IRRADIATION OF THIN MAGNETIC FILMS

by

John Barclay Brown, Jr.

A Thesis Submitted to the
Graduate Faculty in Partial Fulfillment of
The Requirements for the Degree of
MASTER OF SCIENCE

Major Subject: Nuclear Engineering

Approved:

Signatures have been redacted for privacy

Iowa State University
Of Science and Technology
Ames, Iowa

1962

TABLE OF CONTENTS

	Page
INTRODUCTION	1
REVIEW OF LITERATURE	2
EXPERIMENTAL PROCEDURE	24
RESULTS	37
DISCUSSION	60
SUMMARY AND CONCLUSIONS	63
BIBLIOGRAPHY	64
ACKNOWLEDGMENTS	67
APPENDIX A	68
APPENDIX B	72

INTRODUCTION

The effects of nuclear environments created by nuclear power plants, nuclear explosions and outer space radiation, cosmic rays, Van Allen and Winkler radiation have been treated with increasing interest since the coming of the second generation of nuclear power systems and orbital space flights. The effects of radiation on magnetic materials has had little attention until the last few years and no attention has been given to the effects of radiation on thin magnetic films.

Thin films are of interest because of the increasing study in their application to electronic equipment. Films have been subjected to extensive study as memory elements in digital computers and have been used in a number of completely magnetic devices.

Because of the possibility of employing thin films in place of transistors in certain electronic equipment the radiation resistant properties of thin films have been investigated with respect to the 60-cycle hysteresis loop. Transistor radiation resistant properties were compared with those of the thin films.

REVIEW OF LITERATURE

Applications for Magnetic Devices

As early as 1860 (Beetz) it was demonstrated that films of ferromagnetic material could be produced with quasi-rectangular hysteresis loops by depositing the material in the presence of a magnetic field. In 1955 Blois inferred that thin magnetic films could be used for memory elements in digital computer systems. Since the investigations of Blois considerable work has been done on thin films for memory applications (Gianola, 1960).

Specific applications of magnetic devices depend upon the shape of the hysteresis loop of the magnetic material considered. For the satisfactory operation of the memory storage devices in computers the rectangular hysteresis loop is necessary. Certain components in the computer operate on the assumption that the storage device has a rectangular loop with relatively sharp corners. If the hysteresis loops were altered the storage devices would malfunction.

Films displaying rectangular hysteresis loops have been shown to be desirable for other applications. Construction of low loss inductors whose self inductance could be varied parametrically was suggested by Read and Pohm (1959). By winding two mutually perpendicular windings around a film one can obtain an inductive device that has many applications. Investigations have been carried out on the thin film parametron (Pohm et al., 1959; Pohm et al., 1960; Schauer et al., 1960; Sanders, 1961), thin film parametric amplifier (Read and Pohm, 1959), the

thin film balanced modulator (Read and Samuels, 1960 and Samuels, 1960), and the passive loaded thin film flip-flop (Daughton et al., 1961). The assumption under which these devices operate is that the magnetic films are characterized by a magnetically induced uniaxial axis of anisotropy (rest direction). Upon destruction of this uniaxial axis of anisotropy these devices fail to operate.

Irradiation Damage in Magnetic Devices

Salkovitz (1960) has pointed out the need for a knowledge of nuclear radiation effects on magnetic materials. Airborne craft employing nuclear power plants could accomplish shielding only at an extreme cost in weight and space; magnetic devices installed as equipment could be expected to encounter nuclear radiation. Nuclear environments created by nuclear explosions where very extreme pulses of radiation are expected should also be mentioned here as a possible damaging source. Cosmic rays, Van Allen and Winkler radiation, and the Aureral radiation (Rohrback, 1961) are not expected to produce atomic displacements to any great degree. The factor that will determine the damage suffered by a vehicle passing through any radiation fields mentioned is time of passage. Space cannot be dismissed for nuclear-propelled vehicles are planned for distant outer space journeys. These vehicles would carry their own reactors and therefore produce radiation environments which could affect components.

Intensive work on the irradiation of magnetic materials has been conducted only within the last few years and largely by the Navy (Salkovitz et al., 1958; Henry and Salkovitz, 1959; Salkovitz et al., 1960).

