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Magnetic thin films for an adaptive weighting element

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MAGNETIC THIN FILMS FOR AN ADAPTIVE WEIGHTING ELEMENT

by

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I. INTRODUCTION

For several years there has been considerable interest in using arrays of adaptive weighting elements for purposes of pattern classification and for simulating certain functions of neuron nets (1, 2, 3). Several applications of arrays of weighting elements have been investigated including character recognition, weather forecasting, disease diagnosis, traffic control, speech recognition, power-load prediction, and the identification of objects on photographs. Experiments with computer simulated elements (4, 5, 6) and small numbers of physical elements (7, 8) have shown that arrays of weighting elements would be quite useful for handling pattern classification problems of this nature. In addition, Mays (9) in a discussion of adaptive machines has suggested that machines composed of weighting elements would be useful for designing switching functions, automatic manufacturing of certain devices, self optimization of decision machines with time variable input statistics, improving the reliability of digital processes, and automatic wiring and testing of microcomponents.

The adaptive weighting element is an analogue memory element which ideally has unlimited, continuously-variable, linear gain which can be set and maintained internally (such as the remanent magnetization of a magnetic core or film). . .

Some device considerations include element size, number of weight levels available, fabrication cost, time required to change weight levels, stability with time and with disturb conditions, repeatable performance, and variations in element characteristics.

The performance required of physical weighting elements depends to a large degree on the complexity of the particular classification problem. For a simple problem involving a relatively small array, element tolerances may be relaxed by increasing the number of elements without significantly increasing the array cost. Some studies have been made on the properties of non-ideal adaptive arrays (5) but the relation between the classification problem and the element properties required has not been investigated in detail. However, the elements which have been constructed can be compared on the basis of cost for equal performance assuming that stability and other factors are the same.

Several methods of constructing weighting elements have been explored. Nagy (8) has reviewed elements constructed of servo-driven potentiometers, thermistors, photochromic films, ferroelectric dielectrics, ferrite cores, and reversible electrochemical reactions. Other devices are magnetic films with magnetostrictive readout of the remanent magnetization (8), magnetic cores with second harmonic readout of the remanent magnetization (10), and a superconducting weighting element (11a). In addition, Pohm et al. (11b) investigated a magnetic thin film adaptive linear decision array. This thesis reports continued work on the magnetic film element which was directed towards improving the performance of the memory portion of the element.

The magnetic thin film version of an adaptive array consisted of elements located at the intersections of input-output lines. The elements acted as transformers which coupled signals on row input lines to the column output lines. Each element had a variable coupling coefficient which was adjusted by coincident selection of that element. The weighted input signals which described the pattern to be recognized were summed on the output lines. The weights of the elements were adjusted according to a "training" routine (algorithm) when a pattern was applied to the input lines. The input patterns were repeatedly applied until each different pattern caused a different output line to have a signal larger than the signals produced on the other output lines. The array had then been "adapted" to recognize the average pattern of each class.

The magnetic film weighting element consisted of two permalloy-plated wires closely spaced. One film with circumferential magnetization was employed as a memory element. The magnetization of the memory element was incremented over several stable states between saturation limits by easy-axis coincident fields. The other film with longitudinal easy axis was used to sense the magnetization state of the memory film. The voltage output of the sense film when operated as a balanced modulator (12) was proportional to a transverse bias field which was provided by the demagnetizing field of the memory element. The sensing element performed satisfactorily, but the plated permalloy memory elements switched too rapidly for convenient use. However, the element was small, fast, and could be easily batch fabricated at low cost. Also, the element gain was easily adjustable in increments by the application of coincident field pulses.

The purpose of this work reported in this thesis was to examine the properties of high coercive force slow-switching compositions of thin magnetic films which were expected to be more suitable for use as analogue memory elements. The coercive force, anisotropy field, and incremental-switching characteristics of nonmagnetostrictive compositions of CoFe, CoNi, and NiFe were examined for several thicknesses of each composition. The magnetization reversal process was studied with the Bitter technique for some of the NiFe films. The experiments were concerned with determining the number of available remanent magnetization states, the reliability of attaining a given state, and the stability of the remanent state when disturb fields were applied.

The experimental results indicated that the performance of the analogue memory element could be significantly improved using CoFe for the material of the element. The CoFe element switched more slowly and was more stable with disturb conditions such as half-select currents or readout currents.

II. THEORY

Before discussing the magnetic film element further, the characteristics of thin magnetic films should be briefly reviewed. A thin magnetic film is usually characterized by a uniaxial anisotropy which results in a magnetic easy axis and a hard axis. Along the easy axis the magnetization has two stable states and the M-H hysteresis loop is almost square, while along the hard axis the M-H loop is nearly closed as shown in Figure 1. Fields applied along the easy axis cause the magnetization to reverse by the movement of magnetic domain walls while fields applied along the hard axis cause the magnetization to rotate. Some parameters most often used to characterize a film are shown on the hysteresis loops and are the coercive force H_c, the anisotropy field H_k, and the saturation magnetization M_s. Usually cgs units of oersteds and gauss are used in magnetic thin film work. Some typical parameters for 81-19 NiFe (permalloy) films 1000 angstroms thick are $H_c = 2$ oe, $H_k = 5$ oe, and $M_s = 980$ gauss.

As operated in an array the magnetization of the analogue memory film would be switched in increments by the coincident application of double-polarity short-duration field pulses and a long single-polarity bias pulse applied along the film easy-axis. As shown in Figure 2a, the total magnitude of the field pulses for one polarity of the double pulse should just exceed

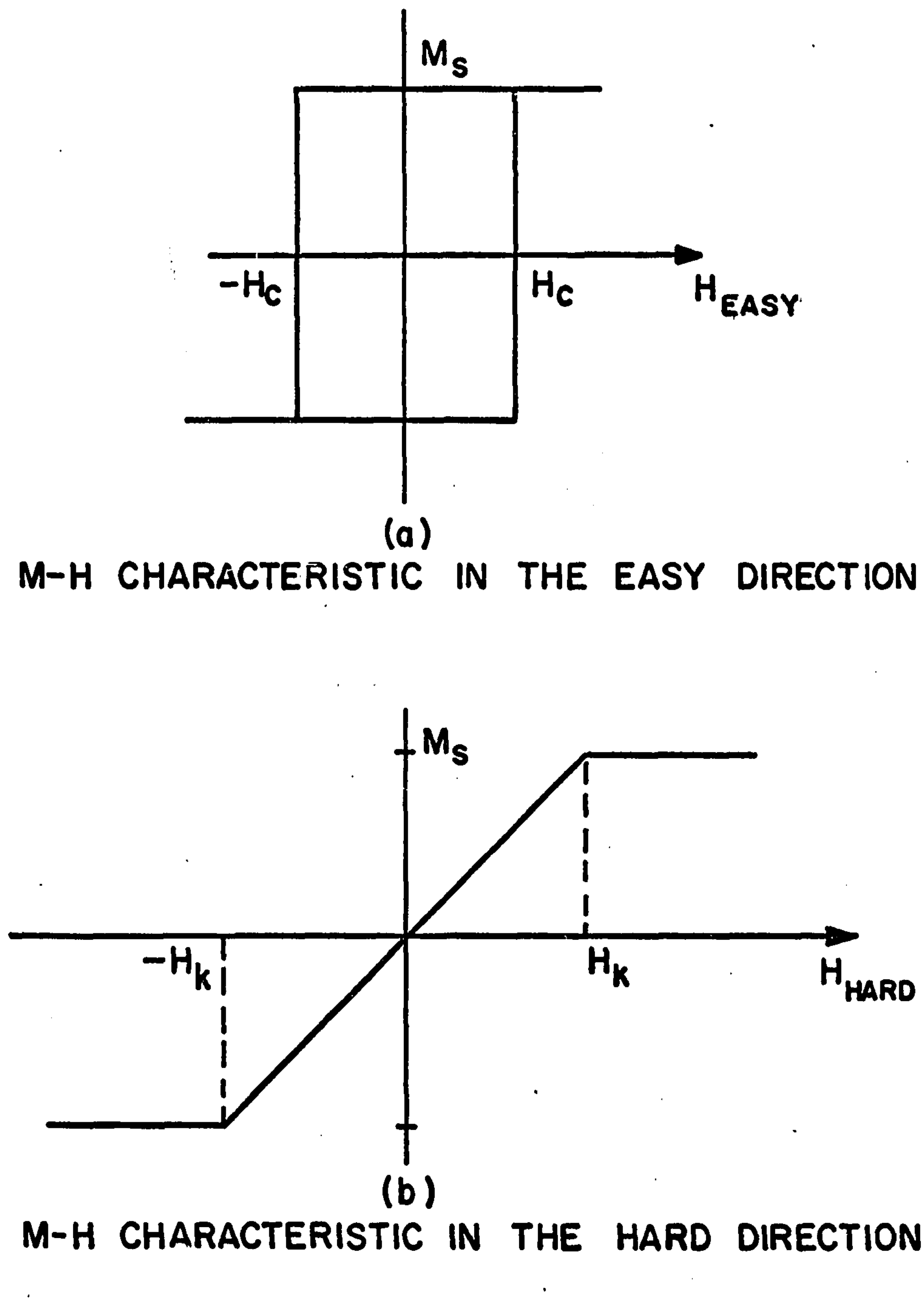
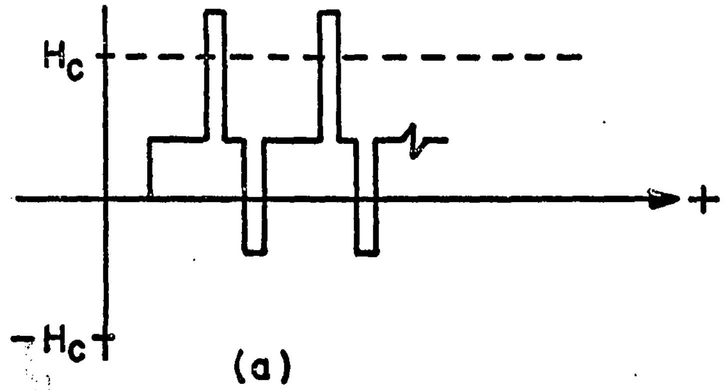
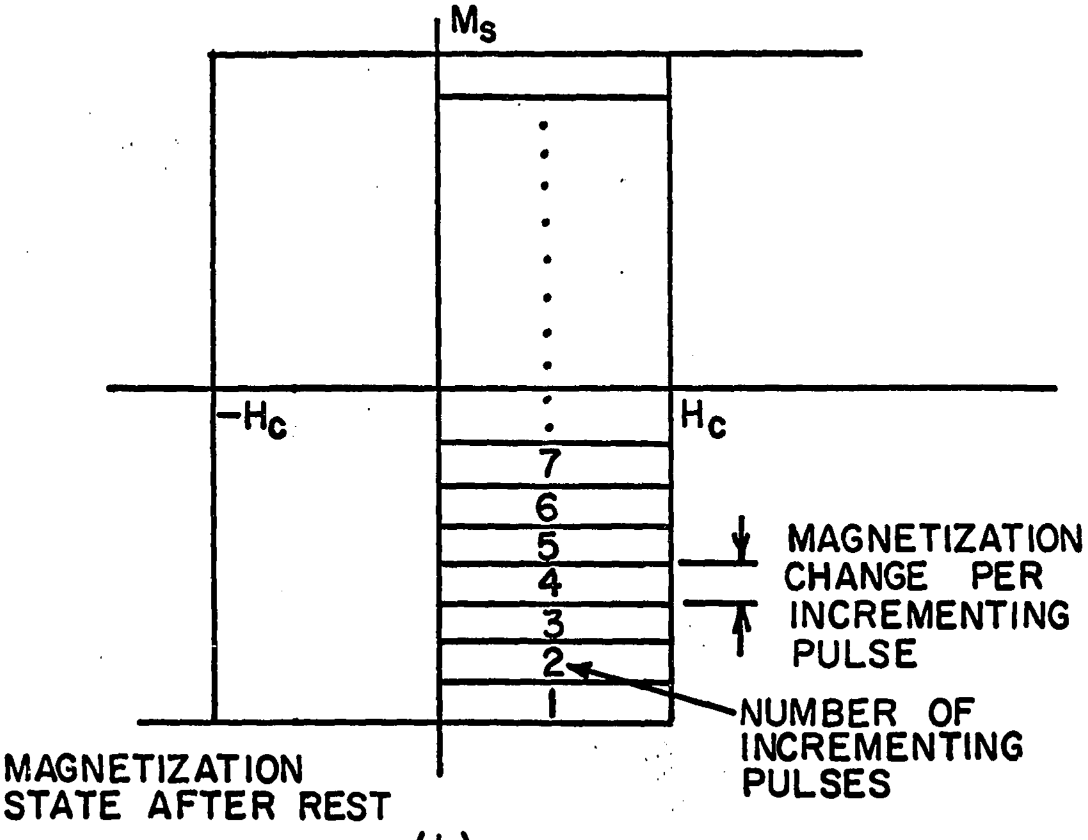


FIG. 1 - THE M-H HYSTERESIS LOOPS OF A THIN MAGNETIC FILM



(a)
COINCIDENT SUM OF INCREMENTING FIELDS



(b)
REMANENT MAGNETIZATION STATES AS ILLUSTRATED BY MAGNETIZATION CHANGES ALONG THE EASY-AXIS

FIG. 2 - INCREMENT SWITCHING USING COINCIDENT DOUBLE-POLARITY PULSES AND BIAS PULSE

the value of field required to move the domain walls and should step the magnetization as shown in Figure 2b. In this way the direction of wall movement can be controlled by the selection of the polarity of bias field. Applying pulses just greater than H_c but much less than H_k (threshold for rotational switching for fields applied along the easy axis) should cause the film magnetization to reverse primarily by the slowest process, that of domain wall motion. The short-duration field pulses should nucleate large numbers of small domains of reverse magnetization. This split state during reversal has been observed in switching experiments (13) and has been attributed to inhomogeneties of the film magnetic properties. It is desired that large numbers of reverse domains be nucleated so that the effects of any variations in the reversal process would tend to be canceled. Each incrementing pulse should cause the reverse domains to expand slightly by moving parts of the domain walls very short distances. It is expected that reverse domains will be nucleated by each of the first few incrementing pulses. Also, the film magnetization will reverse by the growth of tip domains located along the film edges.

The results of the investigation of the magnetic film element (11b) indicated that a slower-switching material would perform better as a memory element. That is, a material in which the domain walls move more slowly could be incremented in more steps between saturation limits. Domain wall velocity has been studied extensively both experimentally and theoretically for many years. Some of the results as reviewed by Dillon (14) and by Sooho (15) are summarized here.

Several experimenters have found for several different materials that the domain wall velocity is well described by the equation $v = R\ (H_a - H_o)$ where R is the wall mobility, H_a is the applied field, and H_o is a constant related to the value of field required to initiate wall movement. Some of the materials investigated were as follows: Williams et al. (16) studied 3% silicon-iron, Galt (17, 18) studied single crystals of magnetite and nickel ferrite, De Blois (19) studied iron whiskers, Dillon and Earl (20) studied manganese ferrite single crystals, Ford (21) studied NiFe films, and Copeland and Humphrey (22) studied NiFe films. The experimental results tend to support domain wall motion theory.

Theoretical investigations of domain wall motion such as by Kittel and Galt (23) using the Landau-Lifshitz equation of motion (24) have predicted that wall velocity should vary directly as the applied field and inversely as a damping constant which is defined in the equation of motion. During domain wall movement energy is dissipated as heat by eddy-currents and by the transfer of energy from the processing electron spins to lattice vibrations. Energy is transferred to the lattice by spin-lattice interactions and by spin-spin interactions called spin waves.

Wall mobilities in non-conducting materials are predicted by relaxation damping considerations while in conducting materials wall velocities agree with the theory (16) based on eddy-current damping. Ford (21) investigated wall mobility in permalloy films and found that relaxation damping was not significant for films as thin as 700 angstroms.

Eddy-current damping theory predicts that wall mobility is inversely proportional to $M_s \sigma T$ where M_s is the saturation magnetization, σ is the electrical conductivity, and T is the film thickness. Bulk values of M_s and σ given by Bozorth (25) for the three compositions investigated in this thesis indicate that the CoFe material may have a slightly lower value of wall mobility than the other compositions.

The relaxation damping constant can be obtained from resonance experiments. Lax and Button (26) have reviewed the theoretical development leading to the equations which relate the measured values to the damping constant,

$$2/T = \gamma \Delta H \quad \text{and} \quad \beta = 1/\omega T$$

where ΔH is the difference between the d-c field values at which the absorption is one-half of maximum, γ is the gyromagnetic ratio ($\gamma/2\text{x}10^6 = 2.8$ mc/oe-sec), T is the relaxation time, $\omega/2\pi$ is the frequency at which the measurements are made, and β is the damping constant.

The resonance data for Co (27) and for permalloy (28) does not indicate a significant difference in the relaxation damping constant of these materials. However there may be a small difference which would be difficult to detect from the data plots given.

Gyorgy (29) has discussed the measurement of relaxation damping and suggests that the damping constant may be dependent upon experimental conditions and that an experimental value may not indicate the damping constant for all types of reversal processes.

This brief investigation of wall velocity did not result in definite conclusions regarding the choice of a slower switching material because not enough information is available on the wall mobilities and damping constants of these materials.

The reversal process can be studied in several ways as reviewed by Dillon (14). In this study the reversal process was primarily observed by recording the percent of magnetization switched during the application of an easy-axis reset pulse which caused most of the magnetization to align in one direction along the easy axis. Short-duration pulses were applied along the easy-axis to increment the magnetization towards the opposite saturation state. During the reset pulse the flux change, dM/dT, was sensed with a pickup coil and integrated. The maximum voltage signal was recorded when the polarity of the reset was alternated with no incrementing pulses applied. This was called the maximum flux change and other signals were recorded as a percentage of the maximum signal. In the experiment, the air flux coupling between reset and sensing field coils was cancelled so that a flux change was equivalent to a magnetization change.

The reversal process was also studied with Bitter patterns and with the Kerr magneto-optic effect. The Bitter solution is a colloidal suspension of iron particles which are attracted to the domain wall by demagnetizing fields which result from the rotation of spins out of the plane of the film. This method can not be used to observe the walls as they move because one to three minutes are required for the iron particles to collect on the walls. Also, this technique does not indicate the directions of magnetization in the domains.

Several attempts were made to use the Kerr effect to observe the reversal process, however no useful results were obtained. In the Kerr effect polarized light is reflected from the film and rotated by the different directions of film magnetization. An analyzer is used to obtain a contrast between the different rotations. The domains can be observed during the switching process with this technique. The results of attempts to use the Kerr effect indicated that perhaps many reverse domains were nucleated which were too small to be seen without magnification. Magnification requires a strong light and good optics which were not available.

From the data presented by Bozorth (25) two nearly zero magnetostrictive compositions of high coercive force materials were selected for investigation and comparison with permalloy as memory elements. These slower-switching compositions were 95-5 CoFe and 80-20 CoNi. The composition of NiFe investigated was 83-17 before deposition.

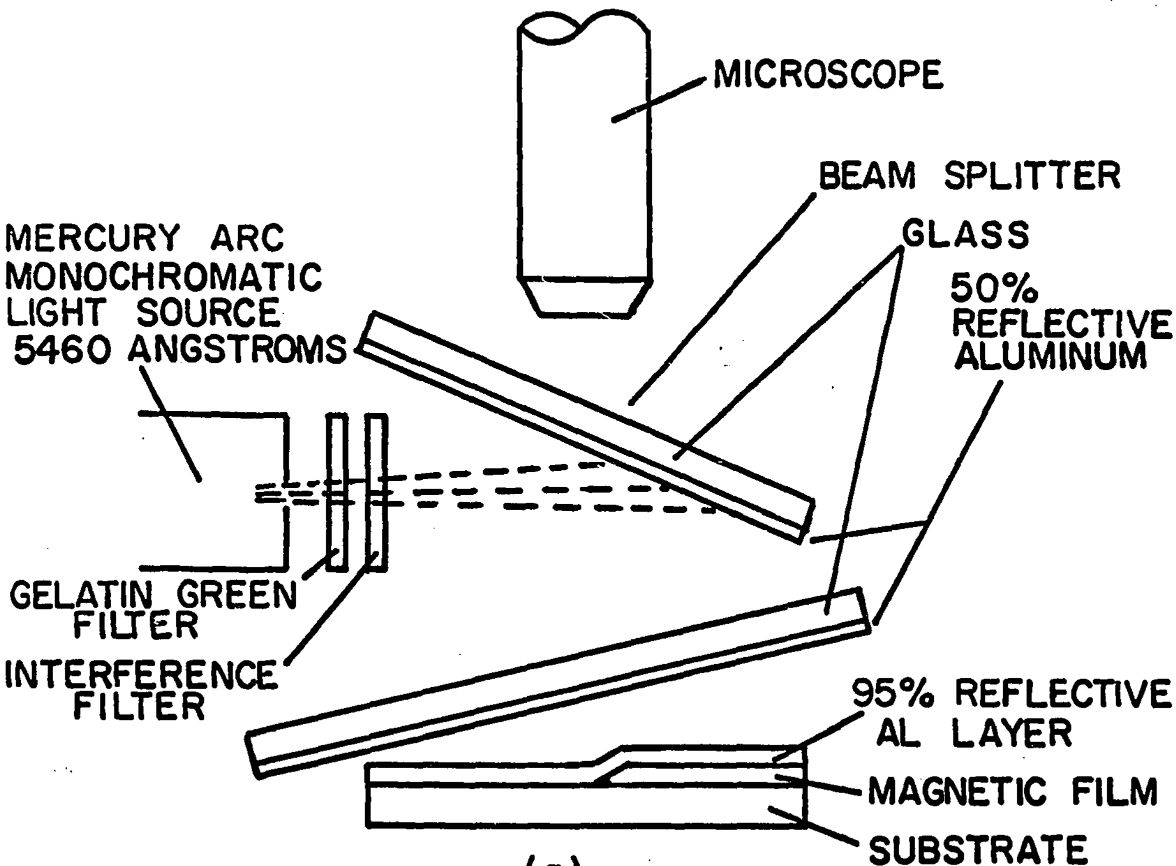
The films examined here were obtained by flash evaporation in a vacuum. Other methods were studied for possible use including electron bombardment, electron-beam technique, sputtering, and induction melting of metals suspended in a magnetic field. However these methods would have required a large investment of time and money. Evaporation of the materials from a crucible and from a tantalum boat were attempted without success because of insufficient temperature and alloying problems with the boat. An excellent reference for deposition work is by Holland (30).

The materials to be evaporated were hung in loops on a metal filament which was placed approximately 6 to 12 cm below the substrate holder. Cover glass slides approximately 9 mils thick and 0.86 inches square were used for substrates, which were heated to roughly 200°C in a vacuum of 5×10^{-5} mmHg. During the deposition the film magnetization was oriented by a 30-40 oe d-c field to produce field-induced anisotropy. The CoFe films were made from loops of 95-5 CoFe alloy, the CoNi films from loops of pure Co and Ni in an 80-20 combination, and the NiFe films from loops of 73-27 NiFe and pure Ni in an 83-17 combination. It was noted by weighing the filament before and after deposition that approximately 50% of the material hung on the filament was not evaporated.

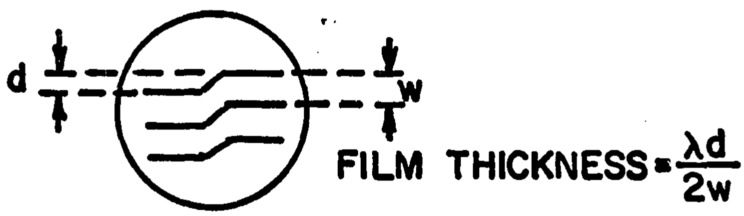
The film thicknesses were measured by the Tolansky method (31) with a home-made version of a multiple-beam interferometer which is shown in Figure 3. Normally the beam splitter shown is mounted inside the microscope as in a metallurgical or interference microscope. The fringes observed were not as sharp as desired and it was estimated that 5-10% accuracy was obtained. Normally 1% or 100 angstroms is the accuracy obtained with the Tolansky method. The film thickness is given by $T = \lambda b/2a$ where a is the distance between fringes, b is the height of the step, and λ is the wavelength of the monochromatic light used. A detailed discussion of the various methods of measuring film thicknesses is given by Holland (30).

