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FERROELECTRICS FOR DIGITAL INFORMATION STORAGE AND SWITCHING

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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FOR
DIGITAL INFORMATION STORAGE
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by
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FOREWORD

This report was originally issued as a thesis report and as such received but limited distribution. So as to extend the distribution to the many who have expressed interest in ferroelectric components for digital information storage and switching, this report is now issued as an M. I. T. Digital Computer Laboratory R-series report.

The author is indebted to Professor Arthur R. von Hippel, Director of the M. I. T. Laboratory for Insulation Research; to Mr. Jay W. Forrester, Director, and Mr. William N. Papian of the M. I. T. Digital Computer Laboratory; and to the staffs of their respective laboratories, whose combined efforts made this work possible.

ABSTRACT

FERROELECTRICS FOR DIGITAL INFORMATION STORAGE AND SWITCHING

by

Dudley Allen Buck

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Materials have recently been discovered within which exist domains of permanent electric dipoles. These materials, named ferroelectrics, can be used to advantage in many electronic applications where ferromagnetic materials are currently used, often in circuits which are the duals of those of their ferromagnetic counterparts. Ferroelectrics can be made in the form of single crystals or rugged ceramics.

Digital information can be stored in a matrix of ferroelectric condensers, and an efficient method of storage-element selection is available in the form of a two-coordinate, coincident-voltage scheme. The matrix can be made on a thin ferroelectric sheet by painting the coordinate rows on one side and the coordinate columns on the other. The information can be taken from the matrix via a simple mixing transformer.

Multi-position switching can be accomplished with a group of ferroelectric condensers. The logical circuitry of such a switch, capable of accomplishing many of the switching tasks in a high-speed information-handling system, can be painted directly onto the two sides of a thin ferroelectric ceramic sheet.

Ferroelectrics for pulsed applications are best studied by pulse methods, which allow their properties to be studied without significant heating of the sample, and with rather low-powered test equipment. A barium titanate ceramic, which, when pulsed, switches in about one microsecond, is on the borderline of suitability for the memory application. The pulsed properties of this material are temperature dependent.

Thesis Supervisor:	Arthur R. von Hippel
Title:	Director of the M. I. T. Laboratory for Insulation Research

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CHAPTER I

INTRODUCTION TO FERROELECTRICS

Engineers have long utilized the residual induction of a ferromagnetic material for information storage. Such devices as the magnetic-wire and magnetic-tape recorders, the magnetic-drum computer memory, the magnetic stepping register, and more recently, the multi-dimensional magnetic-core memory all depend upon residual induction for their operation. The existence within a material of domains of permanent magnetic dipoles is a requisite for the phenomenon of residual induction.

Recently, materials have been discovered within which domains of permanent electric dipoles exist.[1,2,3] These materials, named ferroelectrics, exhibit residual displacement and have hysteresis loops in the D-E plane similar to those of the ferromagnetic materials in the B-H plane (Figs. 1,2). The residual displacement of ferromagnetic materials is a basis for digital information storage, making possible the use of ferroelectrics in applications similar to those in which ferromagnetic materials are currently used.

The phenomenon of ferroelectricity has been observed in three groups of materials whose representatives are Rochelle salt, dihydrogen potassium phosphate, and barium titanate. It was decided at the outset that the investigations of this thesis should be made on materials of the third group, represented by barium titanate. Barium titanate, unlike the others, can be

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1. A. von Hippel and co-workers, NDRC Reports 14-300 (August, 1944), 14-540 (1945).

2. A. von Hippel, "Ferroelectricity, Domain Structure, and Phase Transitions in Barium Titanate," Laboratory for Insulation Research Technical Report XXVII, Massachusetts Institute of Technology, March 1950; Reviews of Modern Physics, Vol. 22, No. 3, pp 221-237, (July, 1950).

3. W. J. Merz, "The Electric and Optic Behavior of $BaTiO_3$ Single-Crystal Domains," The Physical Review, Vol. 76, No. 8, pp 1221-1225 (October 15, 1949).

prepared in the form of a rugged ceramic which exhibits ferroelectricity over a wide temperature range, and which, when compounded with other titanates, can be tailored to a wide variety of electrical properties.

The remanent charge of a ferroelectric condenser (the residual displacement integrated over the area) is not to be confused with the charge of an ordinary condenser which has been subjected to a direct voltage. The charge of an ordinary condenser will "leak off" with time, whereas the remanent charge of a ferroelectric condenser will remain over a period of weeks even though the condenser terminals are short circuited. The remanent charge of a ferroelectric condenser represents a stable state for the dielectric; for an ordinary condenser, the only stable state is that with zero charge.

Ferroelectrics can be used in circuits which are, in general, the duals of those in which their ferromagnetic counterparts are used. Voltages sources must be substituted for current sources as drivers, and current detectors must be substituted for voltage detectors for observing changes in stored information (Fig. 3).

When a magnetic core, as it switches, moves from a saturated region of its hysteresis loop out onto a steep region and demands power to supply its switching losses, it does so by raising its impedance as seen by the driving winding. For this reason, it is best driven by a current source. A ferroelectric condenser, as it switches, lowers its impedance when it requires more power, and therefore should be driven by a voltage source. If driven by the incorrect source, both the magnetic core and ferroelectric condenser may switch quite slowly, the switching speed being limited by the source and not necessarily by the physical properties of the material.

Information is stored in a magnetic core in the form of remanent flux, either in a positive direction or a negative direction. Changes in the stored information (changes in the flux) manifest themselves as voltages across a winding on the magnetic core. Therefore, a voltage detector is needed to detect information changes in a magnetic-core circuit. A ferroelectric condenser, on the other hand, stores information in the form of a remanent electric charge. Changes in the stored information (changes in the charge) allow currents to flow in the condenser circuit. A current detector is therefore needed to detect information changes in ferroelectrics.

With this dualism in mind, we can explore the possible applications of ferroelectrics to digital information storage and switching circuits which at present involve magnetic cores. Two additional characteristics of ferroelectrics which distinguish them from magnetic cores must be kept in mind:

1. Because Div B = 0, one must provide a closed path for the lines of flux in a magnetic circuit, particularly if one desires a rectangular hysteresis loop. For this reason, magnetic cores in this application are usually made in the shape of rings or toroids. An electric field, however, can terminate on any charge-carrying material; this fact allows ferroelectric condensers to be made in the form of thin sheets with electrodes plated, or fired, on the sides.

Information is ordinarily transferred in a digital information-handling system in the form of electric pulses. With magnetic cores, a transformation between an electric field and a magnetic field must take place when information is being stored and again when it is being read. Ferroelectrics, however, store information in the form of an electric charge; this fact relieves ferroelectrics of the difficulties involved in obtaining flux linkages.

2. During switching from one remanent state to the other, or more simply, when the sign of the remanent flux or charge is being changed, energy is dissipated. On a per-unit-volume basis, ferroelectrics often have an energy loss due to switching more than one hundred times that of the ferromagnetic materials. This poses a heating problem due to switching losses. Fortunately, the thin-sheet fabrication of ferroelectrics facilitates cooling. This large difference in switching loss is illustrated in Table I. Losses for the various materials are computed as twice the product of the remanence times the coercive force, and as such are but approximations.

Table I Loss Comparison

T = 25 C	Material	Approximate Hysteresis Loss Joules /m^3
Ferro-electric	$BaTiO_3$ single crystals[1]	5,000
	$BaTiO_3$ ceramic[2]	15,000
Ferro-magnetic	Deltamax[3]	23
	Silectron[3]	302
	4-79 Molybdenum Permalloy 216[4]	11
	Ferramic[5] A	36
	(Ferrite) B	40
	C	90
	D	21
	E	20
	G	4
	H	4

Key

1. M. I. T. Laboratory for Insulation Research
2. The Glenco Corporation, Metuchen, New Jersey
3. Allegheny Ludlum Corporation, Brackenridge, Pa.
4. ARMCO Steel Corporation, Middletown, Ohio
5. General Ceramics and Steatite Corporation, Keasbey, New Jersey

Both ferromagnetic and ferroelectric materials operate as such only below a certain maximum temperature. This temperature, known as the Curie temperature, or Curie point, is the temperature at which the dipole domains within the material are no longer able to spontaneously align themselves against the randomizing action of thermal vibrations. At the Curie temperature, the hysteresis loop disappears. For pure barium titanate, the Curie temperature is approximately 120 C, and impurities or additives have been observed to lower it. Most of this thesis investigation was carried out on a barium titanate ceramic body designated "X-18", made by the Glenco Corporation of Metuchen, New Jersey. This body, containing certain additives, was selected because its hysteresis loop is slightly more rectangular than that of ordinary barium titanate ceramics. Because of the additives, the Curie temperature is lower than 120 C (Fig. 2).

The lower Curie temperature of barium titanate is a disadvantage in applications in which the dielectric must exhibit a hysteresis loop during operation, especially in view of the high switching loss which leads to dielectric heating. Long before the Curie temperature is reached, however, many changes occur in the electrical characteristics of barium titanate. These changes with temperature are not very evident from the sequence of hysteresis loops shown in Figure 2, but the tests of Chapter II of this thesis show what a radical effect the temperature can have on the pulsed characteristics of the material. As already mentioned, it is fortunate that the thin sheets of ceramic, as the material is usually fabricated, are in a form which can be easily cooled.

An additional factor to be considered in engineering designs employing ferroelectric ceramics is long-term drift, or aging, of the electrical properties—a problem which is shared by ferromagnetic materials. Rzhanov[4,5] has reported temporary changes in the shape of hysteresis loops

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4. A. V. Rzhanov, <u>Zhur Exsp. Teoret. Fiz.</u> 19,335-45 (1949). Reported in English by reference 5.

5. D. R. Young, "Temporary Enhancement of Hysteresis Loops in Barium Titanate Samples," <u>The Journal of Applied Physics</u>, Vol. 22, No. 4, (April 1951).

due to high-field excitation above the Curie Temperature, followed by a slow drift back to normal with a time-constant of the order of 100 hours. In this thesis investigation, certain ferroelectric condensers were observed to acquire asymetric properties, as though a "built-in" bias were present, upon sitting idle for several days.

Figure 4 shows the samples put to test in the thesis investigation. The various samples are:

A. Glenco body "X-18" — .025" thick, silver paste electrodes.
B. General Ceramics and Steatite body #66431 various sizes and thicknesses, silver paste electrodes.
C. Glenco body "X-18" — .010" thick.
D. Glenco body "X-48" — .010" thick.
E. Body made from Ticon B (Titanium Alloy Manufacturing Company, New York, N. Y.) by the Electrical Ceramics Laboratory of the M. I. T. Laboratory for Insulation Research.
F. Glenco bodies "X-48" and "X-18", .010" thick with evaporated silver electrodes.

In spite of the present limitations of barium titanate ceramics, the use of the material for pulsed operation in digital information-handling systems poses exciting possibilities. As will be shown, circuit components made with barium titanate ceramic promise unique and compact packaging plus very rapid operation. In addition, the material can be easily fabricated and promises to be most inexpensive.

Chapter II of this thesis describes methods, equipment, and the results of pulse tests performed on barium titanate ceramics, while Chapter III describes a proposed ferroelectric two-dimensional matrix memory and Chapter IV describes a multi-position ferroelectric switch.

CHAPTER II

PULSE TESTING OF FERROELECTRICS

A. PULSE METHODS VS. STEADY-STATE METHODS

Dielectrics can be studied by pulse-test methods, by sinusoidal steady-state test methods, or by a combination of the two. In principle, the same information can be obtained from any of these test methods.[6,7,8] Because the comparison of information obtained from one method with that obtained from another is often mathematically difficult, it is usually desirable to test a dielectric by the method most closely approximating the conditions under which that dielectric will be called upon to operate. Ferroelectrics for digital information storage and switching will probably be pulse-operated. Pulse testing, therefore, naturally suggested itself as the proper method for evaluating ferroelectric materials for use in these applications. The application was the prime factor in the selection of the test method.

Pulse testing has at least three additional advantages over the other test methods:

1. Between pulses, an arbitrary length of time can be allowed for cooling of the dielectric. Although switching power is high during a pulse, a pulse-repetition frequency can be chosen which is low enough that heating of the dielectric is negligible. The minimization of heating during the experiment is especially important for the barium titanate ceramics which were studied because their electrical properties vary remarkably with

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6. B. Gross, "On the Theory of Dielectric Loss," The Physical Review, Vol. 59 p. 748, (May 1, 1941).

7. M. F. Manning and M. E. Bell, "Dielectric Theory and Insulation," Reviews of Modern Physics, Vol. 12, p. 215, (1940).

8. Unpublished papers of Professor A. R. von Hippel, Laboratory for Insulation Research, Massachusetts Institute of Technology, Cambridge, Massachusetts

temperature. During the course of the thesis it was suggested that the high-field-strength relaxation spectrum (plot of dielectric constant versus frequency) as obtained from steady-state measurements be compared with the relaxation spectrum as computed from pulse measurements. It was concluded that heating of the dielectric would prohibit high-field-strength steady-state measurements. In fact, the small condenser shown at A in Figure 4 (1-square-centimeter electrodes on the two sides of a 0.025-inch sheet) would dissipate over 1,000 watts in a field of 8.2 volts per mil at 10^6 cycles per second--providing that it remained at room temperature. It would be difficult, if not impossible, to control the temperature while making a measurement of the dielectric constant. In addition, there would be driving difficulties. This brings up the second point.

2. Pulse-test equipment also can rest between pulses. Although the equipment must be capable of supplying the peak power demanded by a ferroelectric sample as it switches, the average power can be quite low. Large pulse energies can therefore be supplied to a sample with rather modest equipment.

3. Breakdown of the dielectric caused by heating (such breakdown is believed to occur in many dielectrics) is prevented by the use of pulses so short that the dielectric does not overheat. Elimination of thermal breakdown as a cause for failure of the dielectric then allows pulse voltage amplitudes to be applied which exceed the steady-state breakdown voltage of the dielectric. Pulse measurements can thus be extended into a region not accessible to steady-state measurements.

B. PULSE TESTS OF THIS THESIS

In the pulse tests a ferroelectric condenser is subjected to voltage pulses of adjustable amplitude and of either polarity in a meaningful sequence. Two sequences were chosen for the tests (Figure 5). The first, designated Mode A, was designed to study the switching speed and the switching losses of a ferroelectric. The second, designated Mode B, was designed to evaluate various ferroelectric materials for use in the two-dimensional ferroelectric memory described in Chapter III of this thesis.

Almost as important as the results of a test is a careful description of the techniques and equipment employed, with special attention to the limitations of the equipment. All too often important effects are masked or blurred by inadequate amplifier bandwidths, and anomalies are introduced which are peculiar to a particular testing sequence. Therefore, before a discussion of the results of these tests, a description of the tests and of the equipment will be given.

1. Mode A Tests

Mode A tests subject a ferroelectric condenser to a pulse sequence consisting of four positive pulses followed by four negative pulses. The first positive pulse and the first negative pulse reverse the polarity of the remanent charge, thereby switching the ferroelectric and producing a switching transient. The remaining three positive pulses and the remaining three negative pulses find the material already switched, and thus they produce non-switching transients. In computer terminology the switching transient is called a ONE, while the non-switching transient is called a ZERO. In addition, the positive pulses are arbitrarily called WRITE pulses and the negative pulses are called READ pulses. The significance of these terms will become clearer during the discussion of information storage in Chapter III. For the present, it will be sufficient to make the observation that a WRITE pulse will result in a ONE transient if preceded by a READ pulse and a ZERO transient if preceded by a WRITE pulse, while a READ pulse will result in a ONE transient if preceded by a WRITE pulse, and a

ZERO transient if preceded by a READ pulse. The pulse sequence and resulting transient sequence can then be written (Table II) for Mode A tests. (The ONE and ZERO are qualified by the word UNDISTURBED, the reason for which will be given in the next section.)

Table II Mode A Test Sequence

Pulse	Transient
1. WRITE	UNDISTURBED ONE
2. WRITE	UNDISTURBED ZERO
3. WRITE	UNDISTURBED ZERO
4. WRITE	UNDISTURBED ZERO
5. READ	UNDISTURBED ONE
6. READ	UNDISTURBED ZERO
7. READ	UNDISTURBED ZERO
8. READ	UNDISTURBED ZERO
etc.	

2. Mode B Tests

Mode B tests subject a ferroelectric condenser to a sequence of positive and negative pulses of two amplitudes. The larger amplitude pulses are called WRITE pulses if positive and READ pulses if negative, just as in Mode A tests. The pulses of lesser amplitude are called + DISTURB if positive and —DISTURB if negative. These disturbing pulses are inserted between a WRITE and a READ pulse to test the ability of a ferroelectric condenser to retain a remanent charge under the operating conditions to which it would be subjected in the ferroelectric matrix memory described in Chapter III. Further discussion of Mode B tests along with the results of Mode B tests follow the memory discussion in Chapter III. For the present, it will be sufficient to define a DISTURBED ONE as the transient associated with a READ pulse which follows a WRITE pulse if one or more —DISTURB pulses have been inserted between the WRITE pulse and the READ pulse. The pulse sequence and resulting transient sequence can then be written for Mode B tests (Table III).

Table III Mode B Test Sequence

Pulse	Transient
1. WRITE	UNDISTURBED ONE
2. WRITE	UNDISTURBED ZERO
3. WRITE	UNDISTURBED ZERO
4. + DISTURB	+ DISTURB TRANSIENT
5. —DISTURB	—DISTURB TRANSIENT
6. —DISTURB	—DISTURB TRANSIENT
7. —DISTURB	—DISTURB TRANSIENT
8. READ	DISTURBED ONE
etc.	

C. EQUIPMENT

1. The Ferroelectric Pulse Tester

The basic ferroelectric pulse-test circuit is shown in Figure 7A. A large condenser is used as the voltage source, and a thyratron is used as the switch. A small series resistance allows the transient current to be measured, and a large resistance in parallel with the ferroelectric condenser under test allows the circuit to stabilize after the thyratron is extinguished, with zero volts across that condenser.

The large condenser is chosen with sufficient capacity so that it loses but a small part of its charge, and therefore but a small part of its voltage, during the pulse (Figure 7B). The thyratron plate drops to V_t when the thyratron fires (Figure 7C). The voltage which is applied to the condenser under test is the difference between the voltage across the large condenser and the voltage across the thyratron and small resistance. (Figure 7D).

Figure 8 is a block diagram showing the way in which the sequences of pulses are generated. A low-frequency pulse generator operates an electronic counter which counts up to four. On every count, the oscilloscope is triggered and, after a short delay, the thyratron switch is fired. On the count of zero the polarity of the condenser under test is reversed. If making Mode B tests, the voltage is changed from the read-write voltage to the disturb voltage, or vice-versa, on the count of three. The thyratron switch is extinguished a short time after it is fired.

Figure 9 is a circuit schematic of the ferroelectric pulse tester. The polarity-reversing switch and the voltage-selection switch consist of relays actuated by thyratron flip-flops. The thyratron switch is fired by a positive pulse on its grid, in the usual fashion, and it is extinguished by a second positive pulse on the same grid. It was noticed that when a capacitively loaded thyratron is operating in the low-current region (close to minimum current) it may be extinguished by a positive grid pulse. This phenomenon was not found in the literature. The following explanation is thought to describe what takes place: The plate is held at V_t, the thyratron voltage drop, during the grid pulse. The grid pulse, which drives the grid more positive than the plate, causes the space charge to drain off onto the grid, thereby deionizing the discharge region. The grid then starts negative and is able to reach its negative bias voltage before the tube can refire, because firing is very slow at such a low plate voltage. Once the thyratron is extinguished, the plate voltage rises exponentially to the read-write voltage or disturb voltage, whichever happens to be selected.

The rise time of the voltage step applied to the sample under test is approximately 0.1 microsecond, and a pulse length of 100 microseconds is commonly used in the tests. Although the pulse has a short rise time, it has a fall time-constant of about 100 microseconds. A pulse-repetition frequency of 70 per second was used.

The method described for extinguishing the thyratron switch has the rather fortunate advantage that the extinguishing pulse does not show up to any extent across the sample under test. All other methods for extinguishing the thyratron which were considered consisted of driving the plate negative with respect to the cathode, resulting in an unwanted extra pulse across the sample in the same direction as the first pulse.

The large resistor in parallel with the sample under test (Figure 9) is made with three identical resistors in series. Coupled directly to the oscilloscope vertical deflection plates, these serve as a voltage divider of the proper size to permit observation of the applied voltage step.

2. The Oscilloscope

The oscilloscope used throughout the thesis investigation was a Browning Model OL-15A (Serial #41). Waveforms of voltages applied to the various ferroelectric samples were observed by directly coupling these voltages into the vertical deflection plates, whose measured deflection sensitivity is 67 volts per inch. Switching waveforms were observed using the vertical amplifier, whose maximum deflection sensitivity is 0.14 volts per inch and whose frequency response is flat within ± 10% from 20 cycles per second to 4 megacycles per second. Voltage measurements, when the amplifier was being used, were made by comparison with a built-in calibration voltage which is direct reading in peak-to-peak volts. Switching-time observations were made using a driven (triggered) sweep whose measured sweep speeds are 0.45, 0.96 and 4.8 microseconds per inch.