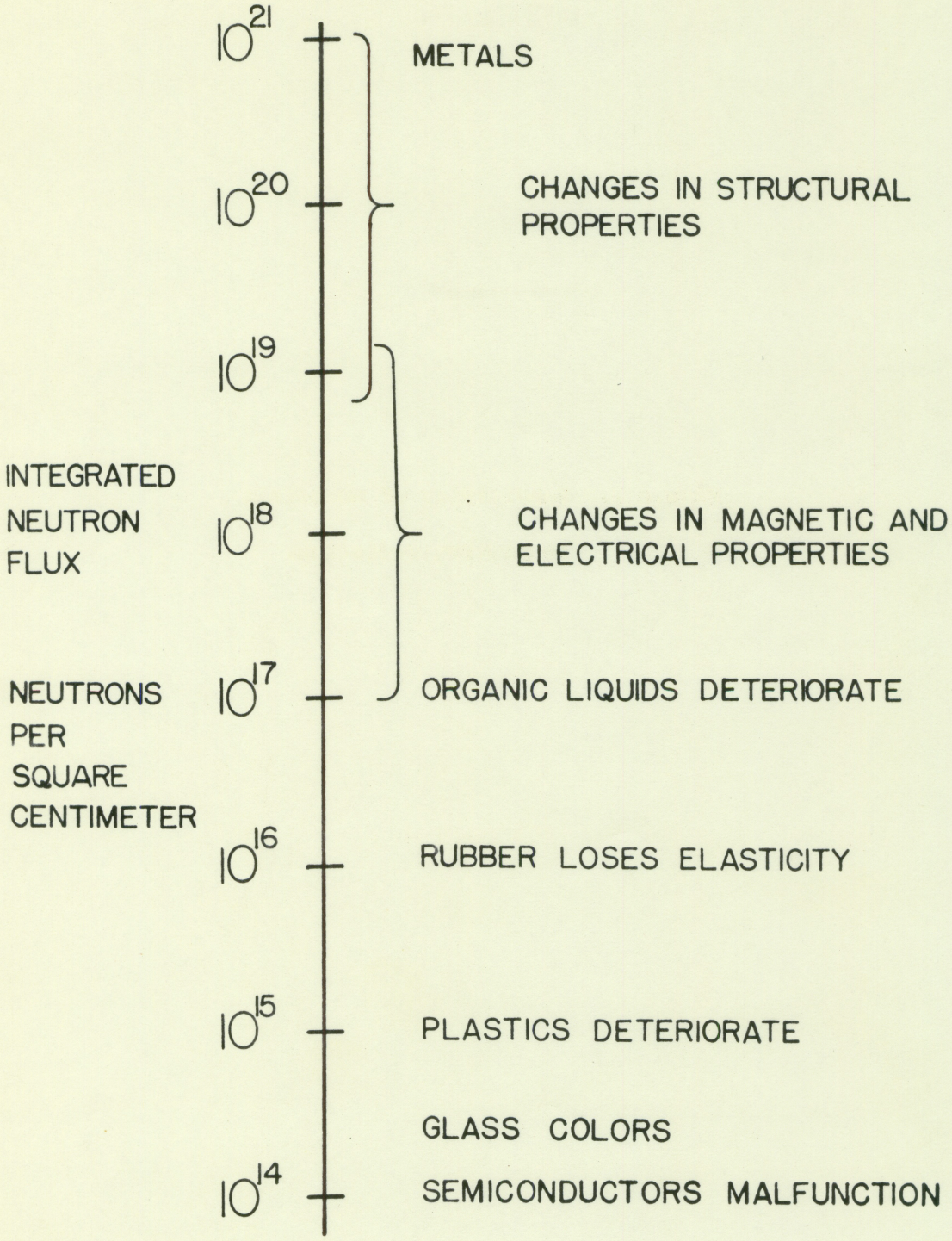
Figure 1 shows radiation sensitivity of various classes of materials. It indicates the total dose of fast or high energy neutrons which specific classes of materials may tolerate before significant damage occurs, i.e., say before a 10 pct alteration occurs in an important property of the material in question. The ordinate scale refers to the total dosage or total number of neutrons striking per square centimeter of material. The sensitivity value of magnetic materials is slightly above that at which organic liquids, such as transformer oils, deteriorate but below the dosage which produces structural changes in metals and alloys.

Salkovitz, formerly with the U. S. Naval Research Laboratory, is now with the Metallurgy Branch, ONR, Washington, D. C. The following results of his work were presented at the 1960 AIME annual meeting.

Magnetic 60-cycle hysteresis loops were obtained on toroid samples of various magnetic alloys before and after irradiation. All measurements were made in the Naval Research Laboratory hot cell using the same circuitry. The samples were irradiated in the Brookhaven graphite reactor operating between 15 and 22 megawatts during the various exposures. The total integrated flux received by the various samples varied between 6×10^{16} and 3×10^{17} nvt. By means of forced cooling, the temperatures of all samples were kept below 75° and some as low as 30° C.

Certain materials were found to be insensitive to radiation with respect to their 60-cycle magnetic characteristics and therefore would not require shielding. These results were also verified by the Navy (Salkovitz et al., 1958; Henry and Salkovitz, 1959; Salkovitz et al.,

Figure 1. Sensitivity of materials to neutron radiation.


INTEGRATED NEUTRON FLUX
NEUTRONS PER SQUARE CENTIMETER
10^{21}
10^{20}
10^{19}
10^{18}
10^{17}
10^{16}
10^{15}
10^{14}
METALS
CHANGES IN STRUCTURAL PROPERTIES
CHANGES IN MAGNETIC AND ELECTRICAL PROPERTIES
ORGANIC LIQUIDS DETERIORATE
RUBBER LOSES ELASTICITY
PLASTICS DETERIORATE
GLASS COLORS
SEMICONDUCTORS MALFUNCTION

1960). The materials included silicon steel and similar alloys (Figure 2) and many types of commercial ferrites (mixed iron oxides). Unfortunately, these steels and alloys do not have very useful magnetic properties and are not used in sophisticated electronic and magnetic devices.