The gross magnetic properties, H_c and H_k, of the films were measured with a 60 cps hysteresis loop tracer. Most of the CoFe and CoNi films examined were either biaxial or isotropic while the NiFe films were usually uniaxial.

The H_c and thicknesses for the films examined are given in Table 1. The value of H_{wall} given was the total magnitude of coincident field required to cause a 10% change in the film



(a)
INTERFEROMETER ARRANGEMENT



(b)
INTERFERENCE FRINGES

FIG. 3 — MULTPLE-BEAM INTERFEROMETER FOR THICKNESS MEASUREMENTS

Table 1. Some properties of films examined for use as memory elements

Material	Film no.	Thickness angstroms	H_c oe	H_{wall} Film oe	H_{wall} Bit oe	Bit dimensions Easy axis mils	Bit dimensions Hard axis mils
CoFe	82	2730	16	21.4	15.5		
	87	1062	17.2	17.1[a]	15.5[a]	40	75
	92	1540	26.3	26.9	25.5		
	97	675	13	14	13.8		
	102	1810	14	19	10.7		
CoNi	106	1475	20.9	23.6[a]	21.9[a]	35	73
	111	1293	33.5	37.2	--		
NiFe	5	860	1.2	4.9	--		
	13	1040	2.1	1.6[a]	0.4[a]	35	50
	14	1503	1.7	1.9	--		

[a]Values of H_{wall} measured using single-polarity pulses.

magnetization.

Several experiments were performed to determine the performance of these films as memory elements. The experiments were concerned with determining the number of usable remanent magnetization states, the reliability of attaining a given state, and the stability of the remanent state when disturb fields were applied. In summary, the percent magnetization change vs the number of incrementing pulses (single-polarity pulses and double-polarity pulses coincident with a bias pulse) was examined for several film thicknesses of each of the three compositions. The single-polarity pulse experiments were performed to provide initial information concerning the number of expected weight levels and to provide information for comparison and explanation of other experiments. The double-polarity pulse experiments provided information as to element reliability, stability, and performance when coincident currents were used to adjust the magnetization.

III. EXPERIMENTAL

A. Apparatus

1. Field coils

The coils for incrementing and reseting the film magnetization and sensing the magnetization change during reset were wound on glass form as shown in Figure 4. This arrangement was chosen so that Bitter pattern studies could be made later. The Bitter technique requires a second layer of cover glass to spread the Bitter solution in a thin layer. Providing for the Bitter pattern experiments greatly increased the problems involved in designing the field coils. Much larger currents were required to provide sufficient field strength to switch the film than would be required if the films could have been placed much closer to the coil. The increased applied voltage results in large capacitively-coupled currents in the sense coil which are difficult to cancel. The capacitive coupling between reset and sense coils was decreased by splitting the reset coil and placing the sense coil in between the two halves.

Both reset and increment coils consisted of 8-turns of No. 44 wire (2-3 mils in diameter) which was arranged as two 4-turn segments placed on either side of the 4-turn sense coil. A 5-mil thickness of mylar was placed between reset coil and the increment coil which was wound on top of the

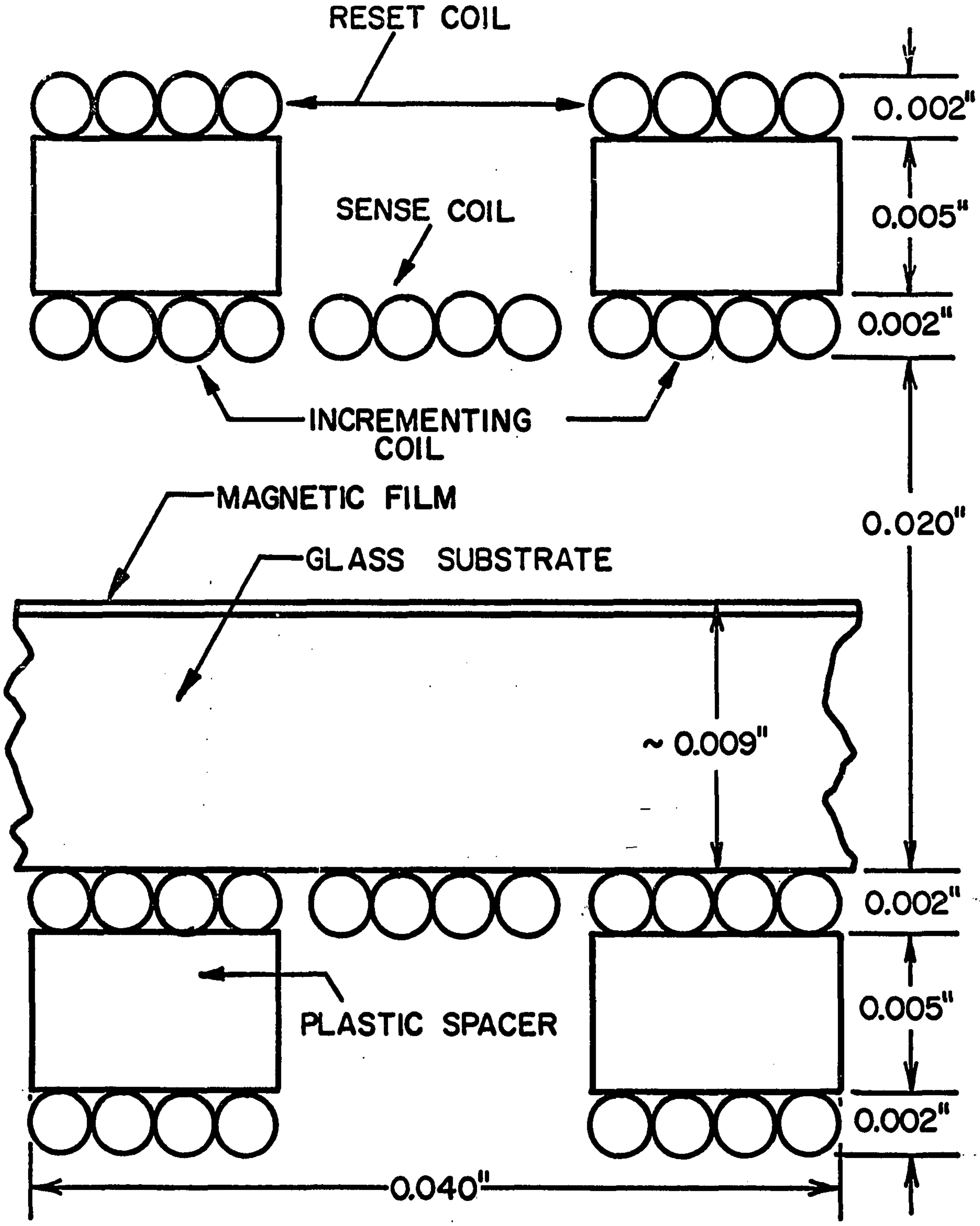


FIG. 4 —COILS FOR APPLYING INCREMENT AND RESET PULSES AND FOR SENSING THE MAGNETIZATION CHANGE DURING RESET

reset coil.

The switching coils were designed to provide the necessary field strength to switch the film and to keep the inductance low enough so that 25 nsec field pulses could be used to increment the film magnetization. During the experiments a second layer of cover glass was placed on top of the film to position the film midway between the field coils.

The mutual air-flux coupling between the three coils was cancelled for the most part by similar coils oppositely wound on the same glass form as shown in Figure 5. The mutual coupling between the reset coil and the sense coil was more closely adjusted to zero by varying the position of a ferrite-powdered strip of cover glass which was partially inserted into the mutual cancelling coils shown on the far right in the middle of Figure 5.

Several experiments were performed with another set of field coils without cancellation between the increment coil and the other coils. It was found that one polarity of the double-polarity incrementing pulse was coupled into the transistor circuits which resulted in a significant decrease in the field produced by that polarity of current.

During the experiments a magnet was used to cancel most of the earth's magnetic field in the vicinity of the film. The cancellation was measured with Hewlett-Packard magnetometer field probe.

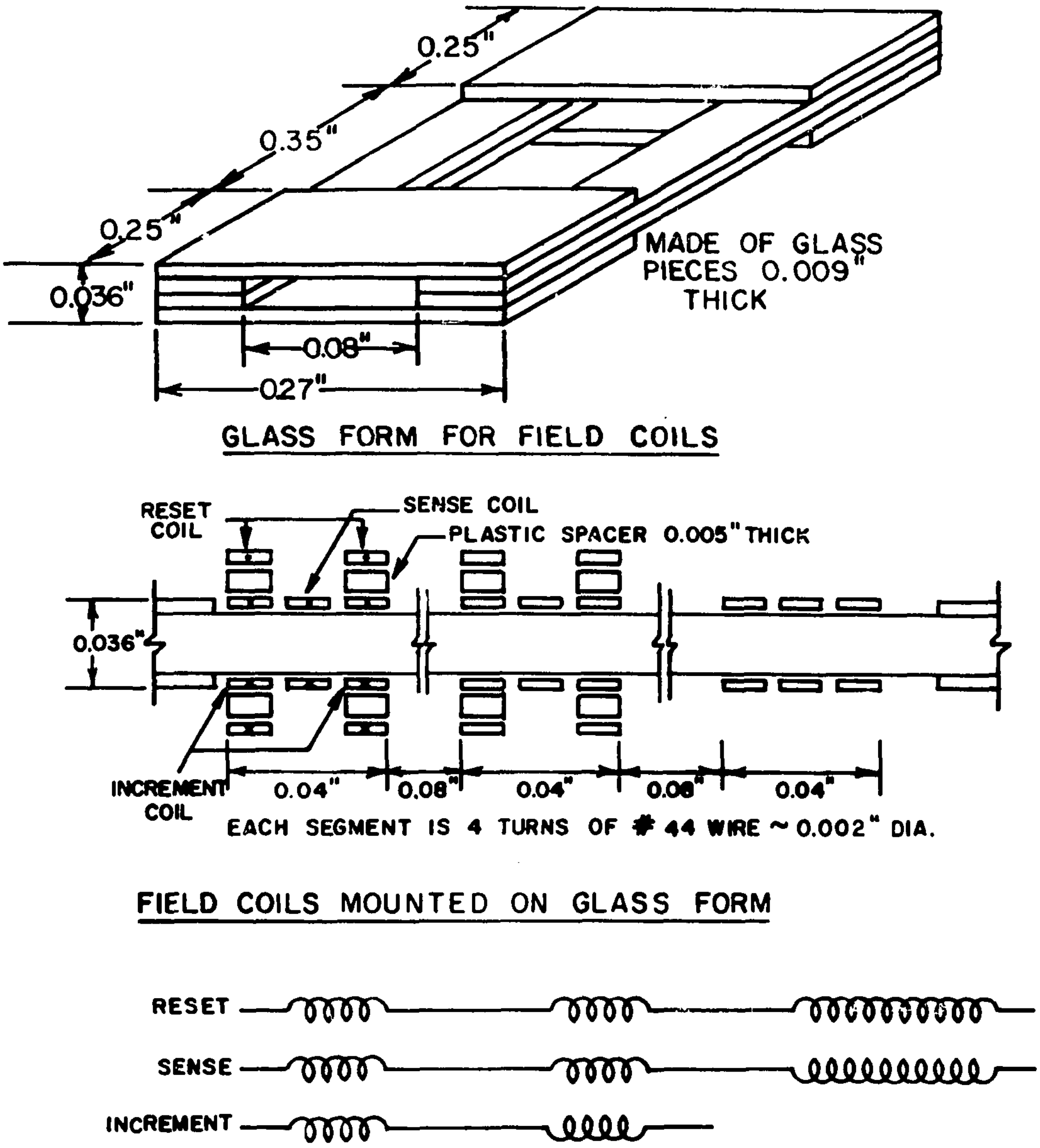


FIG. 5 —ARRANGEMENT OF FIELD COILS ON GLASS FORM

The incrementing coils produced a computed maximum field (d-c calculation) on the coil axis of 61.1 oe/amp which occurred near the center of each 4-turn segment. The average (effective) field between the points at which the field was one-half of the maximum value was computed as 52.25 oe/amp. In the experiments described later the field values mentioned are effective fields. The maximum reset field was approximately 40 oe/amp. The method of calculating the maximum and effective fields is given by Hoper (32).

2. Circuits

The arrangement of the equipment used to perform the experiments is shown in block diagram form in Figure 6. The purpose of the equipment was to provide incrementing and reset pulses in a sequence as shown in Figure 7. The reset pulses were generated every 100 msec and the incrementing pulses were produced within 70 msec. The bias field was applied continuously or as a long pulse coincident with the incrementing field pulses.

The circuits which were designed to produce the reset pulse and double-polarity incrementing pulses are shown in Figure 8 and photographs of the pulses produced are shown in Figure 9. A reset pulse of sufficient magnitude to switch all the films examined was provided by the transistor pulse amplifier which mainly consisted of three transistors placed in

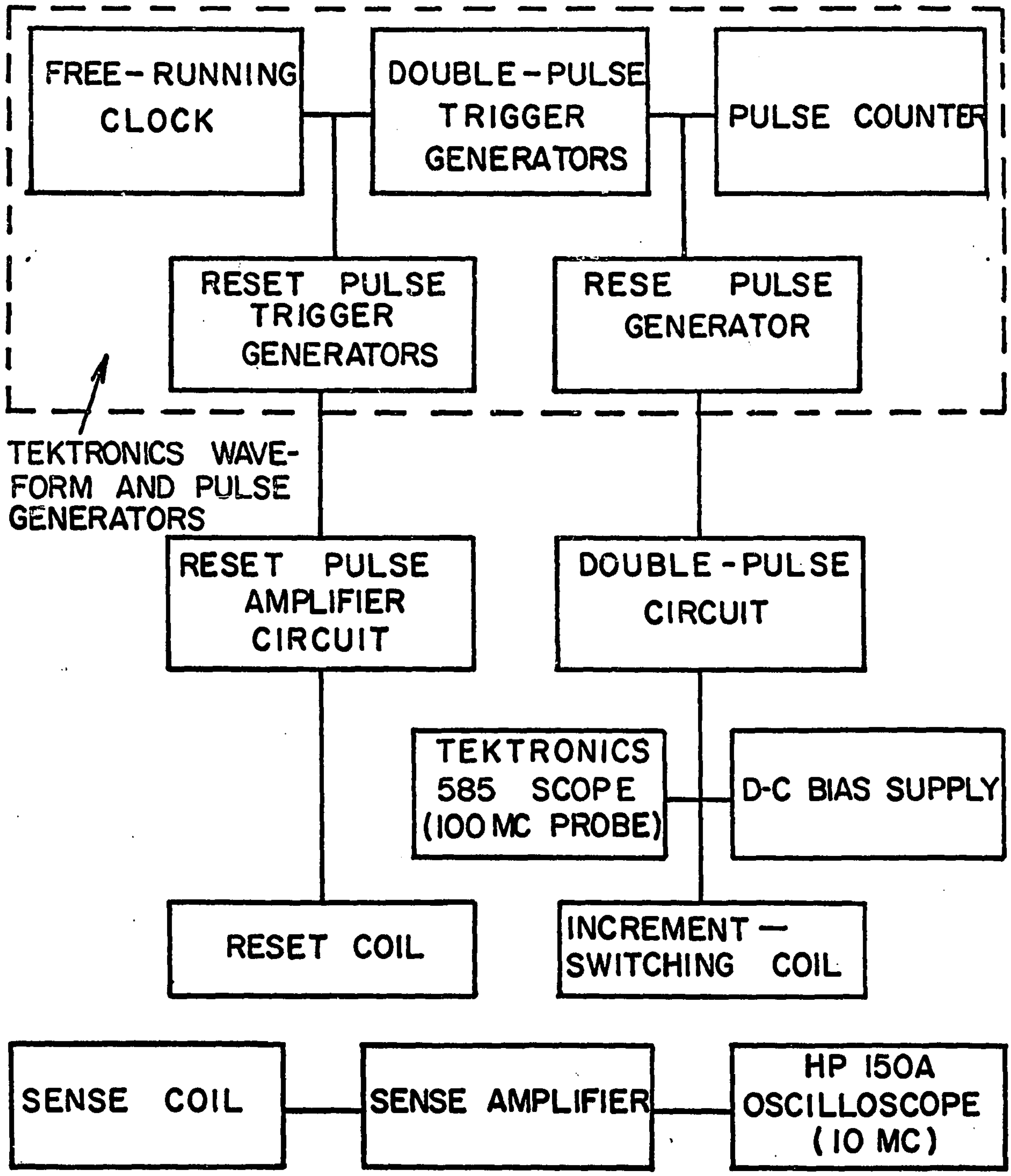


FIG. 6 — EQUIPMENT ARRANGEMENT IN BLOCK DIAGRAM FORM

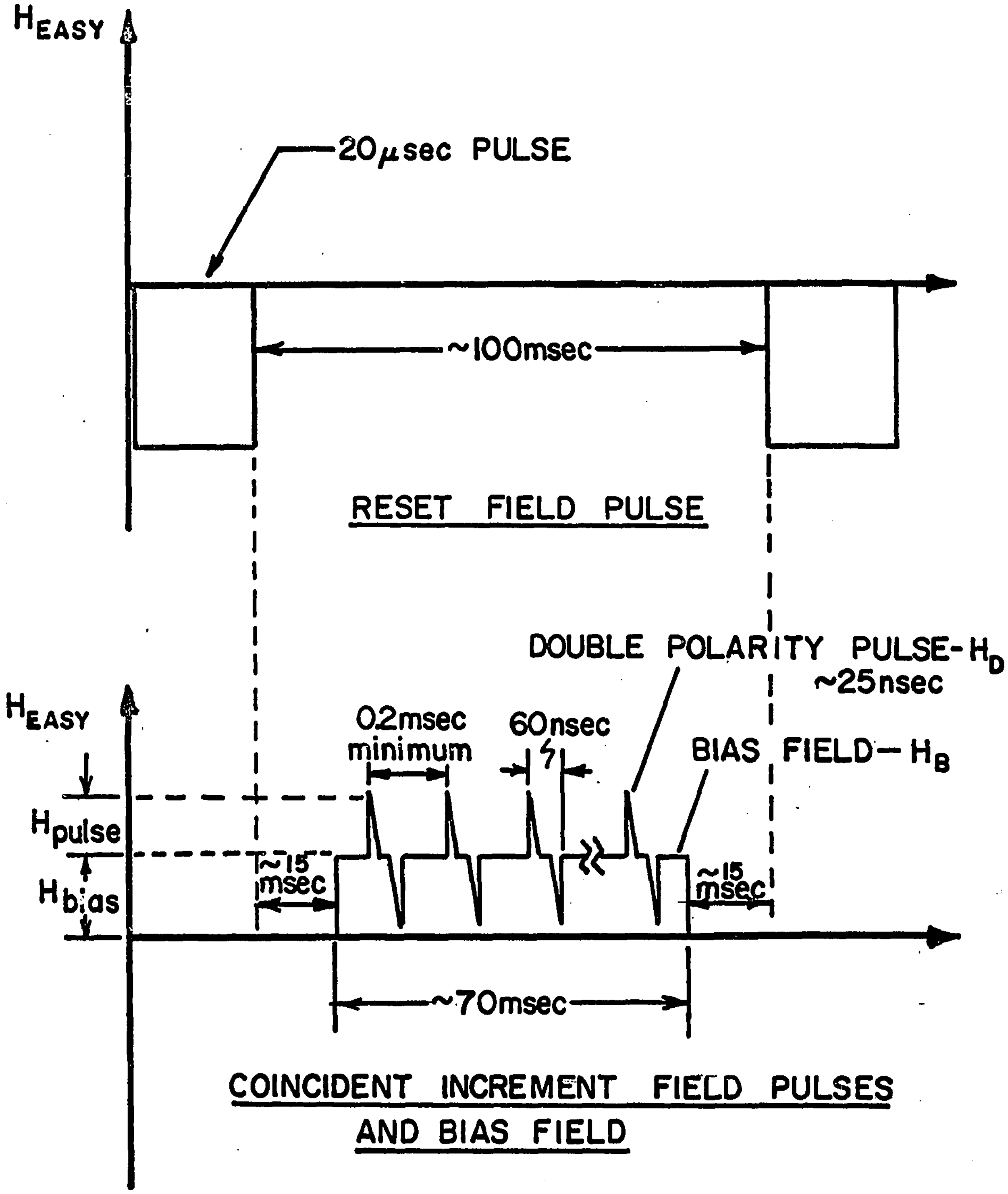
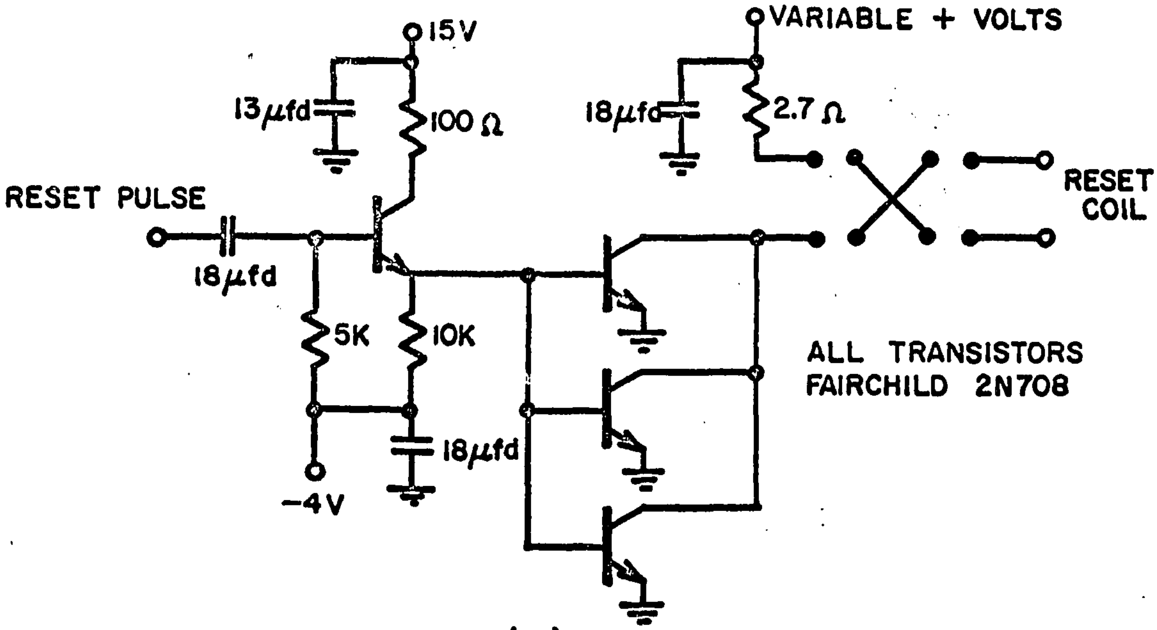
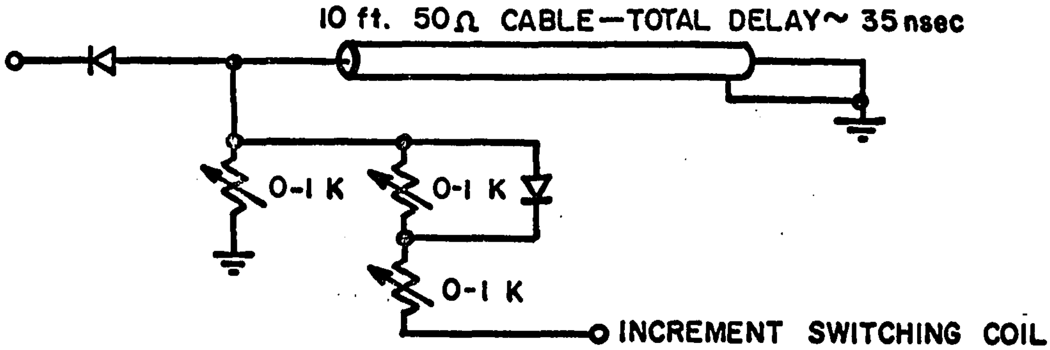


FIG. 7 — TYPICAL APPLIED FIELD SEQUENCE



(a)

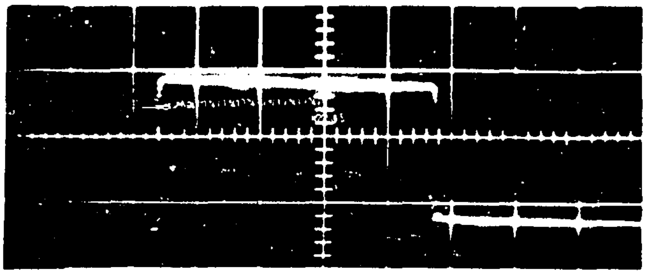
RESET PULSE AMPLIFIER CIRCUIT



(b)

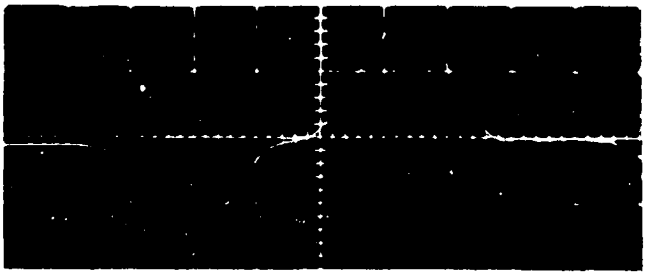
DOUBLE-PULSE FORMING CIRCUIT

FIG. 8 — RESET AND INCREMENT PULSE FORMING CIRCUITS



(a)

RESET PULSE— ~ 150 nsec RISE TIME, 35 oe Vertical- 1 v/div Horiz.-5 μsec/div



(b)

DOUBLE-POLARITY INCREMENT PULSE Vertical- 6 oe/div Horiz.- 10 nsec/div

FIG 9 — RESET AND INCREMENT FIELD PULSES parallel for increased current. The rise time of the reset pulse was about 150 nsec.