3. The Sample Holder; Temperature Measurement and Control Apparatus

Figure 10 is a photograph of a ferroelectric sample being tested. The sample is mounted in a holder and submerged in Dow 550 fluid (Lot BB-86), a Silicone oil. All measurements versus temperature were taken with falling temperature starting at 125 C. A mercury thermometer was used for temperatures above 0 C and a pentane thermometer below 0 C. Dry ice was added to the oil in chunks whenever measurements were made below room temperature.

D. RESULTS OF MODE A TESTS

As already mentioned, the results of Mode B tests are deferred until Chapter III because Mode B tests are so intimately connected with the ferroelectric matrix memory. Here, the results of Mode A tests are discussed.

With a given condenser in the sample holder, two parameters were variable in the experiments:

1. Pulse amplitude
2. Temperature

Measurements were made as a function of one of these two variables with the other held constant. Figures 11, 12, and 13 are photographs of the switching transients at constant pulse amplitude (8.2 volts per mil). They are included as an example of the many runs made, so as to show the approximate shape of the switching transients and the remarkable temperature dependence of the transient shapes. The two lines in each photograph are actually the result of the eight traces of the Mode A. test superimposed. The current is measured at a point in the circuit at which it is always of the same polarity. Two UNDISTURBED ONE's merge in the larger of the two transients, and six UNDISTURBED ZERO's in the smaller for every major cycle of eight pulses.

Because the applied pulse is a constant-voltage pulse, the area under these transients has the dimension of energy. The area under the larger transient is a measure of the energy associated with the ferroelectric condenser switching, while the energy under the smaller transient is the non-switching energy.

The difference in area between the switching transient and the non-switching transient is what we shall here define as the <u>dielectric switching loss</u>. This area, as shown in Chapter III, is somewhat related to our ability to discriminate between the switching transient and the non-switching transient.

1. Dielectric Switching Loss as a Function of Temperature at Constant Pulse Amplitude

With the difference of these two areas taken as a measure of the dielectric switching loss, this loss is plotted as a function of temperature for Glenco body "X-18" (Figure 14) at three pulse amplitudes. The loss is divided by the volume of the sample used so as to yield joules per cubic meter. As can be seen, the switching loss varies with temperature. It is roughly constant in the region between -30 C and room temperature, at which point it drops off. At about 70 C it reaches a second, smaller peak and then goes to zero at the Curie temperature.

It is interesting to note that approximately the same dipping curve of loss versus temperature has been observed with steady-state loss-tangent measurements at moderately high field strengths. Such a curve has been included (Figure 15) for comparison.

The hysteresis loops at various temperatures of Figure 2, taken at 250 cycles per second for the same material, do not seem to show this dipping curve. This points up the fact that hysteresis loops can be used only as a rough indication as to the probable pulsed characteristics of a material. Vertical movements on the hysteresis loop are made up of a combination of reversible and irreversible changes. One does not know at any instant of time what portion of the integrated changes up to that time are reversible and what portion are irreversible; from an arbitrary point on the hysteresis loop, one does not know in advance what the exact path of the trace would be if the field were suddenly removed. Since it is the irreversible changes which contribute to the loss, the poor correlation between quasi-static hysteresis loops and the pulsed characteristics is understandable.

2. Approximate Switching Time as a Function of Pulse Amplitude at Constant Temperature.

Of concern to the engineer who is to use ferroelectrics in pulse-operated circuits is the speed with which they can be switched. The switching

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speed has been observed to be a function of the amplitude of the applied pulse. Figure 16 is a plot of switching speed versus pulse amplitude for a piece of Glenco body "X-18" barium titanate ceramic 0.025-inch thick with 0.006-square-inch silver-paste electrodes fired on opposite sides. The pulse amplitude has been converted to volts per mil (1 mil = 0.001 inch) rather than MKS units because thin barium titanate ceramic sheets are spoken of as being "so many mils" thick, not only by the manufacturers, but also by nearly all users. Included in Figure 16 is a plot of the approximate length of the non-switching transient.

It is difficult to define switching time; hence, the qualification "approximate." In the data presented in Figure 16, the switching time is defined as that time required for the transient to fall from its peak amplitude to 10% of its peak amplitude. The 10% level would correspond to 2.3 time-constants if the transient decayed exponentially, and we could then say that the transient is substantially over at about twice the switching time of Figure 16, five time-constants being the usual allowance. The transient is far from being exponential in shape, however. On tracing paper, exponentials of various time-constants were drawn whose initial amplitudes corresponded to the initial height of the transients in the photographs of Figures 11, 12, and 13. An attempt was then made to match up each transient with the exponential most closely resembling that transient, but with little success. It was concluded that all switching-time definitions were equally poor but that a consistent definition allowed a plot to be made which at least indicates the order of magnitude of switching times, and which in the case of this barium titanate ceramic shows that it indeed switches rapidly enough for our present applications.

For high pulse amplitudes, Figure 16 shows that switching time seems to asymptotically approach a lower limit in the region of 0.25 microseconds.

Low-field-strength bridge measurements indicate a drop-off of the dielectric constant of barium titanate between 10^8 and 10^{10} cycles per second. This would predict a much faster switching time than that observed. The measurements strongly suggest that switching of the dielectric involves a much slower mechanism than the one studied with low-field-strength bridge measurements.

3. Approximate Switching Time as a Function of Temperature at Constant Pulse Amplitude

A glance through the sequence of photographs of Figures 11, 12, and 13 will show that at a constant pulse amplitude the shapes of the transients vary with temperature. An attempt has been made, once again, to define a switching time so as to measure to some extent the change in the transient waveshape with temperature. Figure 17 is a plot of switching time versus temperature at two pulse amplitudes for a piece of Glenco body "X-18" 0.025-inch thick with 0.015-square-inch silver-paste electrodes fired on opposite sides. The data were taken from two of the runs of photographs. The two dotted regions are where the complete transient did not get in the picture. The plot gives a rough indication as to the temperature variance of switching time.

CHAPTER III

THE FERROELECTRIC MEMORY

Figure 19 is a photograph of a 64-cell ferroelectric memory. The part which actually stores information is the one-inch square of thin barium titanate ceramic on the top shelf. The compactness and simplicity of a ferroelectric memory along with the promise of high operating speed was the prime motivation behind this research. In the following paragraphs, it will be shown how information can be stored in ferroelectrics, why this particular design was chosen, how the matrix memory works, and how well it might work. It must be said parenthetically that the memory shown in Figure 19 does not actually work, but that a material has been uncovered which is on the borderline of suitability for the application. The batch of material from which the memory of Figure 19 was made later turned out to have electrical properties inferior to those of previous samples of the same material.

A. INFORMATION STORAGE IN FERROELECTRICS

Digital information, when presented in binary form, consists of a group of elementary yes or no answers, commonly called ONE's and ZERO's, which can be stored in a group of bi-remanent devices. A ferroelectric condenser is one such device, the remanent charge having always one of two polarities. We can arbitrarily define a positive remanent charge as a ONE and a negative remanent charge as a ZERO. We then can say that a ferroelectric condenser "remembers" a ONE or a ZERO which has been placed in it. To recover the stored information—that is, to read the bi-remanent storage device--we have merely to apply a reference pulse and then observe the nature of the resulting transient. Let us arbitrarily say that the reference pulse, or READ pulse, is negative. If the condenser contains a

ONE, we will observe a switching transient (undisturbed ONE) when the reference pulse is applied. If, on the other hand, the condenser contains a ZERO, we will observe a non-switching transient (undisturbed ZERO). The ability of a given ferroelectric condenser to store information, therefore, depends upon our ability to discriminate between these two kinds of transients. This we can do.

Application of a READ pulse to a ferroelectric condenser leaves that condenser in the same remanent state (containing a ZERO) regardless of whether it contained, just prior to application of the READ pulse, a ONE or a ZERO. The information is therefore destroyed during reading. A memory which is read in this way is said to have a destructive read. We must replace the information by re-writing. This is accomplished by following each ONE transient by a WRITE pulse.

B. SELECTION OF MATRIX LAYOUT FOR MEMORY

Having a method for storing and reading information, however, is but the first step in the design of a working memory. It has become increasingly clear as digital information handling systems have developed that the most difficult problem for which to find an economical solution is that of selecting among the storage cells of a memory. Certain of the completed memories have found their solution in making time one of the coordinates in the selection of memory cells. The mercury-delay-line and the magnetic-drum memories fall into this category. For the attainment of truly high-speed operation, however, a random-access memory in which time is not one of the selection coordinates is felt to be necessary. The electrostatic storage tube as used in the Whirlwind computer is one of the few working memories to fall into this latter category.

The possibility of locating the storage elements in a multi-dimensional matrix where selection is inherent in the storage elements themselves is a recent and most promising scheme for solving the selection problem.[9,10] This basic idea is being investigated for ferromagnetic storage using a matrix of small toroids at the M. I. T. Digital Computer Laboratory. It will now be shown how the same basic idea can be used for ferroelectric materials, as first suggested by Jay W. Forrester. The three-to-one selection scheme to be described was the outgrowth of work done by R. R. Everett.[11]

C. DESCRIPTION OF THE MATRIX MEMORY

An economical method for selection among N objects is to arrange them in a square matrix so that by the selection of one row and one column the object at the intersection of that row and column is selected. The selection problem is at once reduced from selection among N objects to the problem of making 2 selections, each from among N objects — one to find the proper row and one to find the proper column. How this method can be used to select among the storage elements of a memory, which in this case are ferroelectric condensers, will now be shown.

Consider the square n-by-n matrix of ferroelectric condensers shown in Fig. 21a. Having selected a single row and a single column, one may redraw the matrix as it is seen looking between this row and column. As can be seen (Fig. 21b), the selected condenser lies between the selected row and the selected column. In addition, condensers connect the selected row to each of the unused columns and the selected column to each of unused rows. Finally, there is a condenser between each unused row and each

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[9] Jay W. Forrester, "Digital Information in Three Dimensions Using Magnetic Cores", Project Whirlwind Report R-187, (September 8, 1950), M.I.T. Servomechanisms Laboratory.

[10] W. N. Papian, "A Coincident-Current Magnetic Memory Unit", Project Whirlwind Report R-192, (September 8, 1950), M.I.T. Servomechanisms Laboratory.

[11] R. R. Everett, "Selection Systems for Magnetic Core Storage", Project Whirlwind Engineering Note E-413, (August 7, 1951), M.I.T. Servomechanisms Laboratory.

unused column.

Regardless of what voltages are applied to the selected row and the selected column, the unused rows will all be, by symmetry, at the same potential, and the unused columns will likewise be at the same potential. We can therefore, for this analysis, join the unused rows and sum the parallel condensers (Fig. 21c). Similarly, we can join the unused columns. We now see that a voltage applied between the selected row and the selected column will be directly across the selected condenser. In addition, this voltage will split among the three summed condensers, giving each of them a lesser voltage. The greatest of these lesser voltages is defined as the disturbing voltage, and the ratio of the voltage on the selected condenser to the disturbing voltage is defined as the selection ratio.

The summed condenser which joins the unused columns and the unused rows is n-1 times as large as the other two summed condensers. If the unused rows and unused columns are left floating (Fig. 22a), a voltage appears across this large condenser equal to 1/(2n-1) of the voltage across the selected condenser. Across the smaller summed condensers a voltage equal to (n-1)/(2n-1) of the voltage across the selected condenser appears. Thus the selection ratio is 1 : (n-1)/(2n-1). For a 2 by 2 matrix, the ratio becomes 1 : 1/3 (three-to-one), and as n becomes large the ratio rapidly approaches 1 : 1/2 (two-to-one). This is illustrated by the Table IV.

Table IV Selection Ratio vs Matrix Size

MATRIX SIZE	SELECTION RATIO
2 x 2	3.00 : 1
3 x 3	2.50 : 1
4 x 4	2.33 : 1
5 x 5	2.25 : 1
6 x 6	2.20 : 1
7 x 7	2.17 : 1
8 x 8	2.14 : 1
16 x 16	2.07 : 1
∞ x ∞	2.00 : 1

Grounding the unused rows and unused columns (Fig. 22b) causes zero voltage to appear across the large condenser and a voltage of one-half to appear across the small condensers. The selection ratio is always 2 : 1 with this scheme regardless of the size of the matrix.

Presumable we would always be somewhere between these two cases, depending upon the internal resistance of the source used to apply voltage to the leads. For a matrix of size 16 by 16, the first scheme gives a selection ratio of $2\frac{1}{15}$: 1 and the second a ratio of 2 : 1, a difference of 3%. It therefore appears that the internal resistance of the voltage source has little effect upon the operation of the matrix for sizes which at present seem to be desirable.

A third scheme for driving the matrix appears to be promising. Instead of letting the unused rows and columns float or be grounded, the selection ratio can be improved by <u>driving</u> the unused rows and columns to voltages such that the voltage across the large summed condenser just equals the voltage across each of the smaller summed condensers (Fig. 22c). Although this scheme involves additional driving problems, it makes the selection ratio 3 : 1 regardless of the matrix size. This means that the hysteresis loop of the ferroelectric material need only be capable of discriminating between two voltages which bear a three-to-one relationship to each other.

Selection of a row and a column allows us to apply a READ or WRITE voltage to one condenser in the matrix while applying a lesser DISTURB voltage to other condensers in the matrix. Figure 20 illustrates the requirements placed on the hysteresis loop by this type of operation. The elementary ferroelectric condenser in the matrix must be able to switch when a READ pulse or a WRITE pulse is applied. At the same time it must be able to retain substantially all of its remanent charge during the application of a large number of DISTURB pulses. The tests described, designated as Mode B, were specifically designed to test a material for this application.

D. MODE B TESTS

As already mentioned, our ability to read information out of a memory is the true measure of the memory's ability to retain information. If the memory, under a large number of disturbances, loses most of its remanent charge and yet we are able to reliably determine the algebraic sign of what little remains, we may have a working memory. It has been the observation thus far, however, that our ability to read out of the memory, that is, to discriminate between the two kinds of transients, is the weak link in the system. On a peak-amplitude basis, discrimination is completely out of the question (glance at photographs in Figs. 11, 12, 13). A more fundamental basis for discrimination is a comparison of the areas under the two transients, such as an integrator would see. Figure 24 is a plot of this area ratio versus temperature for Mode A operation (no disturbances) at 8.2 volts per mil for Glenco "X-13" barium titanate ceramic. The four-to-one area ratio is just barely usable for reliable discrimination. When disturbances are inserted between WRITE and READ, however, this ratio falls to a low value, defying discrimination.

As we look at the transients in search of a means to discriminate between them, we notice that the most striking difference is in their waveforms. There is a time, about a microsecond or so after the waveform starts, when the non-switching transient has dropped almost to zero and the switching transient, due to its slowness, still has considerable amplitude. If the waveform is sampled at a time when the amplitude ratio between the two transients is a maximum, good discrimination is possible.

The problem of detecting the current transient on the selected row (or column) of a matrix is nicely handled by transformer coupling. Using single-turn coupling, wires to all of the rows can be threaded through a ring-shaped magnetic core (Fig. 25C lower). A secondary winding can then be coupled into a sensing circuit. If half of the wires are threaded through in one direction and half in the other direction, the small unwanted transients on the unused rows will tend to cancel. With this latter arrangement, however, the sensing amplifier must be prepared to look at either a positive-going waveform or a negative-going waveform due to the transient in the selected row.

The upper nine photographs (3 x 3 matrix) of Figure 25A is an introduction to the Mode B measurements. The left-hand column are Mode A waveforms for a 100-volt READ-WRITE pulse. The pulse itself is shown in the top row, the transient as seen across a resistor in the middle row, and the transient as seen when transformer-coupled in the bottom row. The middle column is an identical sequence for a 50-volt DISTURB pulse, once again Mode A. The right-hand column is the 100-volt READ-WRITE pulse and the 50-volt disturb pulse superimposed in a Mode B test. The details of the transformer coupling is shown in the upper part of Figure 25C. The sample used in these tests is a piece of Glenco body "X-18".

The lower photographs of Figure 25A illustrate the time-amplitude discrimination principle. Due to transformer coupling, the UNDISTURBED ONE and DISTURBED ONE are of opposite polarities.

Figure 25B is a sequence of photographs showing the drop in amplitude of a DISTURBED ONE as the amplitude of DISTURB pulses is increased. The READ-WRITE voltage is held constant. It can be seen that with this material a 3 : 1 selection ratio will allow discrimination whereas a 2 : 1 selection ratio will not.

It was found that most of the loss of amplitude is due to the first DISTURB pulse. All changes in charge due to DISTURB pulses are either of a reversible or an irreversible nature. Those of an irreversible nature cause the remenant charge to diminish, while those of a reversible nature cause no loss of remanent charge. It appears as if the first DISTURB pulse "uses up" all, or nearly all, of the irreversible changes so that subsequent DISTURB pulses cause little or no further diminution. To test this hypothesis, the Mode B test was temporarily modified to give twice as many DISTURB pulses. The change in the DISTURB ONE waveshape when this change was made was less than the width of the scope trace.

CHAPTER IV

THE FERROELECTRIC SWITCH

A multi-position ferroelectric switch is proposed which can accomplish many of the switching tasks in an information handling system; in particular, it can select among the rows and columns of a ferroelectric memory. The logical circuitry of the ferroelectric switch can be painted directly onto the two sides of a thin ferroelectric sheet.

The non-linear electric displacement-versus-field characteristics of a ferroelectric can be utilized to construct a condenser whose capacitance is a function of the applied voltage. This phenomenon, which makes possible the operation of a dielectric amplifier,[12,13] is the basis for the ferroelectric switch. Figure 26 illustrates the operation of the basic switch element—a simple R-C filter which uses a non-linear condenser as its series branch. With no direct voltage across the condenser (Fig. 26A), the circuit behaves like any ordinary π-section R-C filter with the exception that distortion will result if the input voltage is large enough to drive the dielectric out of its linear region. Transfer characteristics are shown for sinusoidal excitation. If a bias voltage V_c is inserted in the circuit as shown (Fig. 26B), the operating point for the transfer characteristics is shifted to a new point on the charge-versus-voltage characteristics of the non-linear condenser. At this new point, the condenser has a much lower capacity and, therefore, the filter characteristics are changed in such a way that the output

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[12] Shepard Roberts, Barium Titanate and Barium-Strontium Titanate as Non-Linear Dielectrics, M.I.T. Sc.D. Thesis, Department of Electrical Engineering (1946).

[13] Development and Application of Barium Titanate Ceramics as Non-Linear Circuit Elements, Final Report Contract No. W36-039 sc-44606 File No. 19028-PH-49-5(4060) Glenco Corporation (August 15, 1950).

diminishes in amplitude. With a fixed-amplitude input voltage, then, the output voltage can be changed by varying the bias voltage V_c. For ferroelectric switch operation, we need but two values for V_c: when $V_c = 0$ the switch is ON, and when V_c is equal to some fixed value high enough to bias the dielectric well into its saturation region, the switch is OFF.

Figure 27A illustrates a two-position ferroelectric switch. The two non-linear condensers are made as a single unit by firing a large electrode on one side of a ferroelectric sheet and two smaller electrodes on the opposite side. With S in position shown, output 2 is biased OFF, and output 1 is ON. In the opposite position, output 2 is ON.

Figure 27B illustrates an eight-position ferroelectric switch. Operation of the first stage, controlled by S_1, is the same as the two-position switch. Subsequent stages, however, have the lower ends of their resistors connected so that the even resistors are connected to ground when the odd resistors are connected to V_c, and the even resistors are connected to V_c when the odd resistors are connected to ground. There are eight possible paths through the switch (Fig. 28) only one of which will have all of its condensers ON. With S_1, S_2, and S_3 of the eight-position switch set as shown, output zero is ON. Outputs 1, 3, and 7 have one condenser OFF, outputs 2, 4, and 6 have two condensers OFF, and output 5 has all three condensers OFF. The number of OFF condensers among the outputs follows a binomial distribution (Table V).

Table V Ferroelectric Switch Analysis

	All ON	One OFF	Two OFF	Three OFF	Four OFF	Five OFF
4-position switch	1	2	1			
8-position switch	1	3	3	1		
16-position switch	1	4	6	4	1	
32-position switch	1	5	10	10	5	1

Successful operation of the switch postulates that a single OFF condenser leading to an output will cause that output to be OFF. To test this, an eight-position switch was constructed (Fig. 29) using a thin (0.025-inch) sheet of barium titanate ceramic (Glenco body "X-18"). All of the non-linear condensers were placed on the same sheet by firing electrodes on the two sides as shown. The signal enters the sheet via a large fired electrode (back view). Two electrodes match this input electrode on the opposite side (front view). Among the two condensers thus formed, one will always be OFF and one will always be ON. Each of these two electrodes is enlarged to match up with two electrodes on the opposite side which are alongside the input electrode. One of each pair of this third set of electrodes will be OFF. Finally the signal goes through the dielectric a third time coming out on one of the eight small electrodes (front view).