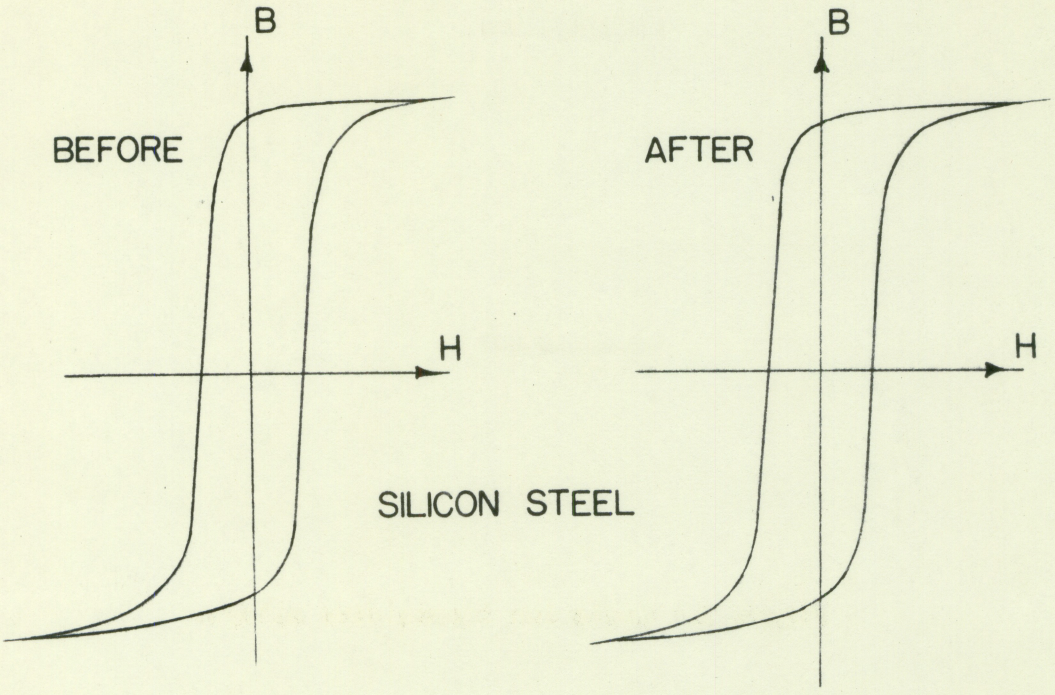
It was also shown that a large class of alloys are grossly affected (Figure 3). In some cases not only were the remanence and coercive forces altered, but constrictions were introduced in the hysteresis loop itself. The practical significance of these changes may be inferred from Figure 4.

Figure 4-A shows an ideal hysteresis loop for a magnetic memory storage device (this can be closely realized by thin magnetic films). The hysteresis loop is rectangular with sharp corners while the feed-out pulse takes the shape of a delta function. A more conventional hysteresis loop is shown in Figure 4-B with its corresponding bell-shaped feed-out pulse. If a constriction is introduced into the hysteresis loop, as shown in Figure 4-C, the feed-out pulse would have two peaks. A device whose operation is based on receiving only single sharp cornered or single bell-shaped responses would fail to function.

Highly sensitive alloys

Those alloys whose magnetic properties showed significant sensitivity to nuclear irradiation were materials which originally had been given enhanced magnetic properties through specially combined mechanical and thermal treatment. Such a treatment arranges the two constituent atoms into a nearly regular arrangement or order. Consequently, atomic displacements produced by impinging neutrons can cause the degree of order to

Figure 2. Radiation insensitive alloys.


B
BEFORE
H
B
AFTER
H
SILICON STEEL

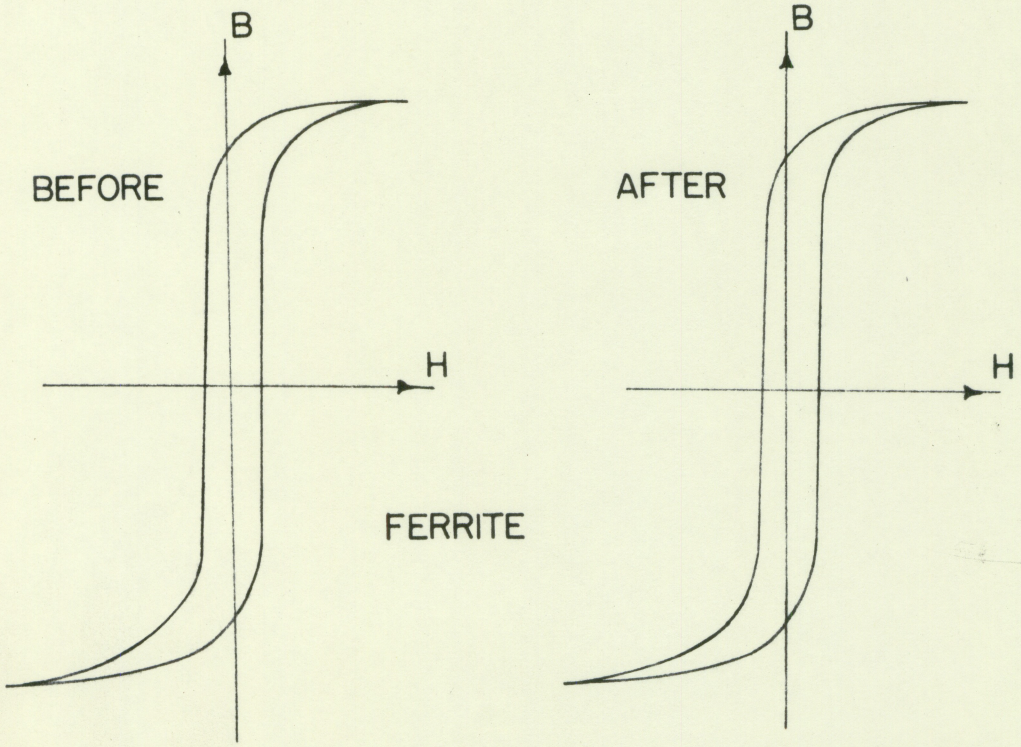

B
BEFORE
H
B
AFTER
H
FERRITE

Figure 3. Radiation sensitive alloys.