The 25 nsec, single-polarity incrementing pulses were obtained from a Rese 1051 pulse generator which uses a mercury wetted relay and a delay line to produce the pulse. A shorted delay line placed in parallel with the incrementing coil and an impedance matching network as shown in Figure 8 was used to produce a delayed pulse of opposite polarity and thus produce the double polarity pulse. The delay line consisted of 10 feet of 50Ω cable which delayed the second pulse by about 35 nsec. The pulse magnitude was monitored with a Tektronics 585 oscilliscope using a 100 mc probe.

Several attenuator heads were used with the 100 mc probe to monitor the magnitude of the incrementing pulses. The attenuator heads and the probe were calibrated by observing flux changes caused by a large number of incrementing pulses of a certain magnitude and recording the d-c bias necessary to cause the same flux change for a decreased pulse magnitude. Several measurements were made with this procedure to insure the calibration. It was noted that the signal height monitored by the probe was changed if the probe was moved slightly. Also, the changed signals differed slightly in shape from previous signals. Thus any change in the probe calibration was easily detected by observing the signal waveshape. The calibration values agreed quite closely with values obtained by adjusting the attenuator heads to give a proper waveshape for a fast rising pulse and then using the calibrated output pulses of the 585 scope to calibrate the attenuator heads and probe.

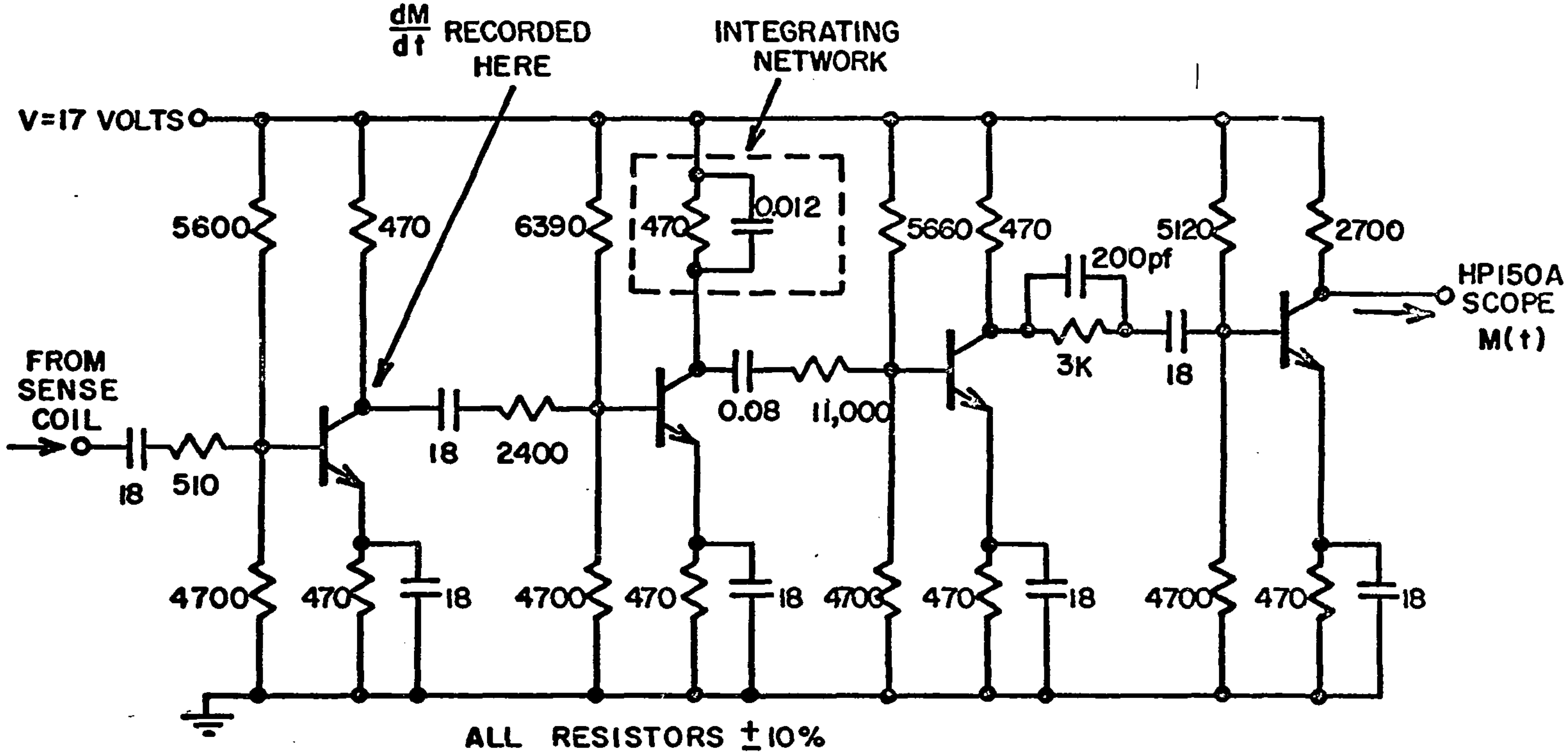
The d-c bias field was supplied as shown in Figure 8 by a d-c power supply placed in series with a manual switch. In some of the later experiments a relay was used in place of the manual switch.

During the application of the reset pulse the film magnetization was returned to the initial saturation state. The voltage signal produced in the sense coil was amplified and integrated with the circuit shown in Figure 10. The circuit was designed to present a large impedance to the sense coil so that the coil would not draw much current and have a short enough time constant to follow most of the switching signal.

The inductance of the sense coil was measured as about 1 microhenry. Assuming some distributed capacitance, the time constant of the sense coil and 500 ohm resistor was estimated to be 5 to 10 nsec. With this short time constant the coil should respond to most of the switching signal.

The integrating network shown had a time constant of about 5μsec which was about 10 times as long as any switching signal observed during the reset pulse.

The performance of the integrator was measured by applying short duration pulses of various magnitudes and pulse



ALL RESISTORS ±10%

ALL TRANSISTORS FAIRCHILD 2N914

CAPACITORS IN μf EXCEPT WHERE NOTED

FIG. 10 — SENSE AMPLIFIER AND INTEGRATOR

widths to the sense amplifier input. The sense amplifier output signal was plotted vs. the area of the input pulse as shown in Figure 11. The rise time of the testing pulse was less than 20 nsec which indicated that the sense amplifier will satisfactorily integrate the major portion of the switching signal during reset.

Some samples of switching signals and flux changes observed are shown in Figure 12 for a fixed number of incrementing pulses with a variable pulse magnitude. The signals shown were recorded using the 100 mc probe. The initial spike voltage shown in Figure 12a was caused by capacitive coupling effects and was not part of the switching signal.

B. Measurements

Presented here are experimental results which indicate the performance of CoFe, CoNi, and NiFe films as memory elements. Experiments were performed to determine the number of usable remanent magnetization states, the reliability of attaining a given state, and the stability of the remanent magnetization state when disturbing magnetic fields were applied. Also, the performance of strips of magnetic film (i.e. continuous film planes) was compared with that of film bits.

The easy-axis remanent magnetization of planar films of the three compositions was incremented between saturation

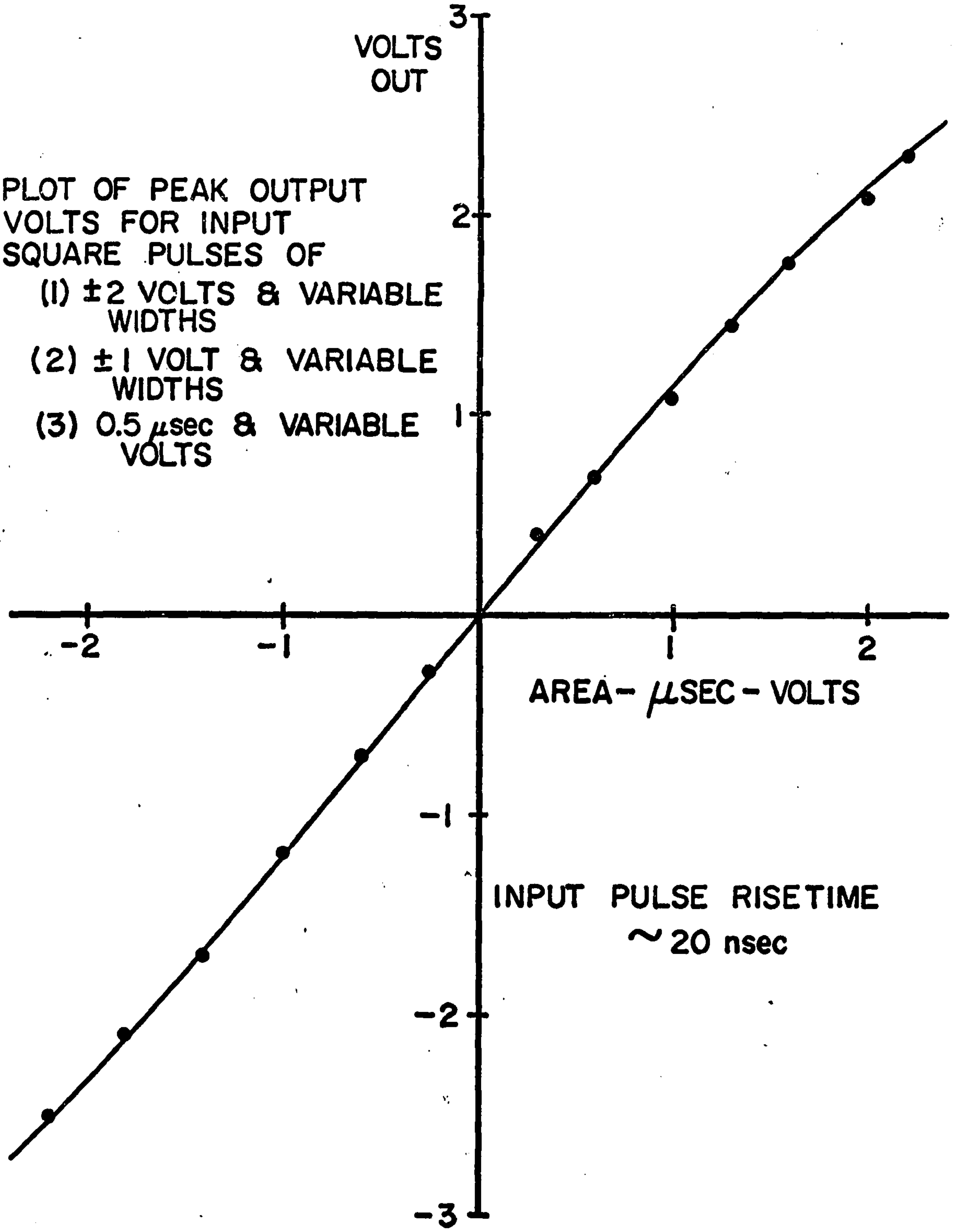
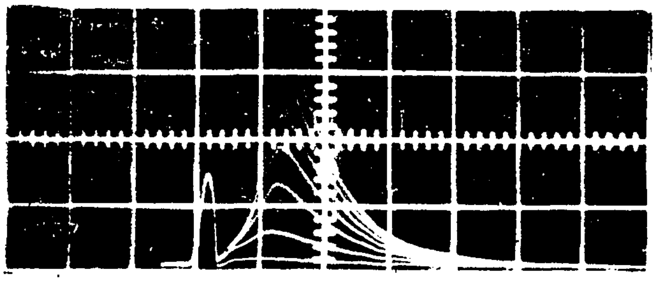
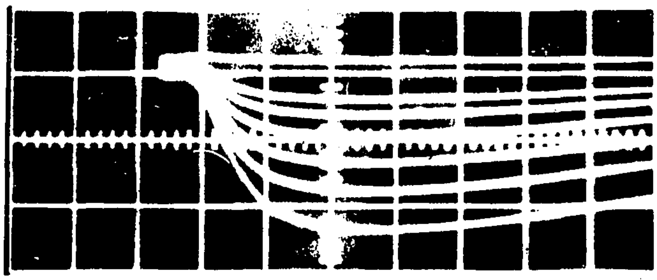


FIG. 11 - SENSE AMPLIFIER PEAK OUTPUT VOLTAGE VS. THE AREA OF SQUARE INPUT PULSES



(a)
SWITCH SIGNAL DURING RESET
Vertical – 0.1 v/cm Horiz. – 0.1 μsec/cm



(b)
INTEGRATED SWITCHING SIGNAL DURING RESET
Vertical – 1v/cm Horizontal – 0.5 μsec/cm

FIG. 12 — TYPICAL SWITCHING AND FLUX CHANGE SIGNALS OBSERVED DURING RESET FOR SEVERAL MAGNITUDES OF INCREMENT FIELD PULSES FOR Co Fe FILM # 87

limits by 25 nsec easy-axis field pulses with magnitudes greater than H_c. The percent magnetization change vs. the number of incrementing pulses was examined for several film thicknesses of each of the three compositions. Domain wall formation and movement were examined with Bitter patterns for some of the permalloy films. Additional measurements were also made with a double polarity pulse field and a slowly varying bias field. Eddy-current damping was investigated as a means of increasing the number of remanent states of the CoFe film bits.

The experimental results for one film of each composition were selected for presentation here. These results are typical for each composition investigated. The results for all 10 films examined are not presented since this would involve an excessive number of data plots. However the additional information provided by these data is discussed.

1. Single-polarity pulse experiments

The increment-switching characteristics of films and bits of film of the three compositions were first investigated by applying 25 nsec single-polarity field pulses along the film easy axis. These data indicated the number of weight levels which could be expected, the field values required to switch the films, and relative switching speeds of the three compositions.

The increment-switching characteristics of the films and film bits are shown in Figures 13-18. The percent of the maximum flux change was plotted vs. the number of incrementing field pulses for various magnitudes of applied field. The parameter, percent of maximum flux change, was used in the figures so that the data might be more easily presented. A maximum flux change was recorded when the film magnetization was switched by alternating the polarity of the reset pulse with no incrementing pulses applied. In the figures a value of 0% $\Delta\phi_{max}$ corresponds to one of the two magnetization saturation states while 100% $\Delta\phi_{max}$ means that the film magnetization was reversed to the opposite saturation state. Since the air-flux coupling was cancelled, a flux change recorded was equivalent to a magnetization change.

The experimental results for the film strips are shown in Figures 13, 14 and 15. In each case the magnetization switched per pulse decreased with an increasing number of pulses. For higher magnitude fields the first few incrementing pulses, 50-100, caused a relatively large change in the film magnetization and slope of the magnetization curves changed rather abruptly to a very gradual slope. The NiFe film strips had the largest number of magnetization states which varied nearly linearly with number of pulses. Over 300 states could be used for an appropriate choice of field magnitude. CoFe had the fewest number of linear states, 50 for