The operation of the switch is illustrated graphically by Fig. 30. With a constant-amplitude sine-wave input of variable frequency, the rms output at terminal 7 was measured as a function of frequency for each of the eight possible combinations of S_1, S_2, and S_3. At 800 cps, the best operating frequency for this particular design, the ratio of ON voltage to the highest OFF voltage is greater than three to one. This operating frequency can be shifted higher or lower by changing the size of the condensers and resistors. Both steady-state and pulse tests on this dielectric indicate that the operating frequency can be shifted up to several megacycles per second. If the resistors are replaced by inductors, the output-versus-frequency characteristics can be improved and losses are lowered.

For pulsed operation of this switch, a non-linear condenser is used in both the series and shunt arms of the filter. Fig. 31A illustrates such a switch which is so arranged that when the series condenser is ON, the shunt condenser is OFF (Fig. 31B); and when the series condenser is OFF, the shunt condenser is ON (Fig. 31C). The filter looks like a condenser voltage-divider to the rising edge of a pulse. The divider has either a large condenser in its upper leg and a small condenser in its lower leg or vice-versa, depending on whether the switch in ON or OFF.

The ferroelectric switch is proposed as a means for driving the rows and columns of a ferroelectric memory and for switching within an information-handling system. Its unique packaging makes it promising in applications where size, weight, and cost are important considerations.

CHAPTER V

SUMMARY AND OUTLOOK

The investigations started in this thesis are being continued in the M.I.T. Digital Computer Laboratory. As the various parts of the thesis are briefly summarized below, an attempt is made to indicate the direction of present and future work in this field.

A. TESTING EQUIPMENT AND TECHNIQUES

This thesis has described equipment and techniques which can be used to evaluate ferroelectrics for digital information-storage and switching applications. The equipment permits observation of switching transients whose total duration is less than 1 microsecond. Provision is made for control of pulse amplitude and temperature.

Pulse-testing of ferroelectrics will continue on a routine basis in search of improved materials for these applications. Two basic pulse-tester improvements are planned for the near future. First, the thyratron will be eliminated in favor of hard tubes so that shorter pulses can be applied. Second, the relay switches will be replaced by electronic switches so that the pulse-repetition frequency can be increased. These changes will result in operating conditions more nearly like those found in a modern information-handling system. In addition, they will make photography easier (many of the photographs shown were two-minute exposures).

B. FERROELECTRIC MATERIALS

Virtually the only obstacle impeding progress in this field is the dearth of suitable materials. Of the samples tested, only Glenco body "X-18" (A in Figure 4) showed promise for storage applications. A subsequent batch of presumably the same material was inferior to the first batch. "Aging" effects were noted when this material sat idle for two days, during which it acquired a small degree of asymmetry in its D-E characteristic.

In spite of the present limitations, there is cause for optimism. Much progress has been made in the science of making ferroelectric ceramics within the past few years. Mostly due to other applications of barium titanate (piezoelectric transducers), uniformity has steadily improved. Researchers have recently discovered many ferroelectric relatives of barium titanate, each of which must be investigated as a possible candidate for these applications. Many of these new ferroelectrics have a higher Curie temperature than barium titanate.

Single-domain barium titanate crystals have been grown which have properties superior to those of the ceramics for our applications. At the Bell Telephone Laboratories, Murray Hill, New Jersey, J. R. Anderson is studying many of the same problems using barium titanate single crystals grown at that laboratory.

C. FERROELECTRIC STORAGE AND SWITCHING DEVICES

This thesis has described a method for storing information in ferroelectric condensers and an efficient means for selecting among a group of such condensers by assembling them in a two-dimensional matrix where selection is accomplished by pulsing one row and one column of the matrix. A means for achieving a 3 : 1 voltage-selection ratio has been devised, and a system has been described for mixing the information-output current pulses of the matrix by transformer coupling. Information writing and reading have been demonstrated under repetitive conditions which simulate matrix operation. Switching time for some ferroelectric ceramics has been shown to be in the 1-microsecond region.

A ferroelectric switch has been described which can accomplish many of the switching tasks in an information-handling system. An

APPROVED FOR PUBLIC RELEASE. CASE 06-1104.

8-position model of such a switch was demonstrated.

Perhaps the most striking feature of the matrix memory and the switch is their packaging. The logical circuitry of both can be painted directly onto the two sides of a thin sheet of ferroelectric ceramic.

If we consider the ferroelectric switch as a box with inputs and outputs, with a unique output for every combination of inputs, we are free to define this unique relationship. We may, for example, define the output as the sum of the inputs, and thereby specify an adder, which can then be painted and packaged as neatly as the memory.

Many interesting fabrication techniques have been suggested to the author during the course of this thesis. One suggestion is to make a mask through which the circuitry can be evaporated or sprayed. Another is to paint the entire ferroelectric ceramic sheet with silver-paste or evaporated-silver electrodes, and then photoengrave the logical circuitry.

Thinner ceramic sheets will allow lower voltages to be used. Mechanical strength places the only practical limit on how thin the ceramic sheets can be made. Sheets as thin as 0.08-mil have been fired on platinum foil.

Fabrication and packaging improvements at first appear rather superficial as compared with the problem of getting a device that works. The engineer who has worked closely with large-scale digital computers, however, immediately sees in ferroelectric painted components a chance to eliminate thousands of the bad joints and soldered connections which have plagued him. The mathematician who has problems which must wait for computers having high-speed internal memories much larger than those of today sees in ferroelectrics the promise of realizing such memories, both physically and economically. The designer of aircraft electronic equipment sees in ferroelectric painted switches a light-weight and compact component for airborne applications. The fabrication and packaging possibilities of ferroelectric components for digital information storage and switching are indeed promising and challenging.

Signed Dudley A. Buck
Dudley A. Buck

Approved JWF
Jay W. Forrester

LIST OF DRAWINGS

Figure	Drawing
1	A-50545
2	A-51351
3	A-50546
4	A-51414
5	A-51158
7	A-51167
8	A-51170
9	C-51416
10	A-51226
11	A-51352
12	A-51353
13	A-51354
14	A-51342
15	A-51402
16	A-51399
17	A-51359
19	A-51413
20	A-50549
21	A-50547
22	A-50548
23	A-50550
24	A-51355
25A	A-51421
25B	A-51419
25C	A-51412
26	A-51155
27	A-51144
28	A-51151
29	A-50906
30	A-51148
31	A-51152

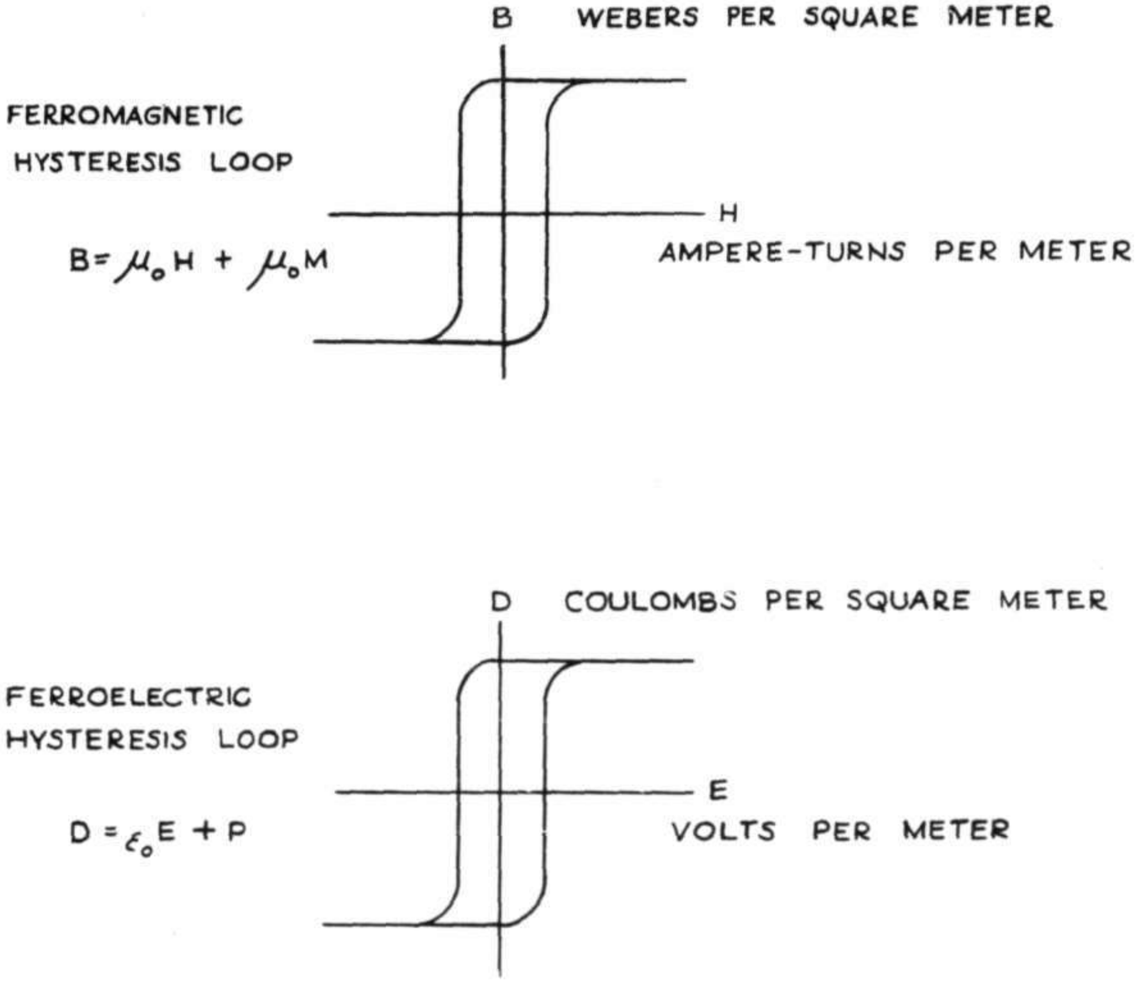


FIG. 1

COMPARISON OF FERROMAGNETIC AND FERROELECTRIC HYSTERESIS LOOPS

A-50545

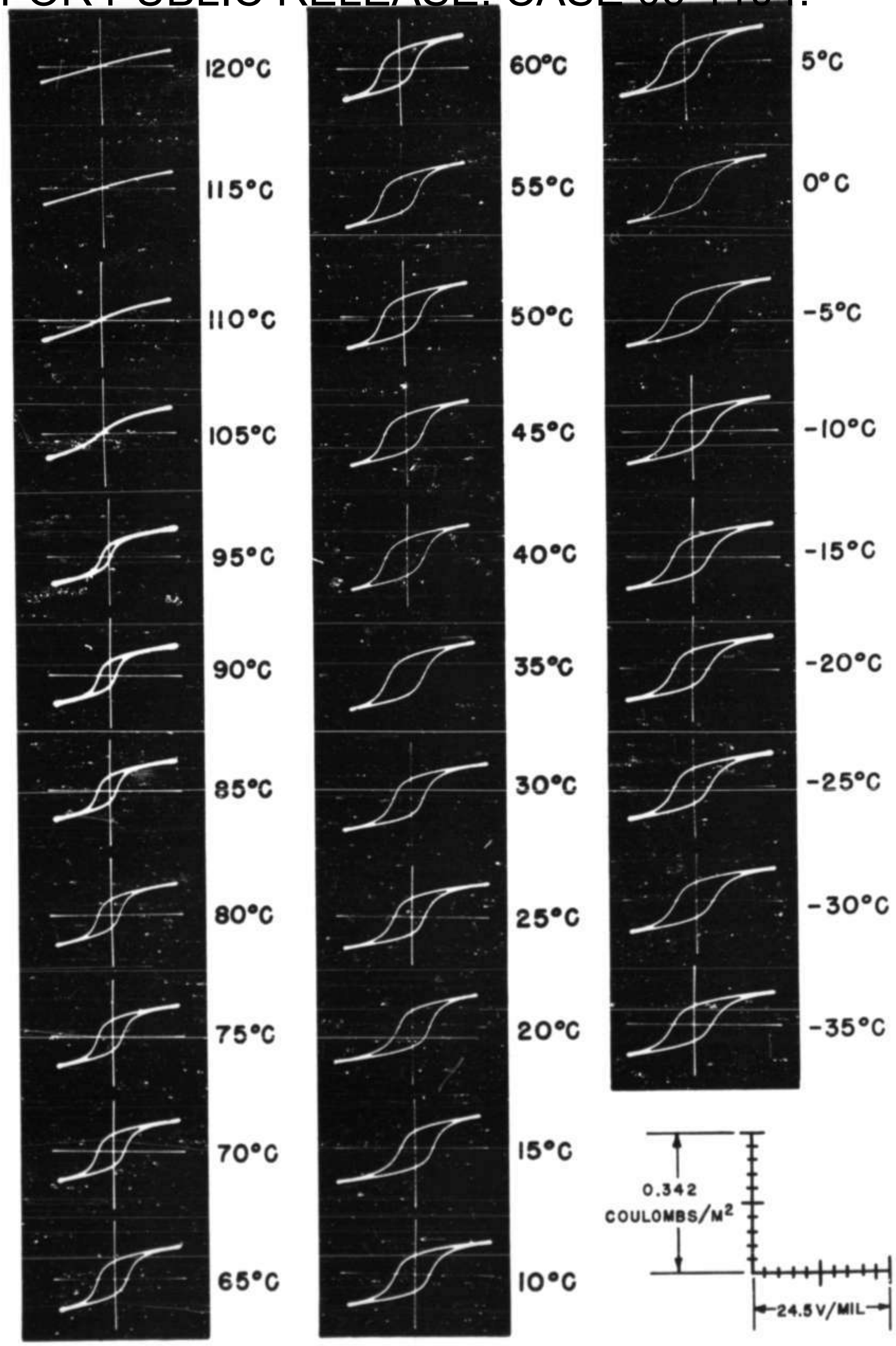
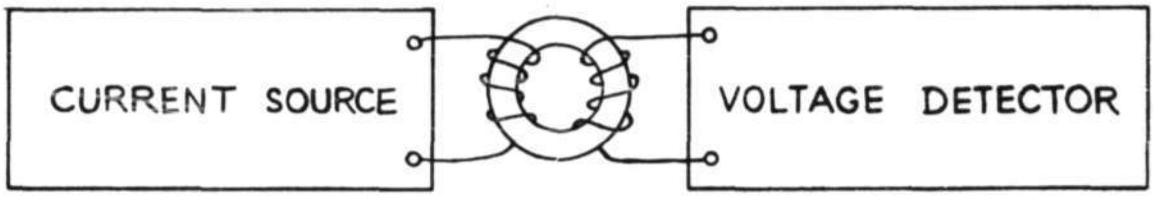


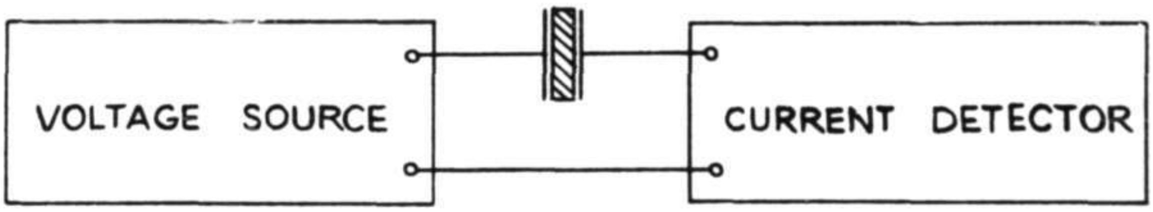
FIG. 2

HYSTERESIS LOOPS OF BARIUM TITANATE
CERAMIC AS A FUNCTION OF TEMPERATURE

A-51351



FERROMAGNETIC STORAGE



FERROELECTRIC STORAGE

FIG. 3

A COMPARISON OF FERROMAGNETIC & FERROELECTRIC STORAGE

A-5141-

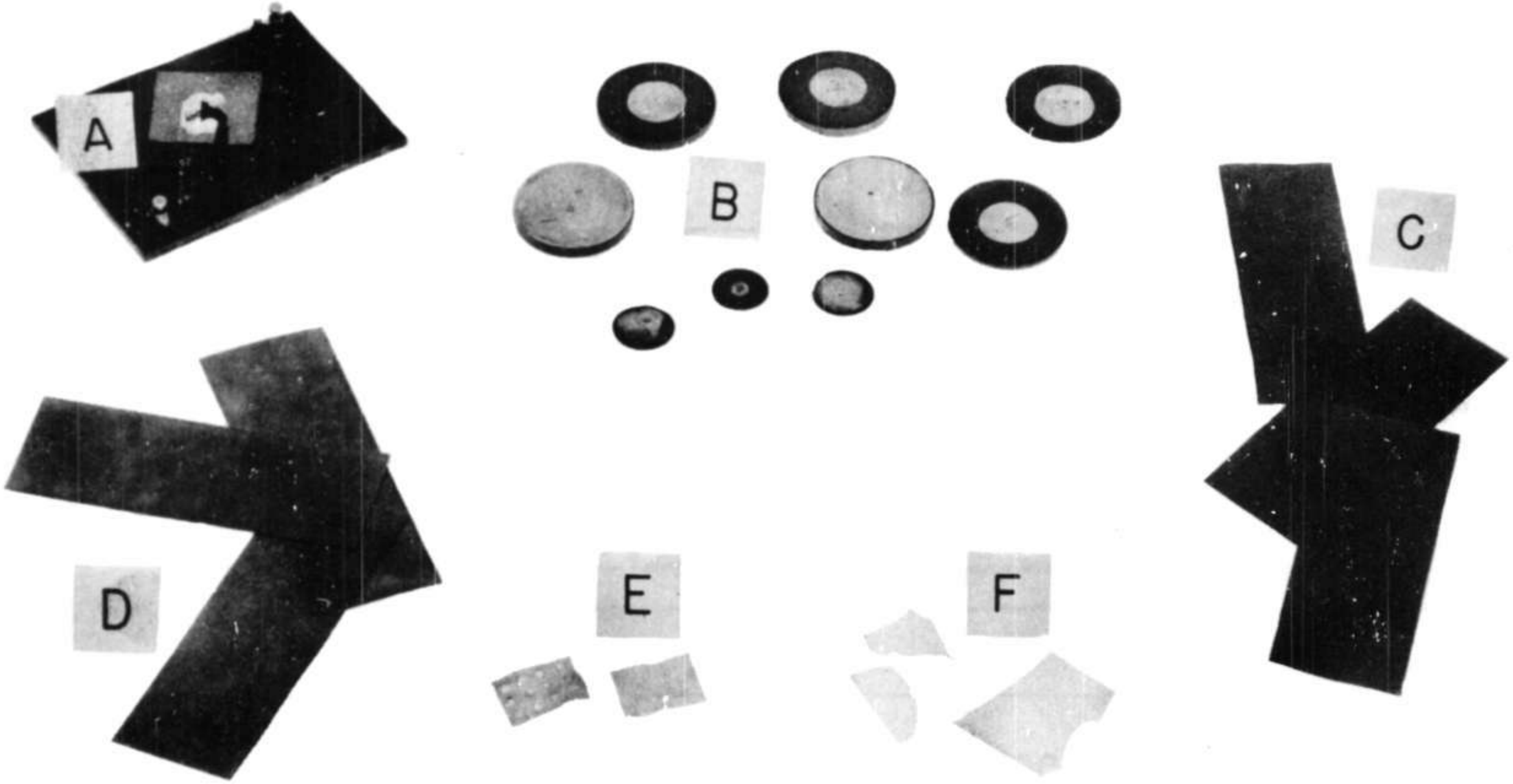
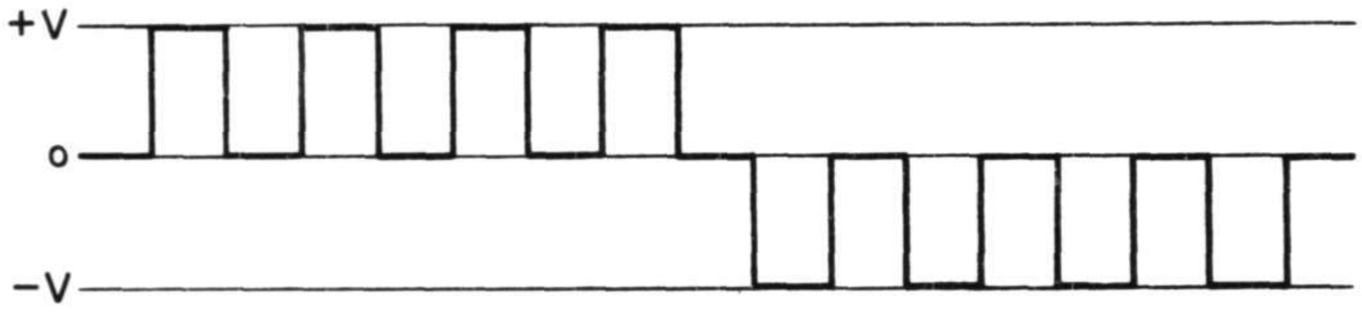


