposes: (1) They optically isolated each switch so that none could experience irradiation effects from another and (2) they gathered practically all the light from a switch discharge and focused it at a convenient place. The light-gathering feature of the reflectors was more significant because it optimized the accuracy of the data by reducing the time required to expose film and it allowed the use of less energetic discharges, which minimized the effects of electrode erosion and contamination.

The upper hemispherical electrode of each assembly was threaded directly onto a micrometer adjustment shaft which was used to set the pertinent clearances of the switch. The shaft was electrically connected to the positive high-potential side of two 500-picofarad, 30-kV "doorknob" capacitors. The other terminals of the capacitors were connected by a wide copper plate to the braids of the load cables. The lower (grounded) hemispherical electrode bolted onto a more coarsely threaded shaft which contained the trigger pin assembly and which furnished a discharge path to the center conductor of the load cable. Both the load cables and the trigger cables were of sufficient length (15.24 meters) to isolate the switches electrically during the transit time of pulses. The transit times were larger than the firing times of interest.

The body of the assembly (fig. 1) was a box with a preformed cavity which accepted the reflector shell. The box was a wood-reinforced fiber-glass structure filled with plastic foam for uniform support of the reflector. The reflector side of the box was completely covered with a 2.54-cm-thick piece of plexiglass which sealed the cavity.

Six light pipes, each 1.83 meters long with acceptance angles of approximately 60°, transmitted the light from the spark gap apparatus to the camera. The front optics of the camera were removed to eliminate as much light loss as possible. (This is the cause of the small defocusing observed on the data streaks of fig. 4.) The camera used the image formed by the light pipes to record the firing times. The image consisted of six round spots arranged in a horizontal line perpendicular to the camera sweep direction. The different firing times of the trigatron switches were registered by the different starting positions of the linear streaks appearing on the photographs as shown in figure 4. (See ref. 1.)

The main switch discharge was initiated by the main trigger generator shown in the electrical diagram of figure 5. This unit was charged to a high negative potential and discharged through a single spark gap switch into six separate 15.24-meter cables. The single spark gap eliminated the possibility of jitter in the trigger voltage applied to the main switches. Care was taken to reduce the inductance of the main trigger generator discharge circuit in order to increase its voltage rate of rise.

The light from the main trigger generator spark gap was used to trigger an electronic unit (trigger delay generator) which, in turn, triggered both the camera and the gigacycle oscilloscope. The camera was triggered by the output pulse of the trigger generator. The optical and electrical delays were arranged so that the oscilloscope sweep was actuated prior to the arrival of the electrical diagnostic signals from the camera and the main trigger generator.

The gigacycle oscilloscope was used to monitor the shutter pulse from the camera and the trigger pulse from the main trigger generator. The shutter pulse was available at a monitor plug at the camera. The main trigger pulse was monitored through an RG-8/U cable equal in length to each of the six main trigger cables. A high-frequency resistor was used at the trigger generator to reduce the voltage at the oscilloscope to a suitable level. The use of this length of cable served two purposes: It duplicated at the oscilloscope the voltage rate of rise experienced at the trigger pins of the main switches (rise time varies with the square root of the length of cable; see p. 291 of ref. 2) and it duplicated the delay time associated with the trigger cables.

The main trigger generator was triggered by a high-voltage thyratron unit. A positive voltage pulse was applied to the trigger pin of the spark gap switch of the main trigger generator through a high impedance. The high impedance prevented the discharge of the main trigger generator from traveling to ground through the thyratron trigger unit. The thyratron trigger unit was, in turn, triggered by the clocked pulse source (plus gate of another oscilloscope). The clocked source allowed 20 seconds for all capacitors to charge.

EXPERIMENTAL PROCEDURE

All measurements were obtained from the system over a period of several months. There were basically two series of runs. Each series was intended to investigate the effects of a particular parameter on the firing time of the spark gap switches. In each run the switches were allowed to fire several times before data were taken.

In the first series of runs data on the effect of variation in switch voltage were obtained. A number of switch firings (25 to 45) were recorded at switch voltages of 15, 16, 17, 18, 19, and 20 kV each. The switch trigger pins were set flush with the grounded hemispherical electrode and the peak trigger voltage was 17 kV. (A slight increase in switch voltage above 20.5 kV resulted in an untriggered switch discharge.)

In the second series of runs data on the effect of variation in trigger voltage were obtained at switch voltage settings of 15 kV and 20 kV. Switch trigger pins were again flush with the grounded hemispherical electrodes. The peak trigger voltage was varied in increments of 1 kV from 14 to 20 kV. More than 30 firings were made at each setting. For each sequence of firings the shot number, date, trigger voltage, switch voltage, and switch number were recorded along with pertinent comments.

Since the number of useful data points generated was anticipated to be excessive, a computer program was devised to process them. The computer served as a calculator, a bookkeeper, and a plotter.

The light streaks of the film were digitized manually with a universal Telereader. Some of the data recorded on the film were recorded on punch cards along with the firing data. If any particular switch of the six fired too late or failed to fire, the readings of all six switches for that particular shot were omitted. Otherwise, digitized data representing the starts of main discharges of switches were recorded on the data cards.

The computer performed, in order, the following operations:

Data read in

Calculation and ordering of firing time according to firing number

Chronological ordering and readout of firing times

Calculation and readout of the average firing times and their standard deviation

Plotting of data

All these operations were performed for each switch separately.

THEORY

It is generally agreed that discharges begin with one or more free electrons and that firing time has two components: a formative time and a statistical time. The statistical time lag is the time required for an electron to appear and/or acquire a proper state to start an avalanche; the formative time lag is the time required for the discharge to develop after the start of an avalanche, all times being measured from the time quasi-static breakdown voltage is reached. (Quasi-static breakdown voltage is the smallest dc voltage at which it is possible for a switch to fire.)

Consider a switch of the trigatron geometry being subjected to a slowly rising voltage a large number of times N. It will break down at a different voltage each time. Lupton (ref. 3) has shown that under these quasi-static conditions (RC time constant for charging, 0.3 second), such a switch exhibits a statistical relationship between the number of firings and switch voltage. His data represented the approximate probability of a switch firing in a voltage interval ΔV. (Fig. 6 is typical.) In the limit ($N \rightarrow \infty$, $\Delta V \rightarrow 0$) the quantified data would fall on a smooth probability curve P_V represented by the dashed line. Since this theoretical distribution curve never crosses the abscissa and since its position on the abscissa varies with the amount of time the switch is subjected to a voltage, quasi-static breakdown voltage is not rigorously defined. The probability curve can be used to establish its definition.

The probability of a switch firing at V or some lesser voltage is given by

$$P = \int_{-\infty}^{V} P_V(x)dx$$

where

$P_V(x)$ probability of a switch firing at V

x dummy variable

The integral is represented by the shaded area of figure 6. For a given subjection time then, quasi-static breakdown voltage can be defined as that voltage at which the value of the integral is $1/N$, meaning that at most only one switch out of N could have fired. This definition serves as a basis for defining formative and statistical lags. With the additional definition that a breakdown has "developed" when it becomes self-supporting, the definitions of formative and statistical time lags are founded.

For illustration, consider the following example: A trigatron switch is subjected to a voltage which increases rapidly with time. At some time T_a the voltage will reach the quasi-static breakdown level (which is taken as the voltage below which the switch could not possibly have fired). After this voltage level is passed, it becomes possible for the switch to fire and the voltage continues to increase. At some time T_b an electron (created by cosmic rays, ultraviolet light, radioactivity, or whatever) will appear in the gap and will initiate an avalanche. At time T_c the avalanche will have grown to such a size that the discharge would be self-sustaining (even if the switch voltage suddenly stopped increasing). The total firing time then would be $T_c - T_a$ and would be composed of a statistical time $T_b - T_a$ and a formative time $T_c - T_b$.

EXPERIMENTAL RESULTS

Figures 7 to 12 illustrate the primary results of the experiment. Figures 7, 8, and 9 pertain to the variation of dc voltage across the switches. Figures 10, 11, and 12 pertain to variations of the peak trigger voltage applied to the switches. Except for the parameters which were varied, figures 7, 8, and 9 correspond, respectively, to figures 10, 11, and 12 in the kind of information presented.

Figures 7 and 10 are firing distributions of a typical switch. Interpreted rigorously, the curves represent the percent of total firings which occurred within the corresponding times. The curves can also be interpreted as one firing of a number of identical switches, in which case each curve would represent the portion of all switches which have fired and are still conducting within the corresponding time. When the latter interpretation is used, the data are representative of the effect of the respective parameters on the firing times of a large number of switches in a capacitor bank.

Time zero in figures 7 and 10 is the time of the trigger pulse arrival at the trigger electrodes. The curves are delayed from time zero by amounts of time which are indicative of the formative time of the discharge plus the time required for the switch to reach quasi-static breakdown voltage. Some data points have been omitted from the well-defined center portions of the curves.

Figures 8 and 11 depict the average firing times of all switches for switch voltage and peak trigger voltage, respectively. Each symbol represents the average firing time of over 30 shots of a switch. The solid curves show the central tendencies of the switches. Compared with figure 11, figure 8 shows a larger total change in average firing time and a greater variation of scatter in data.