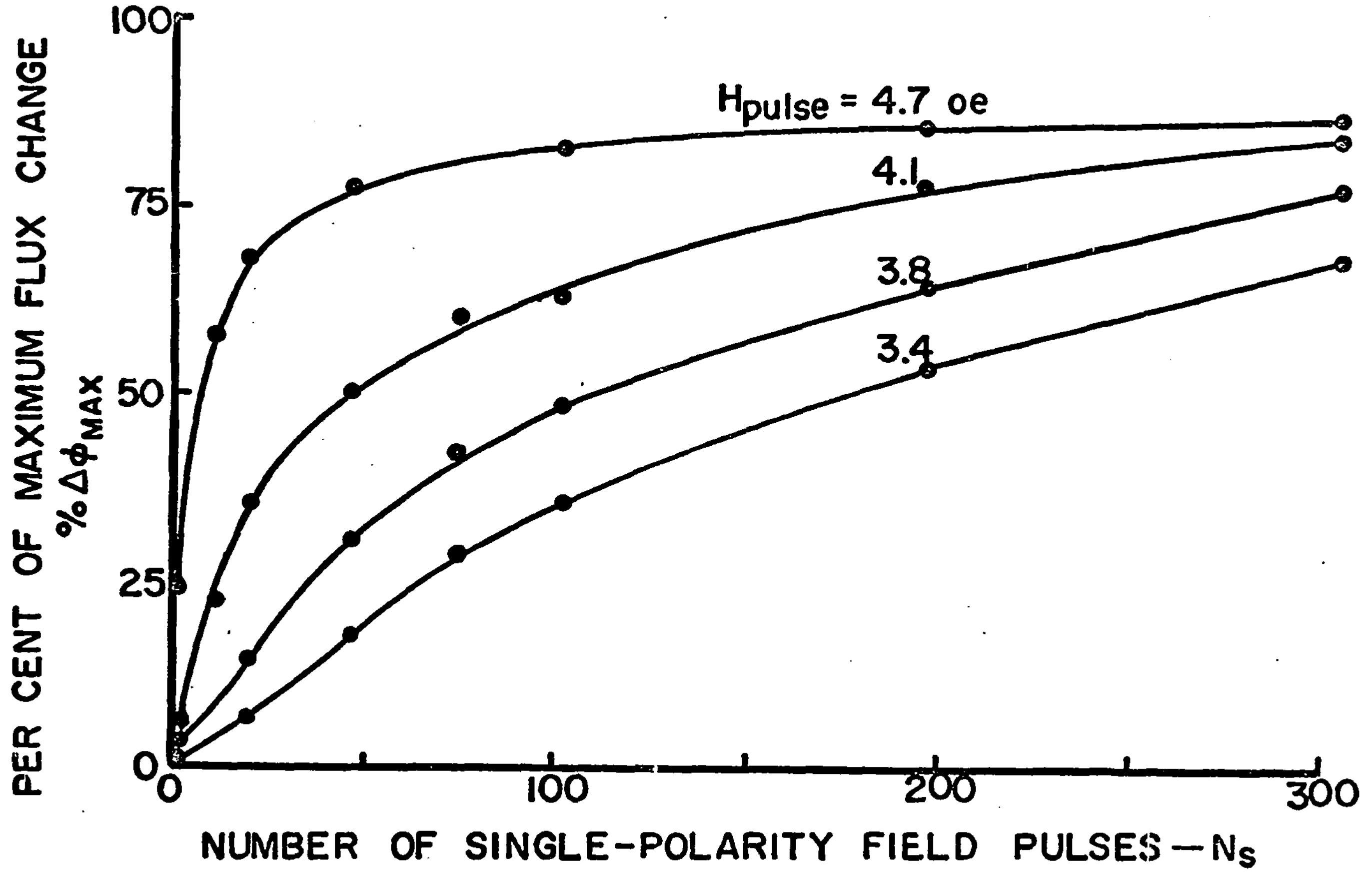


FIG. 13 — EASY AXIS REMANENT MAGNETIZATION OF Ni Fe FILM #13 INCREMENTED BY SINGLE-POLARITY EASY-AXIS FIELD PULSES

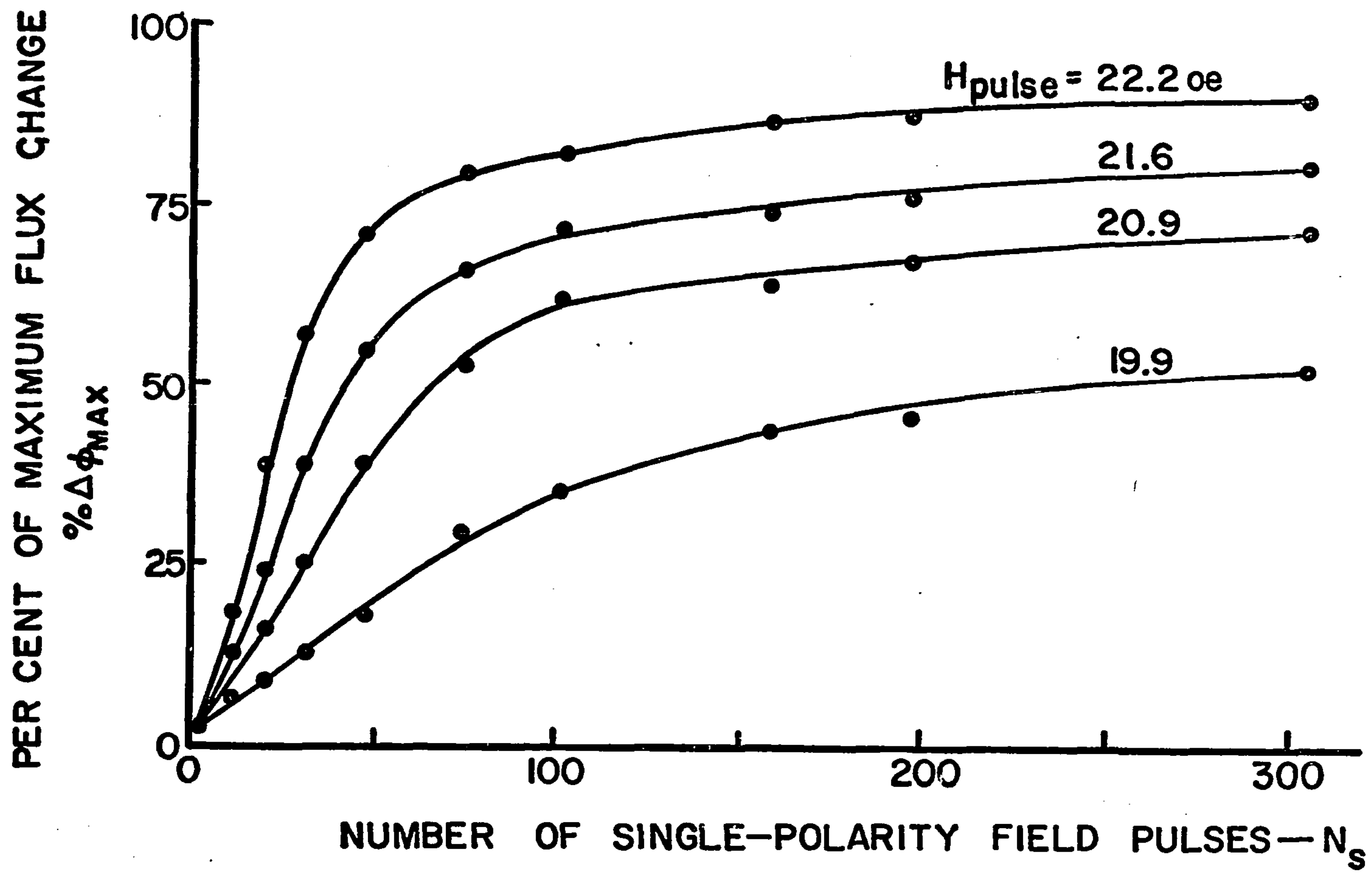


FIG. 14 — EASY AXIS REMANENT MAGNETIZATION OF Co Fe FILM # 87 INCREMENTED BY SINGLE-POLARITY EASY-AXIS FIELD PULSES

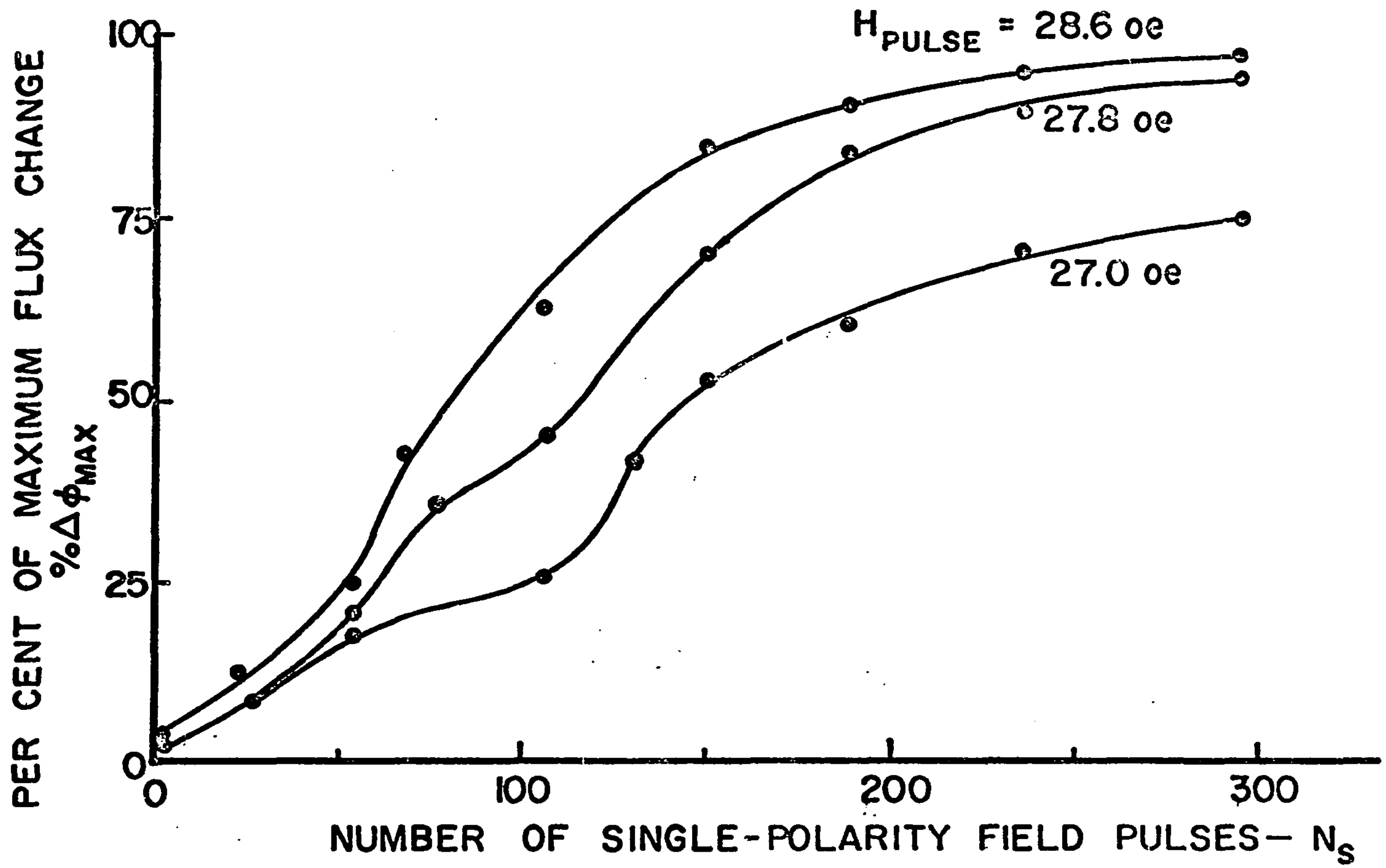


FIG. 15 — EASY-AXIS REMANENT MAGNETIZATION OF CoNi FILM # 106 INCREMENTED BY SINGLE-POLARITY EASY-AXIS FIELD PULSES

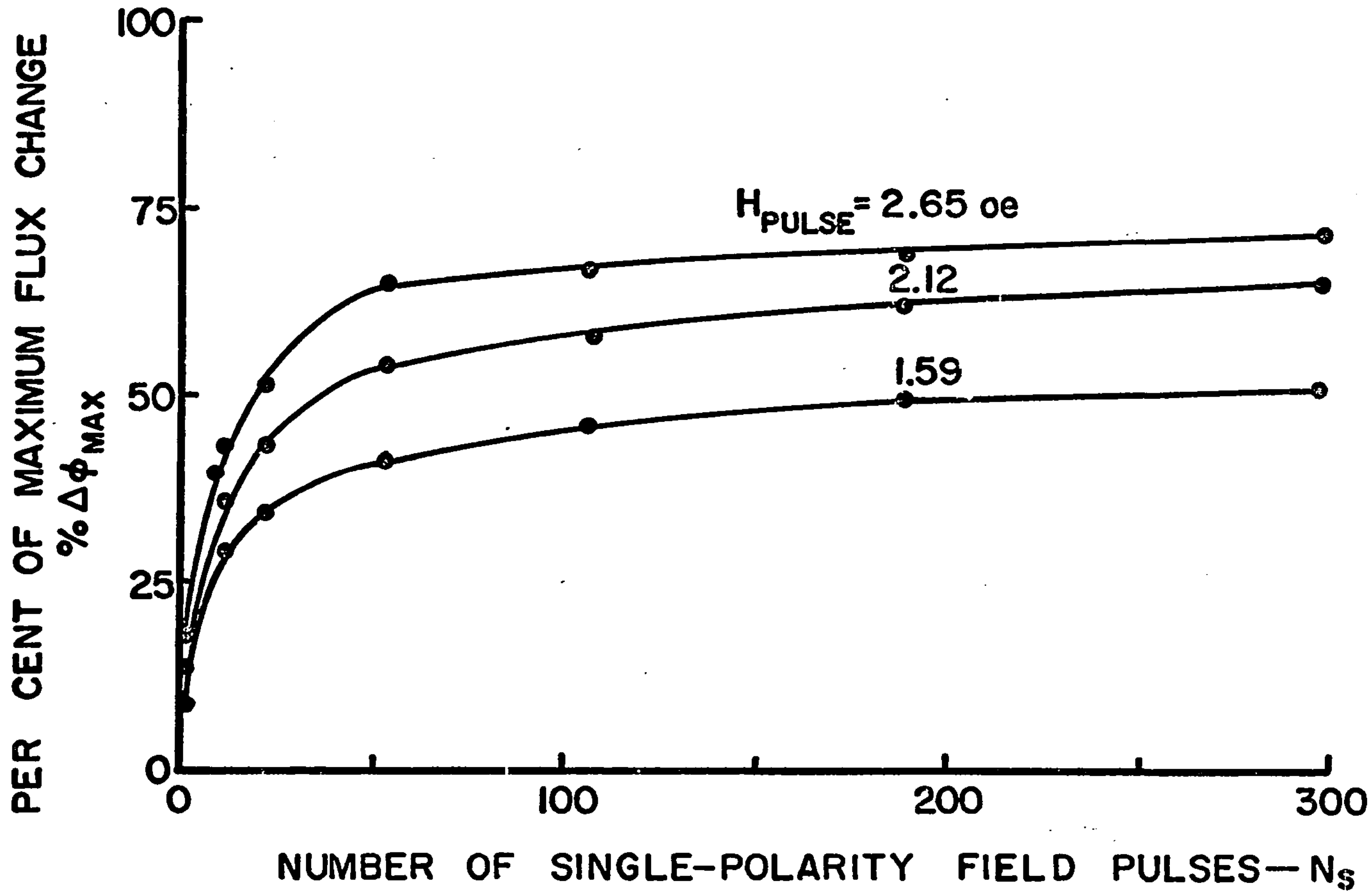


FIG. 16 — EASY-AXIS REMANENT MAGNETIZATION OF Ni Fe FILM BIT #13 INCREMENTED BY EASY-AXIS SINGLE-POLARITY FIELD PULSES

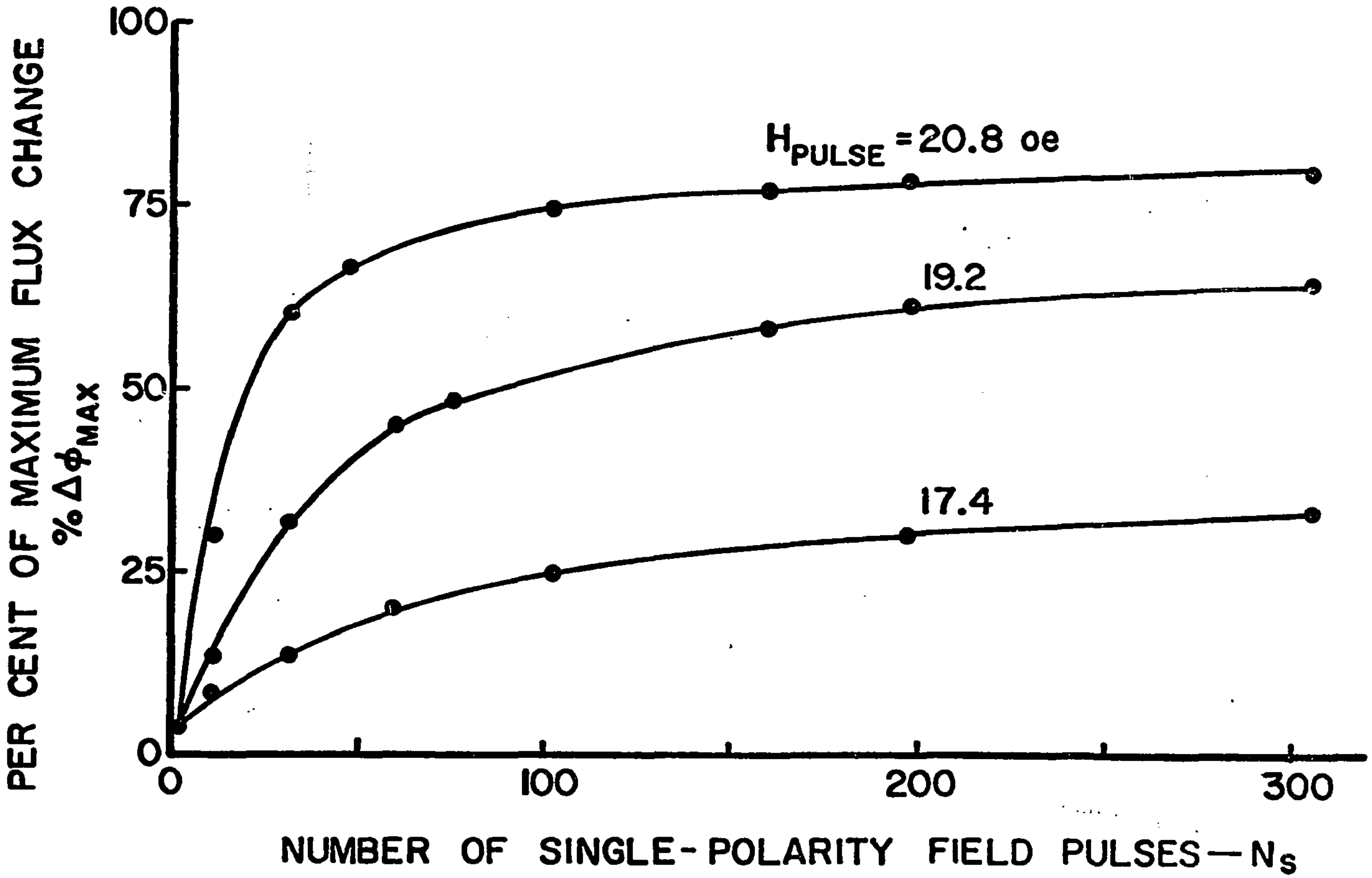


FIG. 17 — EASY-AXIS REMANENT MAGNETIZATION OF CoFe FILM BIT #87 INCREMENTED BY SINGLE-POLARITY EASY-AXIS FIELD PULSES

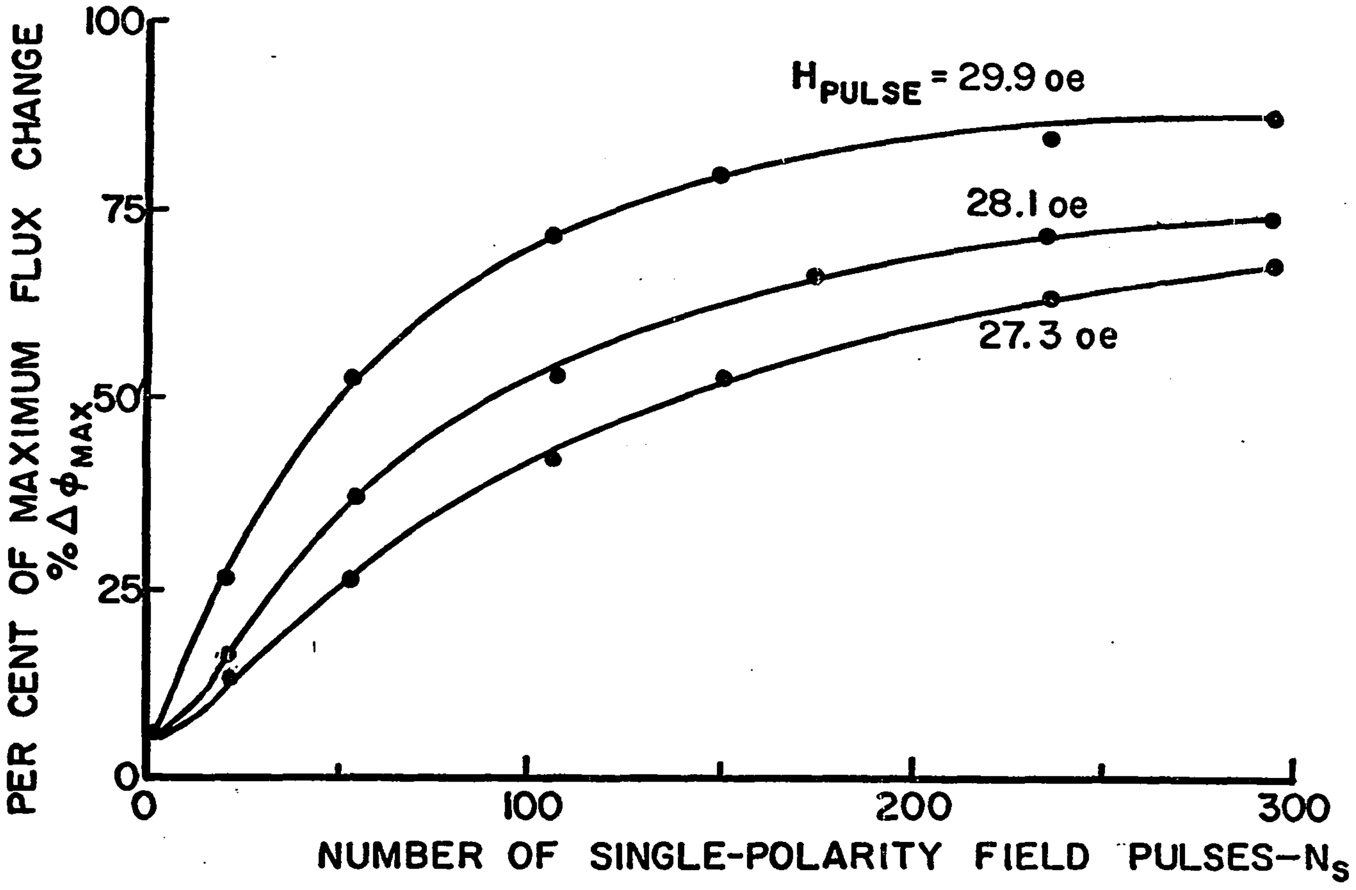


FIG. 18 — EASY-AXIS REMANENT MAGNETIZATION OF Co Ni FILM BIT # 106 INCREMENTED BY SINGLE-POLARITY EASY-AXIS FIELD PULSES

large magnetization changes and about 150 for smaller applied fields.

The incremental switching characteristics of the film bits are shown in Figures 16, 17 and 18. As compared with the results for the film strips the initial magnetization change per applied pulse increased greatly for the NiFe composition and increased slightly for the other film samples.

The magnetization change for a large number of incrementing single-polarity pulses was measured as the magnitude of the pulse was varied. The results of these measurements are shown in Figures 19 and 20 for the film strips and film bits. Examination of the slope of the curves reveals a decreased slope for the film bits which was probably caused by demagnetizing fields from the film edges. Of interest here are the field magnitudes required to initiate and to complete the reversal process. This is important because the results of double-polarity pulse experiments discussed later indicate that the coincident field magnitudes when added cause nearly the same flux change as single-polarity pulses of that magnitude. Therefore, Figures 19 and 20 show what combination of double-pulse magnitude and bias magnitude can be used to switch the film magnetization. Also indicated are the shakedown or partial-switching effects of the coincident currents when applied individually.

As shown in Figure 19 for the film strips, coincident

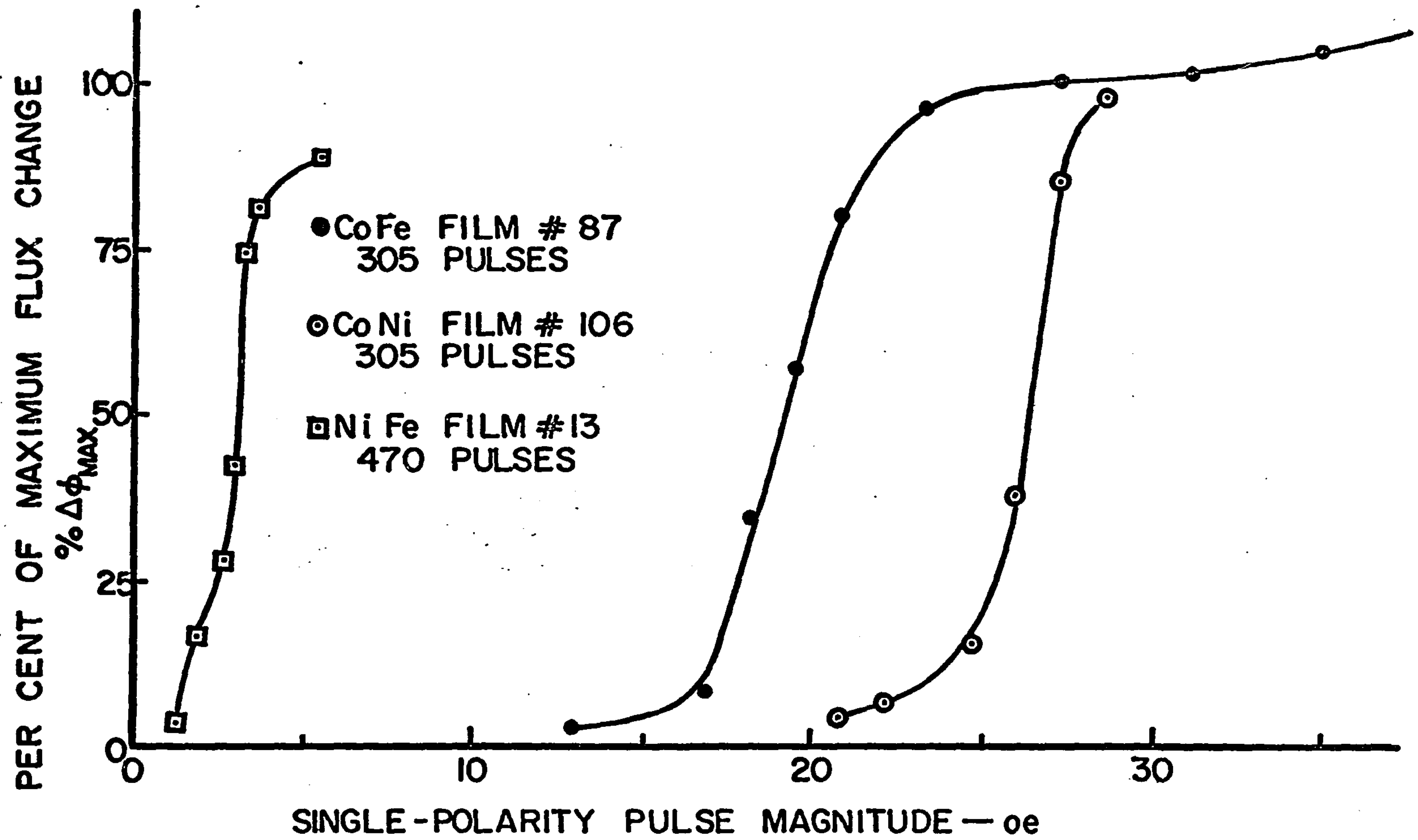


FIG. 19— EASY-AXIS REMANENT MAGNETIZATION OF CoFe, CoNi, AND NiFe FILMS INCREMENTED BY MANY SINGLE-POLARITY EASY-AXIS FIELD PULSES

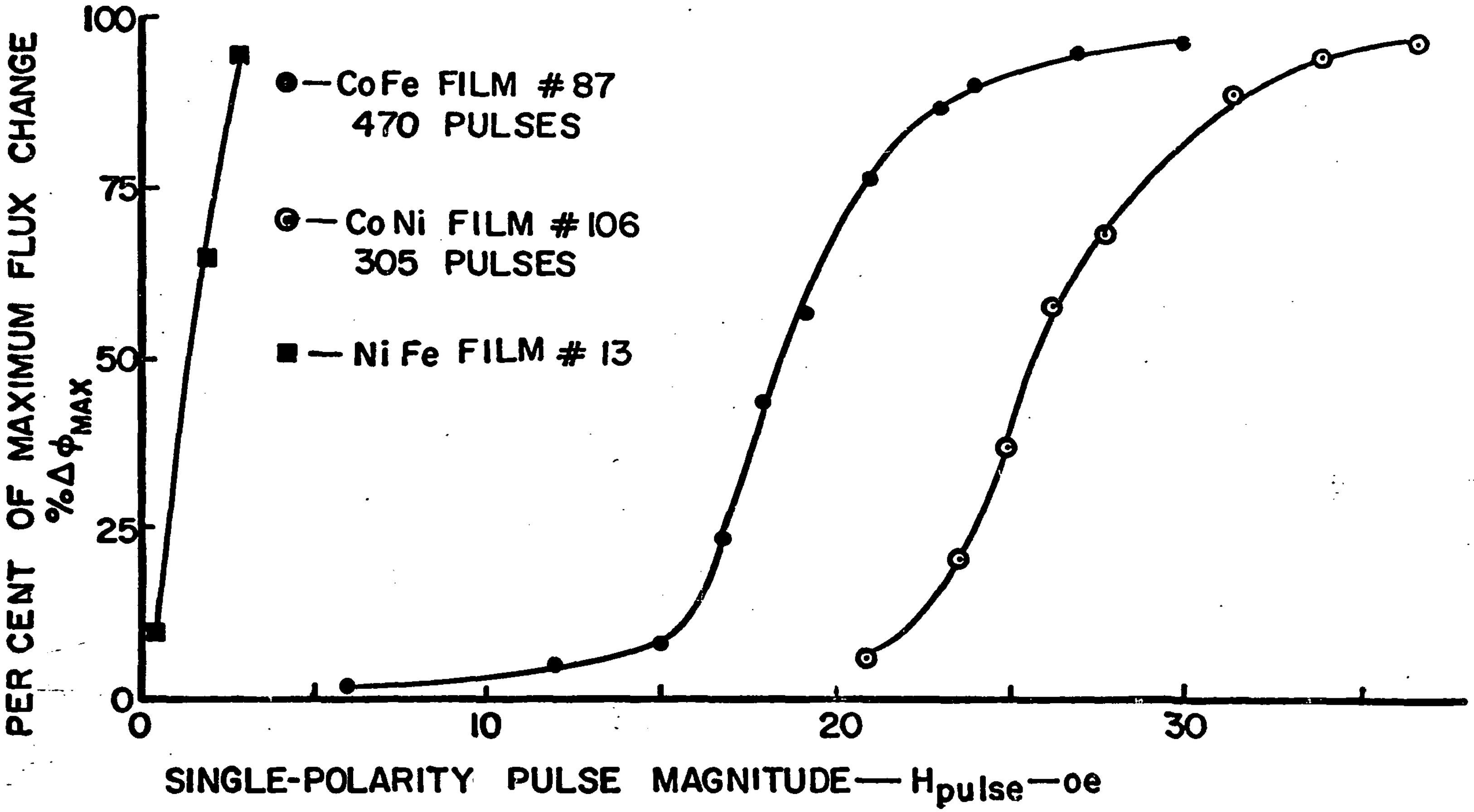


FIG. 20 - EASY-AXIS REMANENT MAGNETIZATION OF CoFe, NiFe, AND CoNi BITS INCREMENTED BY MANY SINGLE-POLARITY EASY-AXIS FIELD PULSES

fields each equal to 1/2 of the total field required to switch most of the magnetization can be used to adjust the remanent state. These fields when applied alone cause less than a 2% change in the remanent state of either the CoFe or CoNi compositions. However, at least a 10% change occurred in the remanent state of the NiFe film and a slight increase in the field magnitude will cause a much greater change.