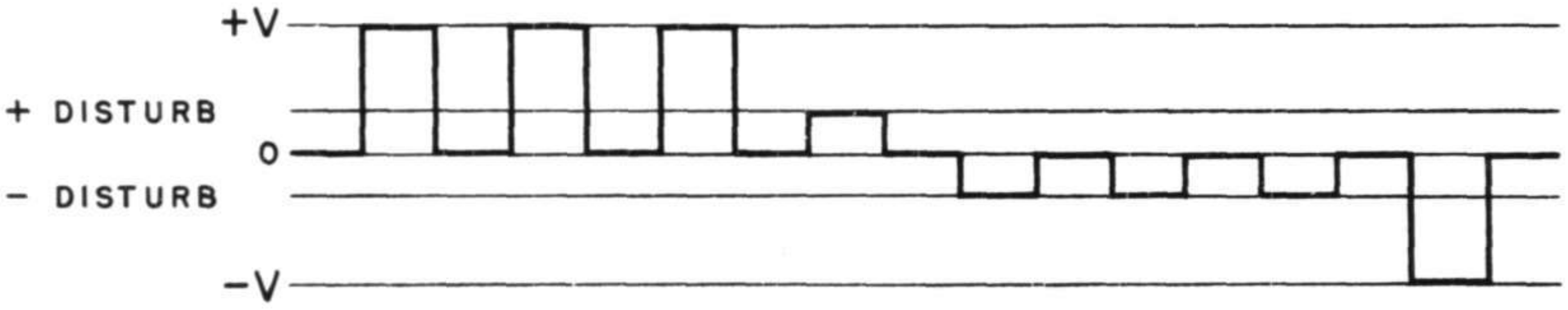
FIG. 4

FERROELECTRIC SAMPLES TESTED

A-51158



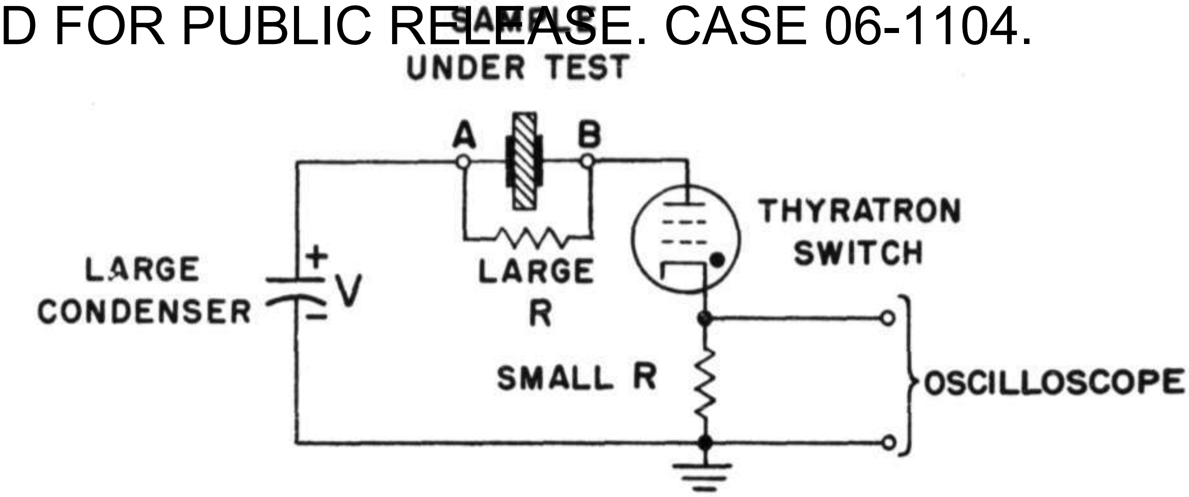
MODE A. WAVEFORM FOR SWITCHING-TIME STUDIES



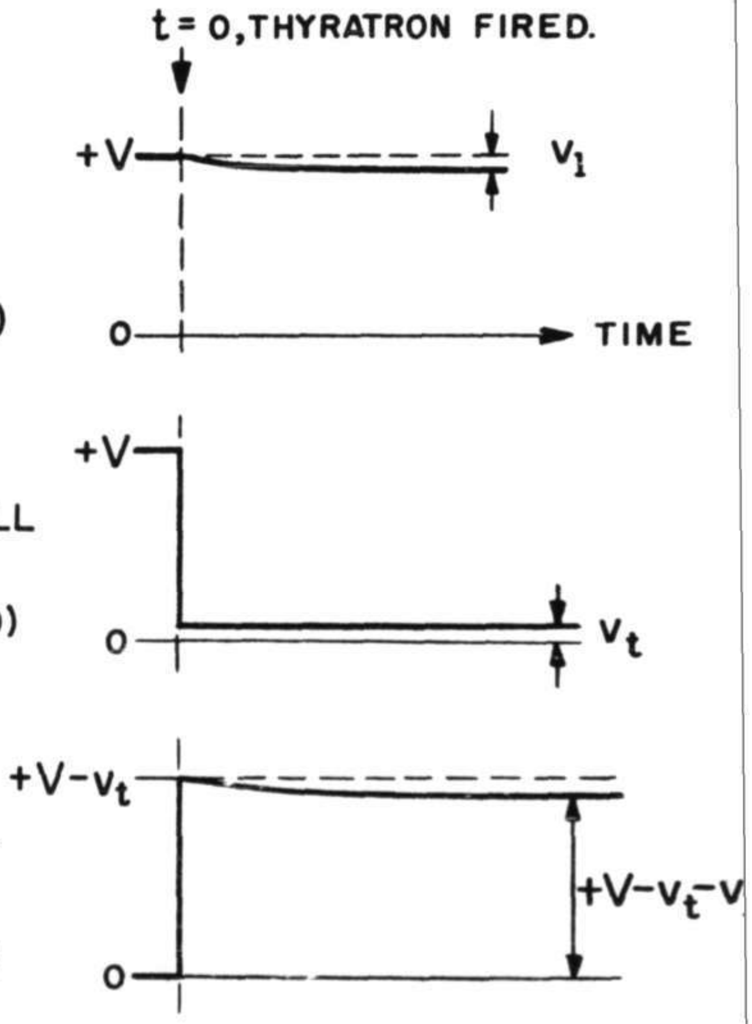
MODE B. WAVEFORM FOR ANALYSIS OF EFFECT OF DISTURBANCES ON RESIDUAL DISPLACEMENT

FIG. 5

IDEALIZED FERROELECTRIC PULSE-TEST WAVEFORMS



A. BASIC FERROELECTRIC PULSE-TEST CIRCUIT



B. VOLTAGE ACROSS LARGE CONDENSER DURING PULSE. (POINT A TO GROUND)

C. VOLTAGE ACROSS THYRATRON AND SMALL R DURING PULSE. (POINT B TO GROUND)

D. VOLTAGE ACROSS SAMPLE UNDER TEST DURING PULSE. (POINT A TO POINT B)

FIG. 7

METHOD OF PULSE TESTING FERROELECTRICS

A-51167

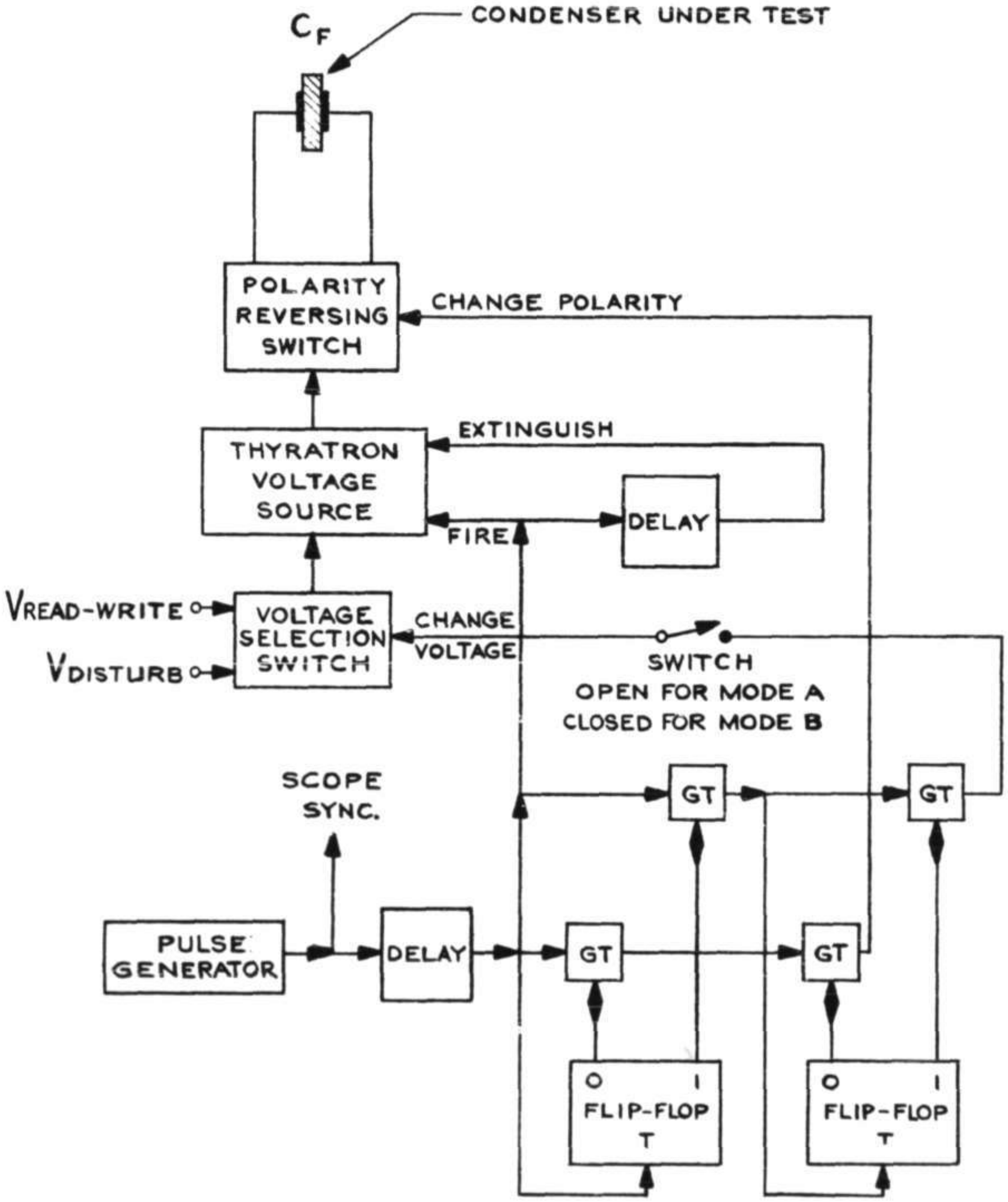
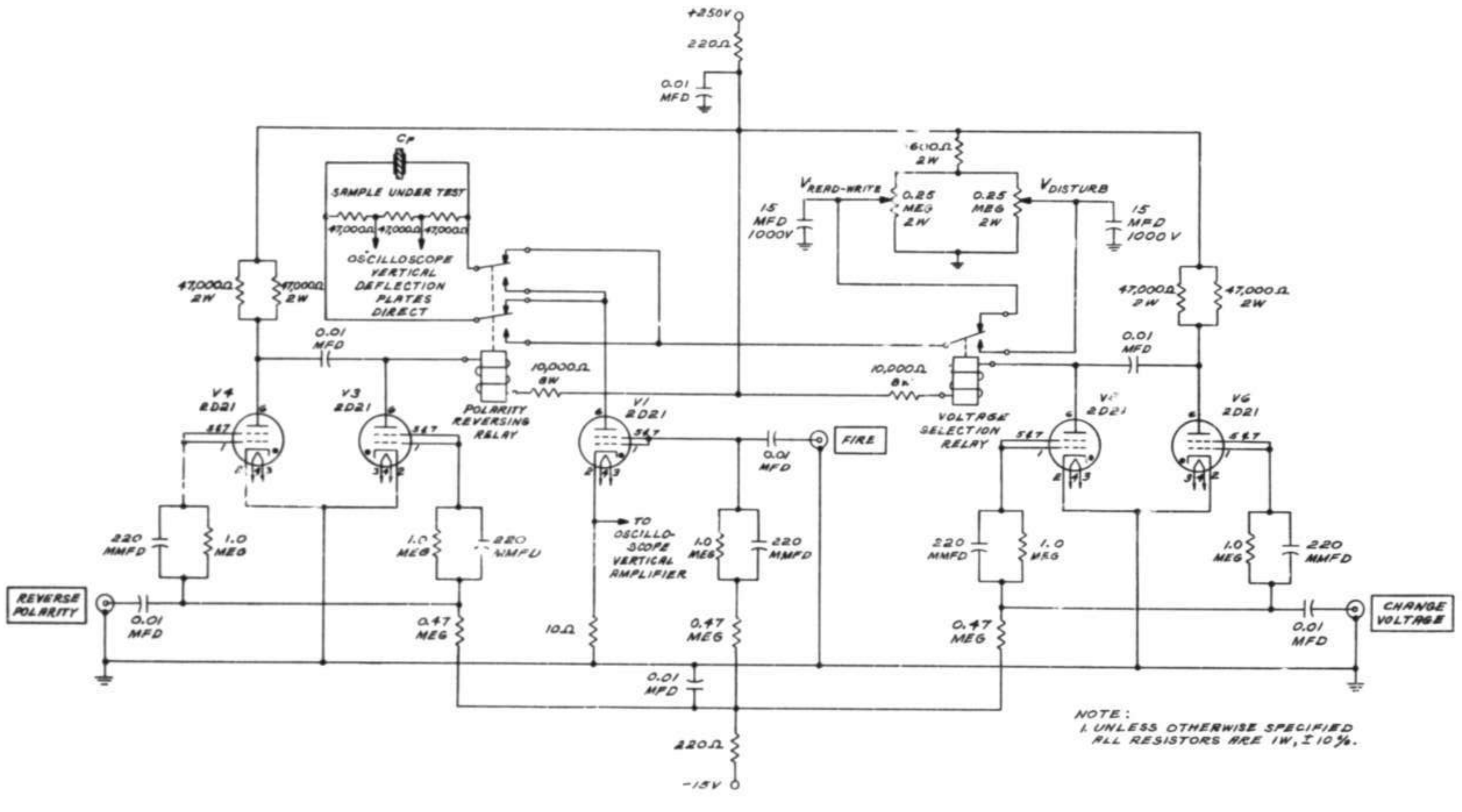


FIG. 8

BLOCK DIAGRAM OF FERROELECTRIC PULSE-TEST EQUIPMENT

A-51170

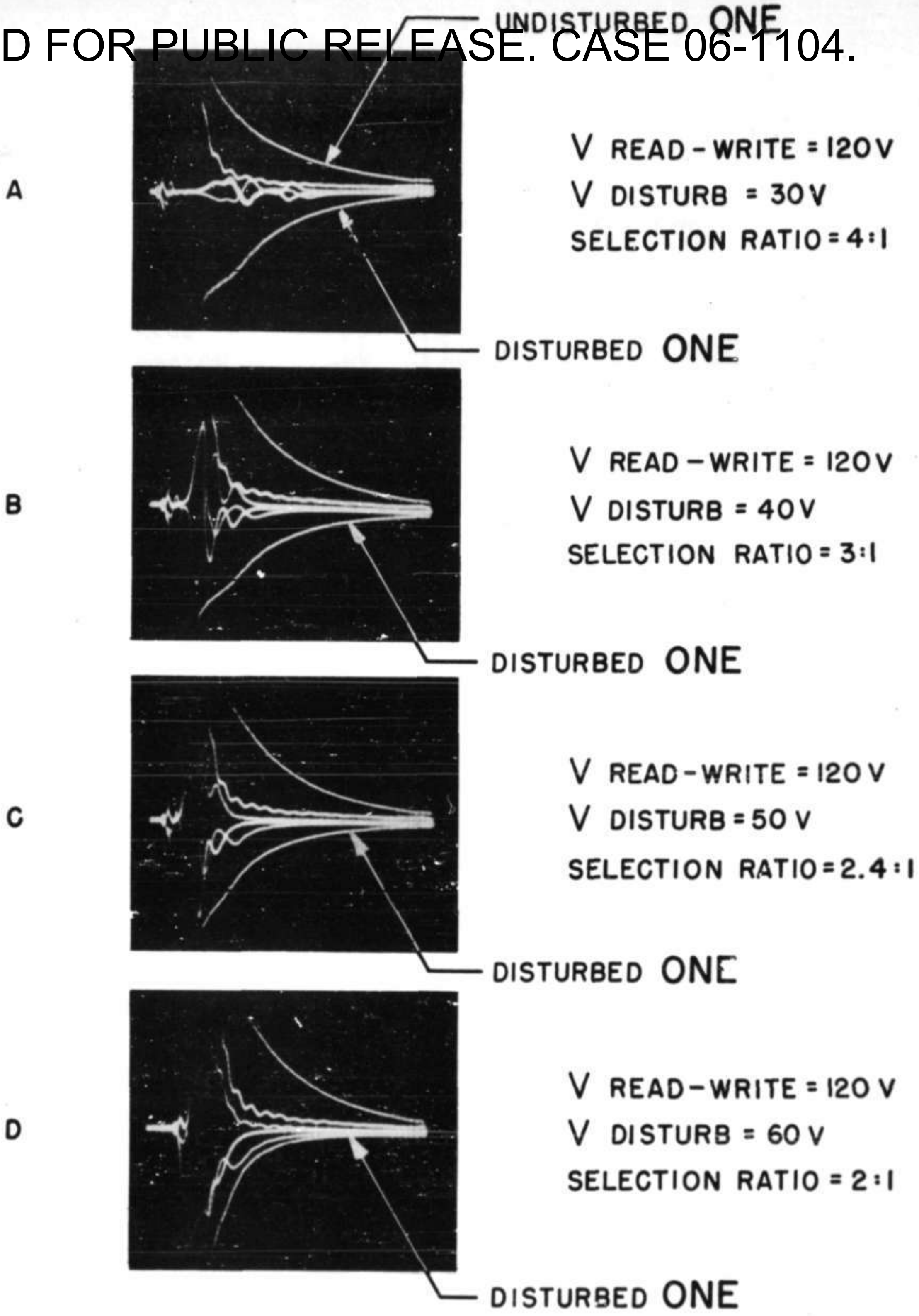
C-51416



NOTE:
1. UNLESS OTHERWISE SPECIFIED ALL RESISTORS ARE 1W, ±10%.