Figures 9 and 12 show the standard deviation of the firing times from the average and are a measure of the jitter performance of the switches as functions of the respective variables (dc switch voltage and peak trigger voltage). Each point represents over 30 firings of each switch. Over the same range of voltages the total change in standard deviation in figure 9 is greater than that in figure 12. The variation of scatter in data is also more significant in figure 9.

During the experiment, the radii of curvature of the hole edges of the lower electrode were 0 in switches 1 and 2, 0.079 cm in switches 3 and 4, and 0.158 cm in switches 5 and 6. Figures 8 and 9 show that at the lower switch voltages, the average firing times are more the same for switches with the same curvature than for switches with unequal curvature. This observation is consistent with the "fast" and "slow" modes of trigatron operation described by Lupton (ref. 3) and photographed by Bunting (ref. 4). However, the order of the pairs does not correspond with their curvatures.

The first and last five recorded switch firings of each switch in each run were compared to determine whether any changes occurred in firing time with the number of firings. The comparison revealed no obvious effect caused by the number of firings.

DISCUSSION OF EXPERIMENTAL RESULTS

Typical firing data represented by figures 7 and 10 are statistically distributed as previously observed by White (ref. 5). Contrary to his assumption, however, they are not simple Gaussian integrals, since they are not true odd functions with respect to their centers. (A theory explaining this asymmetry is presented in the appendix.)

The data of figures 7 and 10 indicate that even when great care is exercised in the construction of switches, there will still remain small physical differences which will make noticeable differences in switch behavior in the 10-nanosecond time domain. These physical differences create average firing-time differences like a component of true switch jitter and only higher dc switch voltages (of the parameters investigated) significantly reduce their magnitude.

Figures 8 and 11 show that the average firing time is more sensitive to changes in dc switch voltage than to changes in peak trigger voltage. A comparison of figures 9 and 12 shows that true switch jitter is also more sensitive to changes in dc switch voltage. Concerning the curvature of the electrode hole edges, the pairing tendency observed in figures 8 and 9 shows that the effect of these curvatures is significant only at lower dc switch voltages. At higher dc switch voltages where the fast mode predominates, the effects are insignificant.

It was expected that the switch pairs would be ordered according to their respective curvatures. The absence of this ordering indicates the possible existence of other related switch differences which affect the firing times.

Similar switching behavior caused by the different curvatures is not as pronounced in the data for variations in peak trigger voltage (figs. 11 and 12). This was probably due to the relative insensitivity of the switches to variation of that parameter.

Switch jitter at the lowest dc switch voltage (fig. 9) decreases at a rate of 13.4 nsec/kV as the switch voltage is increased, whereas the corresponding rate of decrease for the lowest peak trigger voltage (fig. 12) was 4.5 nsec/kV. At the highest dc switch voltage and peak trigger voltage, the rates of decrease are 0.23 nsec/kV and 0.1 nsec/kV, respectively. These numbers demonstrate quantitatively the relative sensitivity of the switches to these respective parameters. Further, they show that for these experimental conditions, increased peak trigger voltage is not very effective in reducing switch jitter. However, no upper limit exists for peak trigger voltage, whereas the allowable dc switch voltage is limited by quasi-static breakdown voltage.

It can be expected that the data of figures 7 to 12 can be used as a basis for making qualitative analyses and quantitative estimates of other similar switching arrangements.

DISCUSSION OF ERRORS

Two significant times were measured in the experiment: average firing time and switch jitter time. Each measurement was affected differently by the system errors and human errors associated with the final data. Specifically, the human errors were those associated with reading data from photographs. The system errors were nonreproducibilities, nonlinearities, and untrue settings of the equipment used.

The average firing time of the switches was of secondary importance in the experiment and was also second in accuracy. The average firing time was subject to the long-term variation in firing time of the trigger delay generator and a similar variation in the ICT camera trigger circuitry. There were no instrument specifications available to define these errors. However, they were estimated by comparing the average firing time of the switches operating under the same conditions at two different times during the course of the experiment. The difference was found to be 8.5 nsec and is believed to be due mainly to variations in position of the light pipe of the trigger delay generator. The error in the average firing time is therefore believed to be less than ±8.5 nsec. Included in this error are also small components due to random variations of the instruments and human readout. These components are diminished in size by the square root of the number of shots and are thus negligible.

The jitter times are measures of the relative positions of light streaks and hence were subject only to human readout error and nonlinearity was negligible. The human error component was due mainly to the uncertainty in the starting positions of the streaks. The uncertainties in starting positions were caused by the black-to-white transition region of the film H and D curve. Light intensity varying with time requires a finite time to pass from the black to the white region, so that for the finite time required, all shades of gray appear in the film streak. The regions of uncertainty were typically 1 mm in length for a streak with a total duration of 200 nsec. Since the total streak length was 5 cm, the uncertainty region represents 4 nsec. With the universal Telereader the same relative position within the uncertainty region could be read consistently within one-third of the total uncertainty; therefore, the error in the start of a typical streak is ±1.33 nsec. The error in the difference of starting times of any two typical streaks in the same shot is

$$\pm \frac{1.33}{\sqrt{2}} = 0.94 \text{ nsec}$$

Occasionally a streak duration of 100 nsec was used. This increased the ability of the observer to pinpoint a reading and, of course, reduced the error by a factor of 2.

The error in the repeatability of the switch firing jitter has been estimated by comparing the two sets of results obtained under the same conditions in the two different series of runs. (Using switch 1, for example, the curve for a switch voltage of 20 kV (fig. 7) can be compared with the curve for a peak trigger voltage of 17 kV (fig. 10).) Such a comparison on all switches operating in the fast mode reveals that the standard deviation of the data from exact repeatability (0 nsec) is 1.37 nsec. This standard deviation was calculated as follows: The interval of time corresponding to 10 percent and 90 percent probability was found for each switch in each run. For each switch, the smaller interval of time was subtracted from the larger to find a sample deviation from exact repeatability. The standard deviation was calculated from all the sample deviations in the usual manner.

Throughout all the runs the spark gap clearances all remained at 0.64 cm (-0.0 + 0.06 mm). Voltage measurements were accurate within ±3 percent. The experiment was performed in a laboratory having heat and humidity control. The temperature was typically $24^{\circ} \pm 2.7^{\circ}$ C. The degree of humidity control is exemplified by a microhygrogram made during the experimental period. During a 24-hour period the maximum and minimum humidity readings outside the laboratory were 87 percent and 39 percent, respectively. Inside the laboratory the maximum and minimum readings were 40 percent and 32 percent, respectively. The sealed cavities of the spark gaps acted as buffers and in effect averaged the humidity of the laboratory over many hours, so that around the spark gaps, the humidity was the average daily laboratory humidity (typically 35 ± 5 percent) with practically no variation. Any dust to which the spark gaps were exposed had the same density distribution as the laboratory air when the cavities were sealed. After sealing, the density in the spark gap became much smaller because of settling, electrostatic attraction, and burning in the arc. No special environmental controls or components were included in the apparatus other than the sealed cavity, and no special servicing or physical preparation other than a high polish on the switch electrodes was required.

CONCLUSIONS

An investigation was conducted primarily to determine how the variation of each of several spark gap parameters affects the firing-time differences (switch jitter) of simultaneously triggered trigatron spark gap switches. The parameters were switch voltage, peak trigger voltage, and curvature of the edge of the trigger electrode hole. From the experimental results, the more significant conclusions drawn are

1. By inference, the physical differences in the members of a switch group create firing-time differences like a component of true switch jitter and only higher switch voltages (of the parameters investigated) significantly diminish their magnitude.

2. True switch jitter is more sensitive to changes in switch voltage than to changes in peak trigger voltage.

3. Increased peak trigger voltage is not very effective in reducing switch jitter.

4. The curvature of electrode hole edges does not significantly affect switch jitter in the "fast" mode of switch operation.

5. The curves of the firing distributions are not Gaussian integrals as previously believed.

As is well known, for least switch jitter and average firing time, switch voltage should be made as close to self-sparkover as the required holdoff time allows. A plot of firing probability as a function of voltage could be used to determine the setting for a particular situation. The trigger voltage rate of rise should also be made as large as practically possible, but adjustments in the switch voltage are at least twice as effective in reducing switch jitter as a similar adjustment in peak trigger voltage. These characteristics can be anticipated in view of the probability surface which has been developed to explain observed phenomena. The probability plane and statistics offer a new approach to the study of gaseous discharges. For example, through a study of covariances and correlation the dependence of one parameter on another can be determined.

The optimum adjustments to be made on trigatron switches are obvious from the conclusions drawn. Any further improvement in regard to switch jitter would be gained by adjustment of another parameter (e.g., pressure) or by altering the switch.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., December 19, 1968,
129-02-01-02-23.

APPENDIX

THREE-DIMENSIONAL SURFACE OF FIRING PROBABILITY

When used in conjunction with work previously accomplished by Lupton (ref. 3) the results of this experiment provide an account of switch performance valid for a single switch or a group of identical switches.

Lupton developed the concept that at each switch voltage, a certain probability exists that a switch will fire. Then, in order to fire a large number of switches with the least jitter, the voltage must be allowed to rise through a range as quickly as possible. That is, a very high voltage rate of rise should be applied to the switches – a fact confirmed by the results of this experiment. Actually, the theory is a special case of a more general theory which will be developed herein.