The results for the film bits given in Figure 20 indicate that the magnetization of the NiFe film bit can not be satisfactorily adjusted by coincident fields. The data show that there is no combination of bias and incrementing pulse magnitudes which can be used to switch most of the film magnetization without having one of the fields large enough such that the field applied alone would cause a considerable magnetization change. This observation was confirmed by the double-polarity pulse experiments. However, the performance of the NiFe bit could probably be improved by decreasing the width of the bit which should decrease demagnetizing effects along the easy axis.

a. Summary of single-polarity pulse experiments The results of incrementing the magnetization of the film strips indicated that the NiFe film switched more slowly than the other films when incremented with the lower magnitudes of applied pulses. However, the NiFe film obviously switched faster than the other films when incremented with the higher values of applied field. This is explained by the measurements made with a large number of pulses (Figure 19). As shown in Figure 19 the NiFe curve of % $\Delta\phi_{max}$ vs. magnitude of applied pulse has a greater slope than the other curves and that CoFe has the least slope. The slope of these curves is important since the flux switched per applied pulse is directly related to the area of the pulse which exceeds the curve. It is apparent that more pulse area exceeds the curve for CoFe than for the other films. However, as the pulse magnitude is increased to values which nearly saturate the film magnetization, the effect of the slope of the curves should become less important. Therefore, the switching speeds of these films should be compared at the higher values of applied field. The comparison at higher fields as mentioned above reveals that the NiFe films switch faster than the CoFe films.

The results of incrementing the film bits agree with the above conclusion. Note that the switching speed of the NiFe bit was increased over that of the NiFe film and was much greater than that of either the CoFe or CoNi bits. However, the slope of the NiFe bit characteristic for a large number of pulses (Figure 20) was greater than the slopes of the other bits. The increased switching speed of the NiFe bit agrees with the decreased slope of the characteristic and the conclusion that the NiFe composition switches faster is not affected by the slopes of the characteristic (if the NiFe bit slope was less than the other slopes then there might be some doubt by the preceding argument).

The results indicate that the performance of the CoFe composition was superior to the NiFe composition in terms of switching speed and stability. Also, the CoFe bit performance can probably be improved by changing the bit shape and by obtaining films with a more "square" hysteresis loop.

2. Double-polarity pulse experiments

As explained earlier, the magnetization of the memory film in an array would be switched in increments by the coincident application of double-polarity pulses and bias pulses applied along the film easy-axis. The experiments discussed here indicate the performance of the film samples when coincident currents are used to adjust the magnetization.

The percent magnetization change vs. the number of incrementing pulses was examined for films and bits of films of nearly all the film samples listed in Table 1 on page 16. Presented in Figures 21-25 are the results for film samples 87, 106 and 13. The films were incremented from both saturation states in order to investigate the symmetry involved. The data were taken in the following manner: the number of incrementing pulses was fixed, the flux change was recorded for one polarity of bias and reset, and then the flux change was recorded for the other polarity of bias and reset. The bias and reset fields were applied in opposite directions.

In order to obtain symmetrical flux changes for the film strips for both polarities of bias field it was necessary to first demagnetize the film by applying a large alternating field along the transverse axis of the film. Sometimes nearly symmetric flux changes were observed after this procedure. In that case a small magnet was momentarily placed near the film with the field applied along the hard axis which caused a slight change in the remanent state. This process was repeated until symmetrical flux changes were recorded. Symmetrical flux changes were always recorded for the film bits. The problems encountered in obtaining symmetrical flux changes for the film strips indicated that fields from the surrounding film seriously bias the reversal process. In fact, these results indicate that continuous film analogue memory elements would not perform satisfactorily unless the entire memory plane could be demagnetized (or magnetized and the effect balanced) before beginning to classify input patterns.

The results of the measurements for the film strips are shown in Figures 21, 22 and 23. A comparison of the results for the film strips indicates that NiFe films switch faster than the other compositions for the larger values of applied fields. The data for the other films examined support this observation.

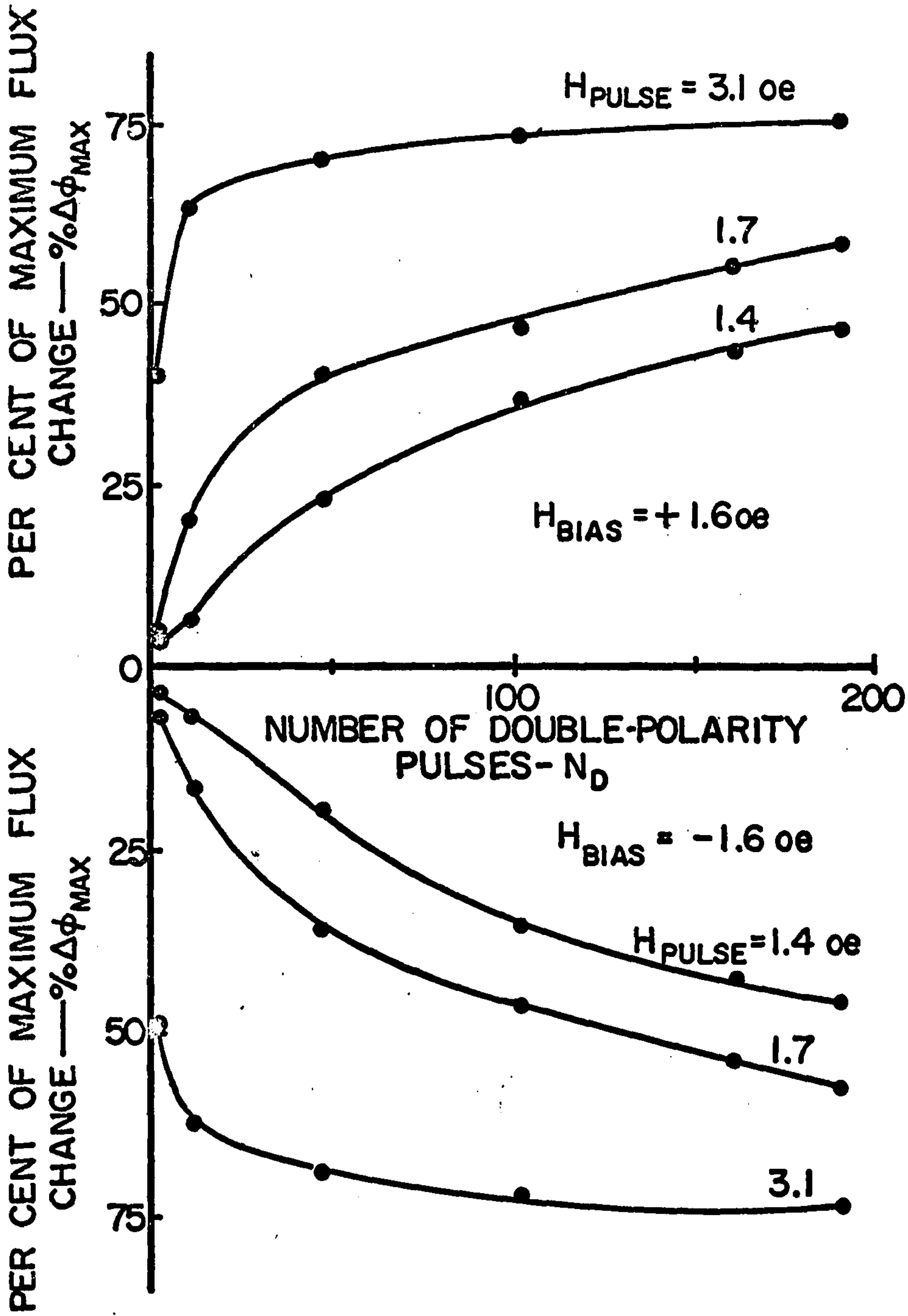


FIG. 21 — EASY-AXIS REMANENT MAGNETIZATION OF NiFe FILM # 13 INCREMENTED BY COINCIDENT DOUBLE-POLARITY AND BIAS EASY-AXIS FIELD PULSES

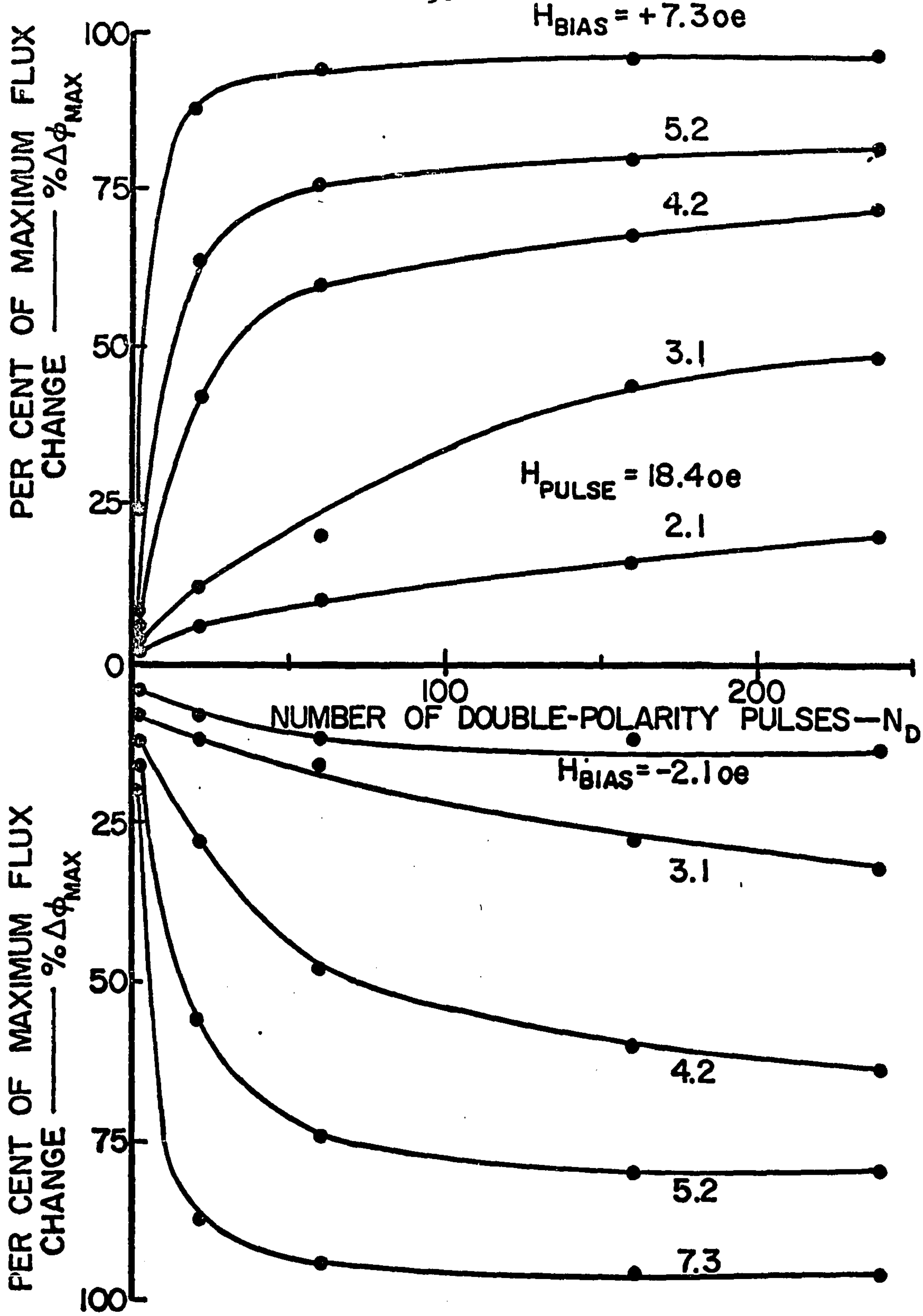


FIG. 22—EASY-AXIS REMANENT MAGNETIZATION CoFe FILM #87 INCREMENTED BY COINCIDENT DOUBLE-POLARITY AND BIAS FIELD PULSES

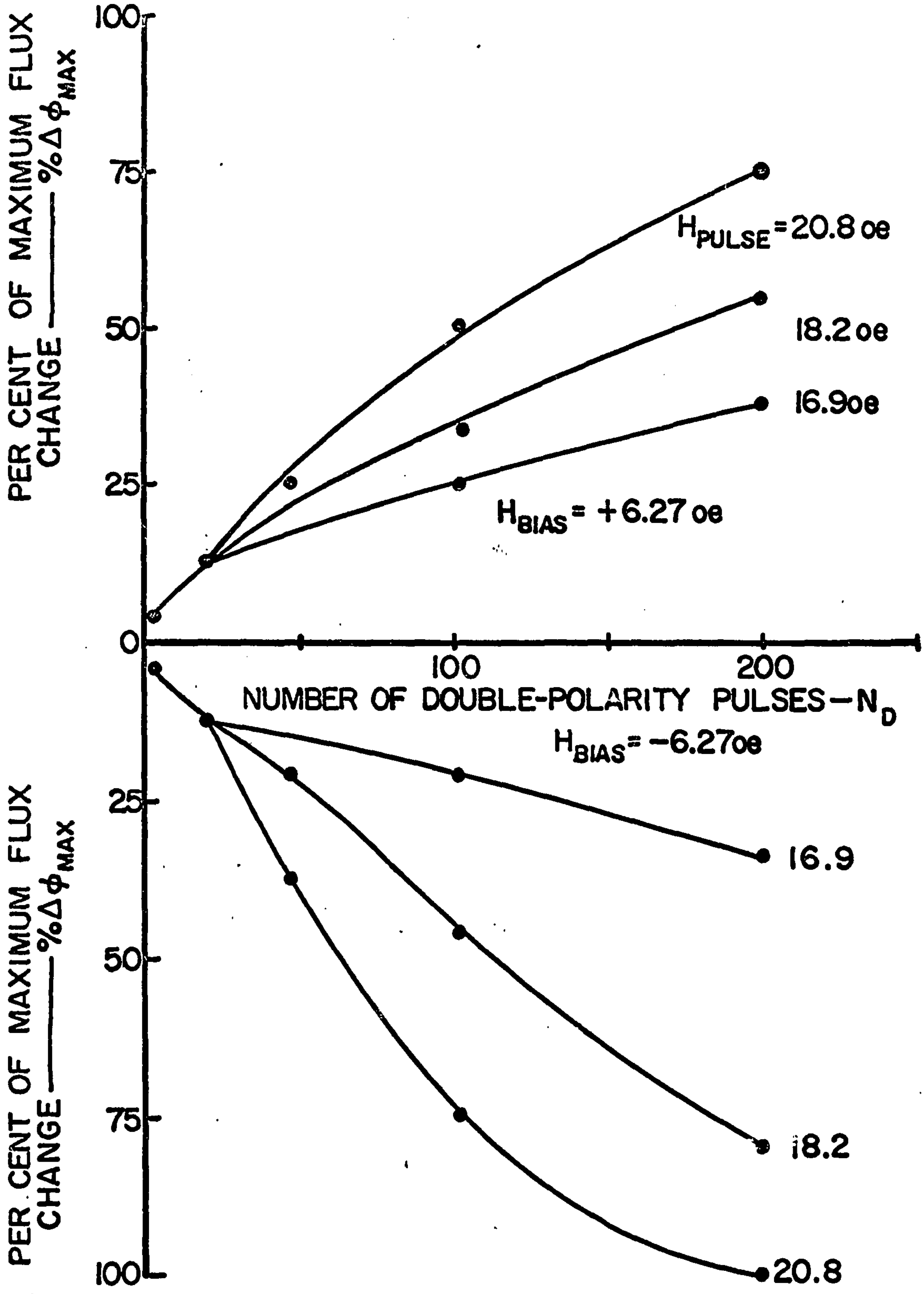


FIG. 23 — EASY-AXIS REMANENT MAGNETIZATION OF Co Ni FILM # 106 INCREMENTED BY DOUBLE-POLARITY EASY-AXIS FIELD PULSES

The performance of the bits incremented with coincident double-polarity pulses and a bias pulse was as before quite different than the results for the films. As was indicated in the single-polarity pulse experiments, the NiFe bit did not perform satisfactorily. The data in Figure 24 for the NiFe bit show that shakedown effects caused by the double-polarity pulses or switching caused by the bias pulse would prevent the successful coincident-current operation of an array of NiFe bits.

The CoFe bit and CoNi bit performed almost the same as film strips of the same compositions. As shown in Figures 25 and 26 a slight increase in the switching speed was observed for the bits; i.e. the initial slopes of the curves are steeper for the bits than for the film strips for equal flux change after a large number of incrementing pulses.

Of the three compositions the CoNi bit apparently had the largest number of linear remanent states. However, one other CoNi film examined did not have as many linear states. All five of the other CoFe film bits examined had nearly the same switching characteristics which indicated that the reversal process was nearly the same for each film.

These data indicate that the CoFe and CoNi film bits can be incremented with coincident easy-axis field pulses over a large range of magnetization with little shakedown or partial-switching for fields applied alone. Also, the film magnetiza-