FIG. 9

CIRCUIT SCHEMATIC, FERROELECTRIC PULSE TESTER


UNDISTURBED ONE

A

V READ - WRITE = 120 V
V DISTURB = 30 V
SELECTION RATIO = 4:1

DISTURBED ONE

B

V READ - WRITE = 120 V
V DISTURB = 40 V
SELECTION RATIO = 3:1

DISTURBED ONE

C

V READ - WRITE = 120 V
V DISTURB = 50 V
SELECTION RATIO = 2.4:1

DISTURBED ONE

D

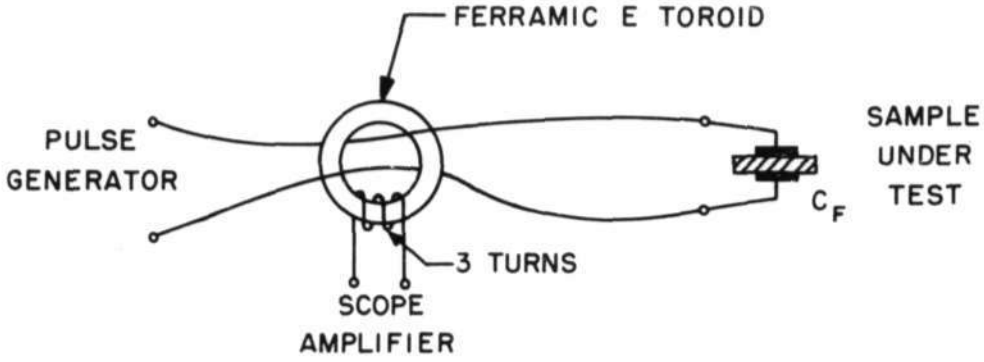
V READ - WRITE = 120 V
V DISTURB = 60 V
SELECTION RATIO = 2:1

DISTURBED ONE

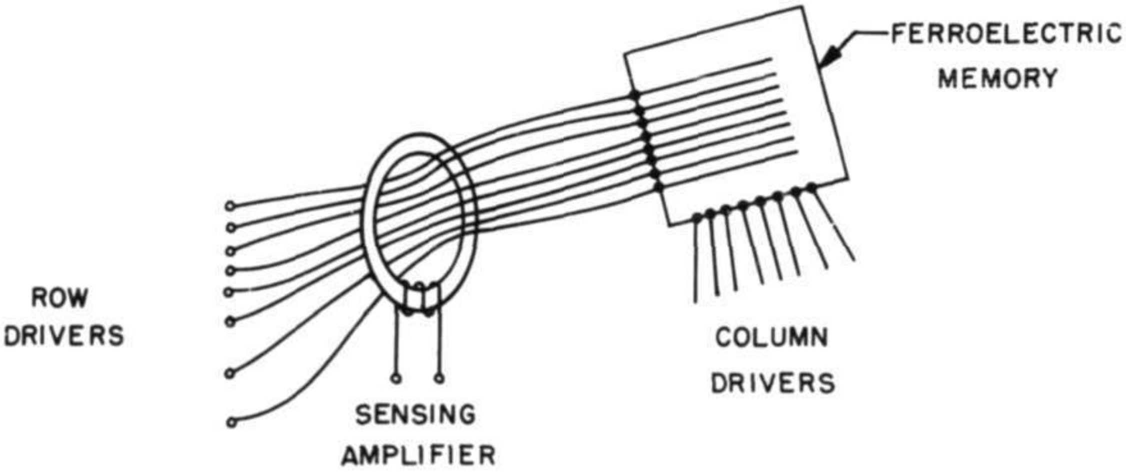
MEASUREMENTS MODE B

AS A FUNCTION OF V DISTURB AT CONSTANT V READ - WRITE

1-51419



A. TRANSFORMER COUPLING USED IN MEASUREMENTS MODE B

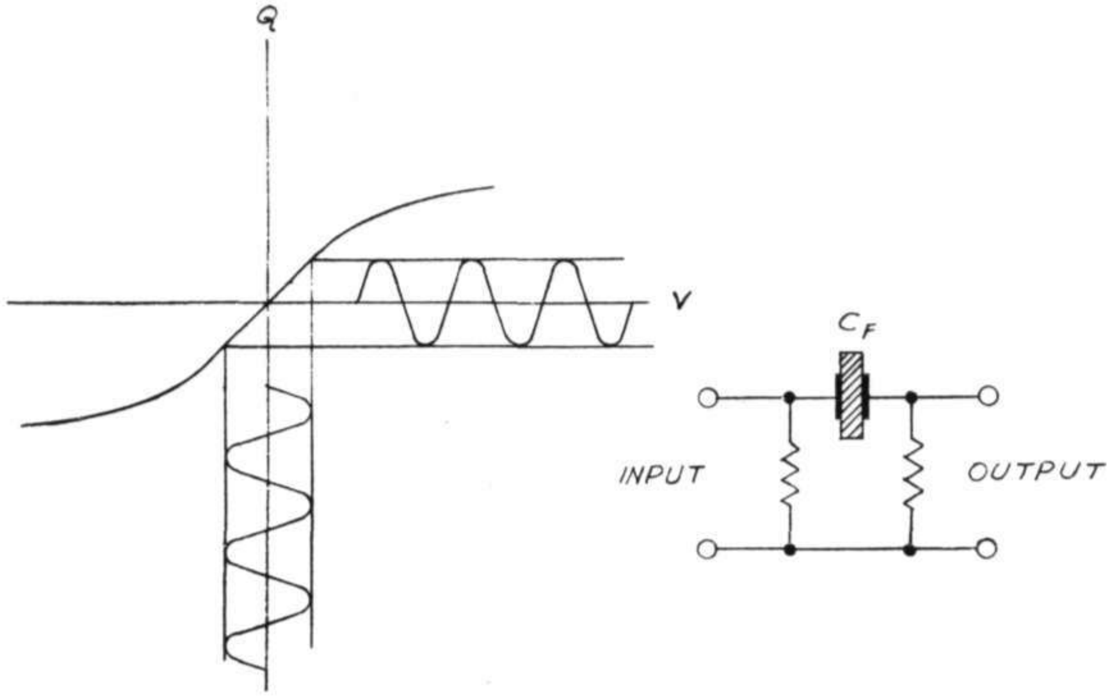


B. TRANSFORMER-COUPLING METHOD FOR SENSING FERROELECTRIC MEMORY

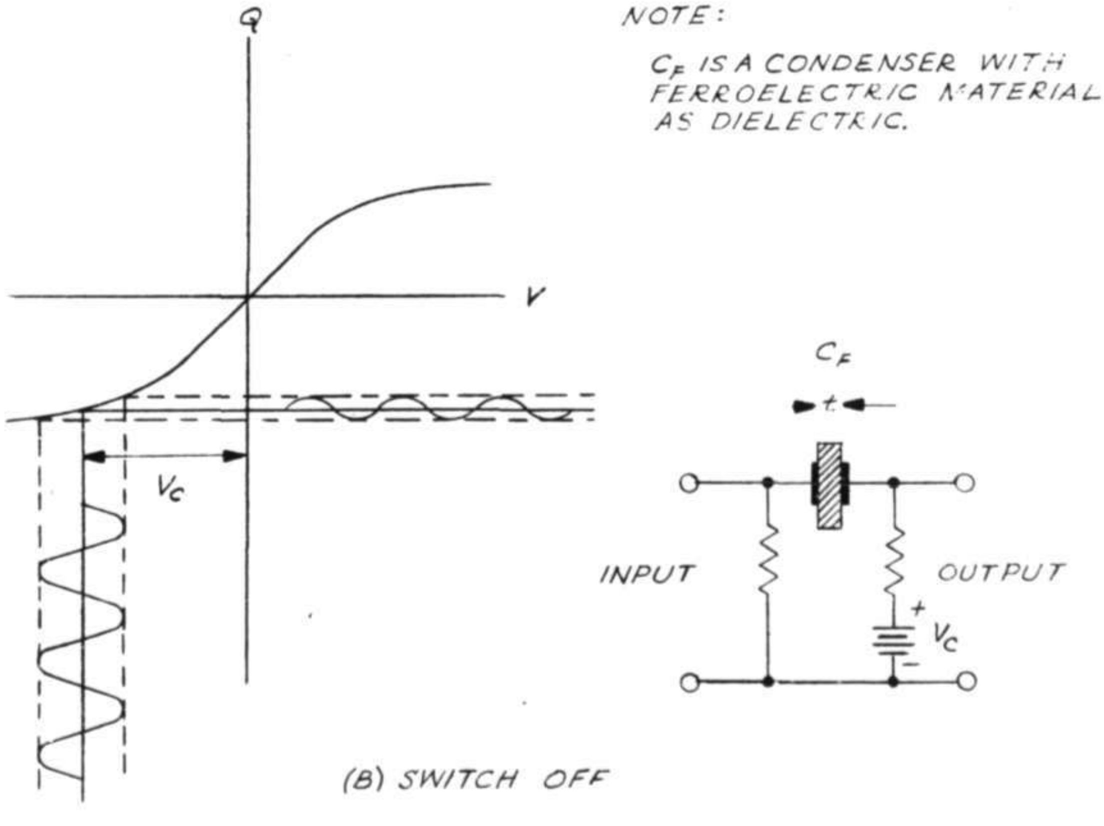
FIG. 25C

TRANSFORMER COUPLING FOR SENSING FERROELECTRIC MEMORY

A-51412



(A) SWITCH ON

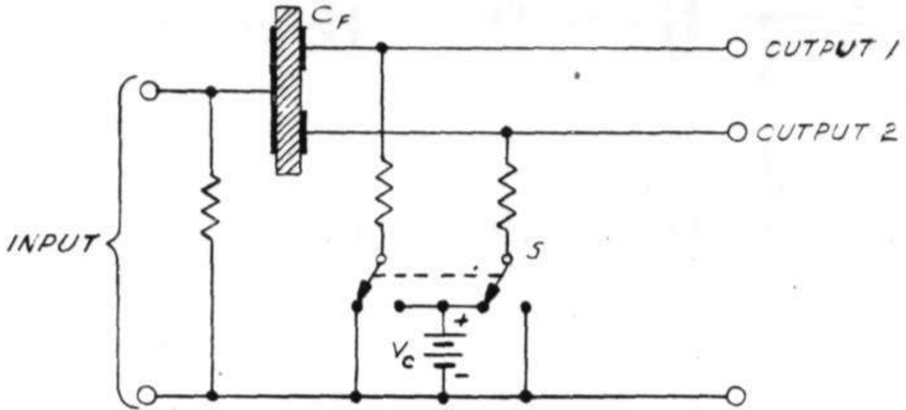


NOTE:
C_F IS A CONDENSER WITH FERROELECTRIC MATERIAL AS DIELECTRIC.

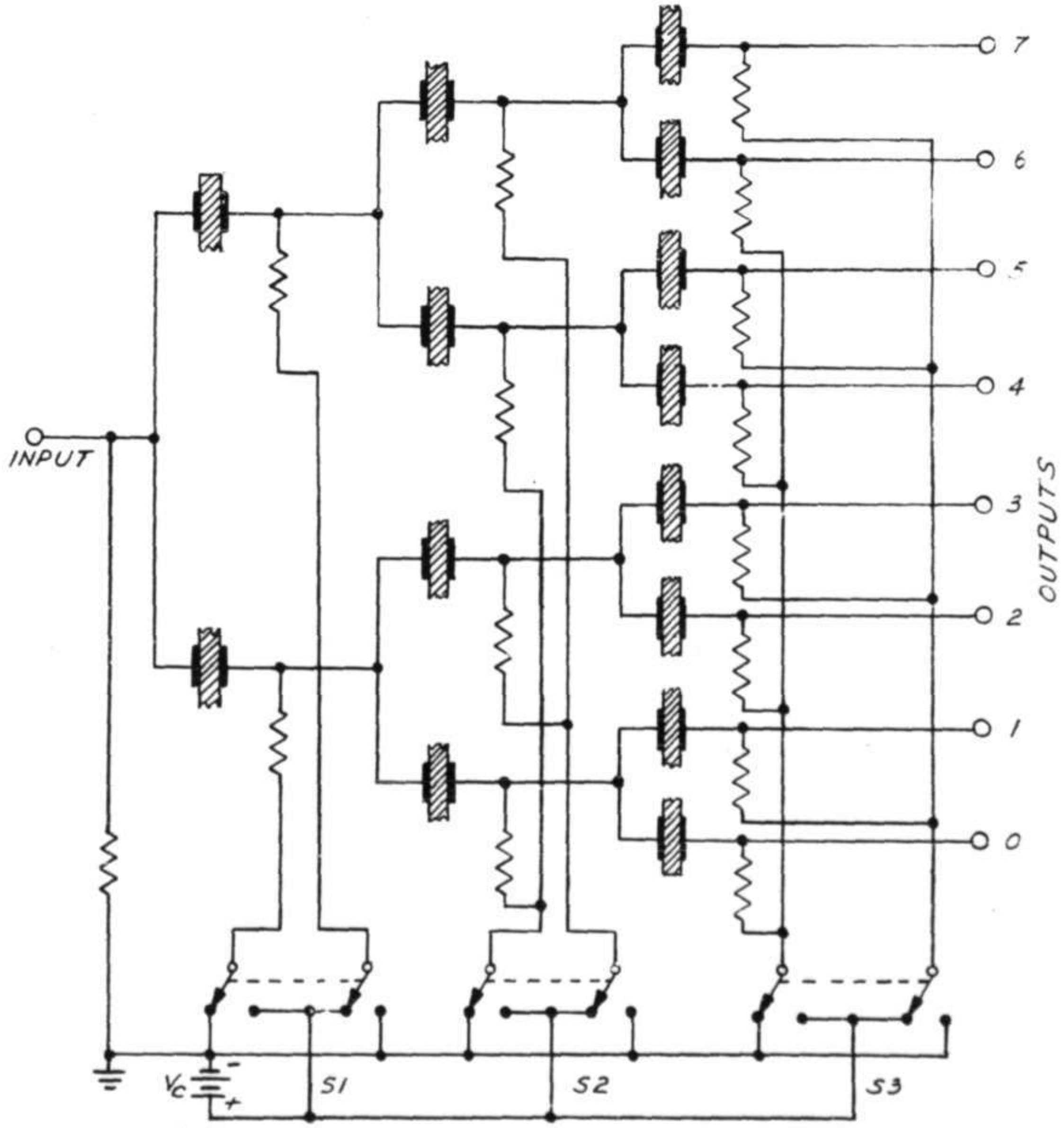
(B) SWITCH OFF

FIG. 26
FERROELECTRIC SWITCH OPERATION

A-51155



(A) TWO-POSITION SWITCH



(B) EIGHT-POSITION SWITCH

FIG. 27

FERROELECTRIC SWITCH SCHEMATIC DIAGRAM

A-51144

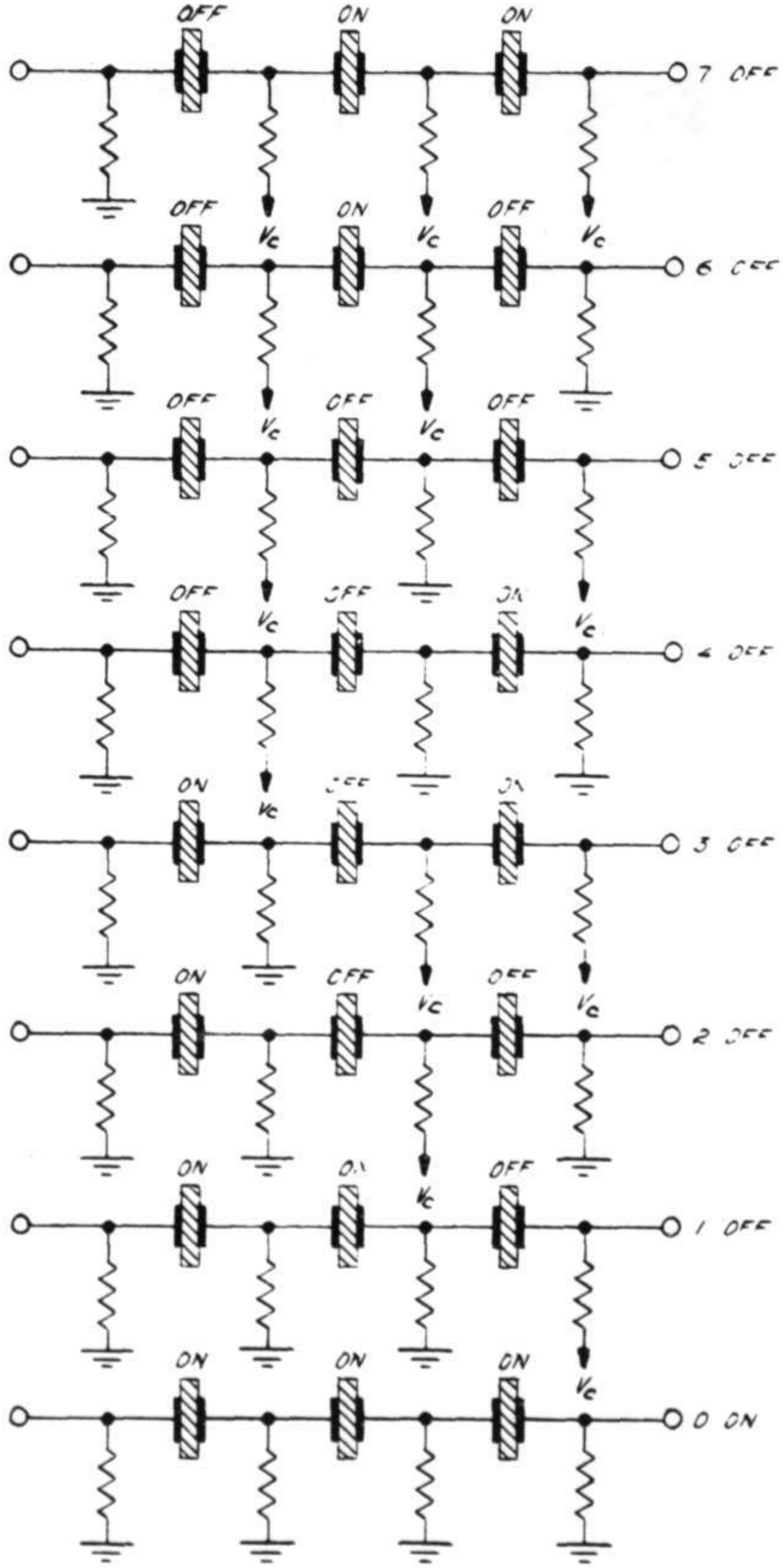
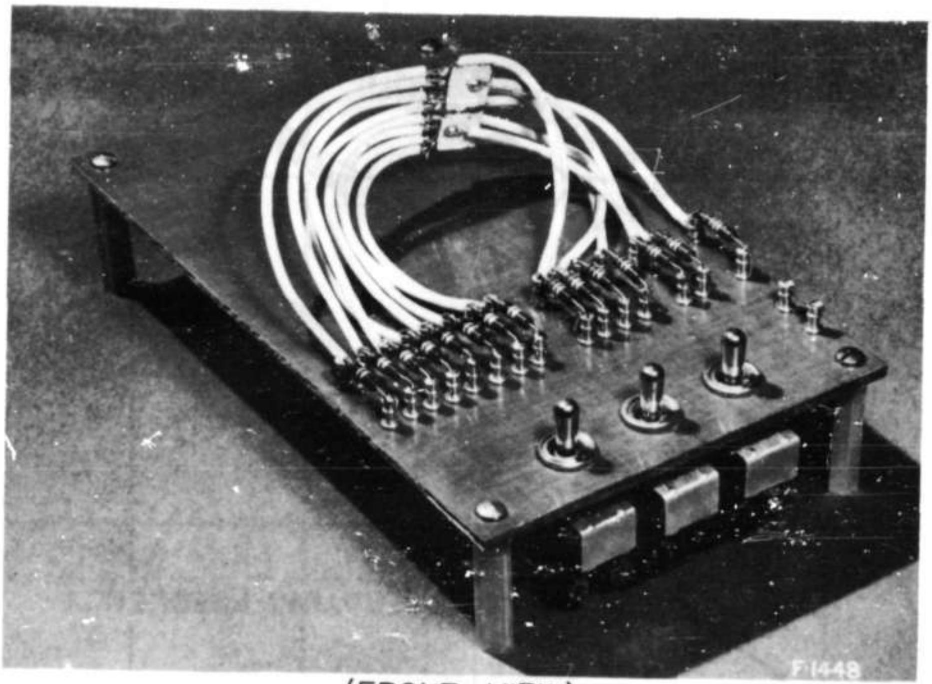


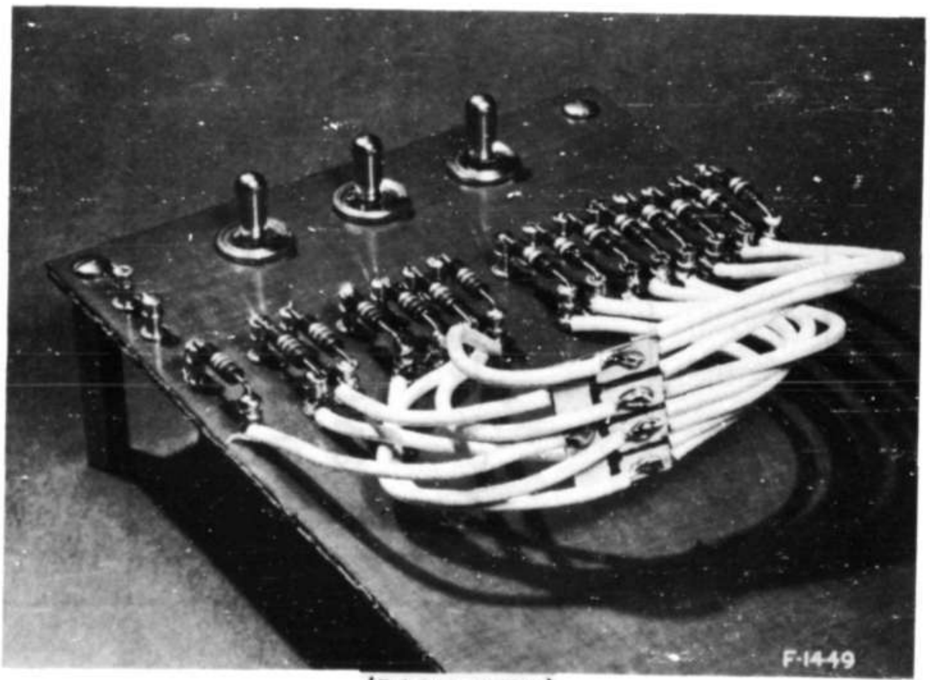
FIG. 28

EIGHT-POSITION SWITCH ANALYSIS

A-51151



(FRONT VIEW)



(BACK VIEW)