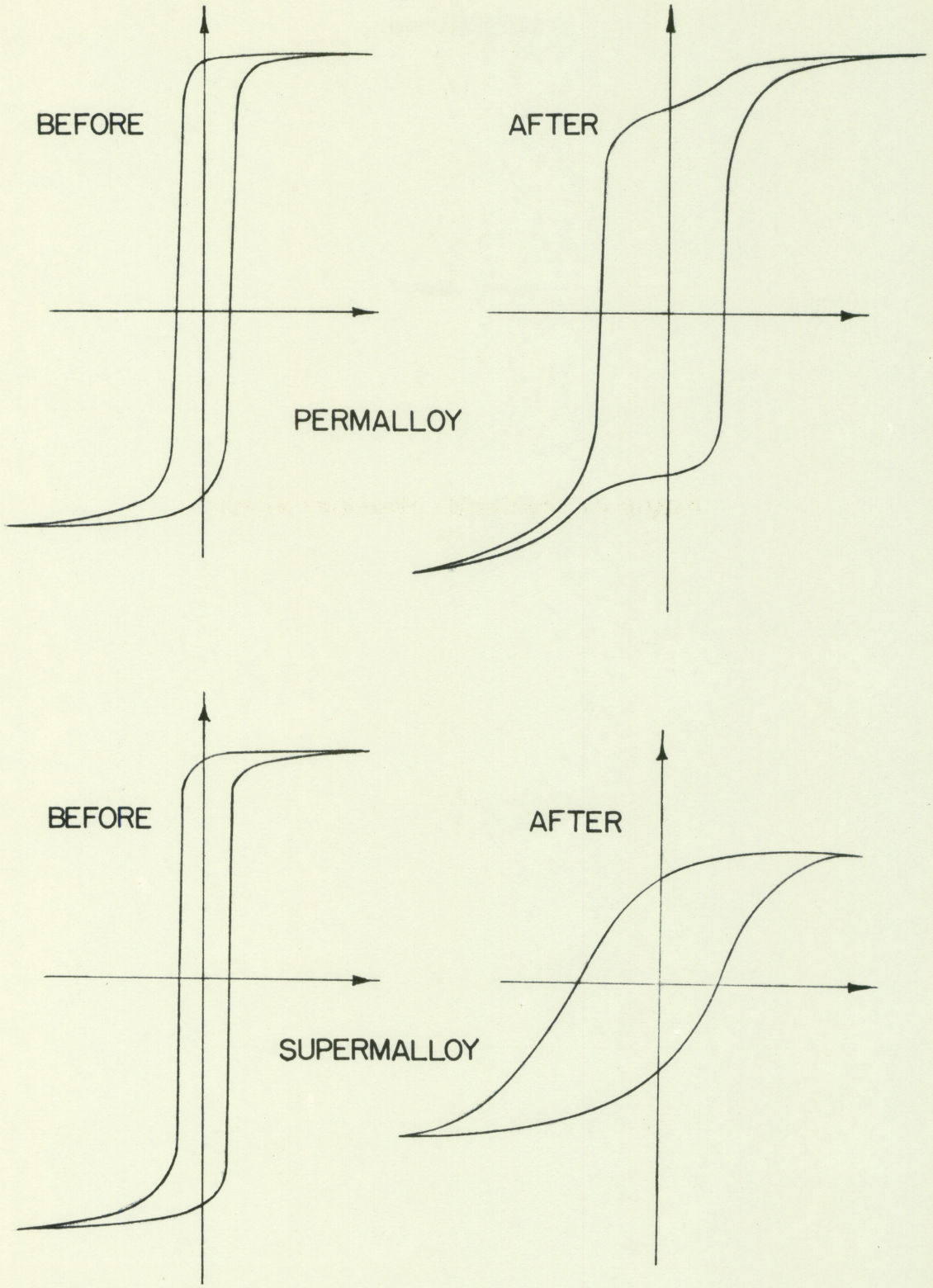
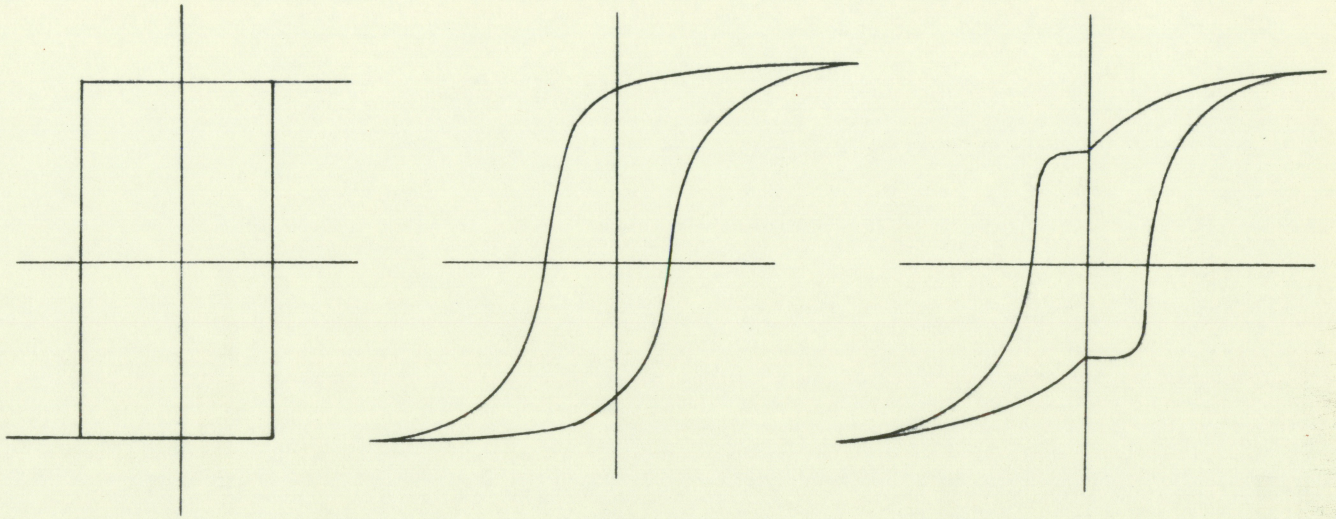