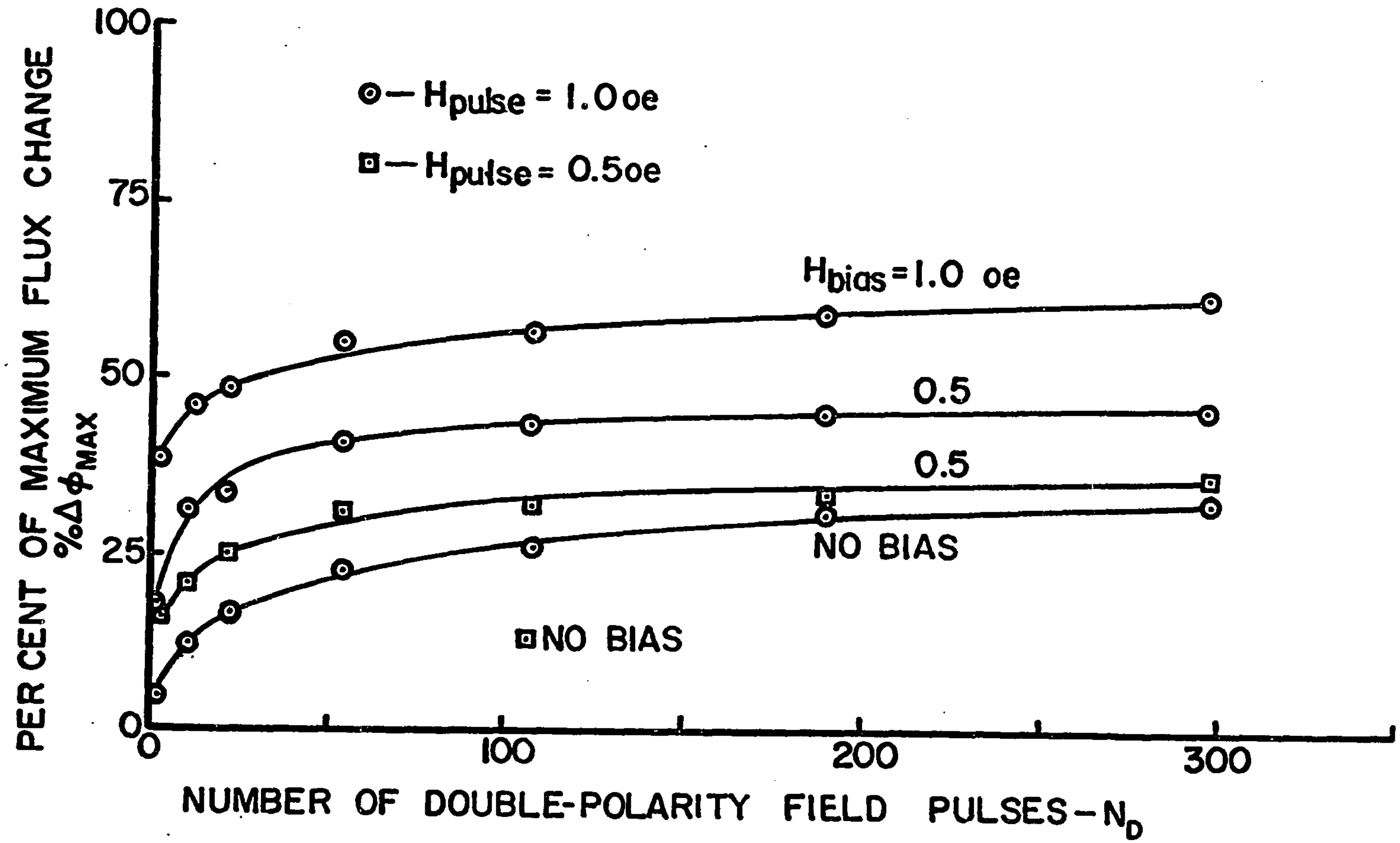


FIG. 24 — EASY-AXIS REMANENT MAGNETIZATION OF Ni Fe FILM BIT #13 INCREMENTED BY DOUBLE-POLARITY EASY-AXIS FIELD PULSES

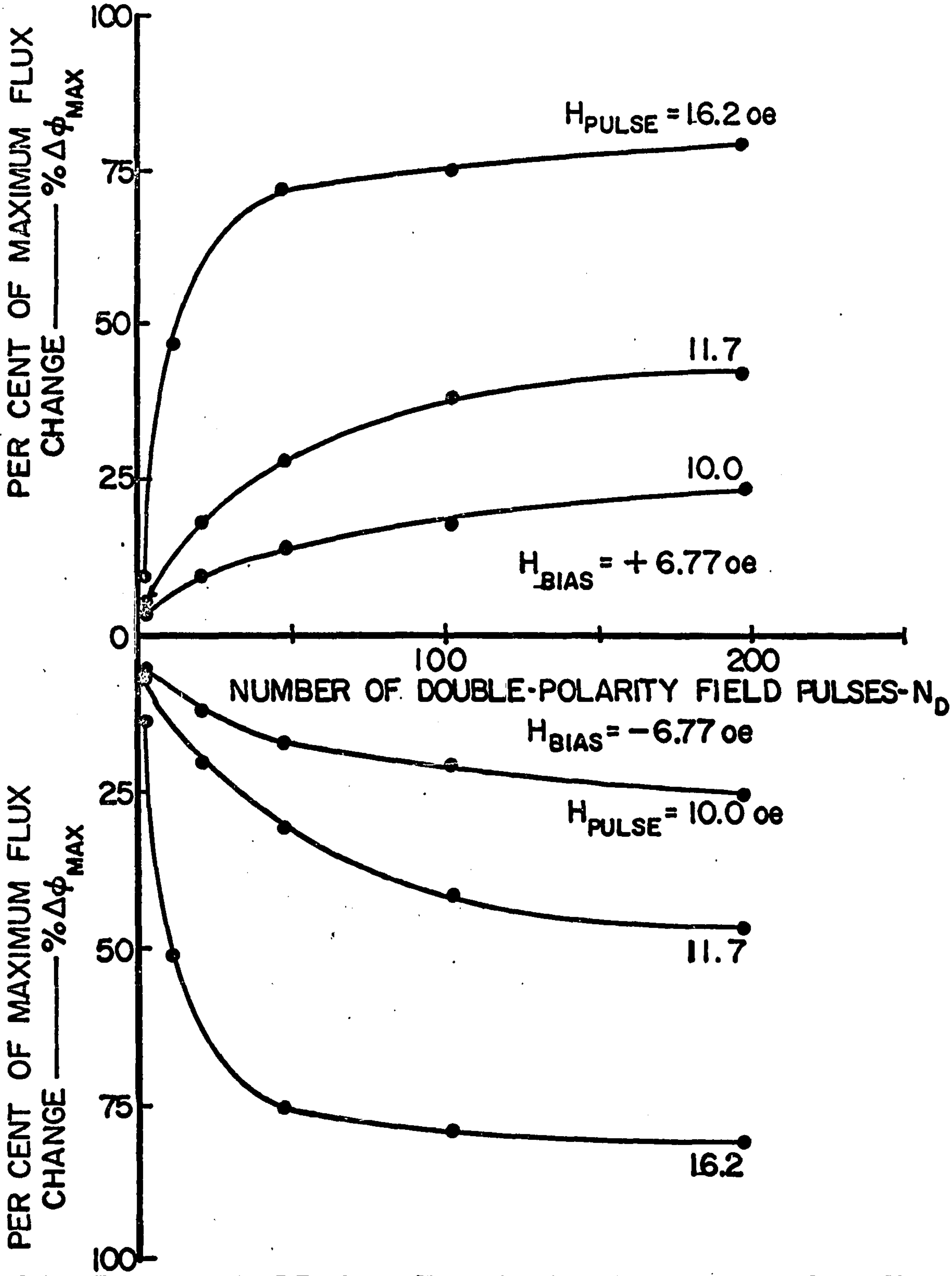


FIG. 25 — EASY-AXIS REMANENT MAGNETIZATION OF CoFe BIT #87 INCREMENTED BY COINCIDENT DOUBLE-POLARITY AND BIAS EASY-AXIS FIELD PULSES

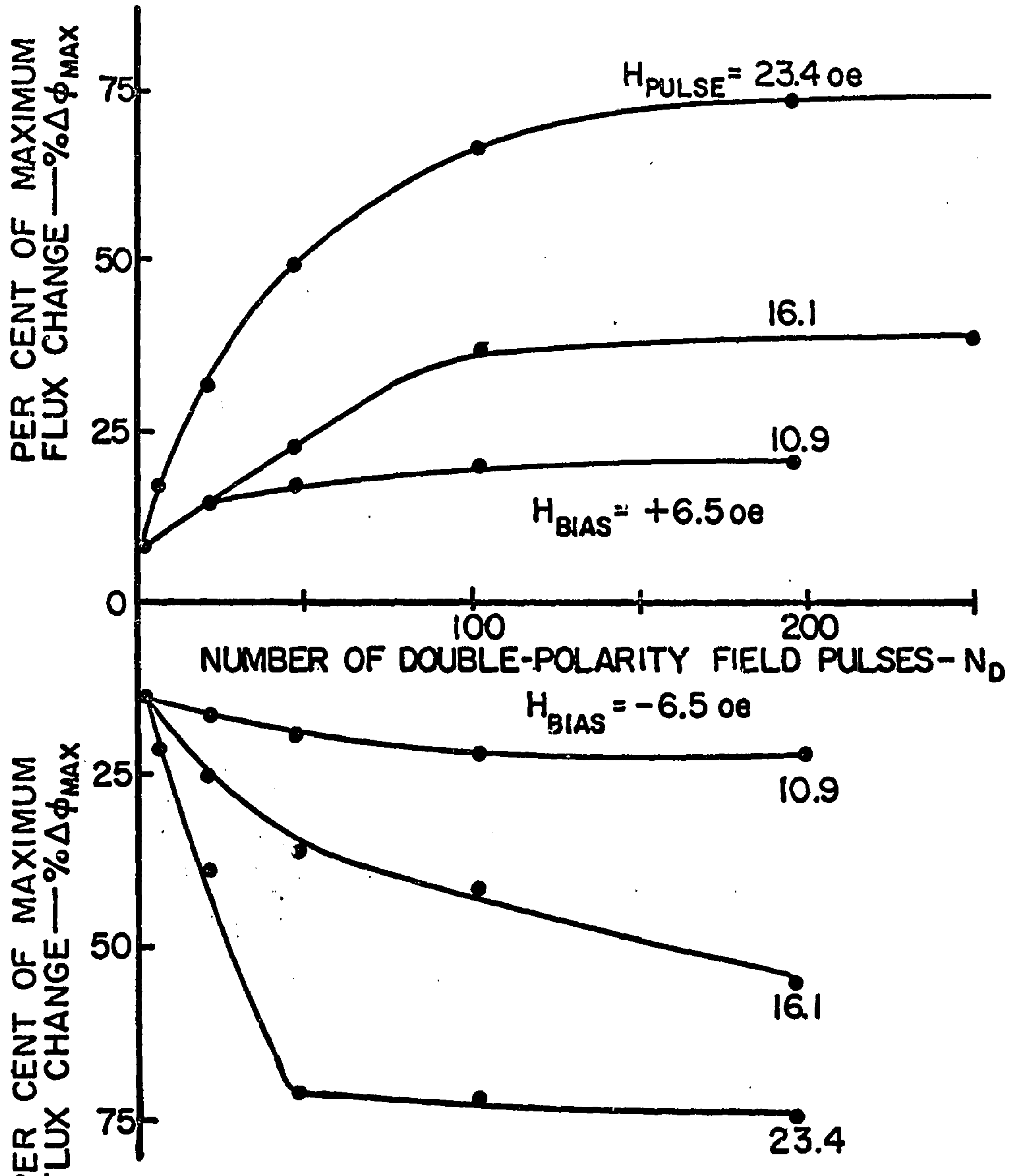


FIG. 26 — EASY-AXIS REMANENT MAGNETIZATION OF CoNi BIT # 106 INCREMENTED BY DOUBLE-POLARITY EASY-AXIS PULSE WITH A BIAS FIELD

tion was repeatedly incremented to a given remanent state after hours of performing experiments which indicated that the reversal process was stable with time and reliable.

The percent magnetization change for a large number of double-polarity pulses was measured as the magnitude of the coincident bias was varied as shown in Figures 27-31. The purpose of these measurements was to determine the characteristics for this mode of coincident adjustment of the magnetization. As shown in Figures 27, 28 and 29 the characteristics for each film composition did not differ significantly for the continuous films. However, the performance of the film bits differed as before. Data are not given for the NiFe bit because the magnetization could not be satisfactorily adjusted by coincident currents without having one of the coincident currents large enough to cause a significant change in the film magnetization when applied alone. The results for film bits of CoFe and CoNi are shown in Figures 30 and 31. Note that the effect of decreasing the pulse magnitude was to shift the characteristics on the bias axis.

3. CoFe operating characteristics

The preceding measurements were concerned with determining the initial incremental switching characteristics of films and bits of films. Of interest also is the character of returning the magnetization towards the initial state by coin-

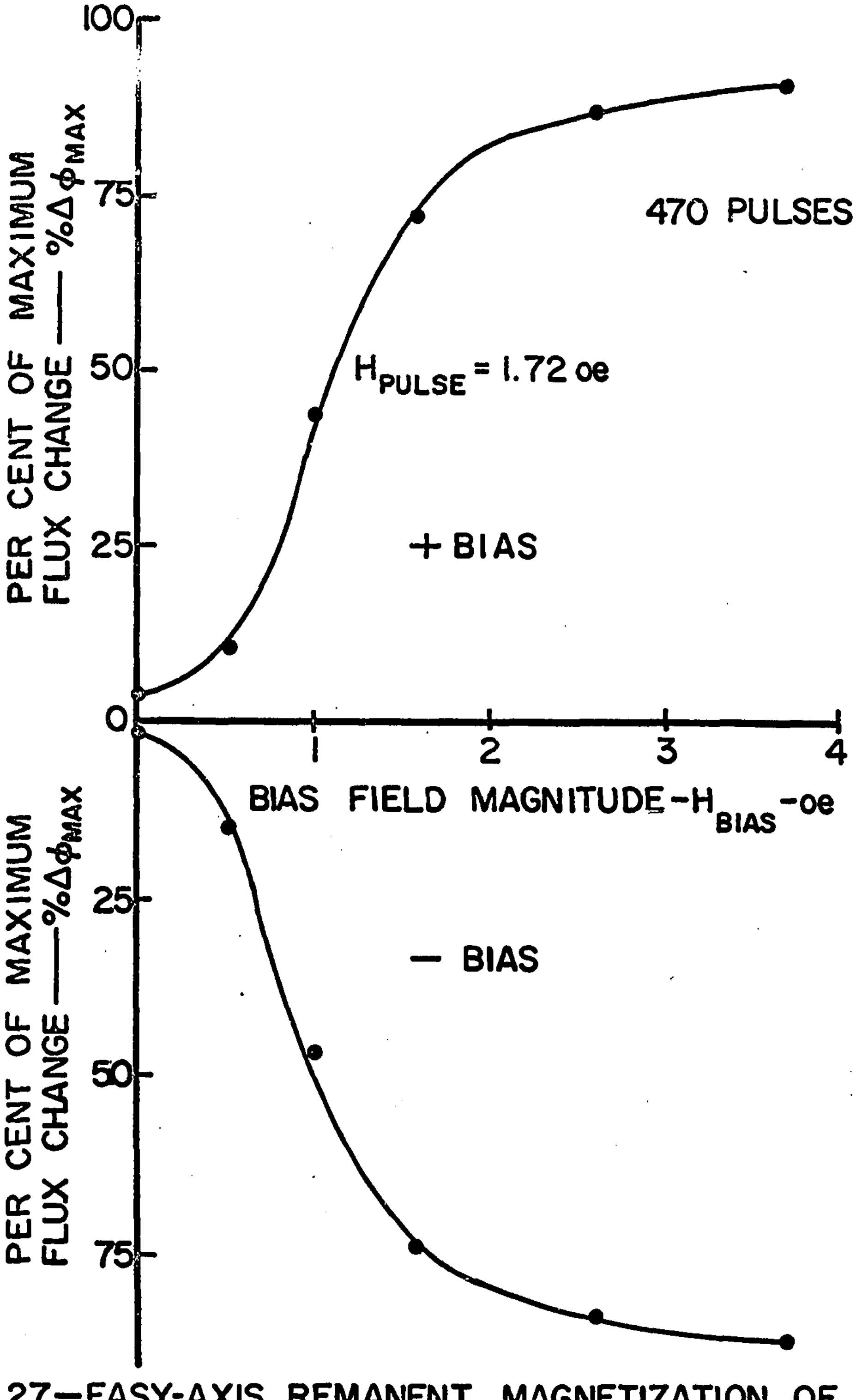


FIG. 27—EASY-AXIS REMANENT MAGNETIZATION OF NiFe FILM # 13 INCREMENTED BY DOUBLE-POLARITY PULSES AND VARIABLE BIAS FIELD

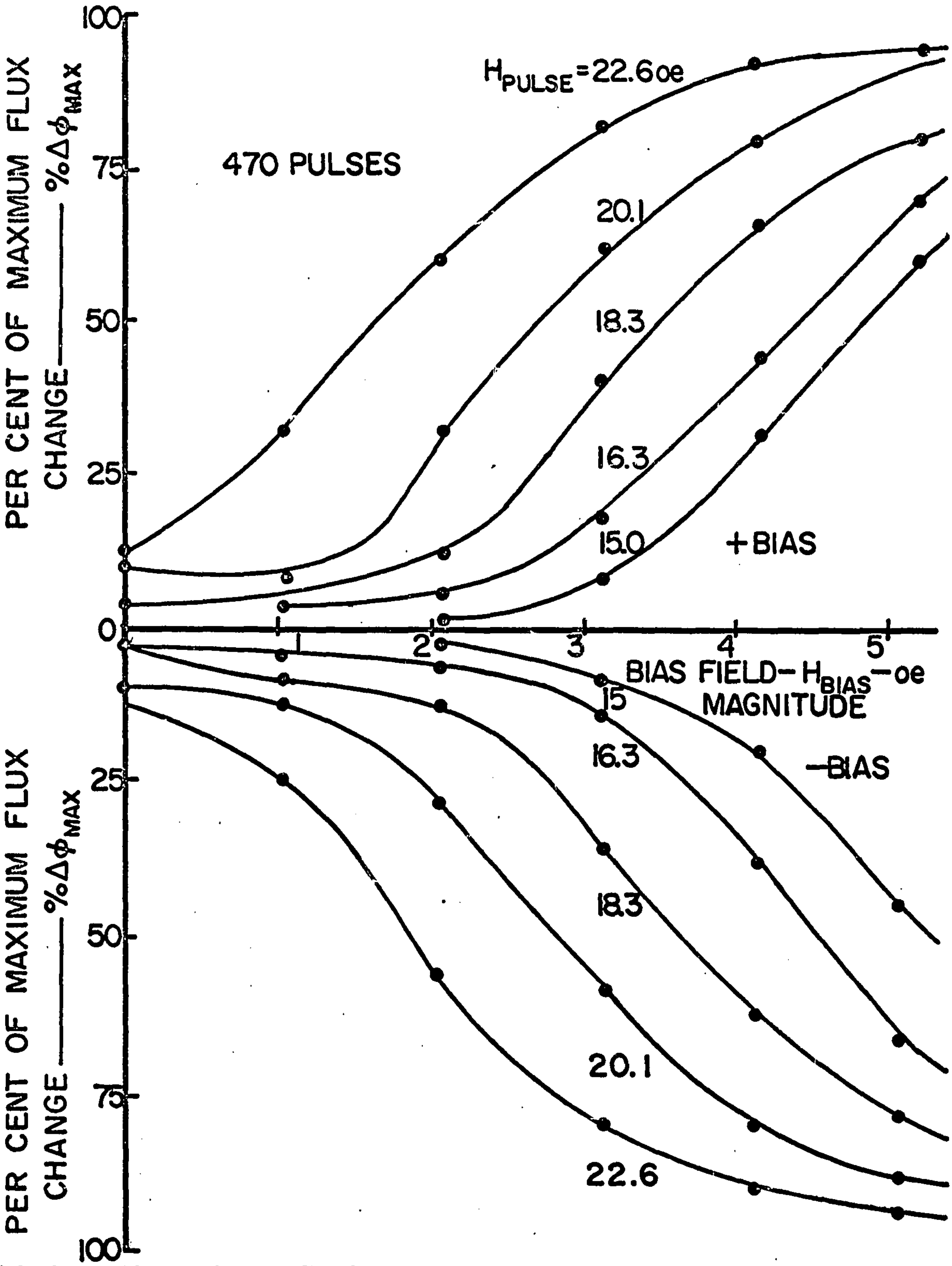


FIG. 28—EASY-AXIS REMANENT MAGNETIZATION OF CoFe FILM #87 INCREMENTED BY DOUBLE-POLARITY PULSES VARIABLE BIAS FIELD

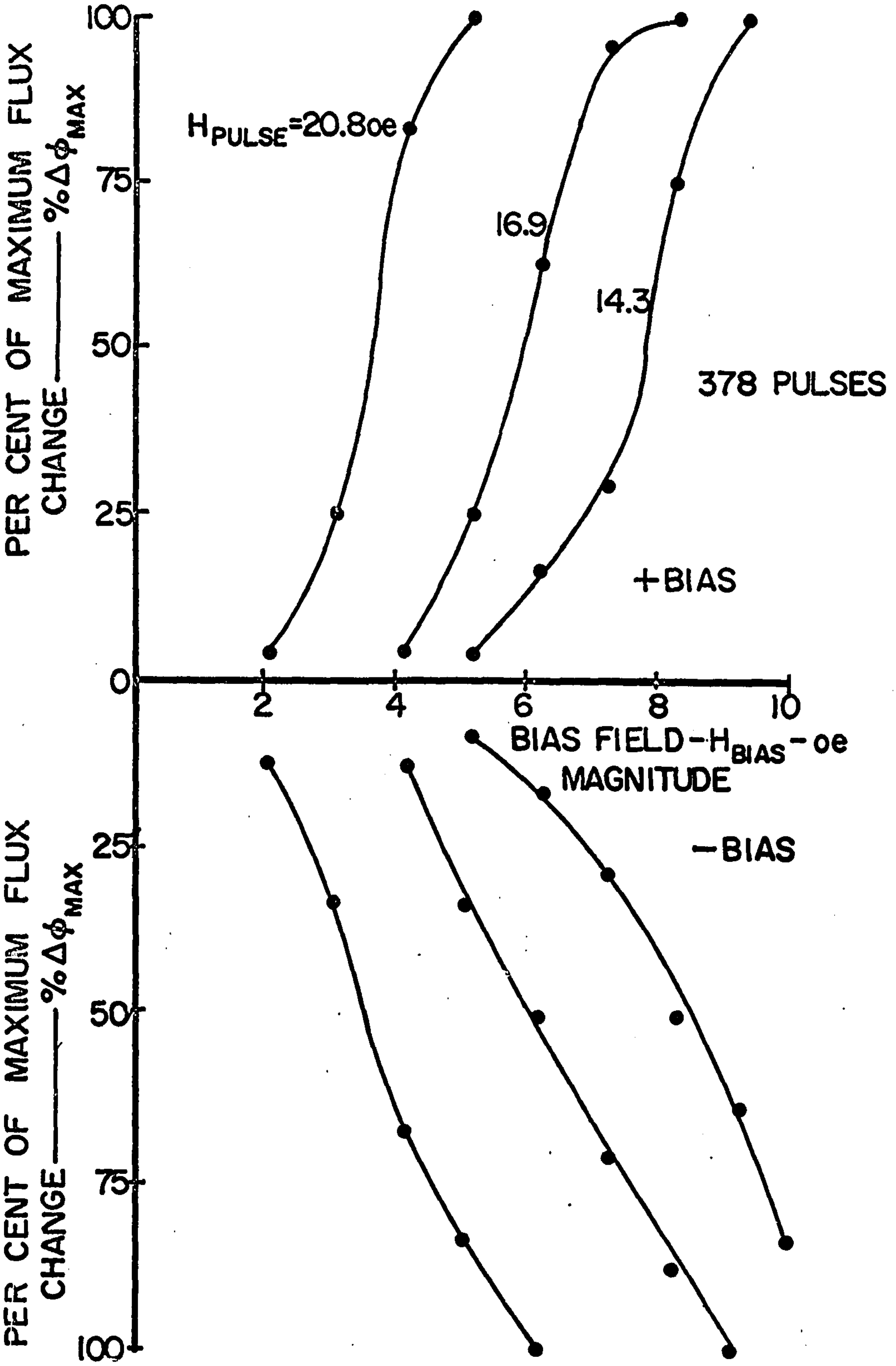


FIG. 29 — EASY-AXIS REMANENT MAGNETIZATION OF CoNi FILM #106 INCREMENTED BY DOUBLE POLARITY PULSES AND VARIABLE BIAS PULSE