The probability plot shown in figure 6 is two dimensional. It will be demonstrated that a more general probability plot is an infinite three-dimensional warped surface. One of its dimensions, switch voltage, was discussed in the body of the paper. Another dimension can be deduced by the following reasoning: If a switch be subjected to a perfect square wave of voltage, the amplitude of which corresponds to a high probability of firing, the switch may nevertheless fail to fire if the duration of the pulse is very small. Therefore, the other dimension is time. In a rigorous sense, a probability with reference to only one dimension has no meaning. For a given switch voltage, a probability exists that the switch will fire at or within a certain time. The distribution function expressing the probability of firing at a certain time would be a bell-shaped function of time. The distribution function expressing the probability of firing within a certain time would be the time integral of the bell-shaped function. By combining the time-integral curve with a similar curve along a voltage axis, the infinite three-dimensional warped surface illustrated in figure 13 is obtained. A commentary on some of the features of this surface will demonstrate its consistency with known facts, its adaptability to switch and/or environmental change, and its usefulness.

The figure is grossly exaggerated at several places to illustrate points and represents only the general qualitative form of the surface. The time T_1, for example, represents the minimum formative time lag for a given switch at high voltage. It can never be smaller than the time required by light to traverse the gap spacing (typically 10^{-11} sec). On the other hand, the times required for a switch to fire at relatively low voltages can get arbitrarily large. The probability of firing within an infinite voltage range and at a time just greater than T_1 is a unit step function at $V = \infty$. The family of orthogonal curves shown all approach a probability of unit as V and T approach infinity, so that in any rectangular cross section (limits on T and V) the greatest probability exists in the quadrant corner diagonally opposite the origin. The fastest way to obtain a given probability, however, is obviously via the voltage axis. This confirms the conclusion reached earlier that least switch jitter is obtained by greater voltage rates of rise. The lower limit of quasi-static breakdown voltage is represented by V_1. The locus of formative time lags and the time required to reach quasi-static breakdown voltage are represented in figure 13 by the dashed hyperbolic curve, which agrees generally with the work of several previous investigators. This curve approaches T_1 asymptotically toward higher voltages and diverges toward lower voltages. The position of the surface and its curvatures vary with the switch and/or its environment.

The present results and those of Lupton correspond to two different axes of the probability surface. Lupton's distribution represents the probability of firing when switch voltage is applied approximately statically (hence, the term "quasi-static"). In figure 13, his data points would lie in a plane almost parallel with the P-T plane. By projecting the data points in this plane onto another plane which is perpendicular to the T-axis, a plot similar to the integral of the curve in figure 6 would be obtained.

The data presented in this report would be located in a plane almost parallel with the P-V plane. By projecting the data points in this plane onto another plane which is perpendicular to the V-axis, firing-time distributions like those of figures 7 and 10 would be obtained.

In the light of the probability surface the marked difference between switch response to trigger voltage changes and to switch voltage changes becomes rather clear. Consider the V-T plane of the probability surface. The trigger voltage changes would be represented by seven lines, each beginning at a point on the voltage axis representing the switch voltage and each having a different slope. The switch voltage changes would be represented by six lines of the same slope, each starting at a different point on the voltage axis. It is apparent that the planes passing through these respective lines and perpendicular to the V-T plane would intercept the probability surface along lines which, when projected onto the P-T plane, would represent the distributions found by experiment and that the distribution for the trigger voltage variation would cover a smaller time range. The surface is applicable to both time varying voltages and static switch voltages. As an example for static switch voltage (which illustrates the relationship between switch voltage and prefire probability), suppose it is desired to adjust the voltage of a number of switches so that none will prefire before time T. At T on the time axis there is one distribution curve perpendicular to the axis. On this curve a voltage which corresponds to a probability of the reciprocal of the number of switches can be chosen. This is the switch voltage below which it is impossible (theoretically) for one switch of the group to fire. Of course, an increased switch voltage means a higher probability of prefires.

APPENDIX

The geometry of the probability surface and the following derived formula can be used to explain the asymmetries of the firing distributions. If the probability P_V along the V-axis is taken to be a Gaussian integral, then

$$P_V = \frac{1}{\sigma_V\sqrt{2\pi}} \int_0^V e^{-\frac{1}{2}\left(\frac{y - \overline{V}}{\sigma_V}\right)^2} dy \tag{1}$$

where

$\overline{V}$ average firing voltage

σ_V standard deviation of firing voltage

y dummy variable for voltage

The voltage applied to a switch can be represented very accurately by a linear function of time:

$$y = ax + y_o$$

$$dy = a\,dx$$

where

a trigger voltage rate of rise

x dummy variable for time

y_o dc voltage initially on switch

Figure 13 indicates that the first-order approximations to average firing time and standard deviation are given by the equations

$$\overline{V} \doteq A_o + \frac{A}{x}$$

$$\sigma_V \doteq Mx$$

By substituting for y, $\overline{V}$, and σ_V and changing limits of integration in equation (1) the following equations are obtained:

APPENDIX

$$P_V = \frac{a}{M\sqrt{2\pi}} \int_0^t \frac{1}{x} e^{-\frac{1}{2}\left(\frac{ax + y_o - A_o - \frac{A}{x}}{Mx}\right)^2} dx \tag{2}$$

$$P_V = \frac{\alpha}{\sqrt{2\pi}} \int_0^t \frac{1}{x} e^{-\frac{1}{2}\left(\alpha + \frac{\beta}{x} - \frac{\gamma}{x^2}\right)^2} dx \tag{3}$$

where

$$\alpha = \frac{a}{M} = 2.53$$

$$\beta = \frac{y_o - A_o}{M} = -2 \times 10^{-8}$$

$$\gamma = \frac{A}{M} = 1.04 \times 10^{-14}$$

A plot of P_V using representative values for the constants does indeed exhibit the general form illustrated by figures 7 and 10 and indicates that the deviation of the firing distributions from Gaussian integral forms is due to the variations of $\overline{V}$ and σ_V as time increases. To illustrate without mathematics, consider a linearly rising voltage in the V-T plane of figure 13 to be approximated by a staircase function. Projected onto the probability surface, the staircase function at each voltage level will follow a true Gaussian integral distribution for each respective time interval, but the parameters for each successive distribution will have changed so that later intervals have less curvature. When a large number of intervals are added end to end and projected onto the P-T plane, the resulting distribution will have the general asymmetry previously noted.

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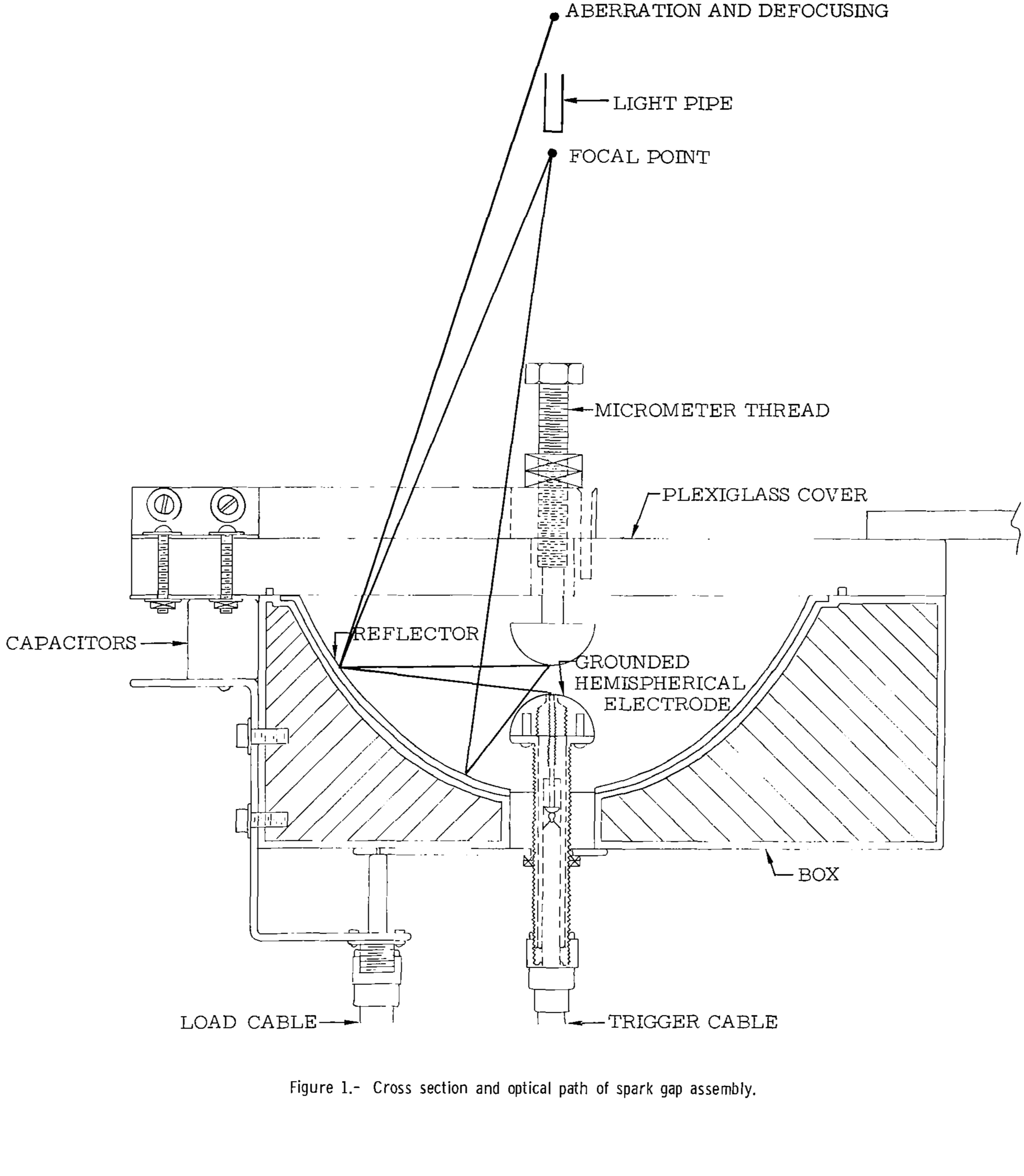

Figure 1.- Cross section and optical path of spark gap assembly.