BEFORE
AFTER
PERMALLOY
BEFORE
AFTER
SUPERMALLOY

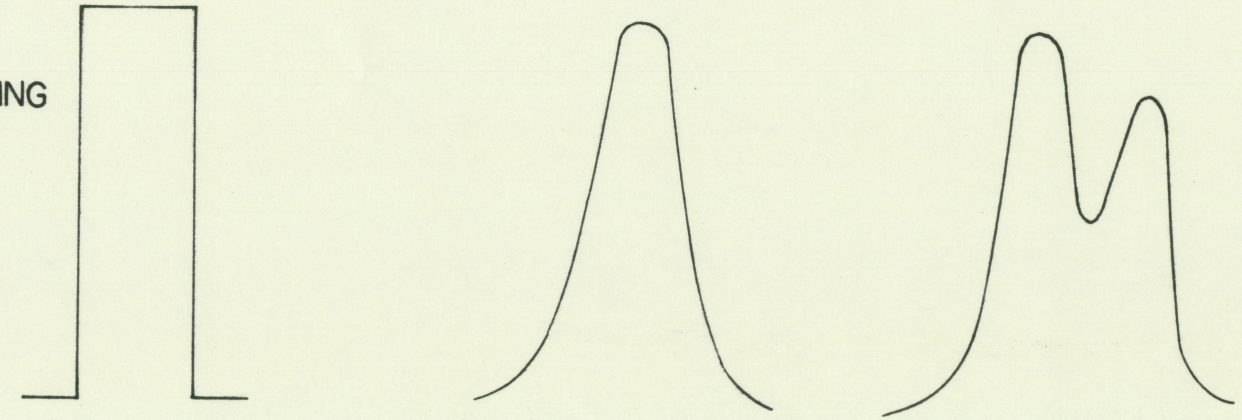
Figure 4. Practical significance to changes in the magnetic hysteresis loop.

HYSTERESIS LOOPS



(A) (B) (C)

CORRESPONDING FEEDOUT PULSES



be altered considerably, and those magnetic properties sensitive to atomic arrangement would be altered. Kaya (1953) has shown a correlation between the shape of the hysteresis loop and the degree of order in permalloys. Schindler and associates (1959) have given a variety of heat treatments to various types of 50%-50% and 75%-25% nickel-iron alloys in the form of tape-wound toroids. These treatments brought each sample to some particular state of order and characteristic hysteresis loop. Each sample was then irradiated, and the new loops recorded. The nature of resulting changes in the loops (Figure 5) were found to be dependent on the nature of the loop of the pre-irradiated sample and, therefore, the degree of order in the original sample. The constricted loop shown in the lower right is characteristic of partially ordered material. A material which orders more readily is supermalloy (75% Ni-25% Fe). Schindler and associates (1959) were able to show that with irradiation a higher degree of order could be obtained than with a given thermal treatment. These results confirmed the work by others (Aronin, 1954; Dienes and Damask, 1958) that the degree of order may be altered not only thermally but also by irradiation and that the two processes are additive.

Magnetic annealing theories

Neel (1954) proposed an explanation for the uniaxial magnetic anisotropy that occurs in binary alloys annealed in a magnetic field. Consider an unordered solid solution of atoms A and B, Figure 6-A where the solid circles represent A atoms and the open circles represent B atoms. For ideal random arrangement, 28 pairs of each type of atom are expected, and 56 mixed. For perfect order no like atom pairs are expected

Figure 5. Irradiation of different ordered permalloys.