FERROELECTRIC MULTI-POSITION SWITCH

A-50906

A-51148

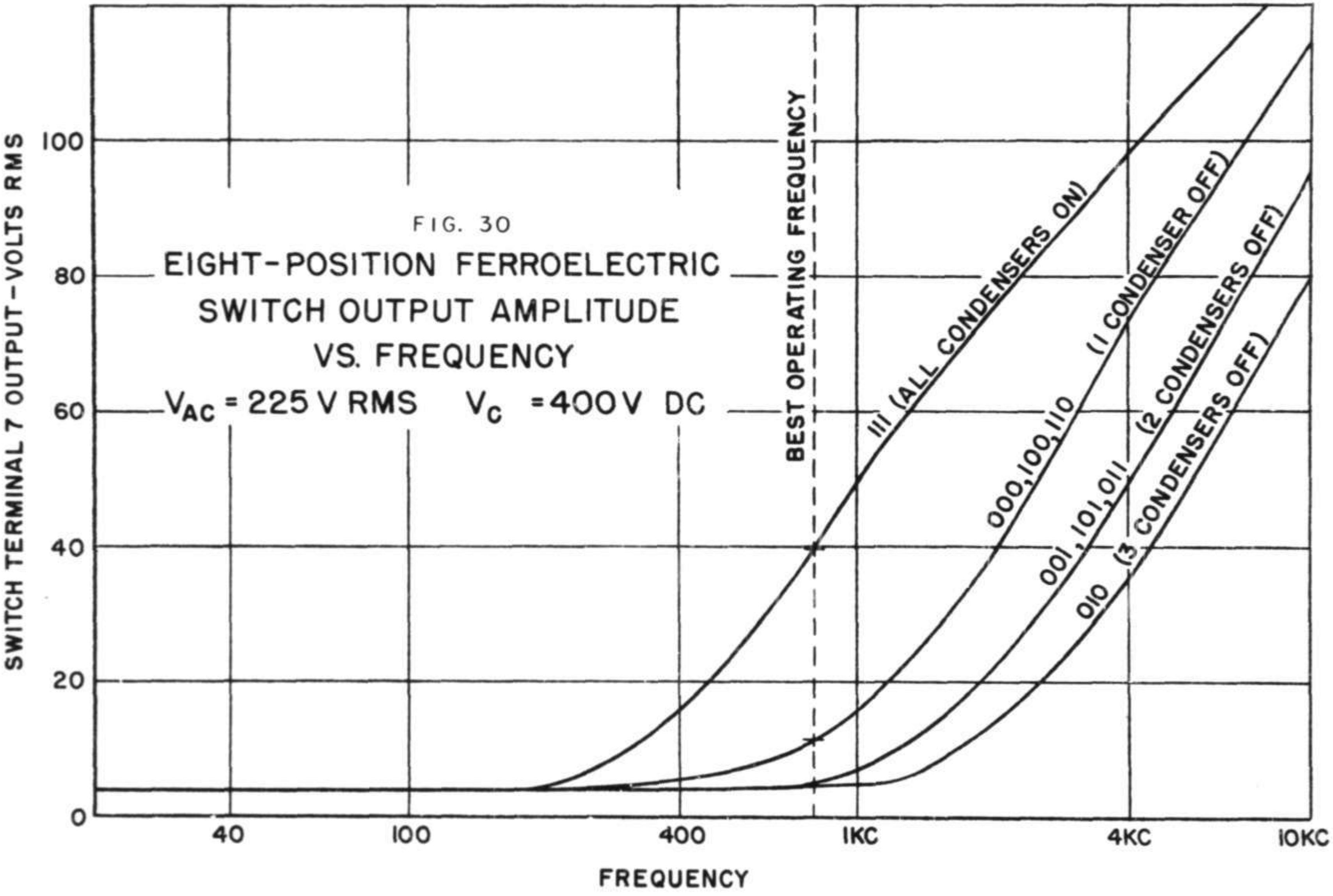
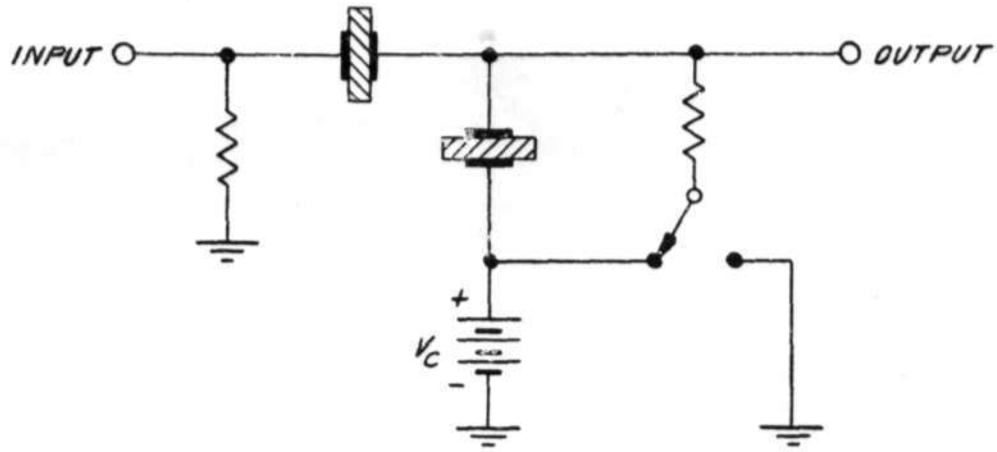