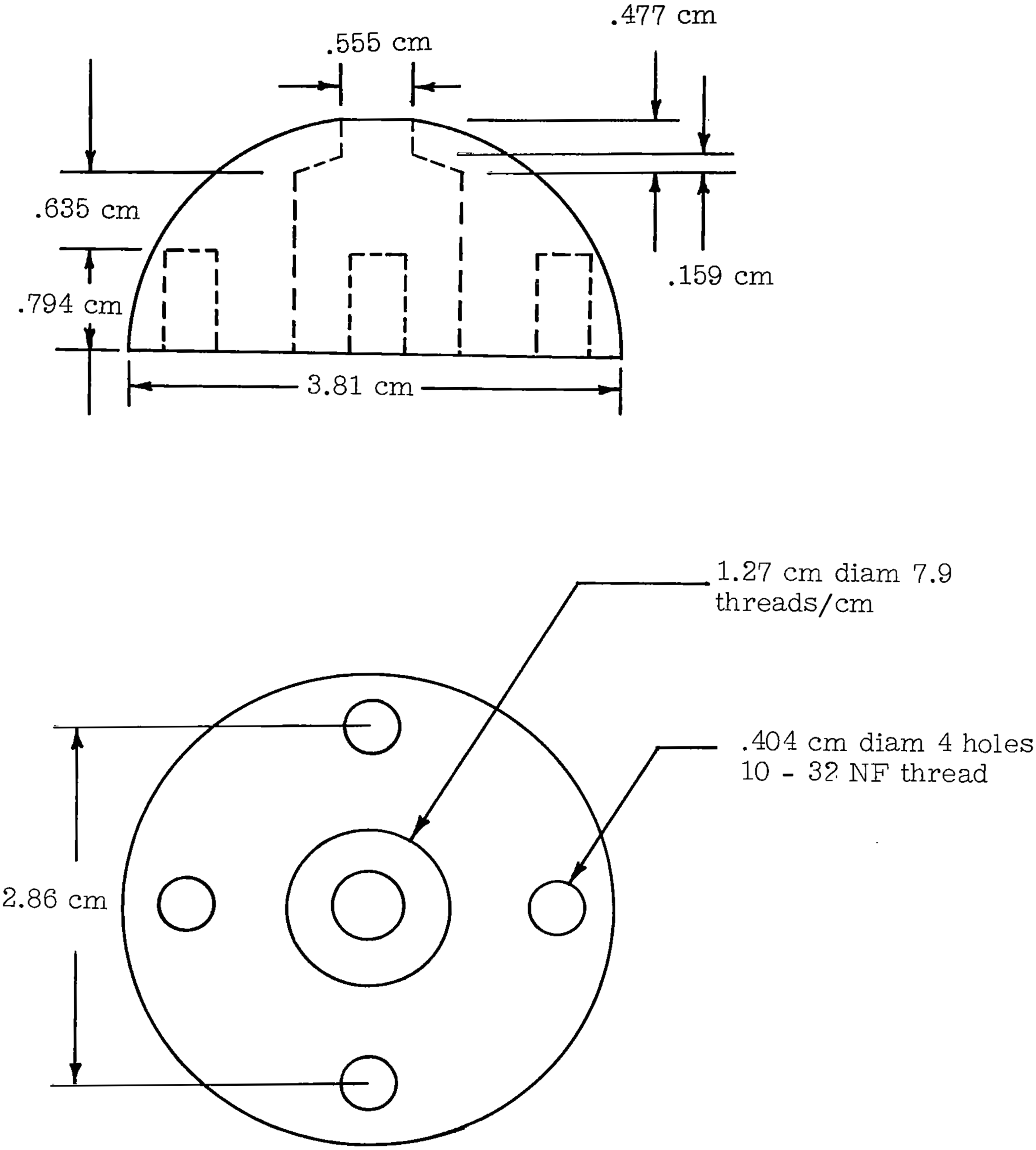

Figure 2.- Grounded trigatron electrode.

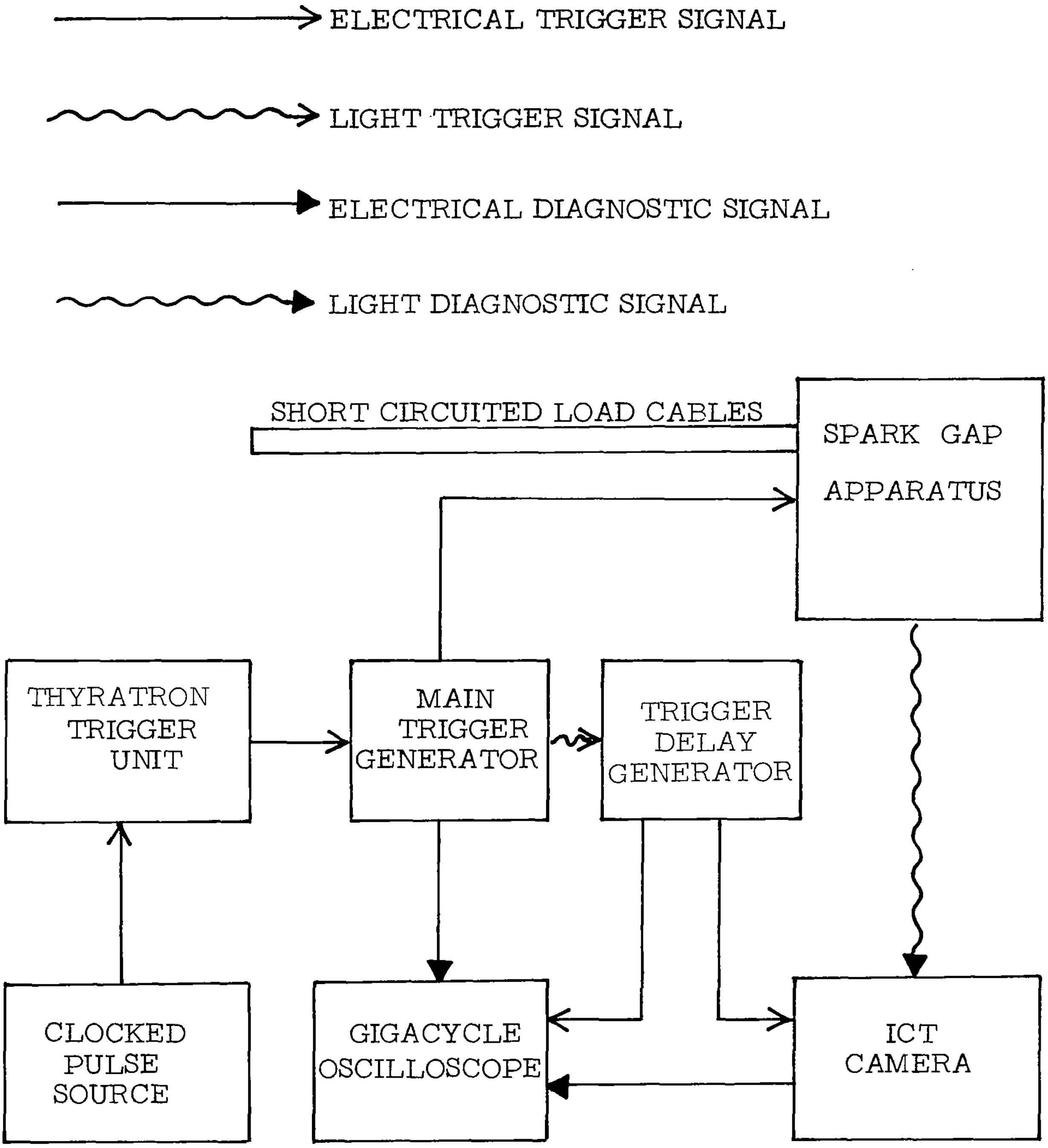

Figure 3.- System for measuring switch firing times.