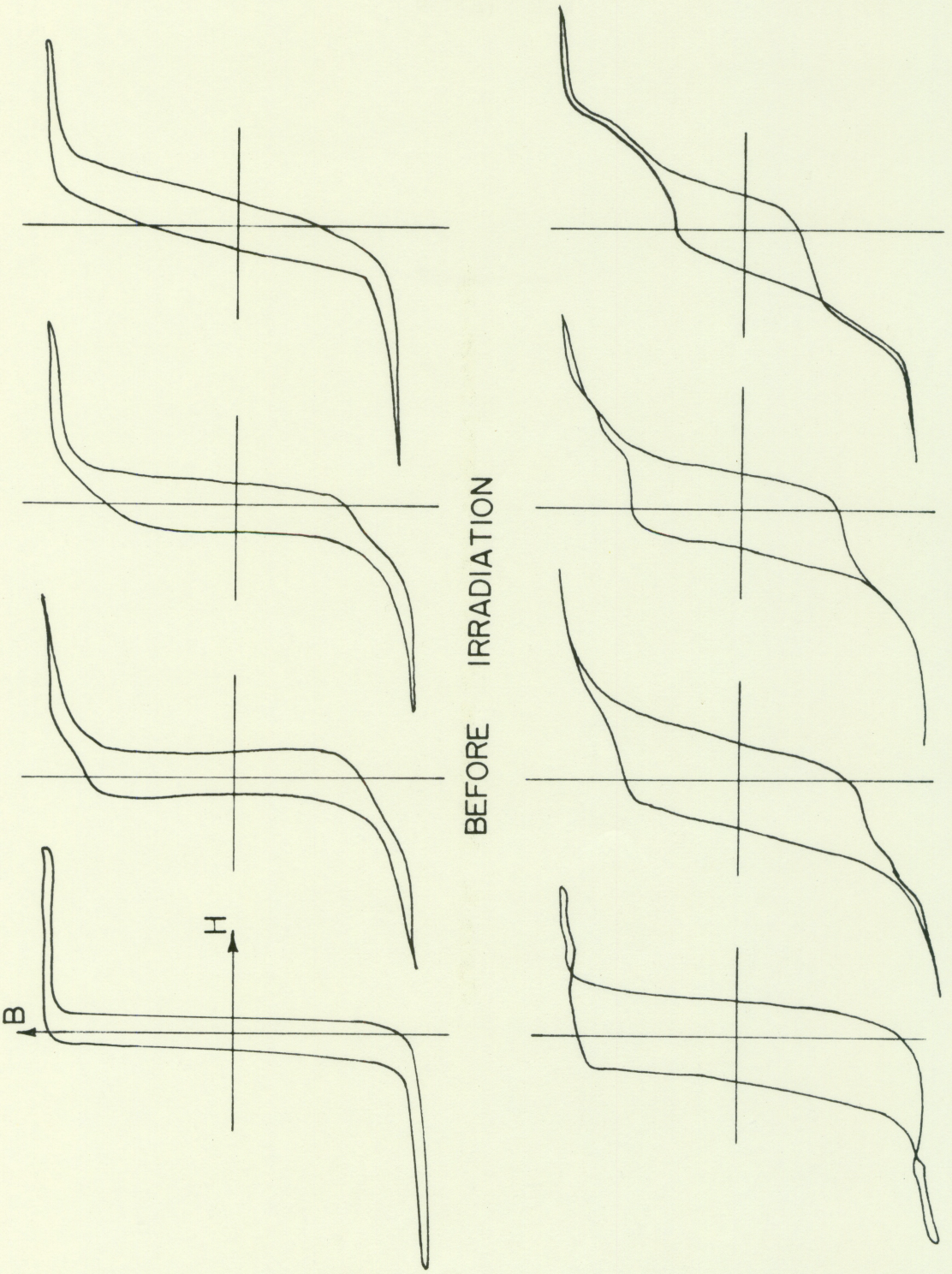
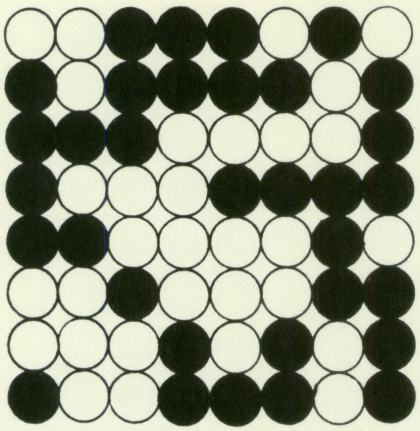
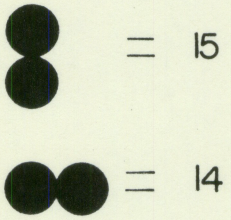

B
H
BEFORE IRRADIATION
AFTER IRRADIATION

Figure 6. Possible arrangement of atoms in a 50-50 alloy of black and white atoms.

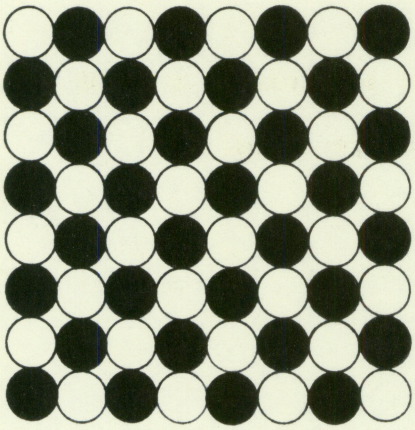
(A)



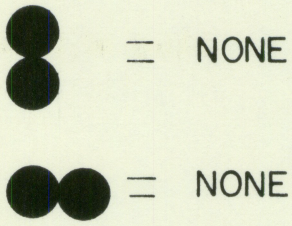
RANDOM SOLID SOLUTION



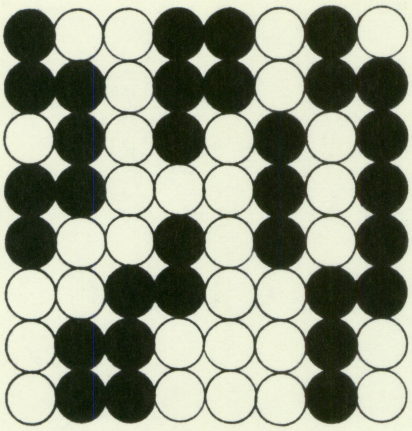
(B)



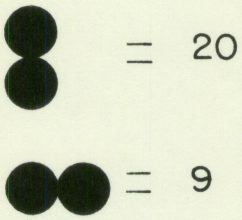
PERFECT ORDER



(C)



DIRECTIONAL ORDER



(Figure 6-B). But there is a third example to consider as shown in Figure 6-C. Here there are 29 pairs of AA atoms, but 20 pairs are in the vertical direction, and 9 in the horizontal. This is not order in the usual crystallographic sense, yet it shows a definite directionality as a result of preferential alignment of like-atom pairs. On such a model Neel (1954) worked.