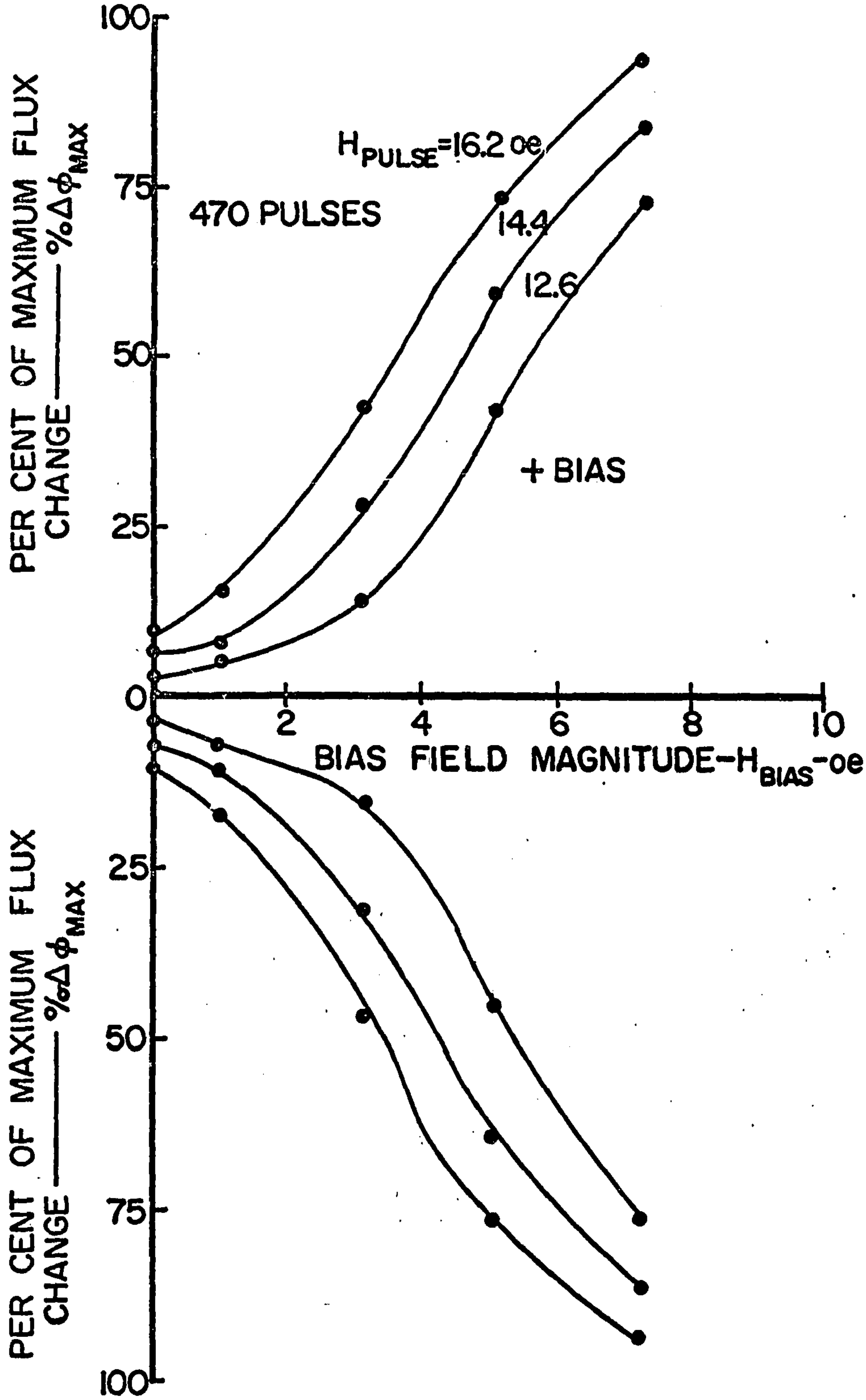


FIG. 30 — EASY-AXIS REMANENT MAGNETIZATION OF CoFe BIT #37 INCREMENTED BY DOUBLE-POLARITY PULSES AND VARIABLE BIAS FIELD

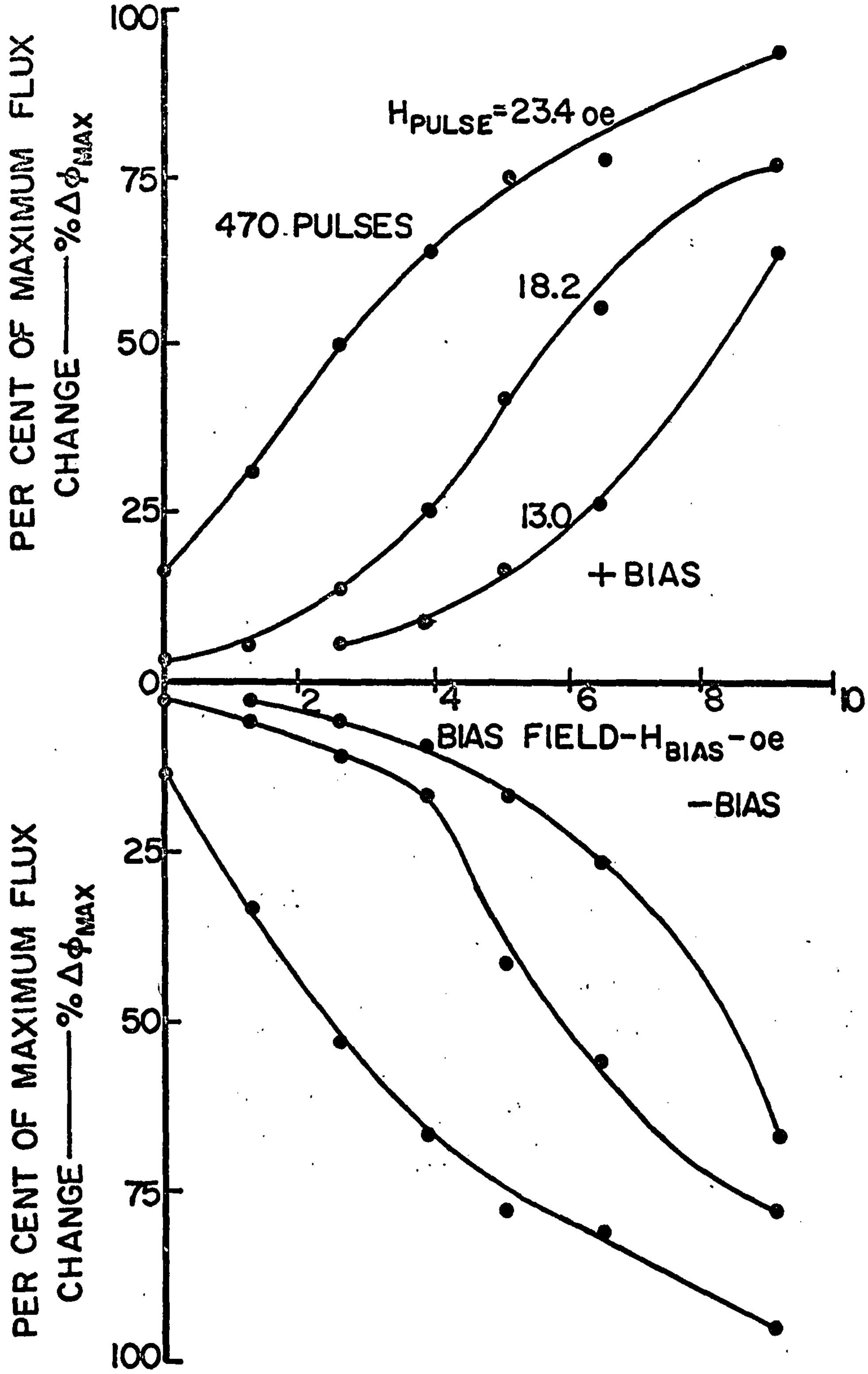


FIG. 31—EASY-AXIS REMANENT MAGNETIZATION OF CoNi BIT #106 INCREMENTED BY DOUBLE-POLARITY PULSES AND VARIABLE BIAS FIELD

cident incrementing pulses. Only CoFe bit No. 87 was examined because the measurements took considerably longer than previous experiments, the relative performance of the various compositions of films and bits of film had already been investigated, and the preceding measurements indicate that a CoFe bit would be the most useful memory element.

The measurements were made by applying a pulse series as follows: a large number of incrementing double-polarity pulses were applied coincident with one polarity of bias, then a variable number of incrementing pulses with the opposite polarity of bias were applied, and finally a large reset pulse was applied. The results of these measurements are shown in Figures 32, 33 and 34 for three values of incrementing pulse magnitude. One characteristic was selected from each of Figures 32, 33 and 34 for summary in Figure 35.

These measurements indicate that the element magnetization can be incremented back and forth between saturation limits over at least 35 remanent states which are nearly linear with the number of applied incrementing pulses. Several hundred states can be obtained for smaller changes of magnetization or for nonlinear operation.

The operating characteristics were also obtained for a large number of incrementing pulses as shown in Figure 36. In this mode of operation the magnetization was adjusted by varying the magnitude of the bias pulse. The pulse sequence

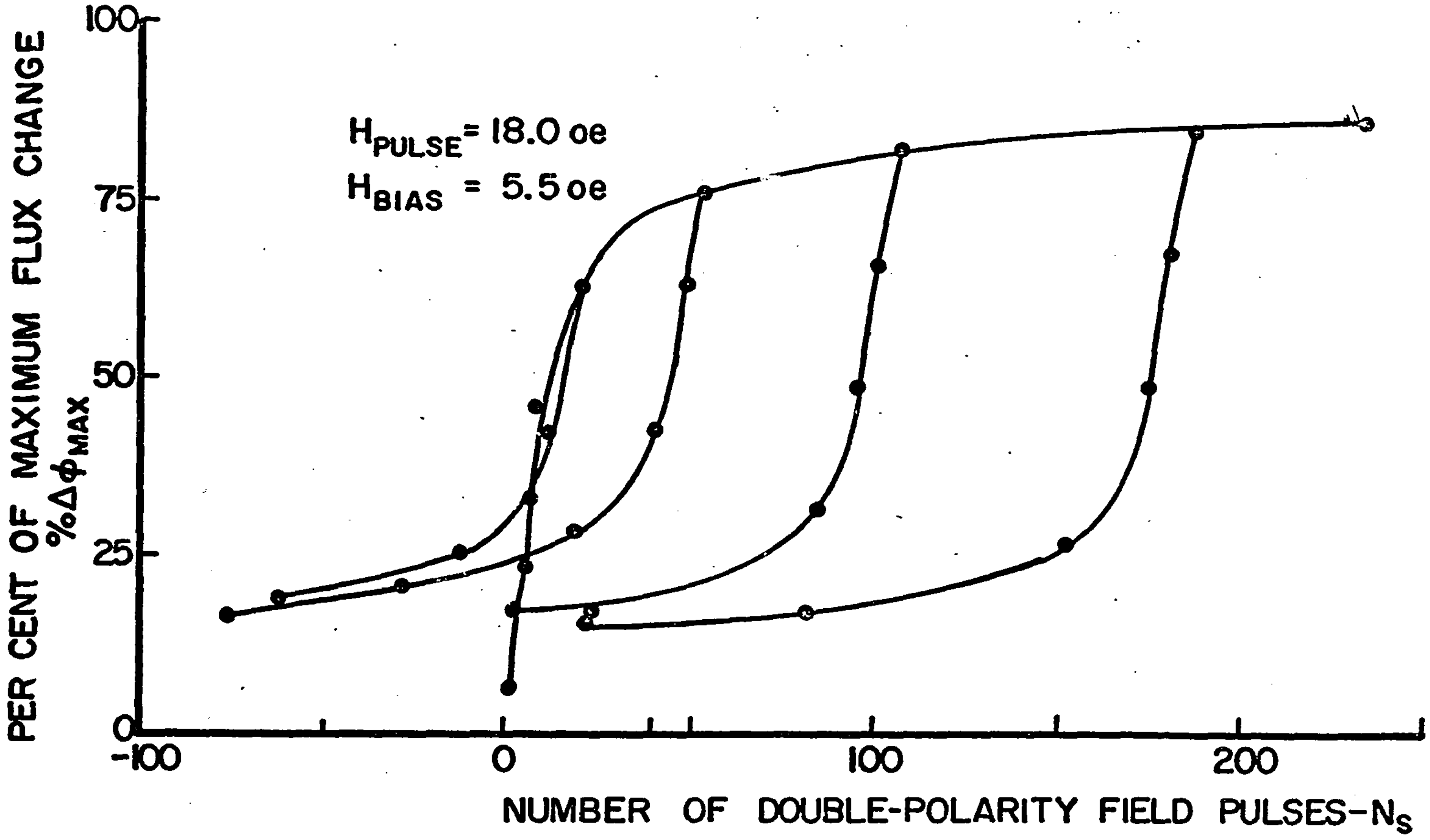


FIG. 32 — EASY AXIS REMANENT MAGNETIZATION OF CoFe BIT # 87 INCREMENTED BY DOUBLE-POLARITY EASY-AXIS FIELD PULSES AND D-C BIAS FIELD

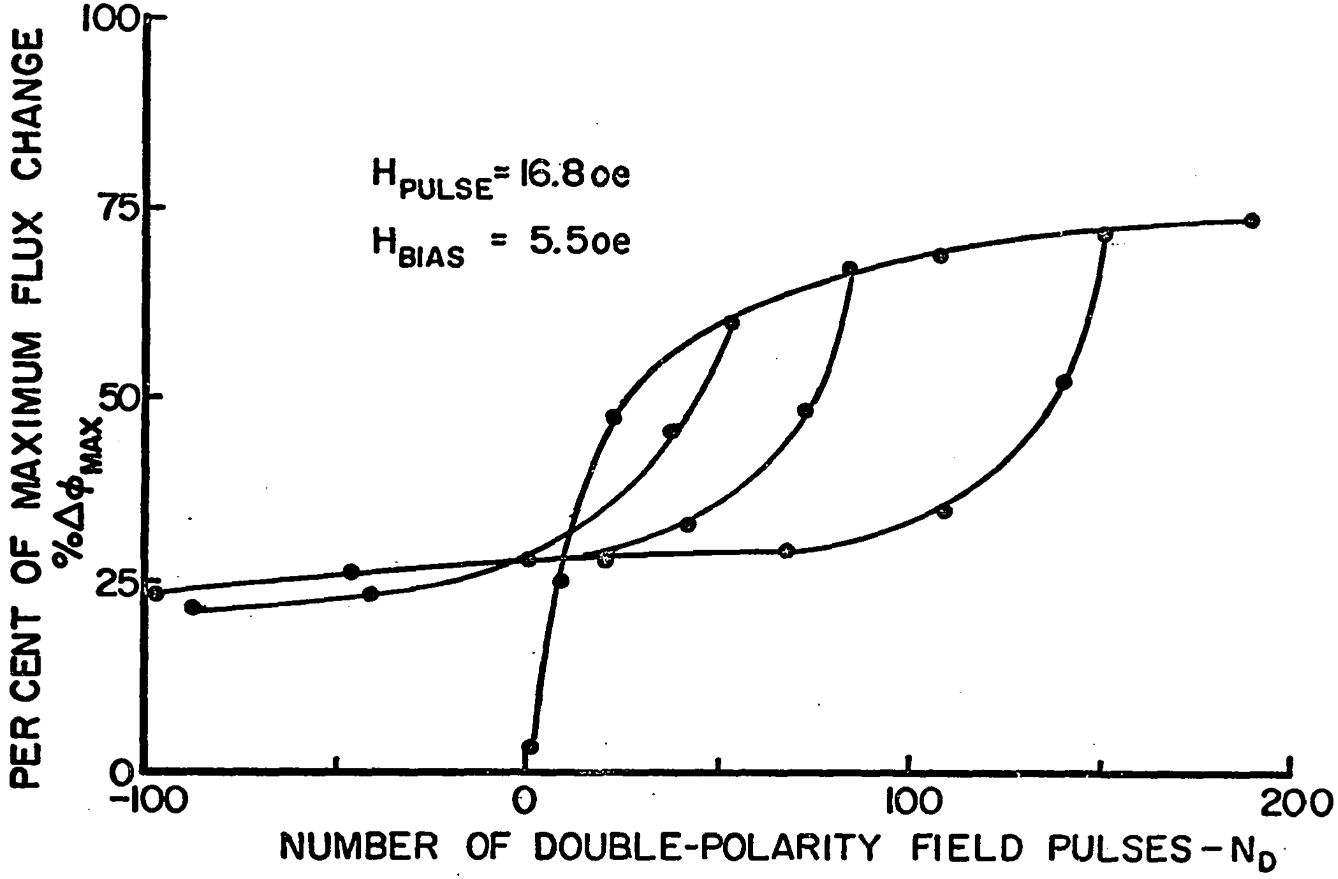


FIG. 33 — EASY-AXIS REMANENT MAGNETIZATION OF CoFe BIT #87 INCREMENTED BY DOUBLE-POLARITY EASY-AXIS FIELD PULSES AND D-C BIAS FIELD PULSE

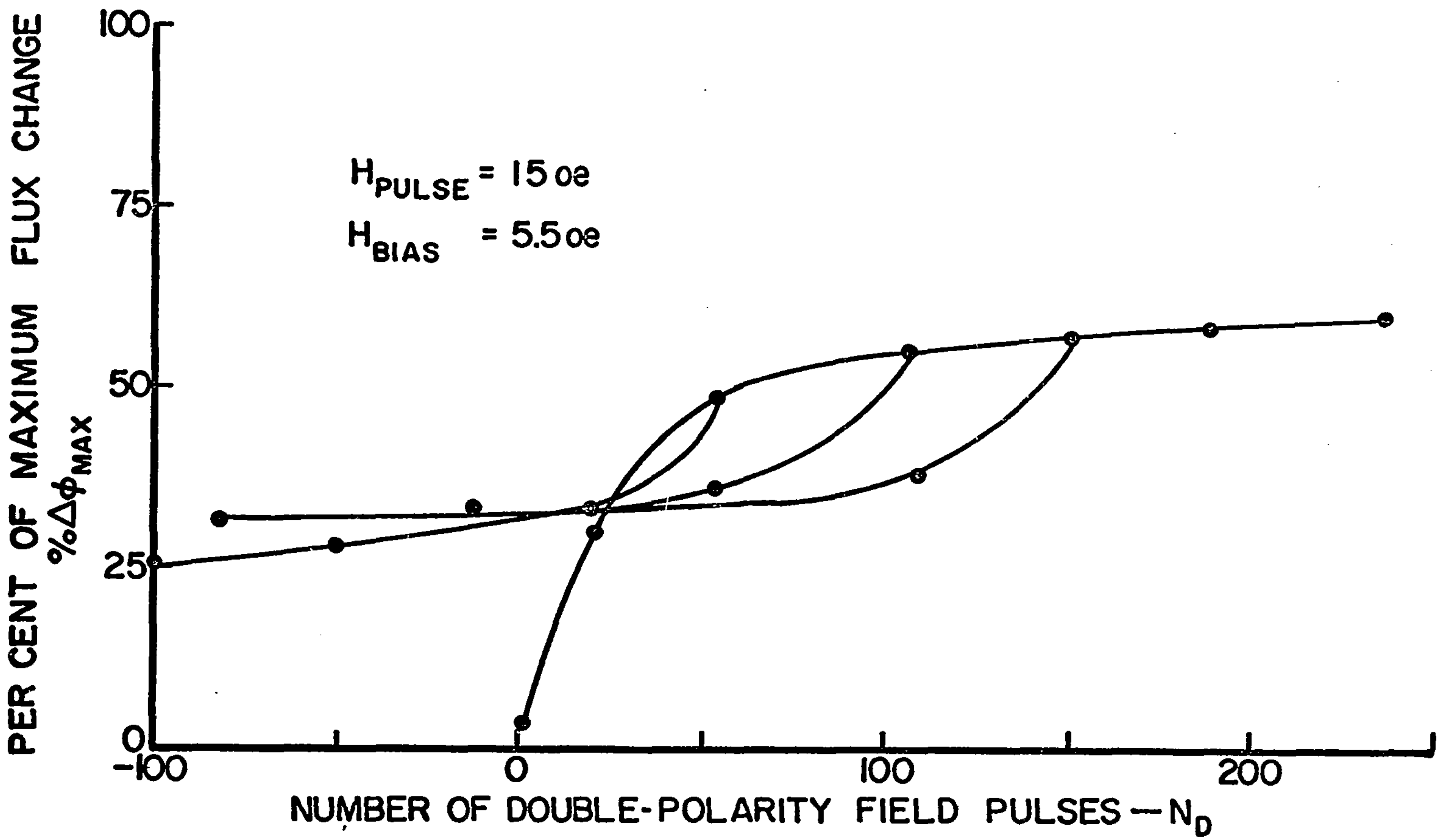


FIG. 34 — EASY-AXIS REMANENT MAGNETIZATION OF CoFe BIT # 87 INCREMENTED BY DOUBLE-POLARITY EASY-AXIS FIELD PULSES AND D-C BIAS FIELD PULSE

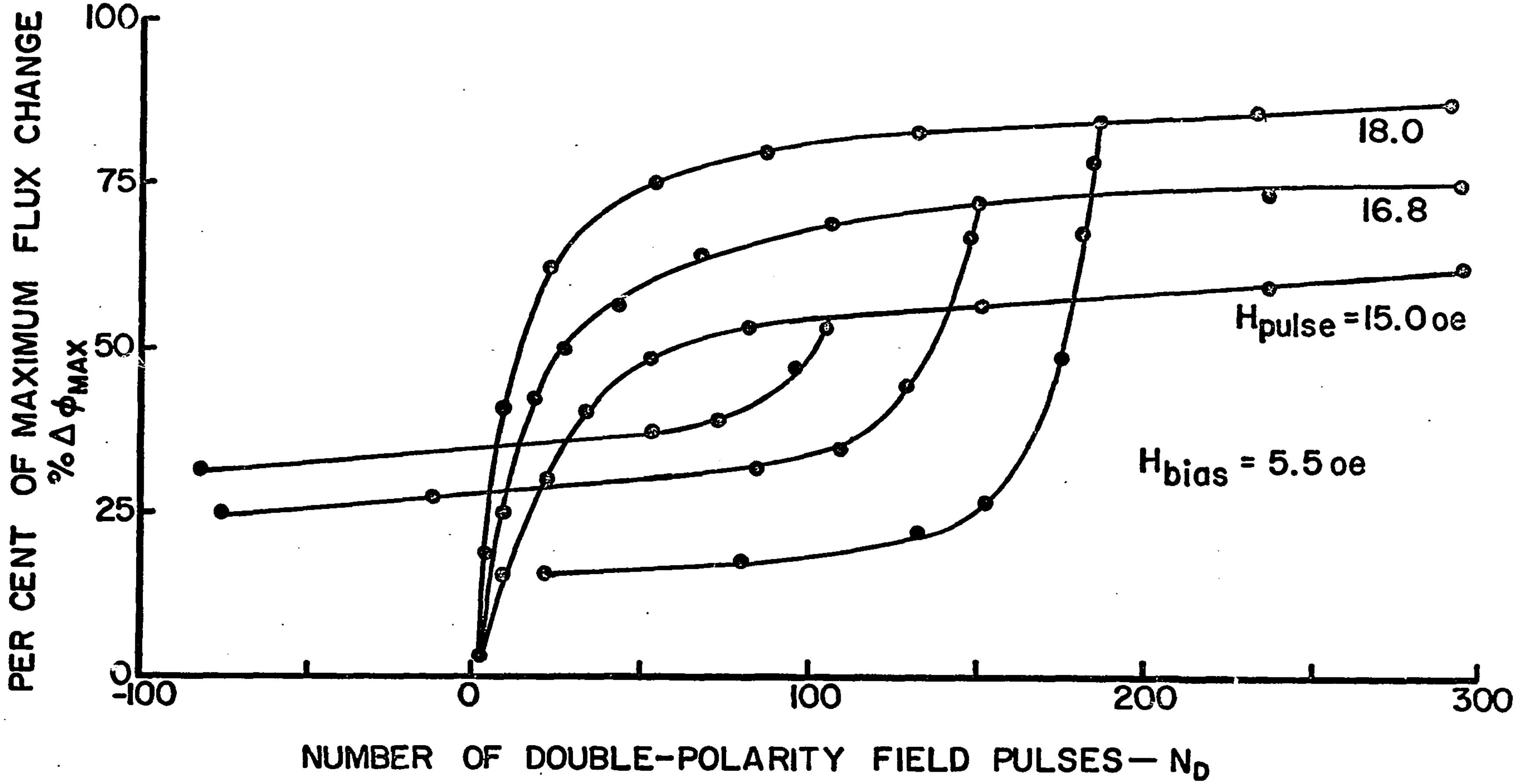


FIG. 35— EASY-AXIS REMANENT MAGNETIZATION OF CoFe FILM BIT # 87 INCREMENTED BY DOUBLE-POLARITY EASY-AXIS FIELD PULSES AND D-C BIAS FIELD

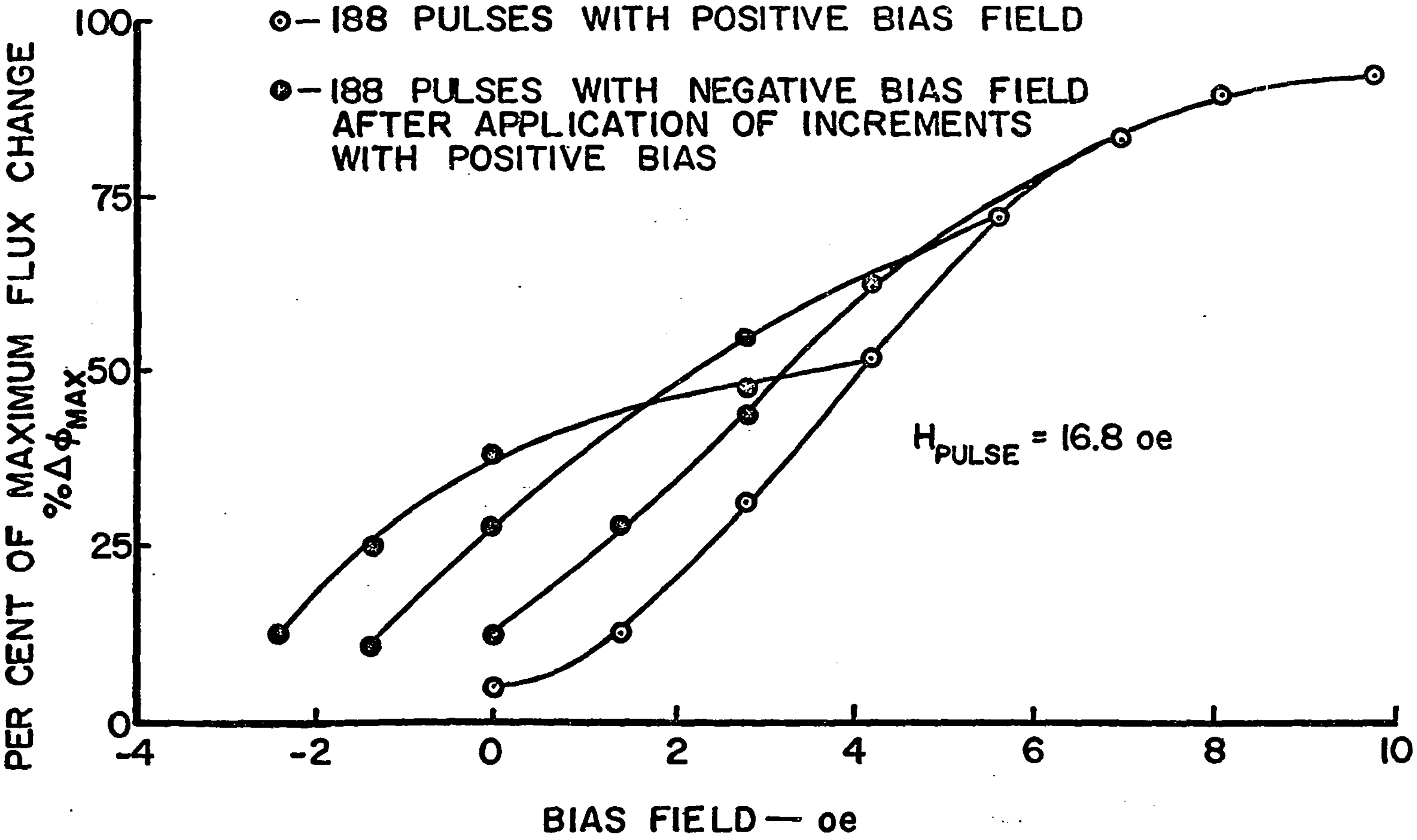


FIG. 36 — EASY-AXIS REMANENT MAGNETIZATION OF Co Fe FILM BIT # 87 INCREMENTED BY 188 DOUBLE-POLARITY EASY-AXIS FIELD PULSES AND VARIABLE D-C BIAS FIELD

for this experiment was the same as for the preceding measurements except the number of pulses was equal for each polarity of bias and the magnitude of the second polarity of bias was varied. An important result was that the "hysteresis" loop was more closed as the film was adjusted over a larger range of magnetization change. Note that the initial slopes of the three "returning" curves vary greatly. Therefore, this mode of adjustment is highly nonlinear and would not be suitable for use in a linear decision array.