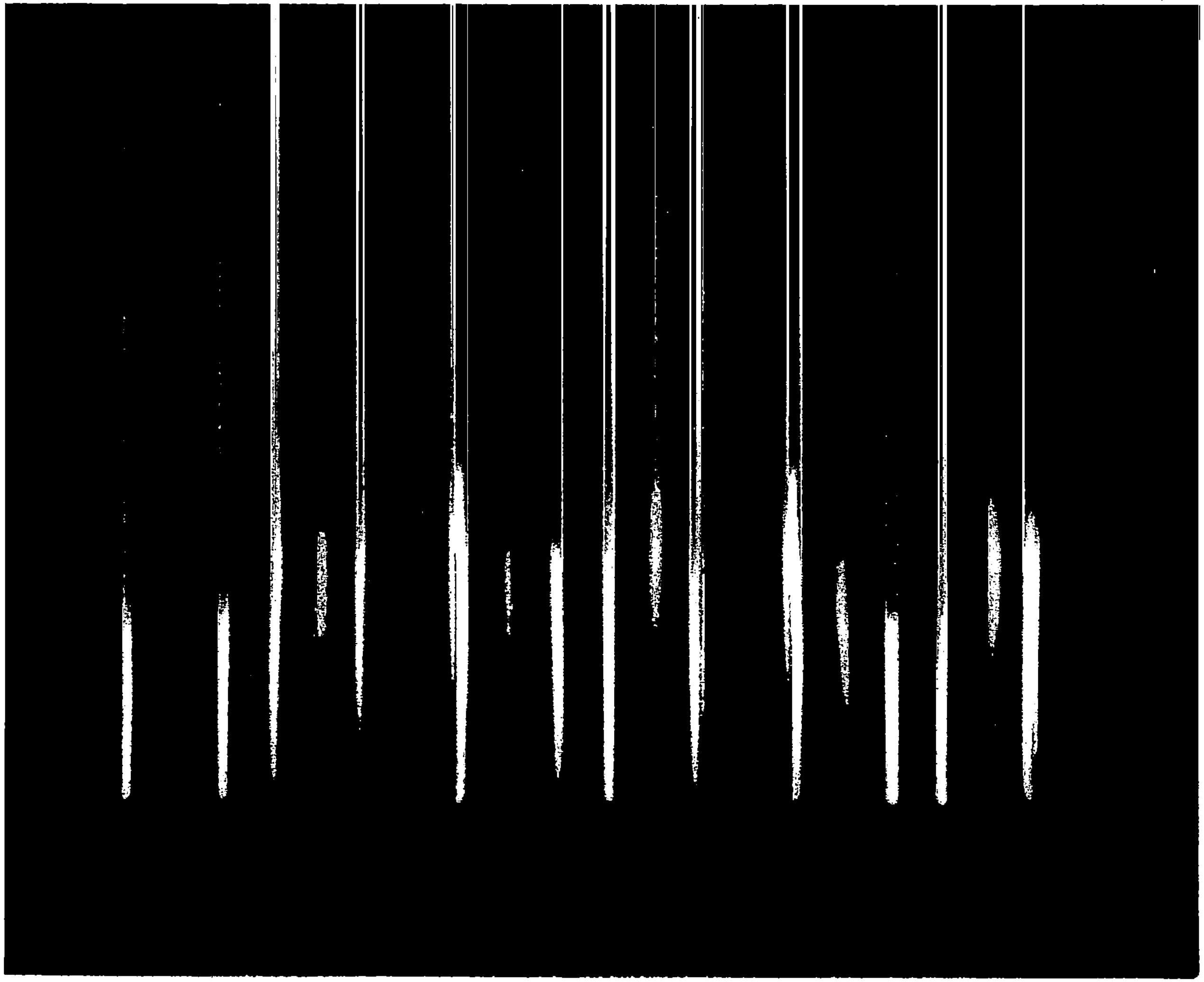

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Figure 4.- Streak representation of three separate firings of the six switches. Streak duration, 100 nanoseconds.

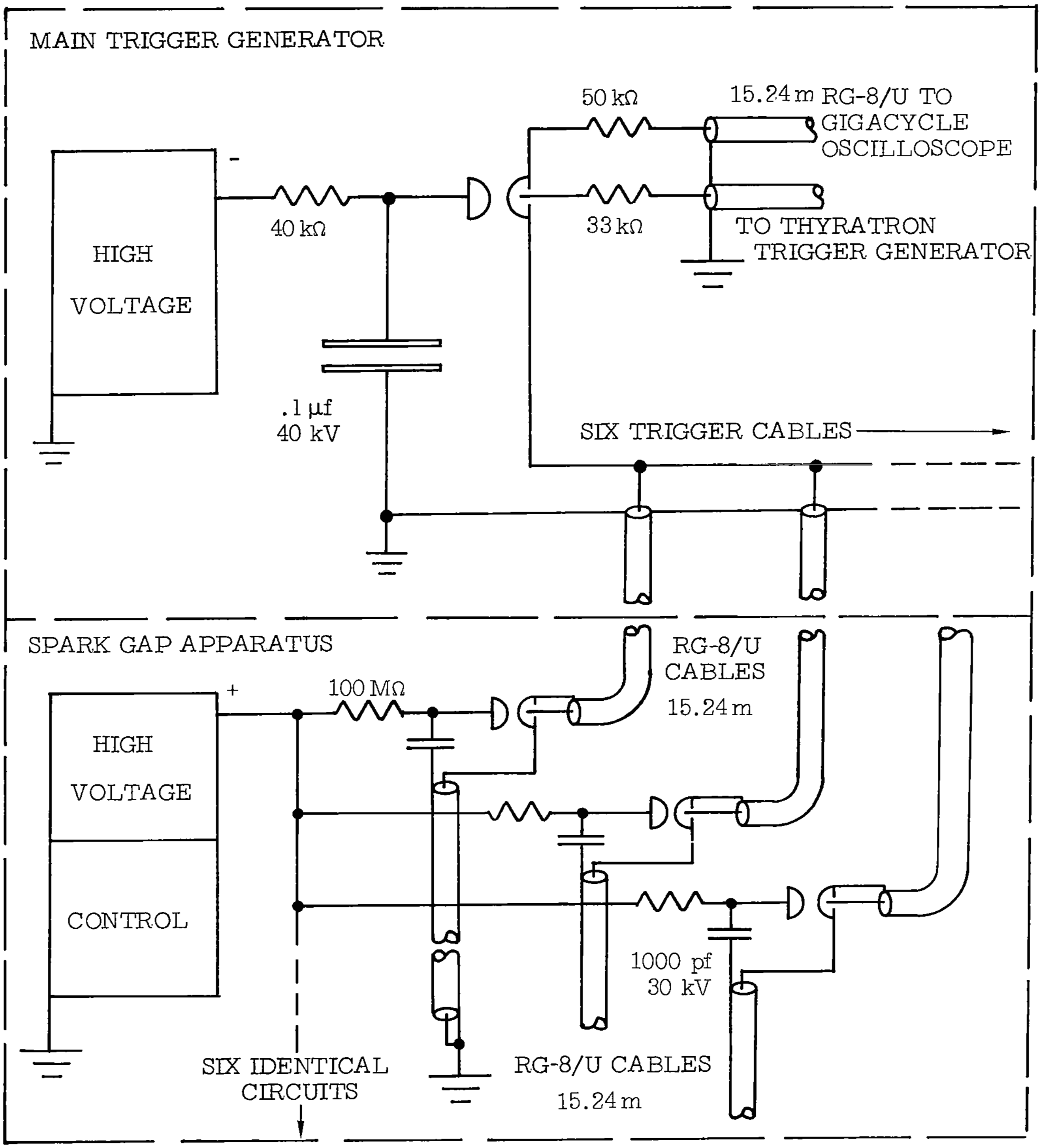

Figure 5.- Circuitry of spark gaps and main trigger generator.

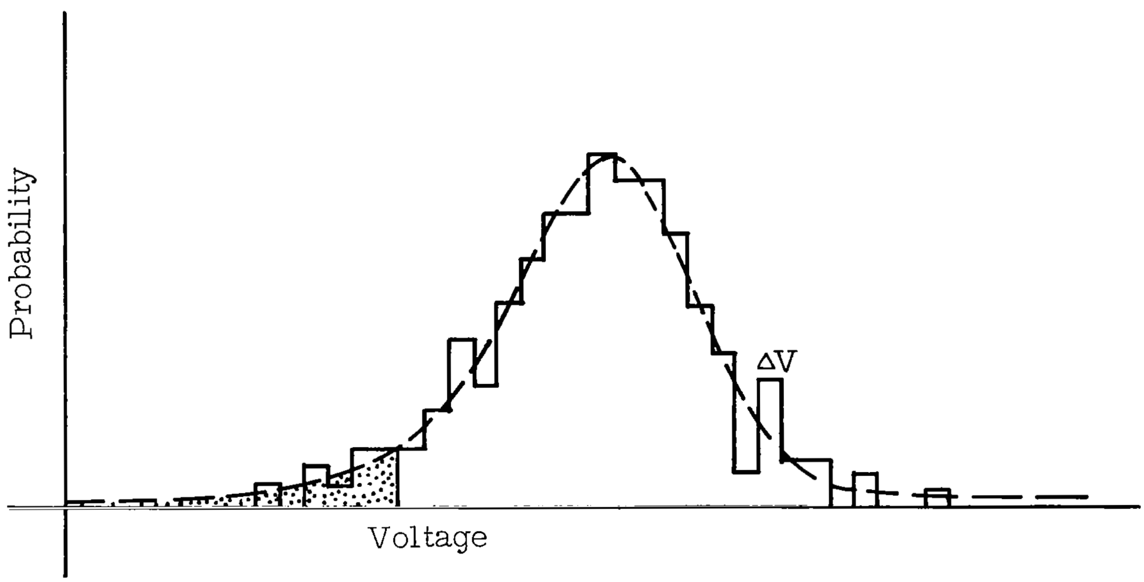

Figure 6.- Statistical character of switch firing for a swept voltage.