If the normal magnetic anisotropy is small, as in the case of permalloys, then any additional uniaxial anisotropy has a strong effect on the magnetization process. The direction of the uniaxial anisotropy that is created by annealing in a magnetic field is the same for all magnetic domains, and this results in a square hysteresis loop. Annealing in the absence of a magnetic field also causes uniaxial anisotropy, but the direction of the anisotropy will be different from domain to domain, and a constricted or kinked hysteresis loop will be obtained.

Additional experiments

With the annealing theories in mind additional experiments were carried out by Salkovitz (1960) in which samples were irradiated in the presence of a saturating magnetic field. The samples used were commercially available toroids, mainly iron and nickel alloys. Pre-irradiation 60-cycle hysteresis loop measurements were taken, and the samples were then irradiated with the following approximate integrated neutron flux:

fast = 1.25×10^{16} to 3.0×10^{16} nvt

epithermal = 2.6×10^{17} nvt

thermal = 5.9×10^{18} nvt

The temperature was kept relatively constant from 80° to 120° C. During irradiation, a saturating, magnetizing direct current was passed through the H coil of one sample of each pair. The field produced was in the same direction as the field applied during hysteresis loop measurements. Loop b, Figure 7, is the hysteresis loop of the sample irradiated in the absence of a magnetic field while loop c is for the sample irradiated in the presence of a saturating magnetic field applied to the toroid. The sample experiencing the saturating magnetic field during irradiation obtained an increased coercive force and remanence magnetization.

The modified loops reflect a change in the uniaxial anisotropy of the state of final order.

In the case of the absence of an applied field, the resulting directional short-range ordering causes constricted hysteresis loops. But in cases of samples irradiated in a magnetic field, the resulting directional ordering causes rectangular hysteresis loops.

Nuclear Radiation Damage in Transistors

The investigation of nuclear radiation damage in transistors is not the main purpose of this study, but has been brought in only as a comparison to the radiation effects to magnetic materials. This comparison might be of some value as it seems feasible that certain transistorized circuitry could be replaced by a complete magnetic circuitry.

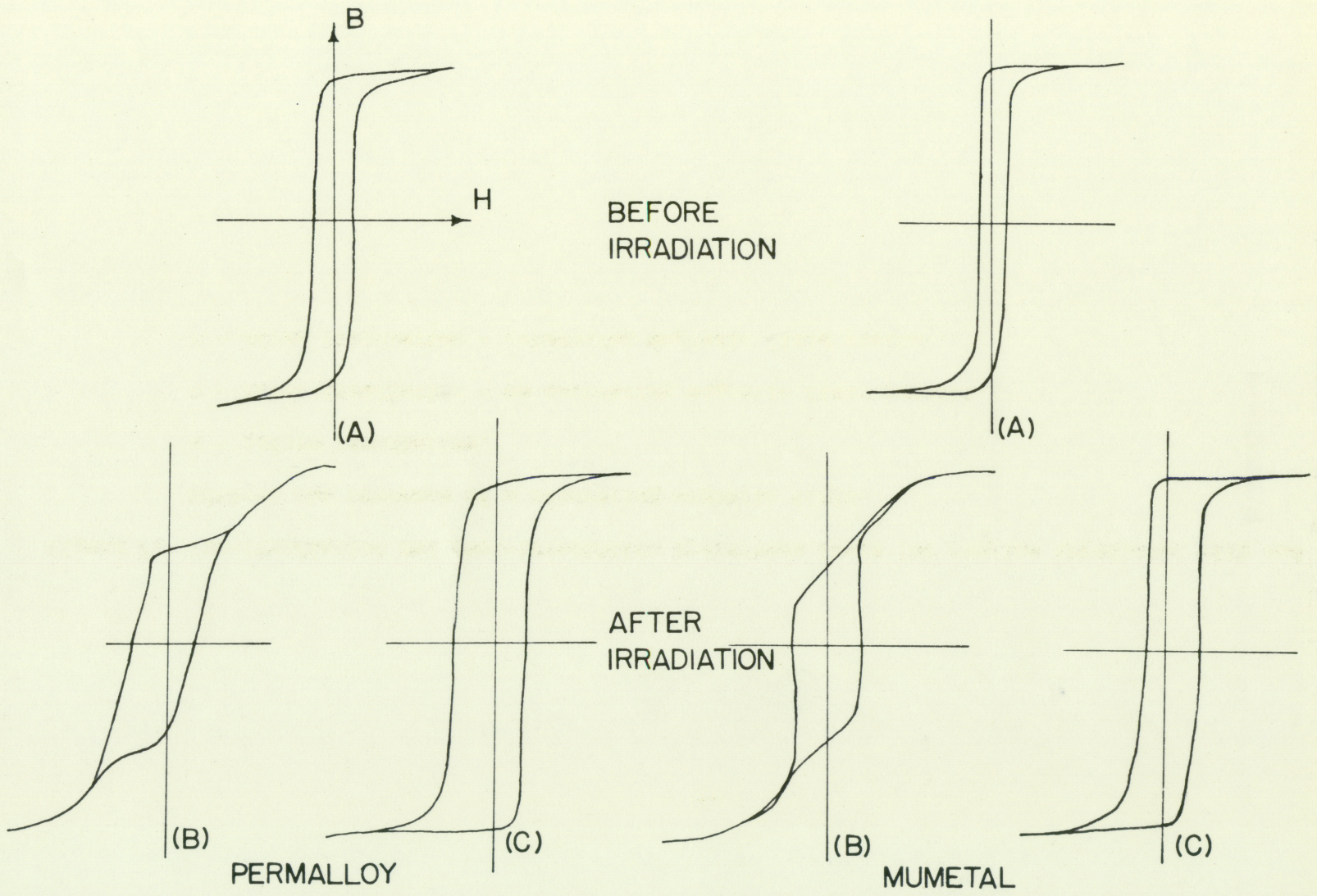
Permanent damage to transistors is usually caused by fast neutron bombardment (Rohrback, 1961) which produces lattice disorder and a subsequent change in characteristics. Primary and secondary ionization, caused by fast and slow neutrons and gamma radiation, result in transient

Figure 7. Pre-irradiation and post-irradiation hysteresus loops for samples irradiated with and without the presence of a saturating magnetic field.

a - before irradiation.

b - after irradiation - no saturating magnetic field present.

c - after irradiation - saturating magnetic field present.