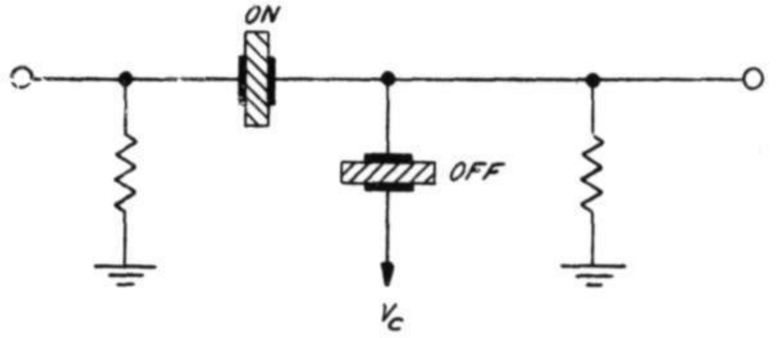
FIG. 30

EIGHT-POSITION FERROELECTRIC SWITCH OUTPUT AMPLITUDE VS. FREQUENCY

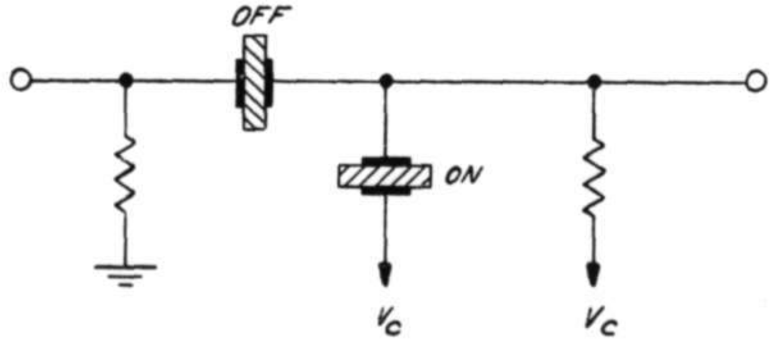
V_{AC} = 225 V RMS V_c = 400 V DC



A. CIRCUIT SCHEMATIC OF PULSE-OPERATED TWO-POSITION FERROELECTRIC SWITCH



B. SWITCH ON

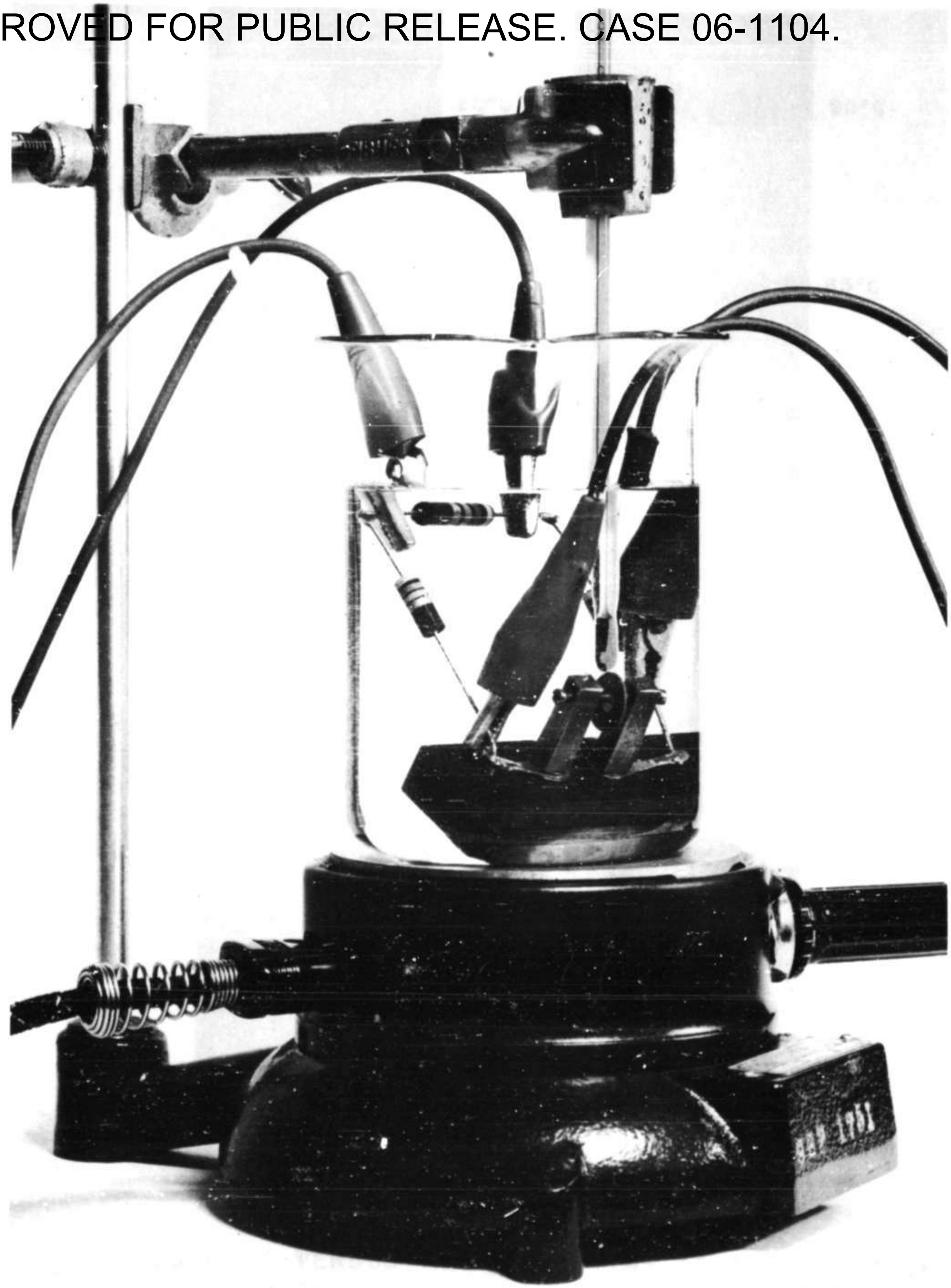


C. SWITCH OFF

FIG. 31

FERROELECTRIC SWITCH FOR PULSES

A-51152



A-51226
F-1487

FERROELECTRIC SAMPLE UNDER TEST

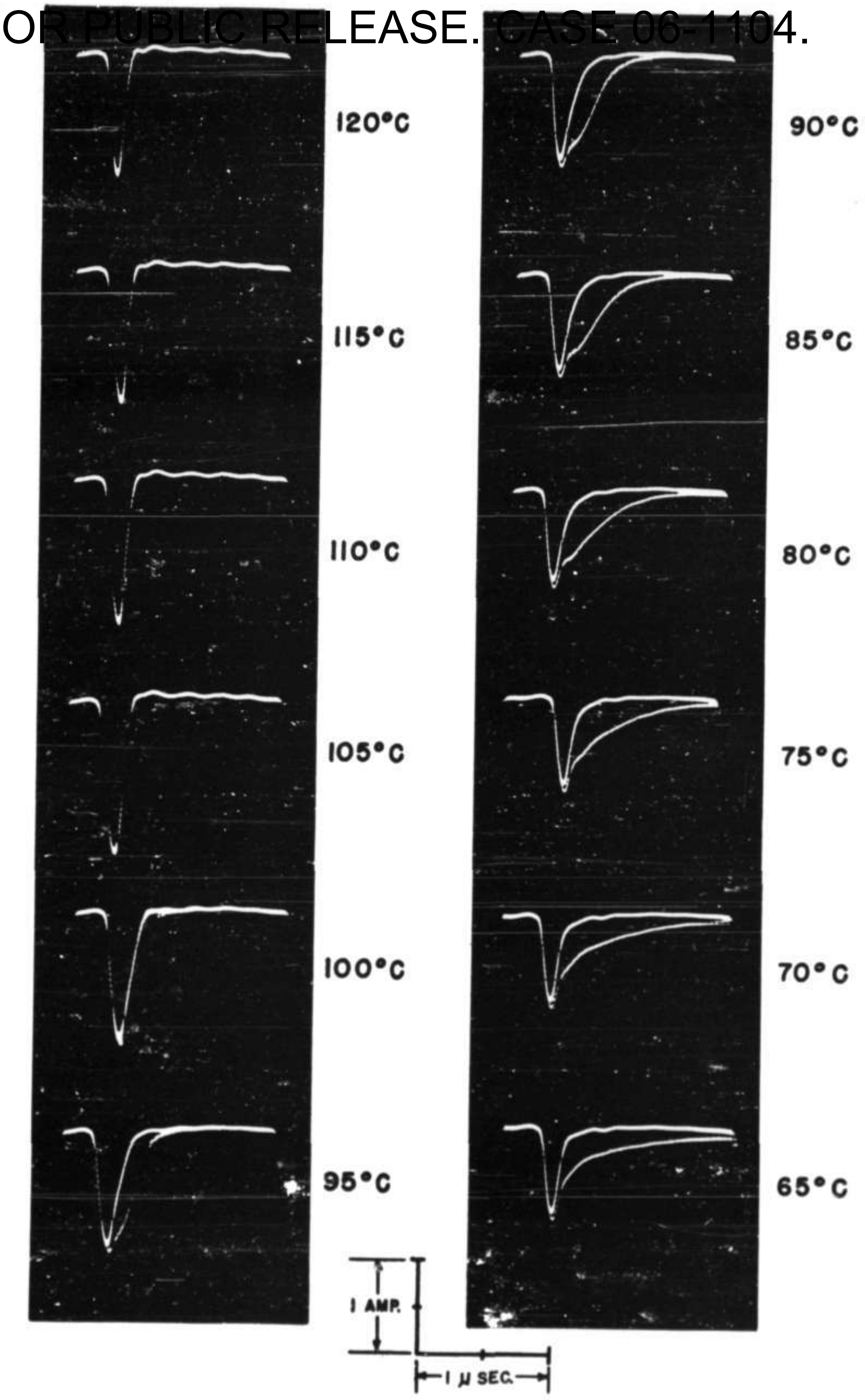


FIG. 11

MEASUREMENTS MODE A-I

CURRENT-VERSUS-TIME WAVEFORMS AS A FUNCTION OF TEMPERATURE AT CONSTANT PULSE VOLTAGE

A-51352

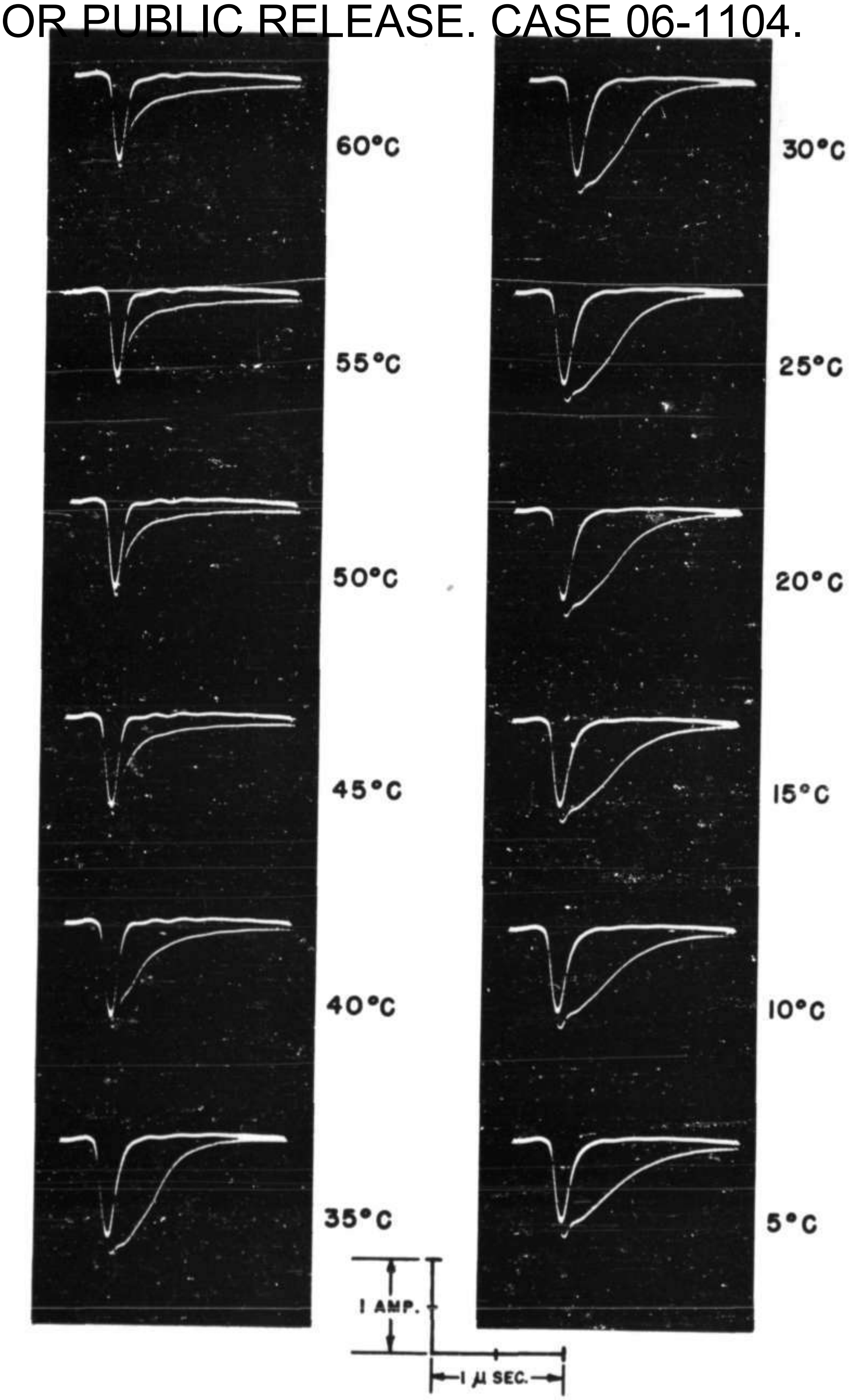


FIG. 12

MEASUREMENTS MODE A-II

CURRENT-VERSUS-TIME WAVEFORMS AS A FUNCTION OF TEMPERATURE AT CONSTANT PULSE VOLTAGE

A-31353

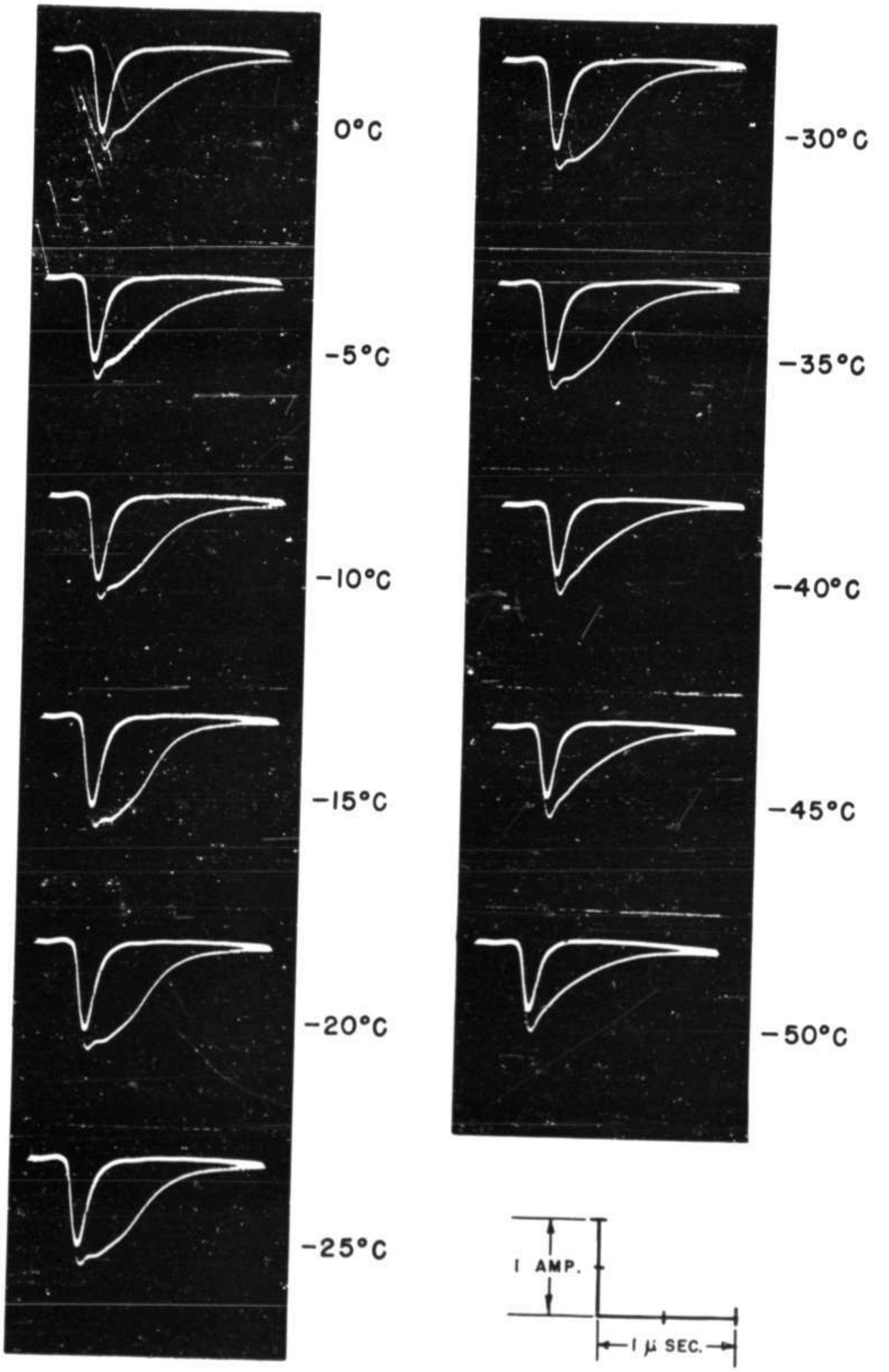


FIG. 13

MEASUREMENTS MODE A-III

CURRENT-VERSUS-TIME WAVEFORMS AS A FUNCTION OF TEMPERATURE AT CONSTANT PULSE VOLTAGE

A-51354

A-51342

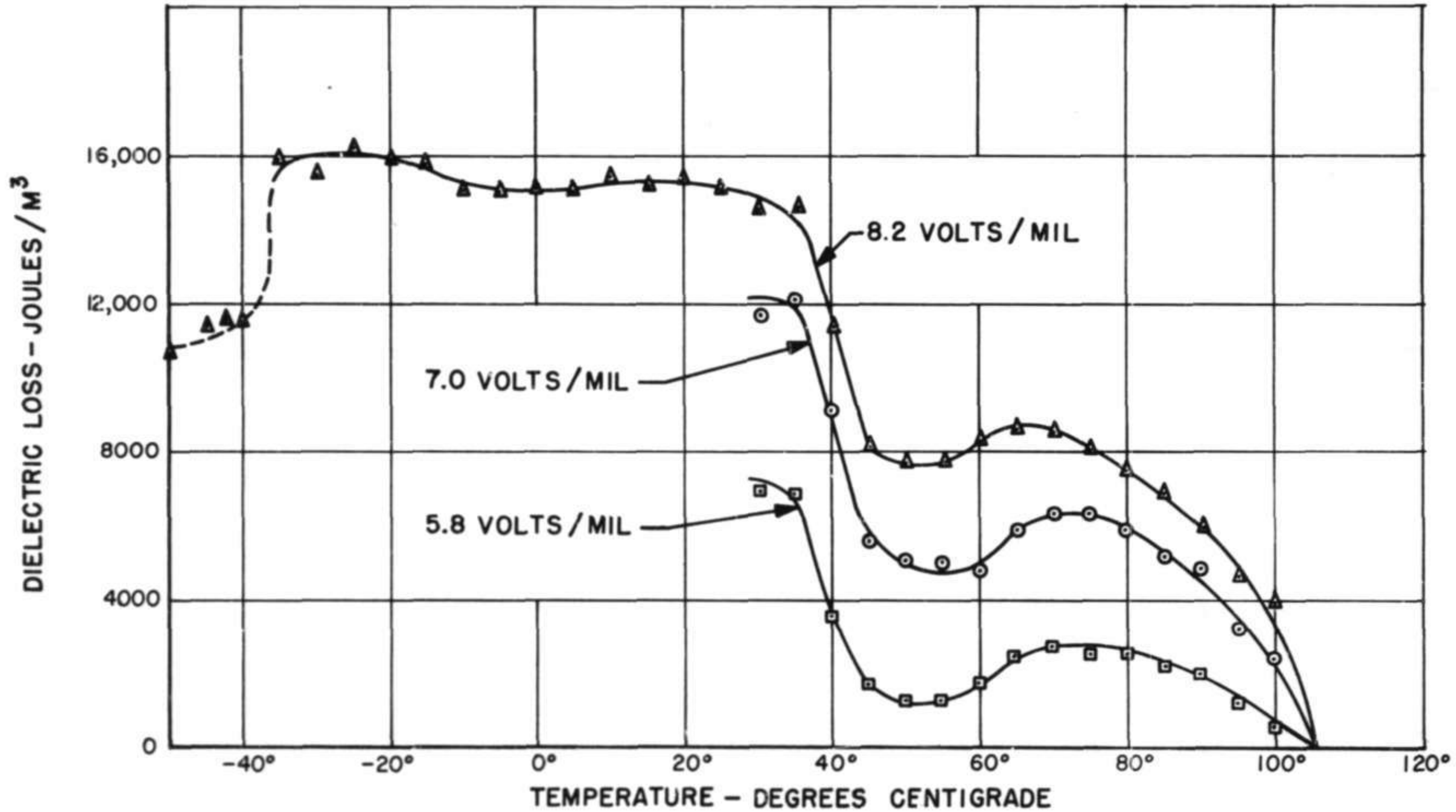


FIG. 14

DIELECTRIC LOSS FROM MEASUREMENTS MODE A

AS A FUNCTION OF TEMPERATURE FOR THREE PULSE AMPLITUDES

A-51402

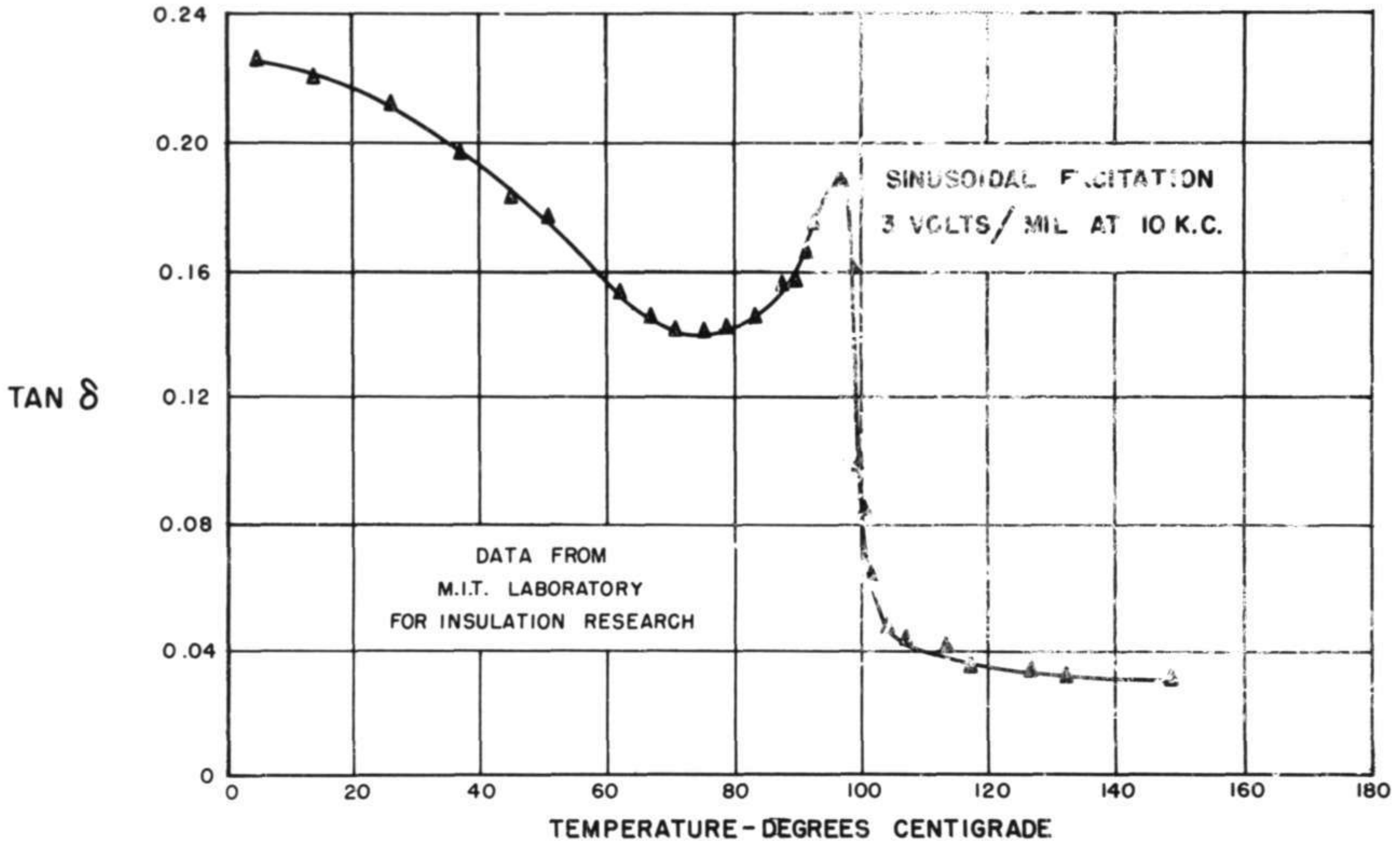


FIG 15