4. Stability

Some data which indicate the stability of the magnetic film memory element have already been discussed. The permalloy bits have been shown to be highly subject to shakedown or partial switching for either of the coincident fields. Although the stability of the higher H_c films of CoFe and CoNi was indicated by the results of the single polarity and double polarity experiments, further measurements were made to determine the effects of shakedown from various remanent states for the CoFe bit.

The data indicate the stability of half-selected elements in an array.

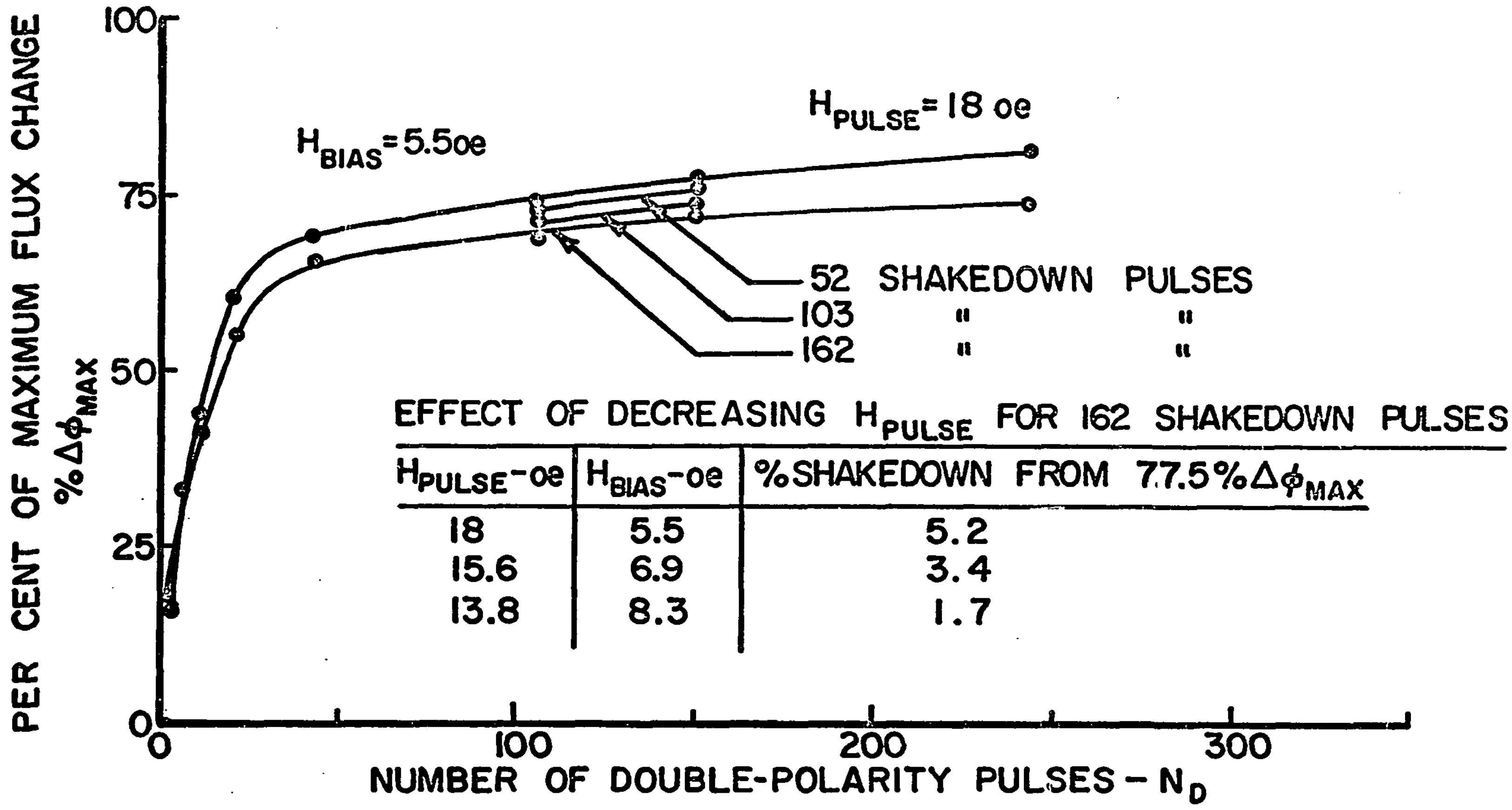
The percent magnetization change vs. number of double polarity pulses with a d-c bias was obtained for one value of pulse magnitude. Then the same data were taken when pulses of the same magnitude were applied as before and in addition a large number of double polarity pulses of that magnitude without bias were applied.

As shown in Figure 37 only a slight change in the remanent state occurred. The percent of magnetization change varied almost linearly with the number of shakedown pulses and was about 5.2% for 162 pulses. Also shown is the effect of increasing the bias magnitude and decreasing the double polarity pulse magnitude while maintaining the same flux change. The shakedown was significantly decreased from 5.2% to 1.7%. The values of bias used here were way below the coercive force (Figure 17) and would not disturb the remanent state when applied alone.

5. Bitter pattern studies

As discussed earlier the Bitter technique was used to study the domain wall formation and movement during the increment switching process. Presented here are results for permalloy film strips. Several unsuccessful attempts were made to observe domain walls in films of the other compositions. It was assumed that the walls of these thin, high coercive force films were too tight to be observed.

For convenience the permalloy film strips with easy axis in the long dimension were placed on top of the field coils. A layer of wax paper along with a layer of mylar were used to



EFFECT OF DECREASING H_{PULSE} FOR 162 SHAKEDOWN PULSES

H_{PULSE}-oe	H_{BIAS}-oe	%SHAKEDOWN FROM 77.5%$\Delta\phi_{MAX}$
18	5.5	5.2
15.6	6.9	3.4
13.8	8.3	1.7

FIG. 37 – EASY-AXIS REMANENT MAGNETIZATION OF CoFe BIT # 87 INCREMENTED BY COINCIDENT EASY-AXIS DOUBLE-POLARITY FIELD PULSES AND BIAS PULSE

contain the Bitter solution in a puddle. A 6 mil cover glass was used to spread the solution in a thin layer. The patterns were photographed with a 35 mm camera through a microscope at approximately 30X. A Layfette microscope adapter was used to obtain the correct focus. The exposure was 1/4 sec, the focus was set at infinity, and the lens was wide open. After each incrementing pulse was applied about 1 1/2 min.were allowed for the iron particles to collect on the domain walls.

Some typical results are shown in Figure 38. The number of incrementing pulses is given beneath each spot. Several interesting observations were made. The wall positions were nearly repeated for each sequence of pulses indicating repeatable performance. No changes in wall positions for a given remanent state were noticed over a period of several minutes as shown midway through the sequence. The nucleation of new walls apparently continued during most of the initial increment-switching process. Each pulse moved existing walls and nucleated new reverse domains.

These results support previous observations that the magnetic film weighting element is reliable and stable with time.

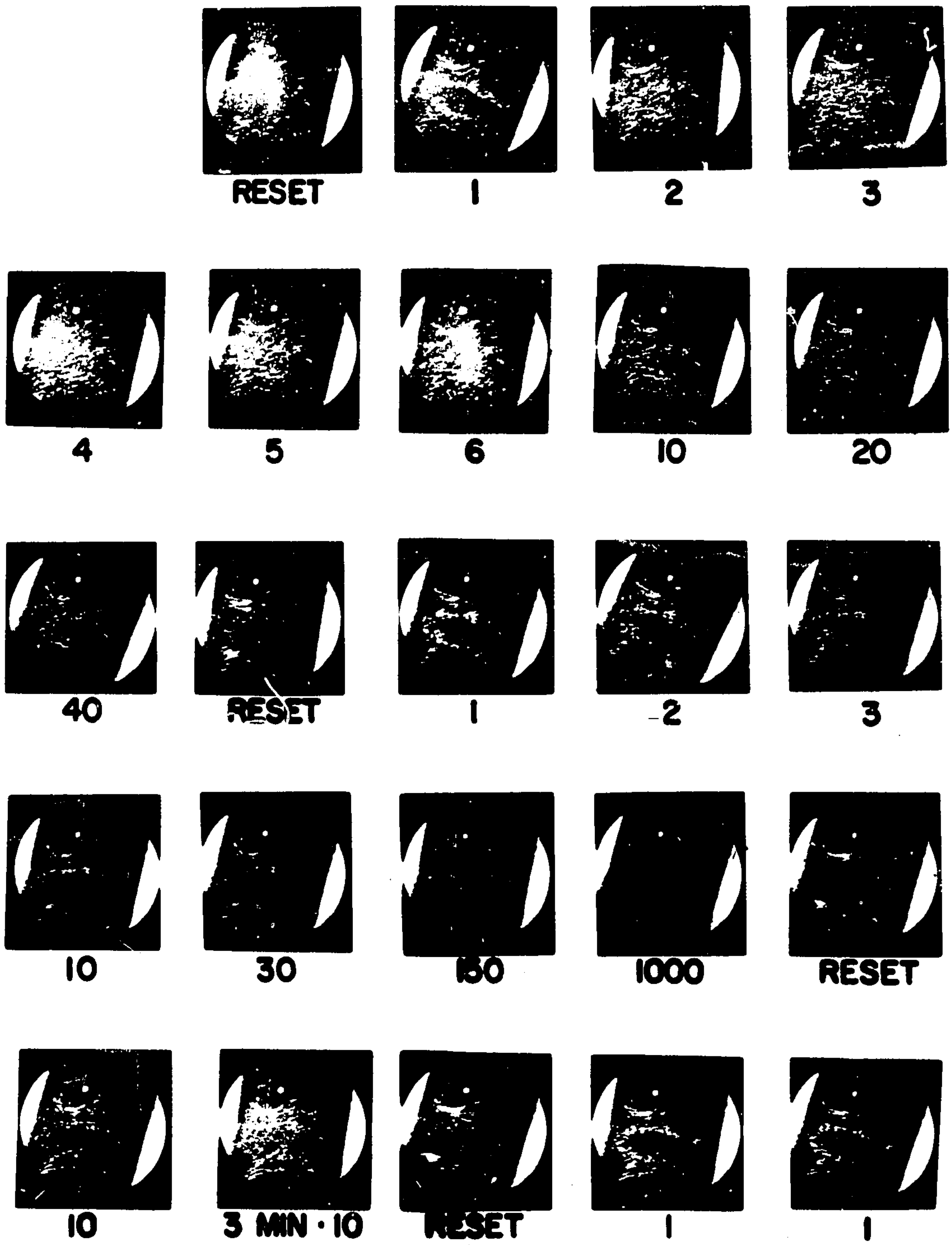


FIG. 38 — SEQUENCE OF BITTER PATTERNS FOR Ni Fe FILM INCREMENTED BY SINGLE-POLARITY FIELD PULSES

6. Eddy-current damping

Although the number of states of the magnetic thin film memory element compares favorably with the performance of other types of elements, a much larger number of weight values would be desirable. Eddy-current damping was investigated as a means of increasing the number of usable remanent states.

The principle of damping investigated here was that eddy-currents induced in a shorted turn by magnetization changes should oppose the wall movements and thereby increase the number of states. The shorted turn should be designed to have a short air-flux time constant which would allow the penetration of incrementing field pulses and a long magnetic flux time constant to oppose the wall movements.

The shorted turn used here consisted of a 90 mil wide bronze strip, 1.2 mils thick, which was wrapped around a permalloy bit on a 1 mil thickness of mica. The permalloy bit was 45 mils wide (hard axis) and 75 mils long (easy axis). The air-flux inductance was calculated using a solenoid approximation, $L = \mu AN^2/d$ where $\mu = 4\pi \times 10^{-7}$ henrys/m, N = 1 turn, A = 1 mil x 65 mils, and d = 90 mils. The resistance was calculated using the d-c resistance formula, $R = \rho d_1/A_1$ where d_1 = 132 mils, A_1 = 1.2 mils x 90 mils, and ρ = resistivity of $9.4 \times 1.724 \times 10^{-6}$ ohm-cm. These calculations give $L = 2.31\times10^{-11}$, $R = 7.8\times10^{-3}$, and $L/R = 3\times10^{-9}$ sec.

The results of the eddy-current damping experiments are shown in Figure 39. The percent of maximum flux change vs. the number of pulses was obtained for three magnitudes of applied field with the permalloy placed in the shorted turn and with the permalloy bit placed between two glass pieces. As shown, eddy-current damping significantly decreased the flux switched per pulse. Further improvement could be obtained using deposited and plated conductors in a more optimum geometry to obtain a better time constant.

The shorted turn geometry required for a decrease in the switching speed was calculated as follows:*

The inverse switching time can be written as

$$\frac{1}{\tau} = S(H - H_c)$$

where τ - switching time

S - switching constant; for permalloy $S = 2.5\text{x}10^6 \frac{1}{\text{oe-sec}}$

H - applied field

H_c - coercive force,

which can be written with damping included as

$$\frac{dB}{dT} = S_m(H - H_c - H_f)$$

where B - film flux density

S_m $2B_r \text{ x } S = 5\text{x}10^{10}$

H_f - field ascribed to eddy-currents.

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*Pohm, A. V., Department of Electrical Engineering, Ames, Iowa. Calculation of shorted turn geometry. Private communication. 1965.

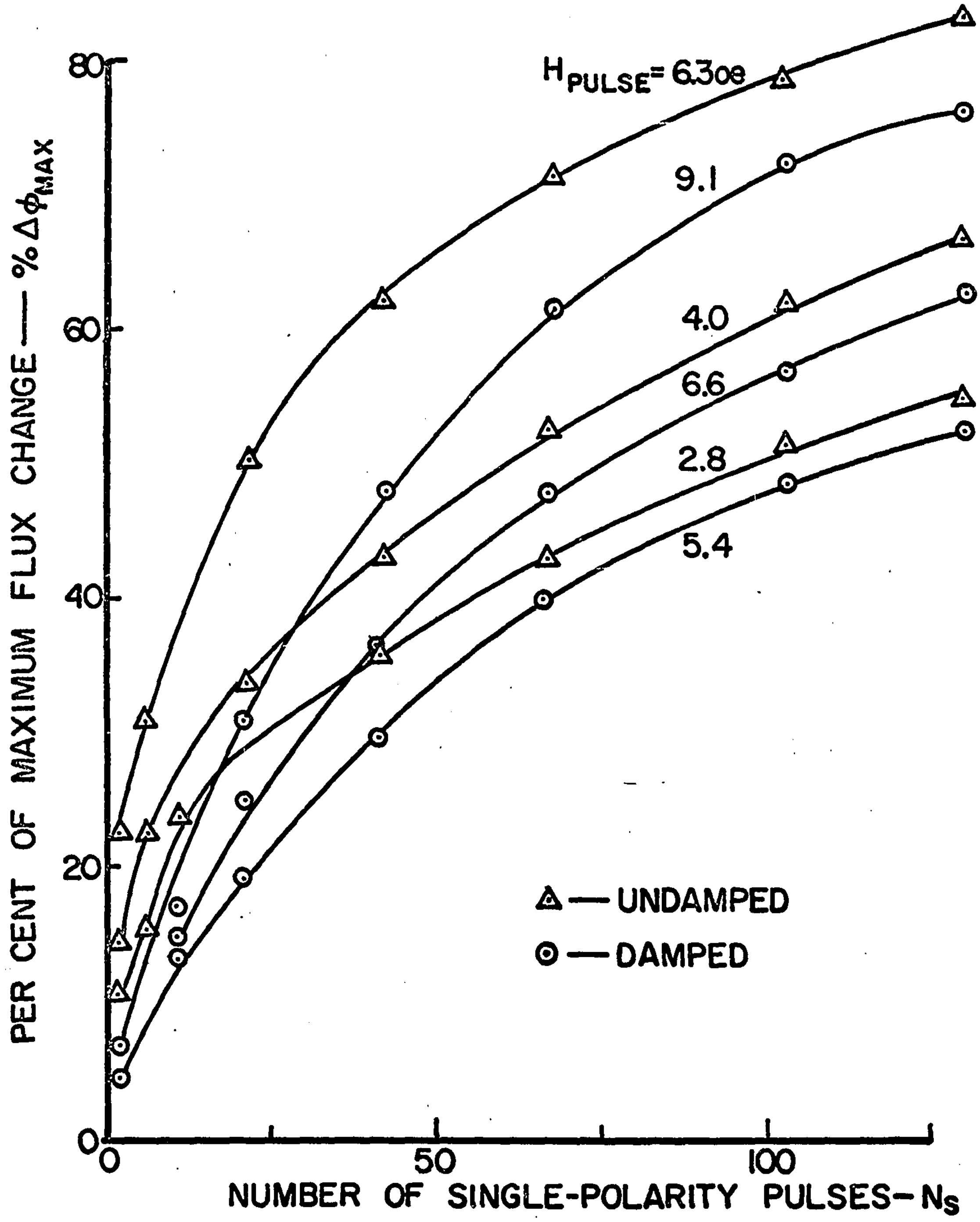

FIG. 39 — COMPARISON OF INCREMENTAL SWITCHING CHARACTERISTICS OF EASY-CURRENT DAMPED FILM WITH UNDAMPED NiFe FILM BIT

H_f is caused by flux changes and is

$$H_f = \frac{kA}{R_L} \cdot \frac{dB}{dT} \times 10^{-8}$$

where k - coupling constant $\frac{0.4}{W}$ for a plane

A - film cross sectional area

R_L - loop resistance.

The inverse switching time can be rewritten as

$$\frac{dB}{dT} = S_m(H - H_c - \frac{kA}{R_L} \cdot \frac{dB}{dT} \times 10^{-8})$$

or

$$\frac{dB}{dT} = \frac{S_m(H - H_c)}{(1 + \frac{kA\ S_m}{R_L} \times 10^{-8})} = \frac{H - H_c}{(\frac{1}{S_m} + \frac{kA}{R_L} \times 10^{-8})} \ .$$

If $\frac{kA}{R_L} S_m \times 10^{-8}$ is equal to 4, for example, then the switching time has been increased by a factor of approximately 4. For this case, R_L would be:

$$R_L = \frac{1}{4}\ kA\ S_m \times 10^{-8} \ .$$

For a 1 cm x 1 cm damping strap using 2000 angstroms film,

$$R_L = \frac{1}{4} \frac{(0.4\pi)(2\times 10^{-5}\ cm^2)(5\times 10^{10}) \times 10^{-8}}{1\ cm}$$

$$= .005\,\Omega \ .$$

Since

$$R_L = \frac{\rho l}{A_l}$$

where l - strap length

A - conductor cross sectional area,

which rearranged is,

$$T = \frac{\rho l}{W_1 R_L}$$

where T - conductor thickness

W_1 - conductor width

ρ - resistivity of copper

or

$$T = \frac{(1.7\times10^{-6}\,\Omega\text{-cm})(2\text{ cm})}{(1\text{ cm})\ 5\times10^{-3}}$$

$$= .54\times10^{-3}\text{ cm} \quad 0.4\text{ mil} .$$

The value of T/2 is 1/2 the skin depth at 40 mc (1/25 nsec) and will allow penetration of the increment fields. However, the flux will wrap around the shorted turn and penetrate the magnetic material; therefore the most important consideration here is the air-flux time constant which limits the build-up of fields within the turn. The time constant for a 10,000 angstrom air gap was calculated as 1 nsec which is much shorter than the pulse rise time and should not affect the build-up of fields within the shorted turn.

This calculation shows that the switching speed can be decreased by a factor of 4 using a 0.4 mil plated shorted turn. Thus the number of linear weight levels can be increased by at least a factor of 4 using this geometry.

IV. DISCUSSION

It has been shown in this investigation that the performance of the magnetic film analogue memory element can be significantly improved by using CoFe for the material of the element. The CoFe composition switched much slower than the NiFe composition and the CoFe film bits were found to have a much larger number of stable remanent states than the NiFe bits. Also, the remanent magnetization of the NiFe bits could not be satisfactorily adjusted by coincident fields. It was shown that half-select currents and readout currents would only slightly disturb the CoFe film but would seriously disturb the NiFe film.

It was found that continuous films would not be suitable for use in an adaptive array because demagnetizing fields from film areas adjacent to the element seriously influenced the memory element. This also indicates that the bit density in an adaptive array may have to be smaller than in magnetic film memories.

The CoNi composition had a few more remanent states than the CoFe element but much larger fields were required to switch the magnetization which would increase circuitry costs.

The CoFe analogue memory element has been shown to be stable with time and with disturbing fields. The element is reliable in that the magnetization can be repeatedly incremented to a given state. It was shown that coincident currents can be used to increment the magnetization back and forth between saturation limits and that at least 35 linear states are available for large changes in magnetization and several hundred may be obtained for small changes in magnetization.

The results indicate that the performance of the CoFe bit can be improved by changing the bit shape so as to decrease the demagnetizing effects which tend to shear the hysteresis loop. Also, obtaining films of CoFe with more "square" hysteresis loops will improve the performance. The performance of the CoFe element can be further improved by using eddy-current damping in the form of a shorted turn as was shown using a permalloy bit.

The characteristics of the magnetic film analogue memory element compare very well with those of other types of elements which have been investigated. As reviewed by Nagy (8) most of the elements have less than 100 weight levels. The elements with more levels are either much too expensive even for small arrays or are unstable with time. Of all the elements constructed the magnetic film element is by far the least expensive, the smallest, and the fastest. In fact, the cost and element geometry would permit the construction of large arrays of 10^4 elements using magnetic film memory techniques.

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