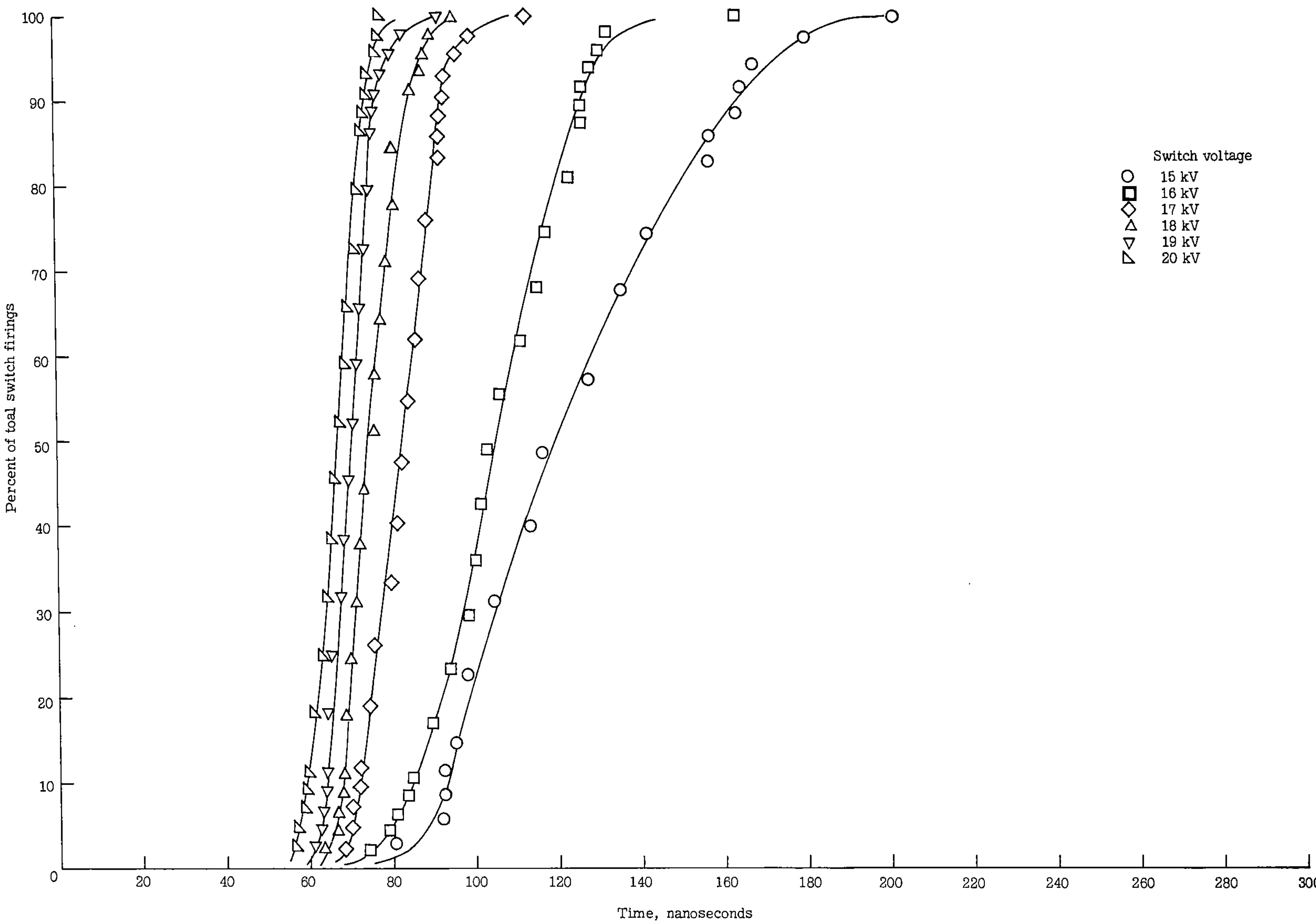

Figure 7.- Distribution of firing times for each switch voltage. Switch 1; gap clearance, 0.635 cm; peak trigger voltage, 17 kV; trigger pin not extended or recessed.

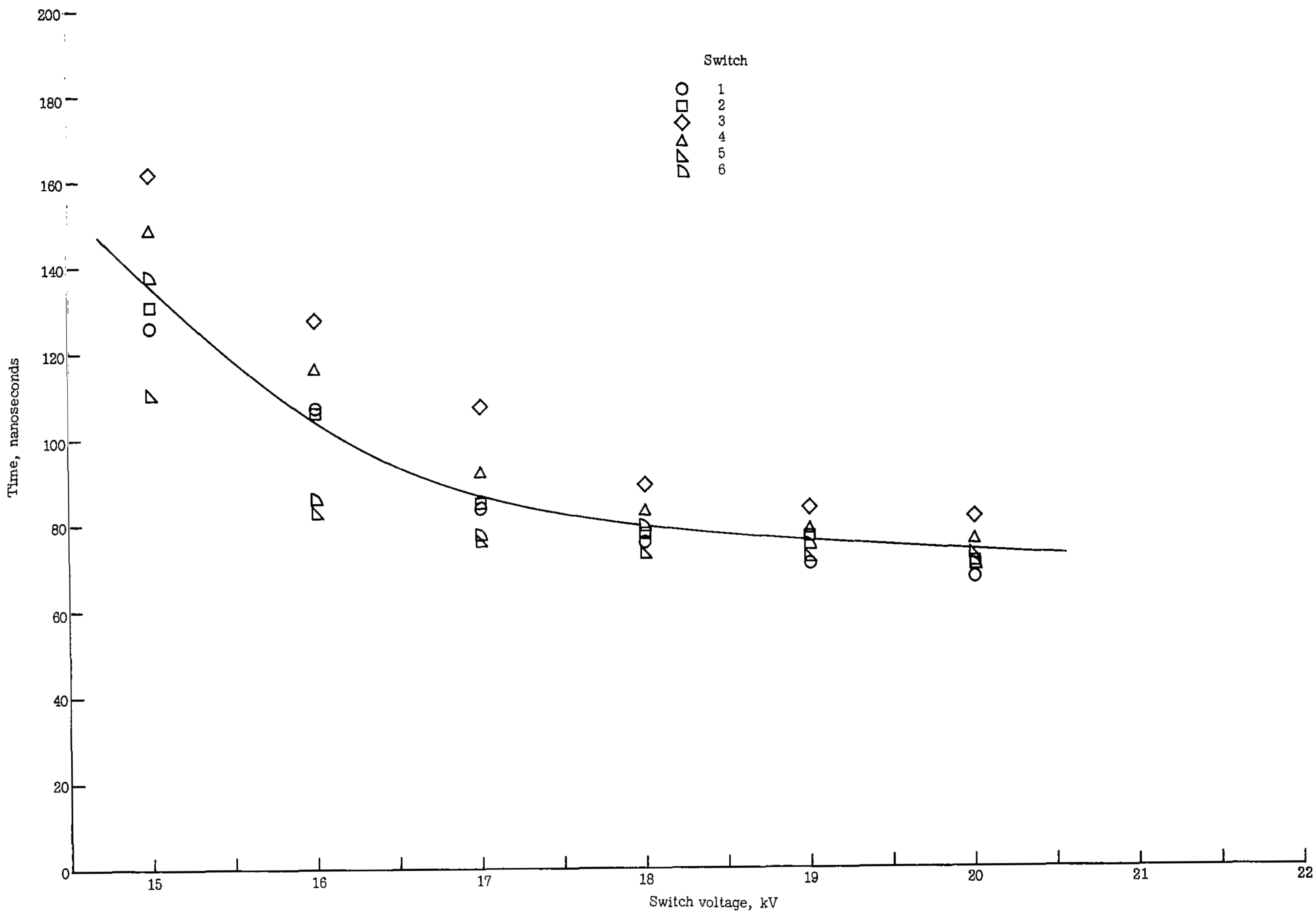

Figure 8.- Variation of average firing time with switch voltage. Gap clearance, 0.635 cm; peak trigger voltage, 17 kV; trigger pin not extended or recessed.