DIELECTRIC LOSS FROM STEADY-STATE MEASUREMENTS

AS A FUNCTION OF TEMPERATURE AT CONSTANT FIELD STRENGTH

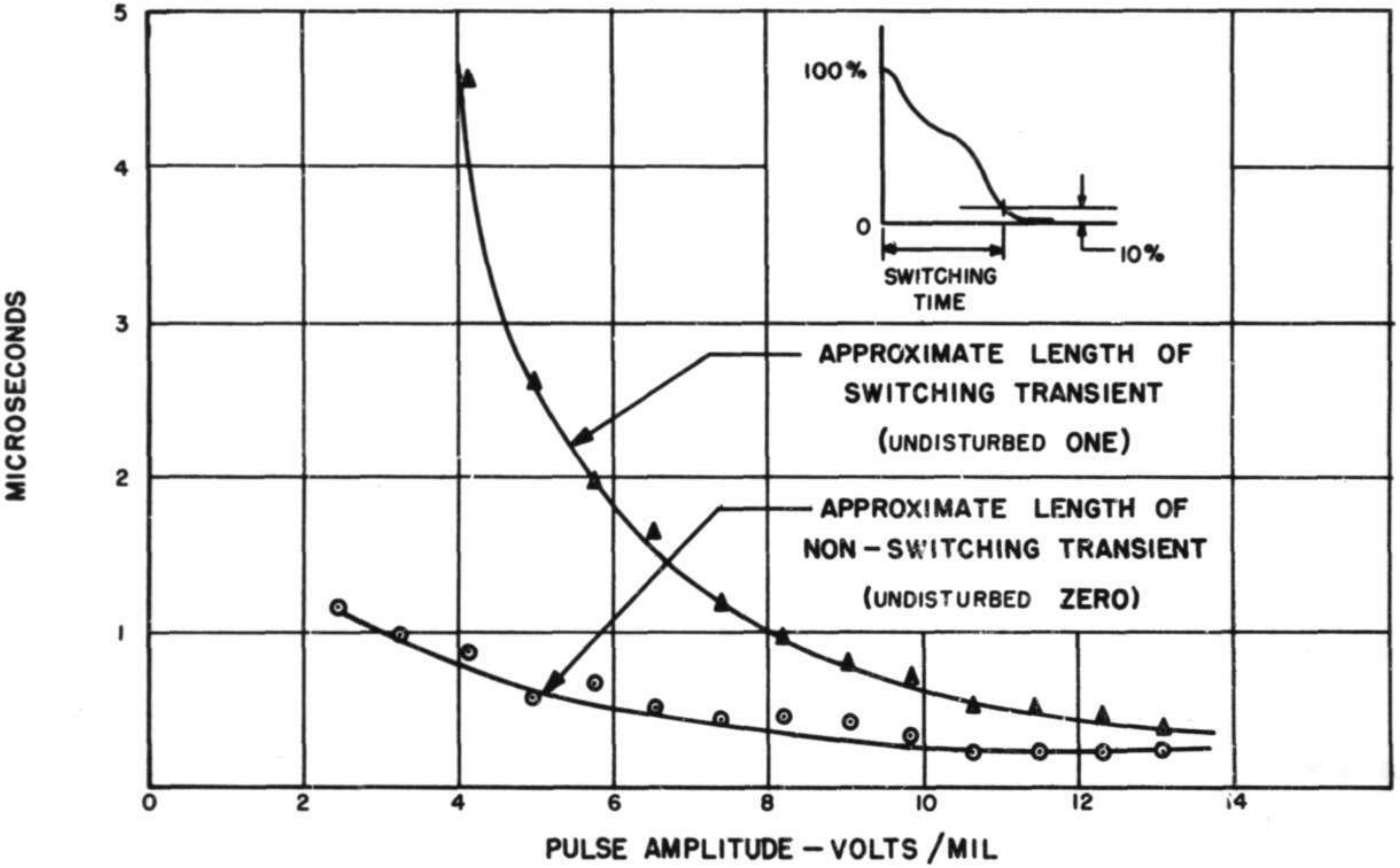


FIG. 16

APPROXIMATE SWITCHING TIME

AS A FUNCTION OF PULSE AMPLITUDE AT CONSTANT TEMPERATURE

A-51359

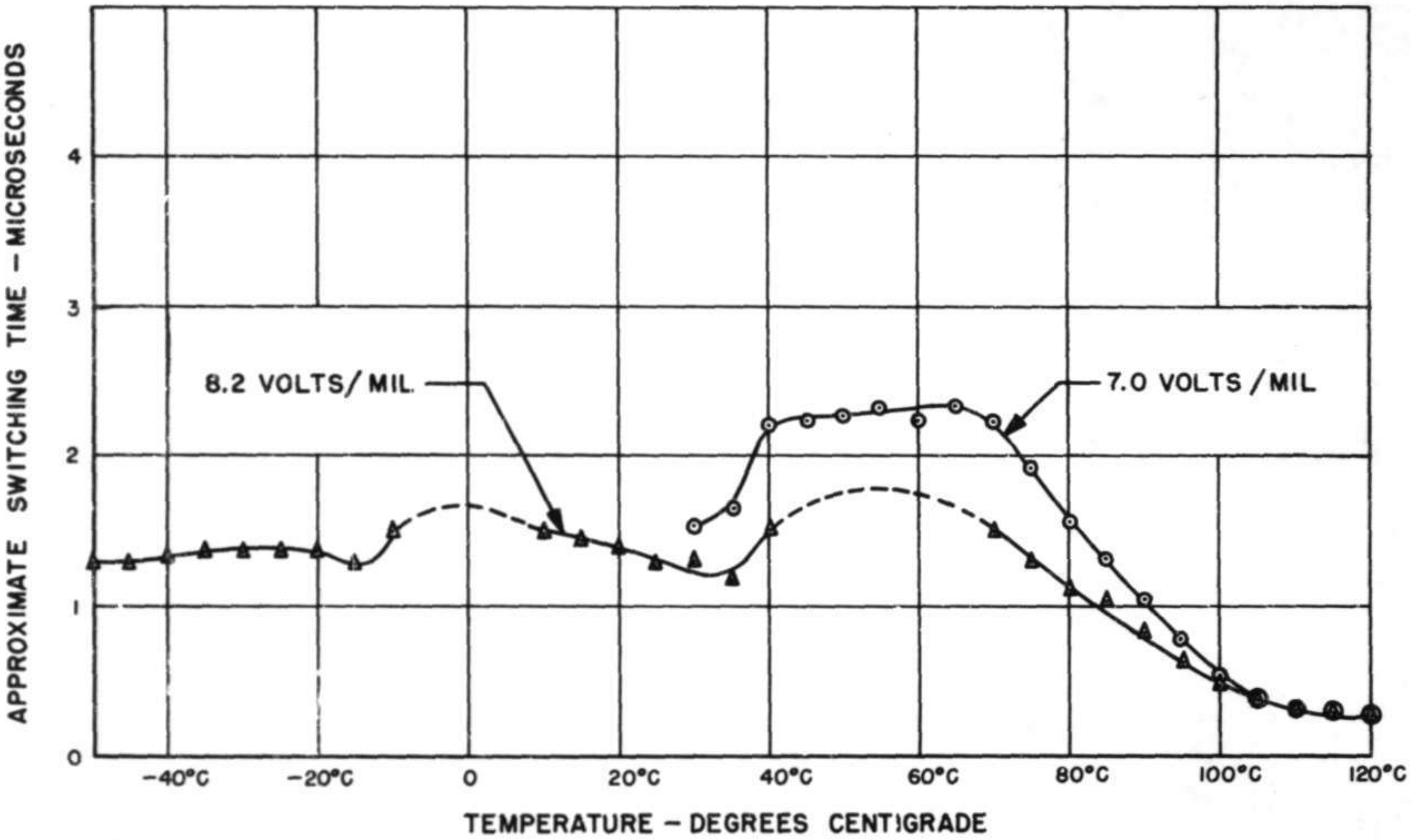


FIG. 17

APPROXIMATE SWITCHING TIME FROM MEASUREMENTS MODE A

AS A FUNCTION OF TEMPERATURE FOR TWO PULSE AMPLITUDES

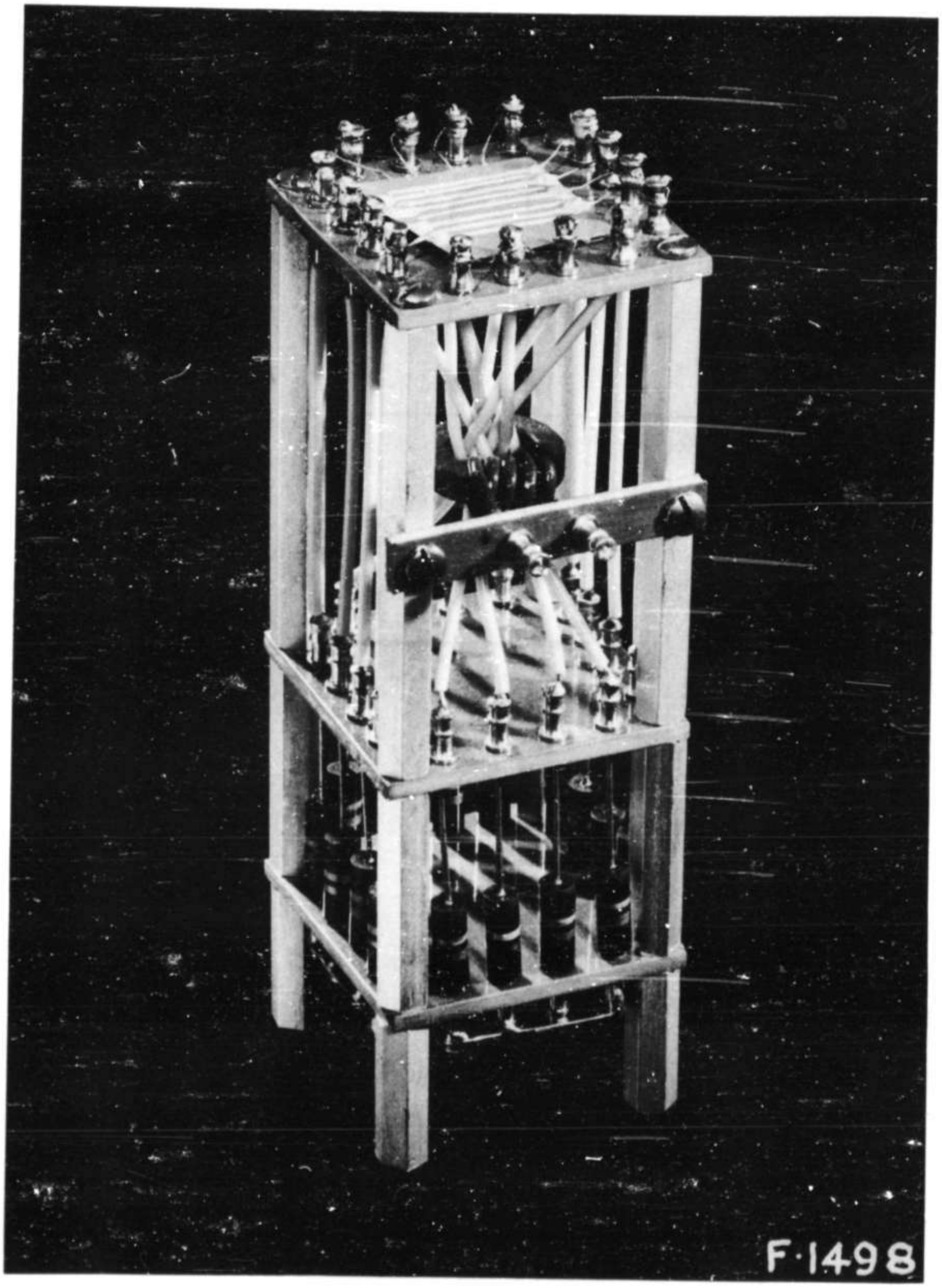


FIG. 19

EIGHT BY EIGHT FERROELECTRIC MEMORY

A-51413

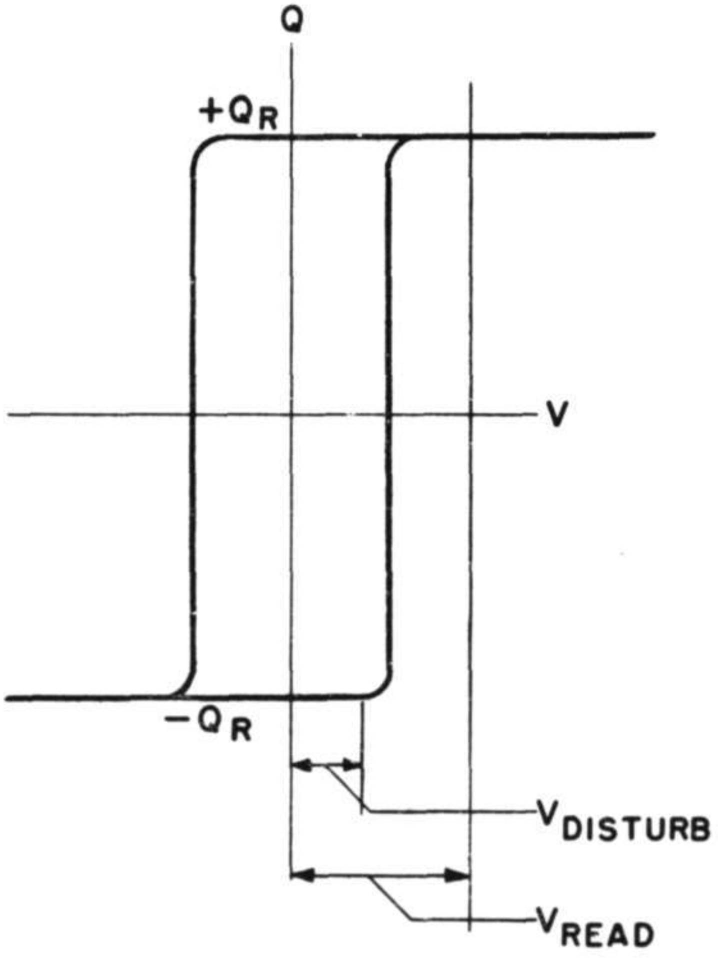


FIG. 20

DISCRIMINATION BETWEEN TWO VOLTAGES REQUIRED OF HYSTERESIS LOOP

A-505

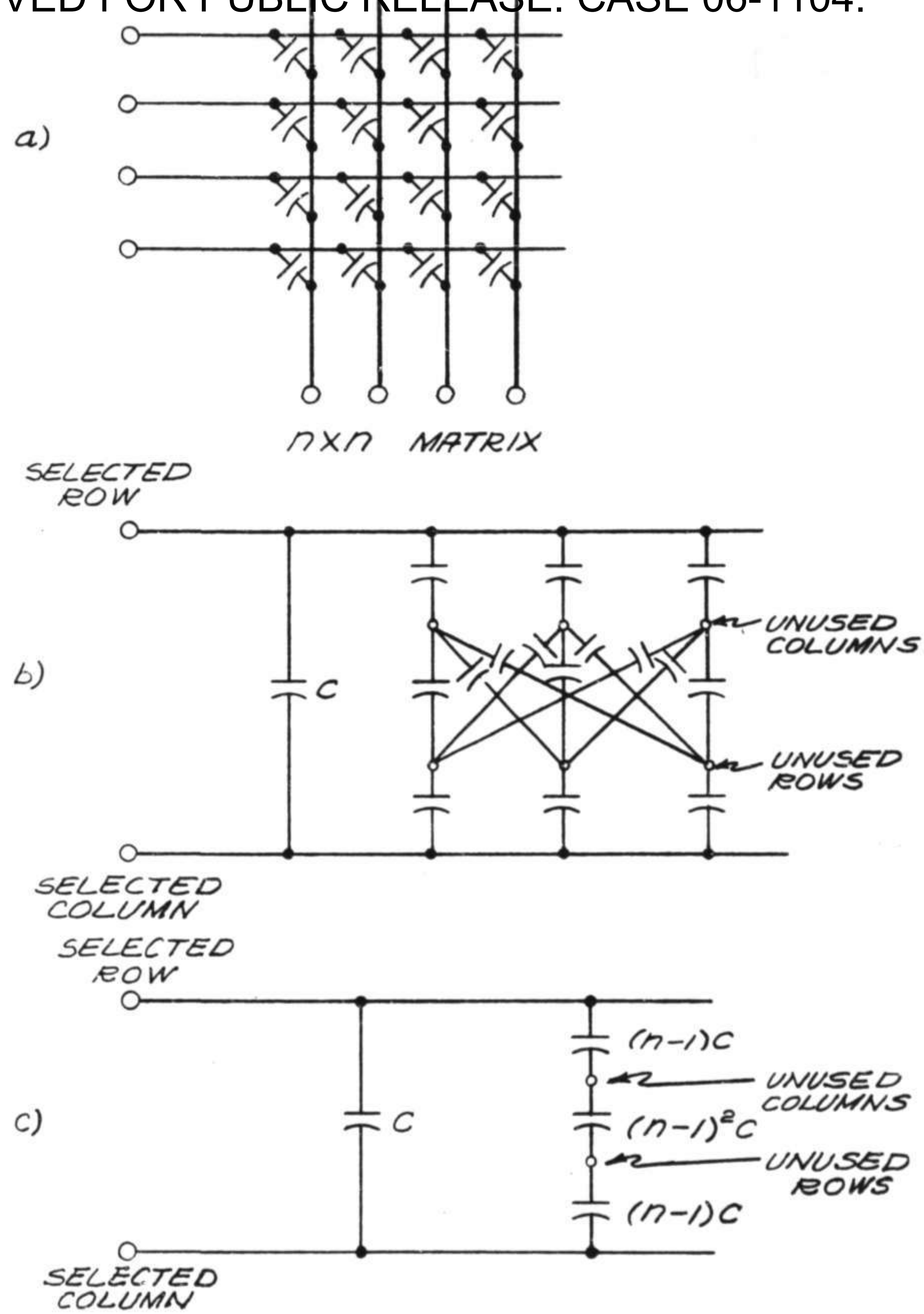


FIG. 21
MATRIX REDUCTION

A-50547

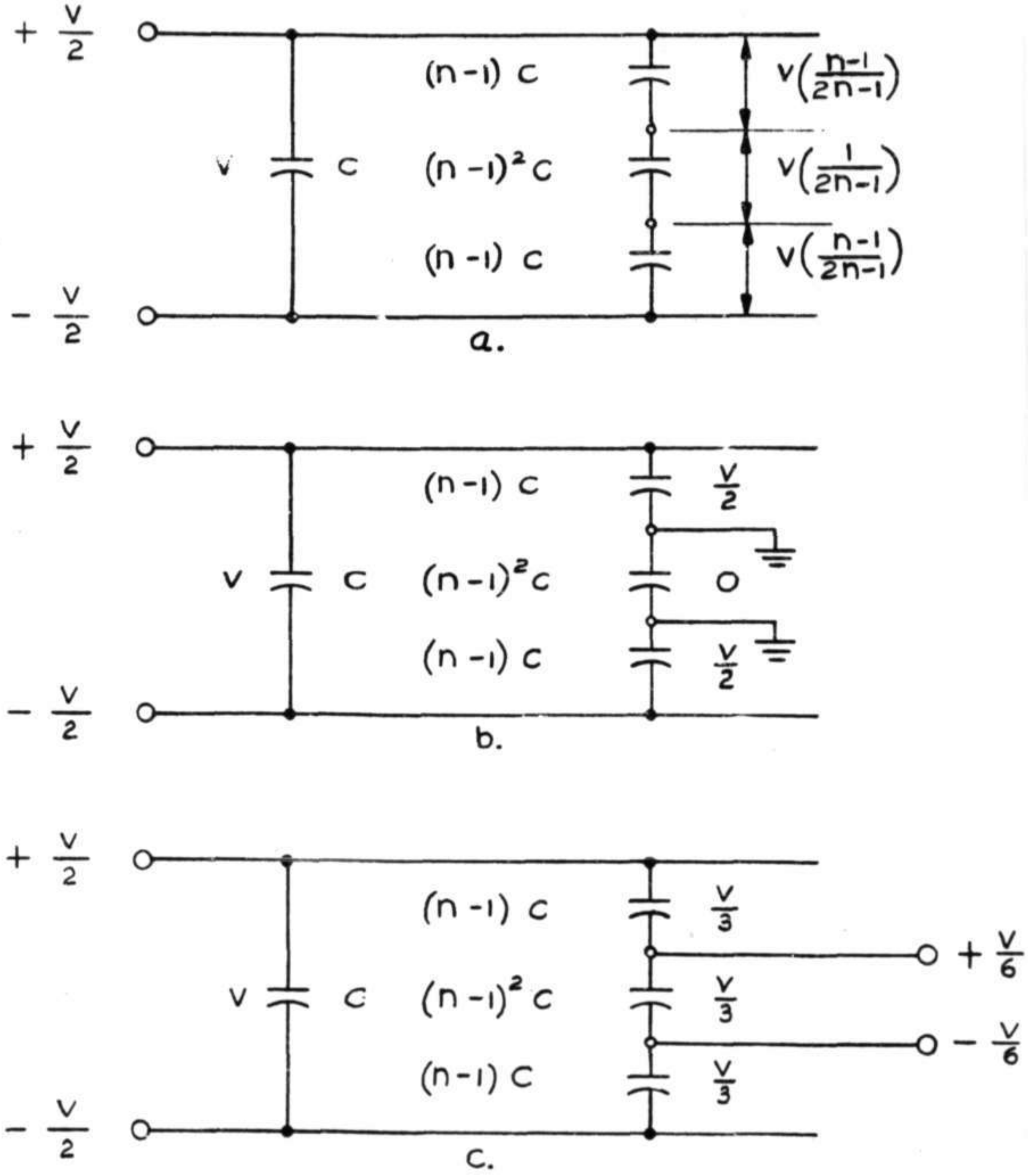


FIG. 22

THREE DRIVING SCHEMES AND RESULTING DISTURBING VOLTAGE

A−50 8

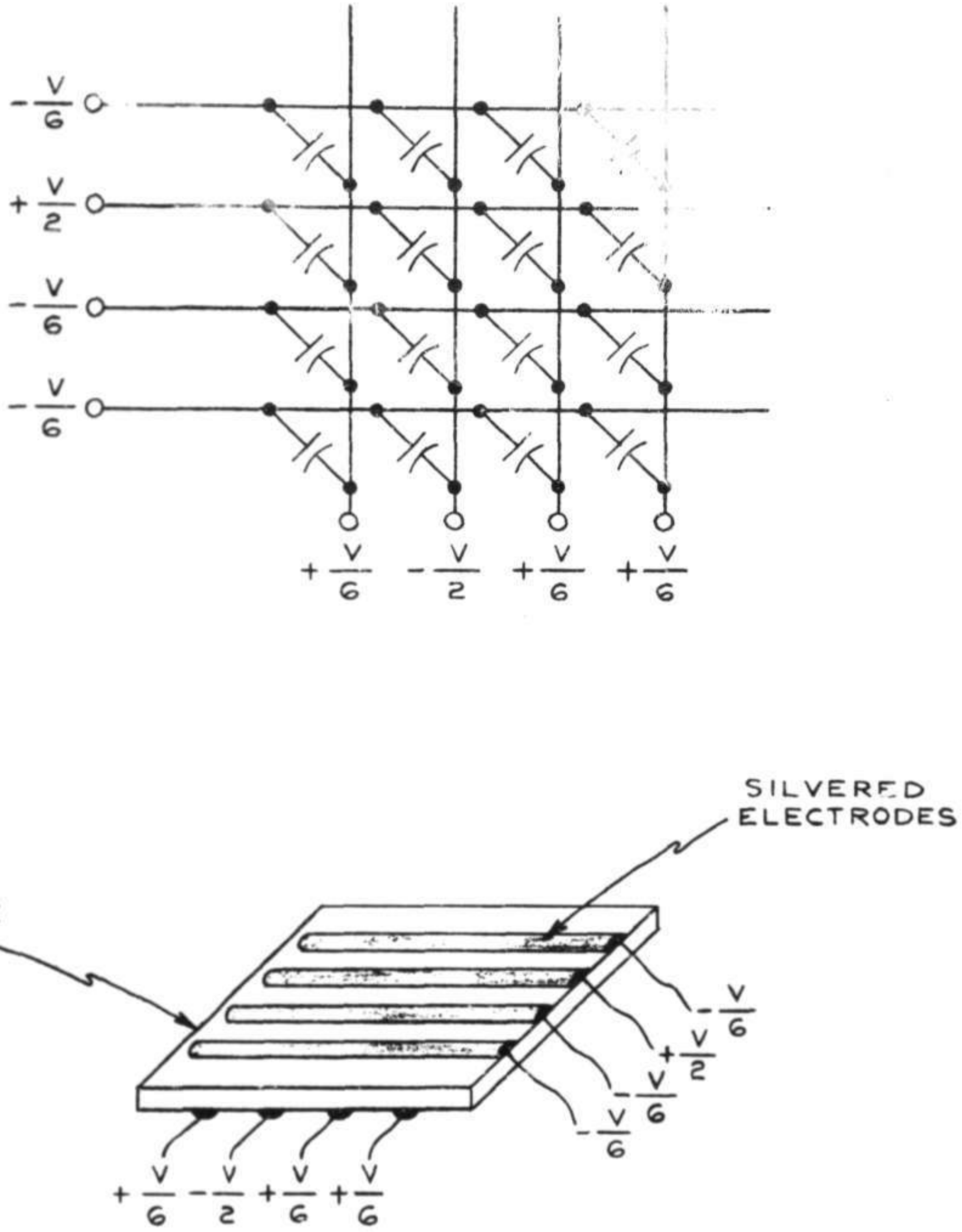


FIG. 23
FERROELECTRIC MEMORY

A-50550

A-51355

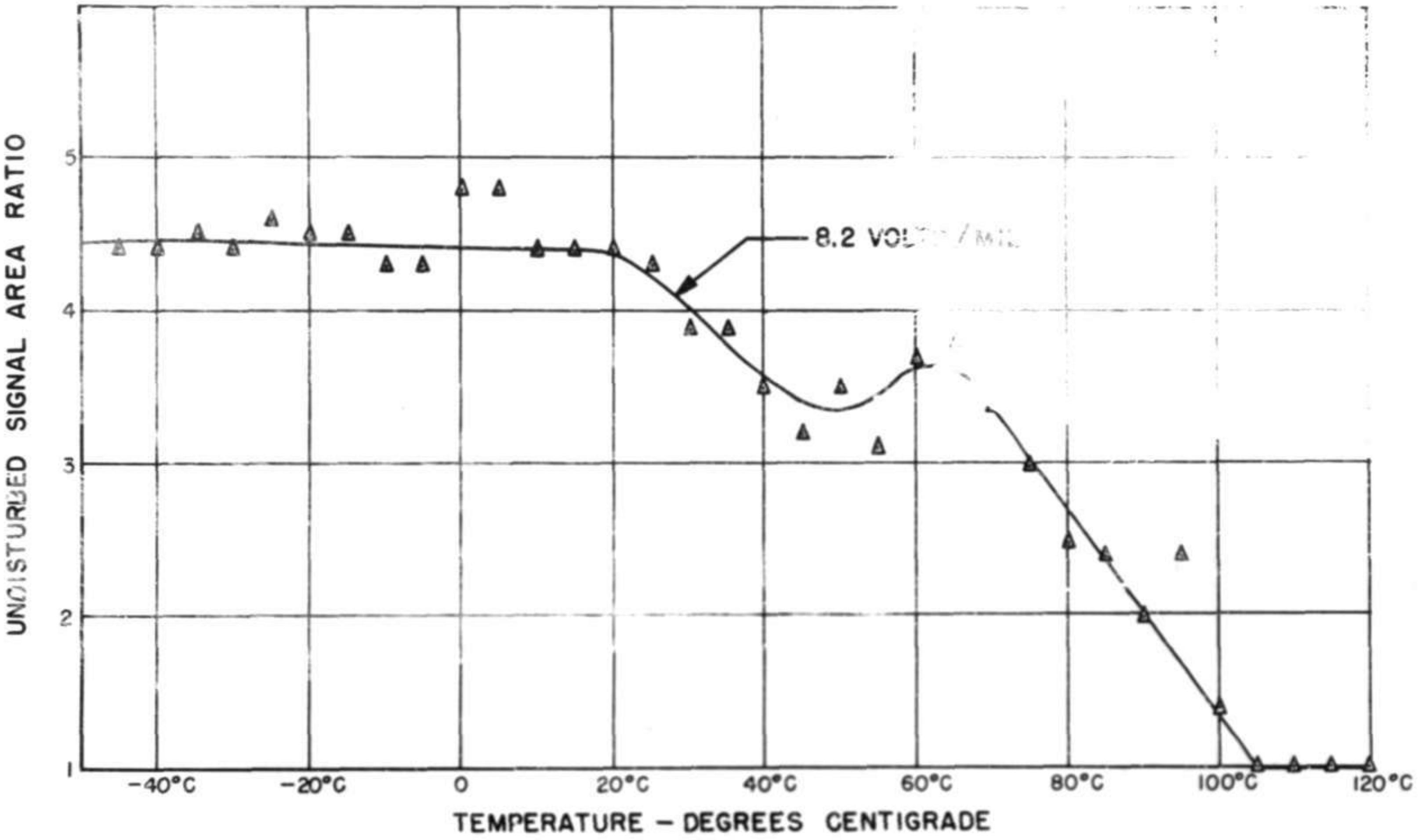
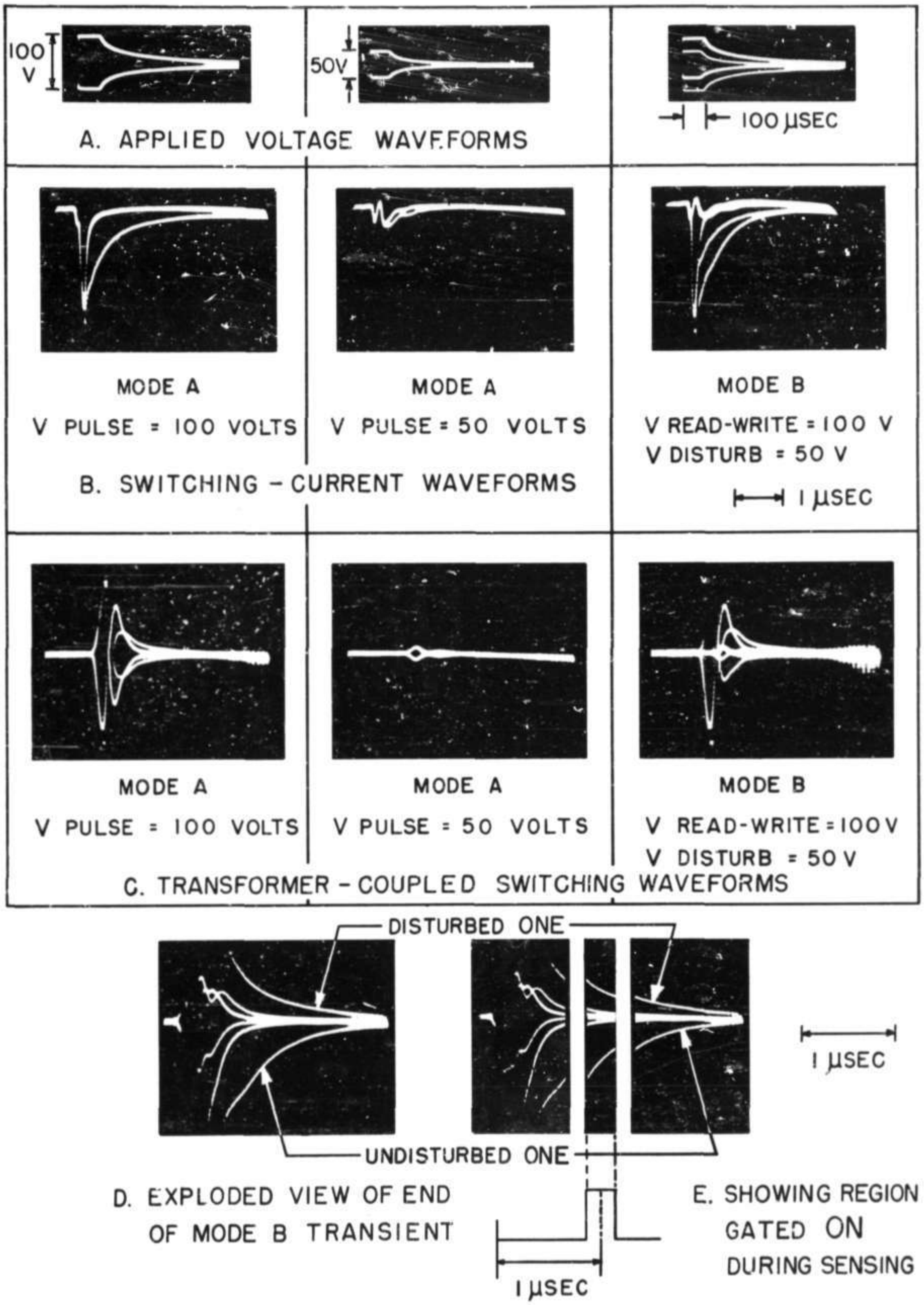


FIG. 24

UNDISTURBED SIGNAL AREA RATIO FROM MEASUREMENTS MODE A
AS A FUNCTION OF TEMPERATURE AT CONSTANT PULSE AMPLITUDE



A-51421

FIG. 25 A

INTRODUCTION TO MEASUREMENTS MODE B