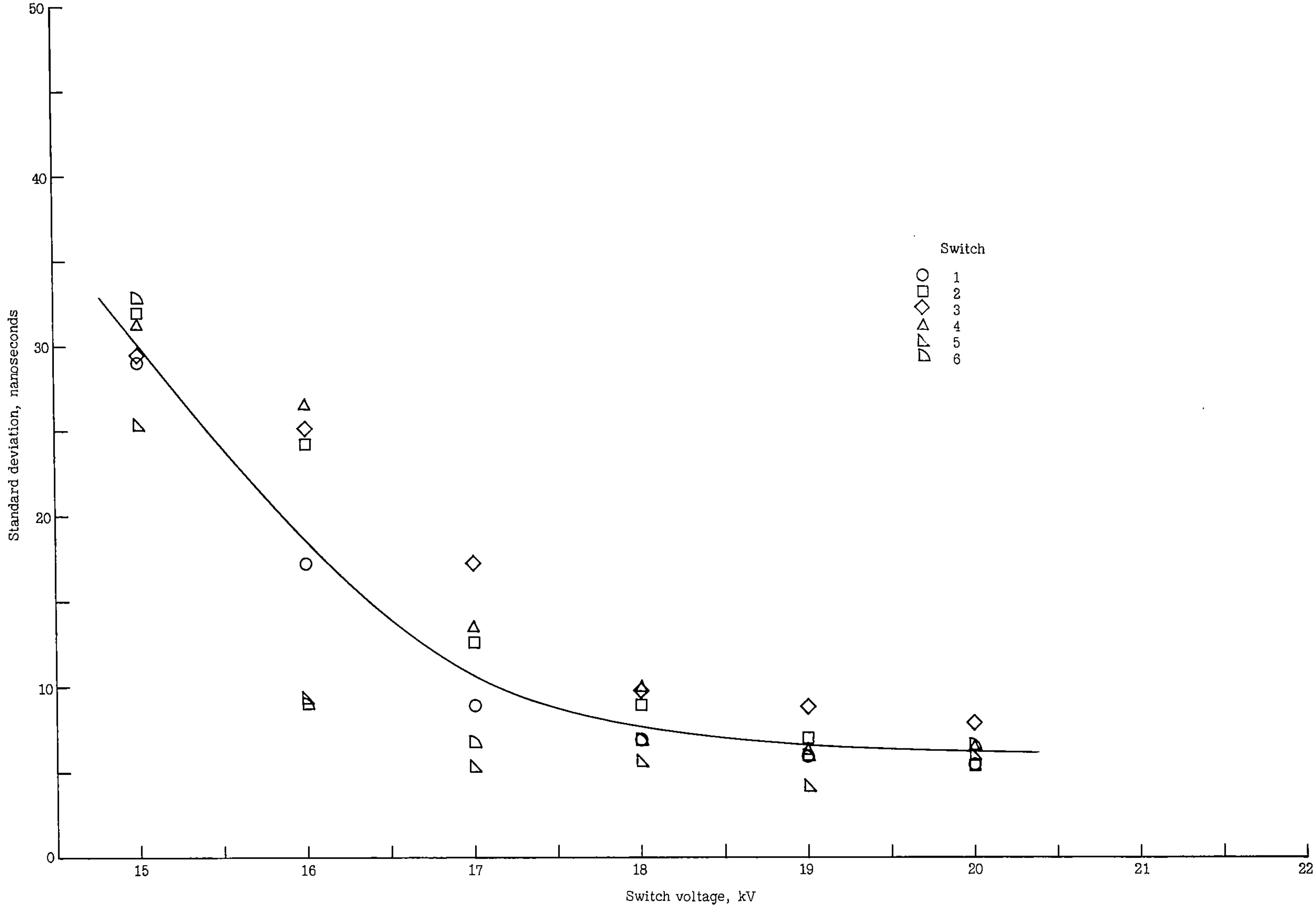

Figure 9.- Variation of switch jitter with switch voltage. Gap clearance, 0.635 cm; switch voltage, 20 kV; trigger pin not extended or recessed.

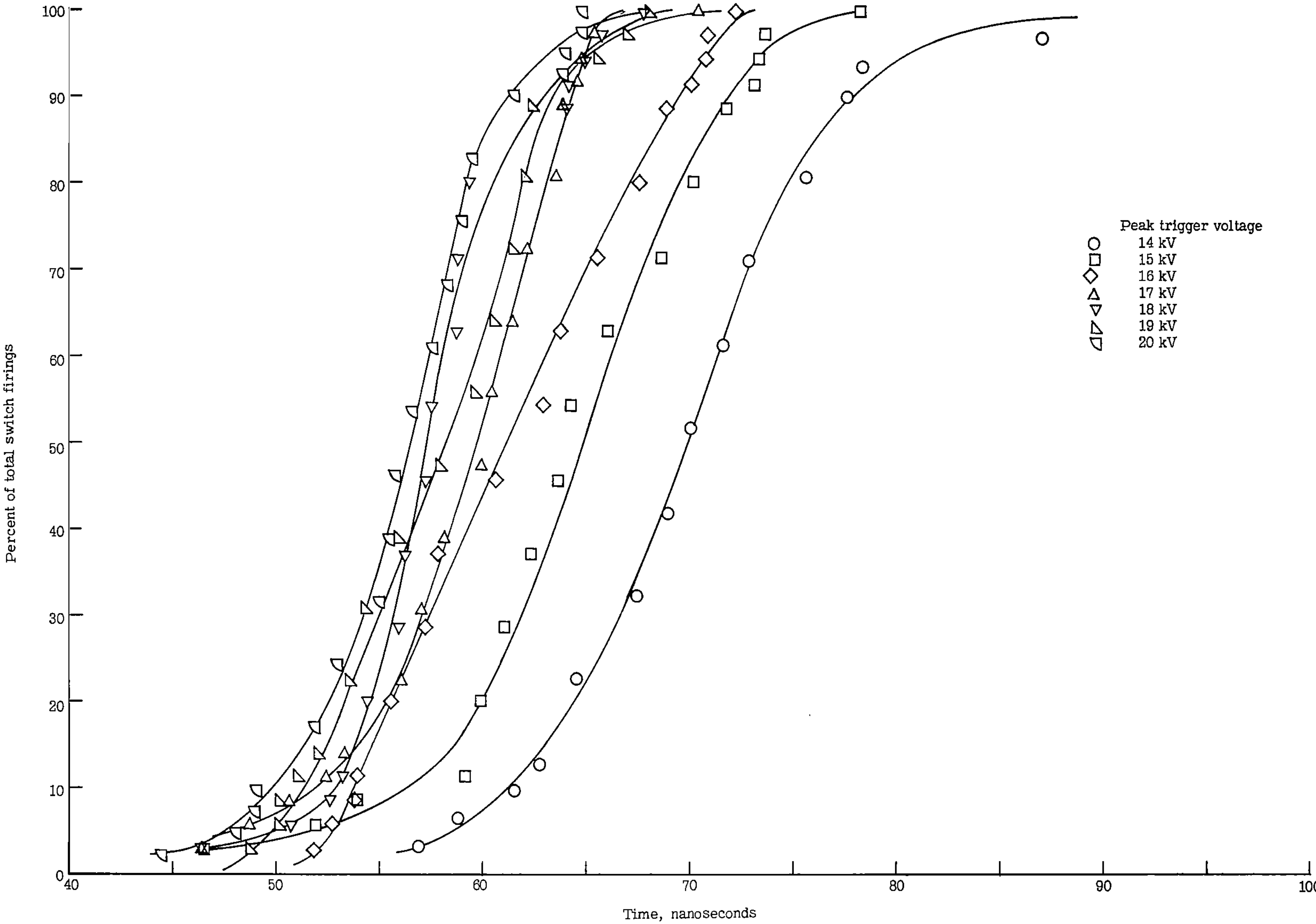

Figure 10.- Distribution of firing times for each peak trigger voltage. Switch 1; gap clearance, 0.635 cm; switch voltage, 20 kV; trigger pin not extended or recessed.

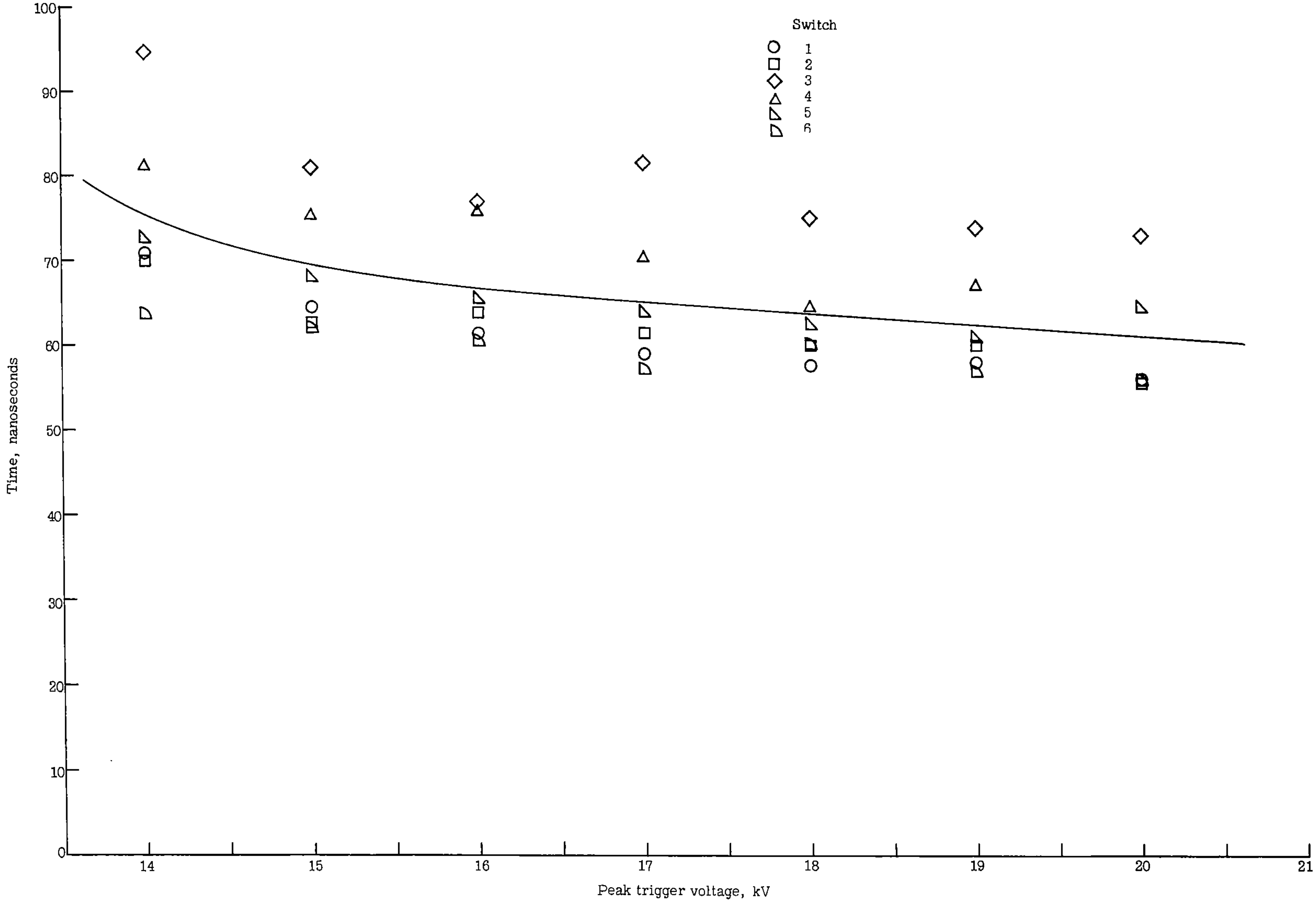

Figure 11.- Variation of average firing time with peak trigger voltage. Gap clearance, 0.635 cm; switch voltage, 20 kV; trigger pin not extended or recessed.

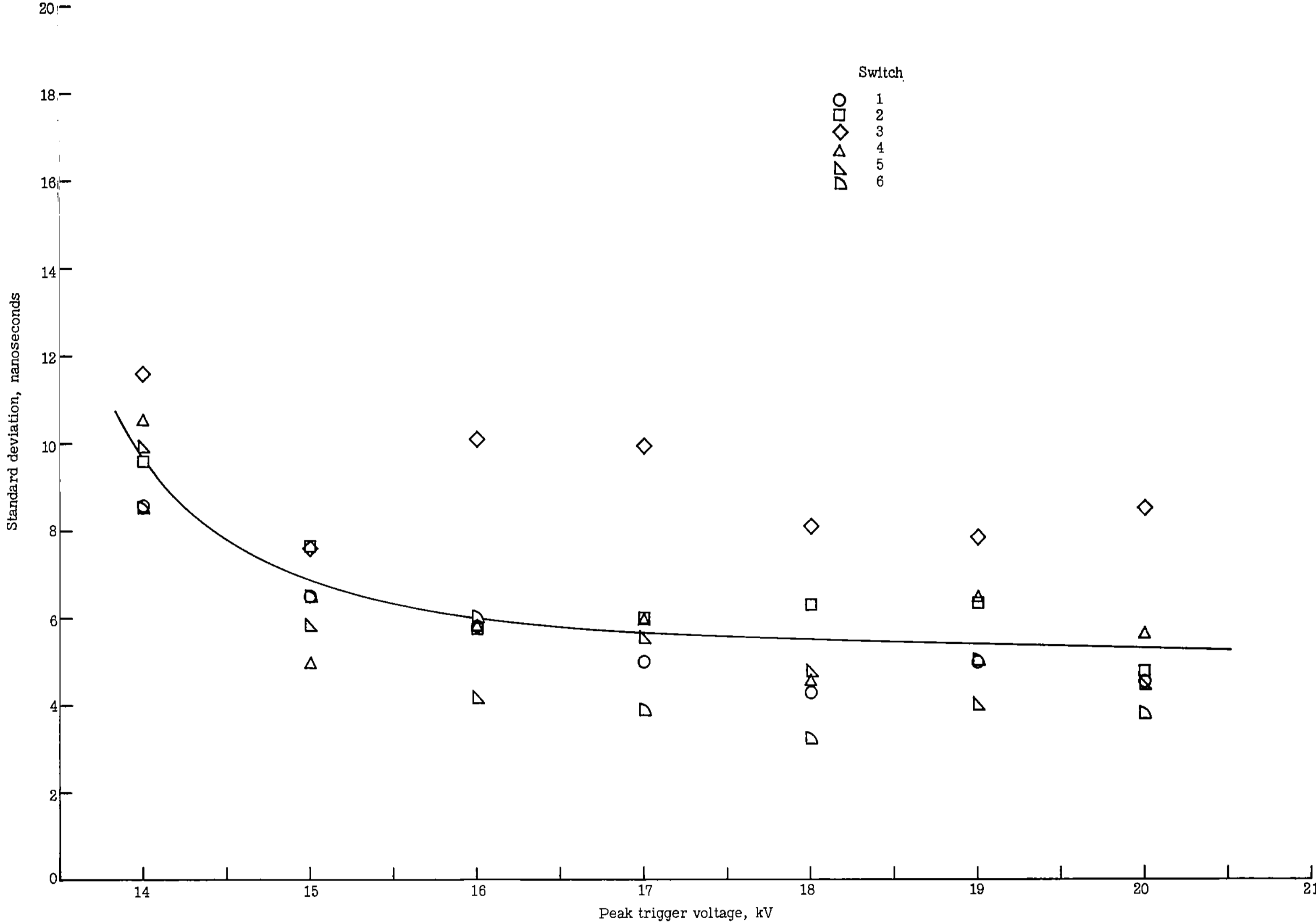

Figure 12.- Variation of switch jitter with peak trigger voltage. Gap clearance, 0.635 cm; switch voltage, 20 kV; trigger pin not extended or recessed.

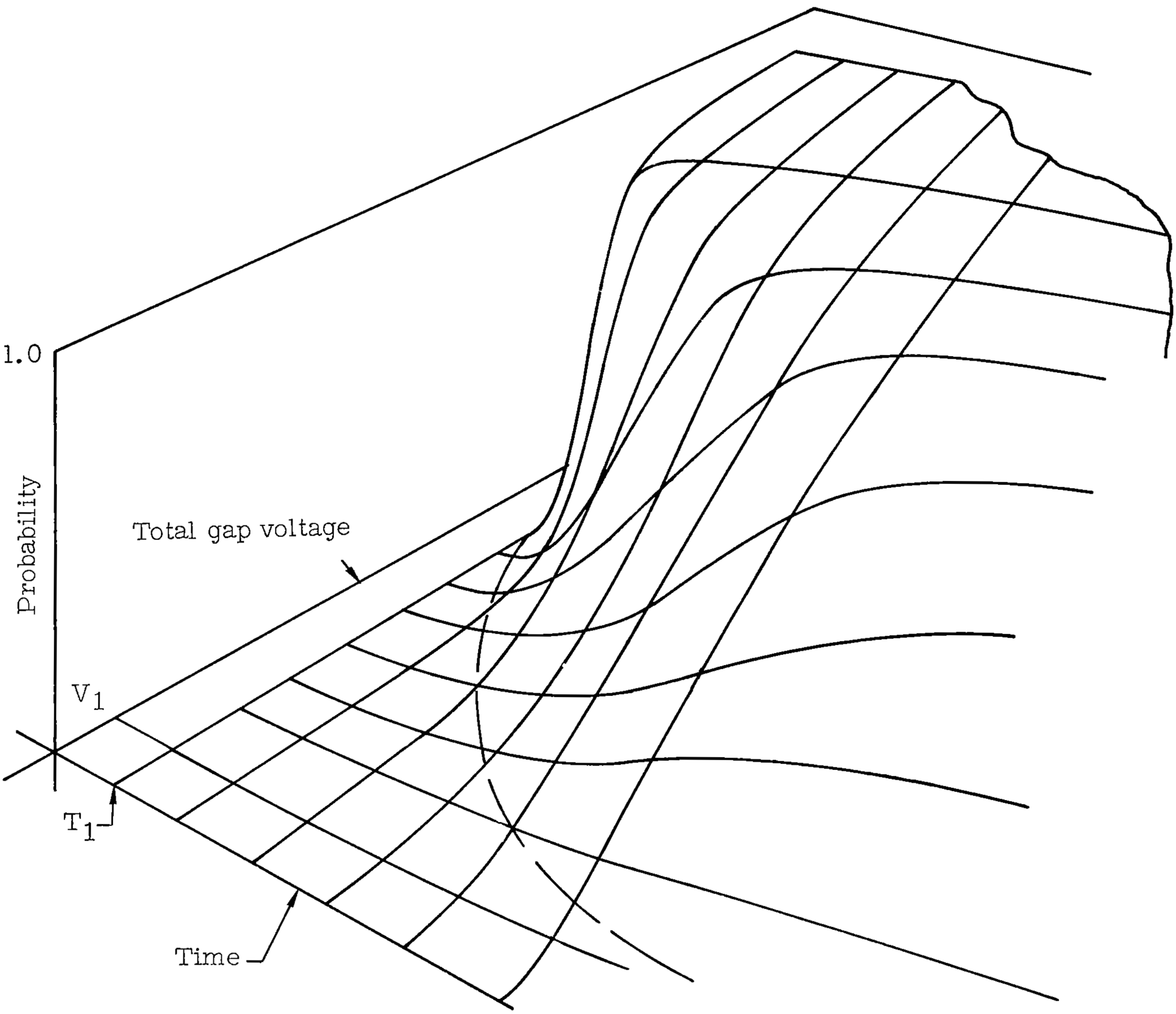

Figure 13.- Three-dimensional probability surface.

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