B
H
(A)
BEFORE
IRRADIATION
(A)
AFTER
IRRADIATION
(B)
(C)
PERMALLOY
(B)
(C)
MUMETAL

changes while the sample is in the radiation field (Rohrback, 1961).

The collector-base amplification factor β, reduces upon irradiation (Laferski, 1958). This reduction can be attributed to changes in the minority carrier lifetime rather than to changes in conductivity.

EXPERIMENTAL PROCEDURE

Radiation Facilities

Facilities used for irradiation consisted of the UTR-10 training reactor and a 1100-curie Cobalt-60 source. Samples to be irradiated were positioned in two of the reactor experimental facilities, the rabbit tube and the thermal column. The rabbit tube has a unique position within the nuclear radiation field and therefore needs no further description. The thermal column has various voids available for the placement of samples for irradiation. The position utilized in this study was located behind the center stringer, through the lead gamma curtain and core reflector flush with the north outer core tank (Figure 8).

The 1100-curie Cobalt-60 source was made available through the courtesy of Dr. Joseph Picken of the Iowa State University Veterinary Research Institute. Dosage attained by the samples irradiated was determined by running a calibration curve on the photon flux for the given geometry.

Experimental Apparatus

To determine any radiation damage to the magnetic films, the magnetic hysteresis loop of the films was examined before and after irradiation. The hysteresis loop is appealing because it shows the relationship of the externally applied magnetic field to the magnetization induced in the thin films.

The 60-cycle hysteresis apparatus, Figure 9, consisted of a cube coil arrangement (Rubens, 1945) to provide the drive field, two separate

Figure 8. UTR-10 thermal column irradiation facility.

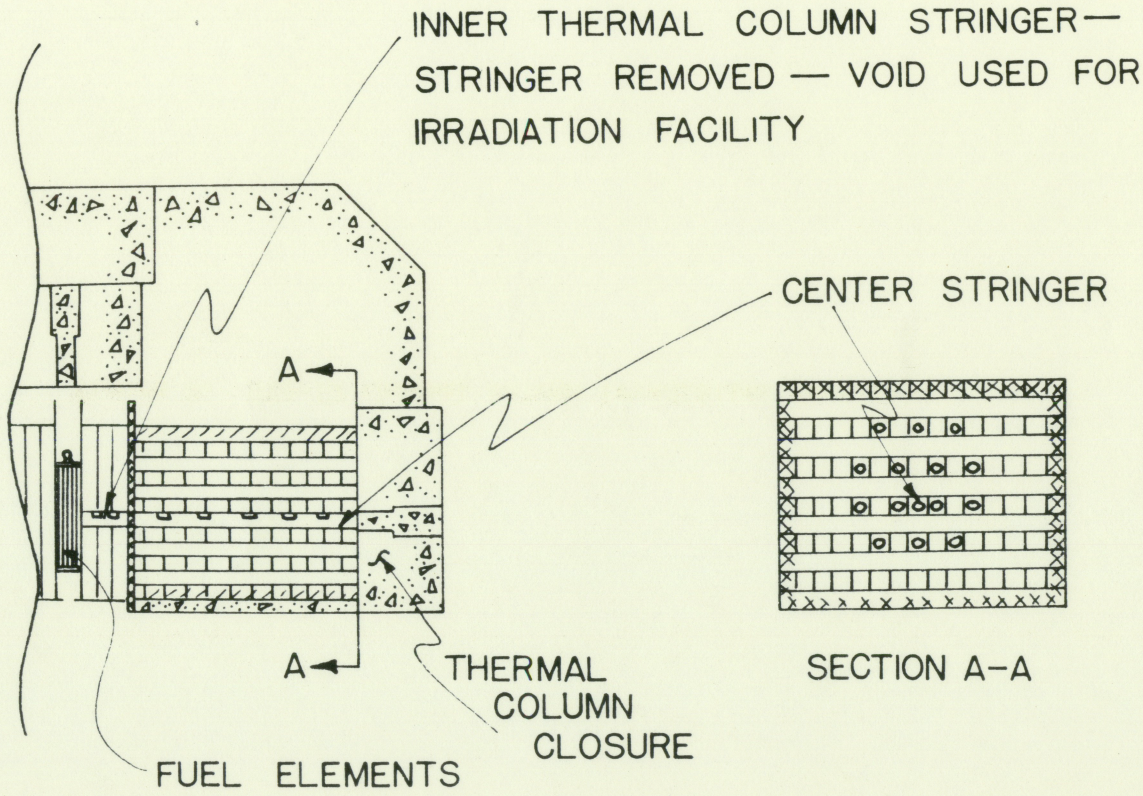

INNER THERMAL COLUMN STRINGER—
STRINGER REMOVED — VOID USED FOR
IRRADIATION FACILITY
CENTER STRINGER
A
A
THERMAL
COLUMN
CLOSURE
FUEL ELEMENTS
SECTION A-A

Figure 9a. The 60-cycle hysteresis apparatus.

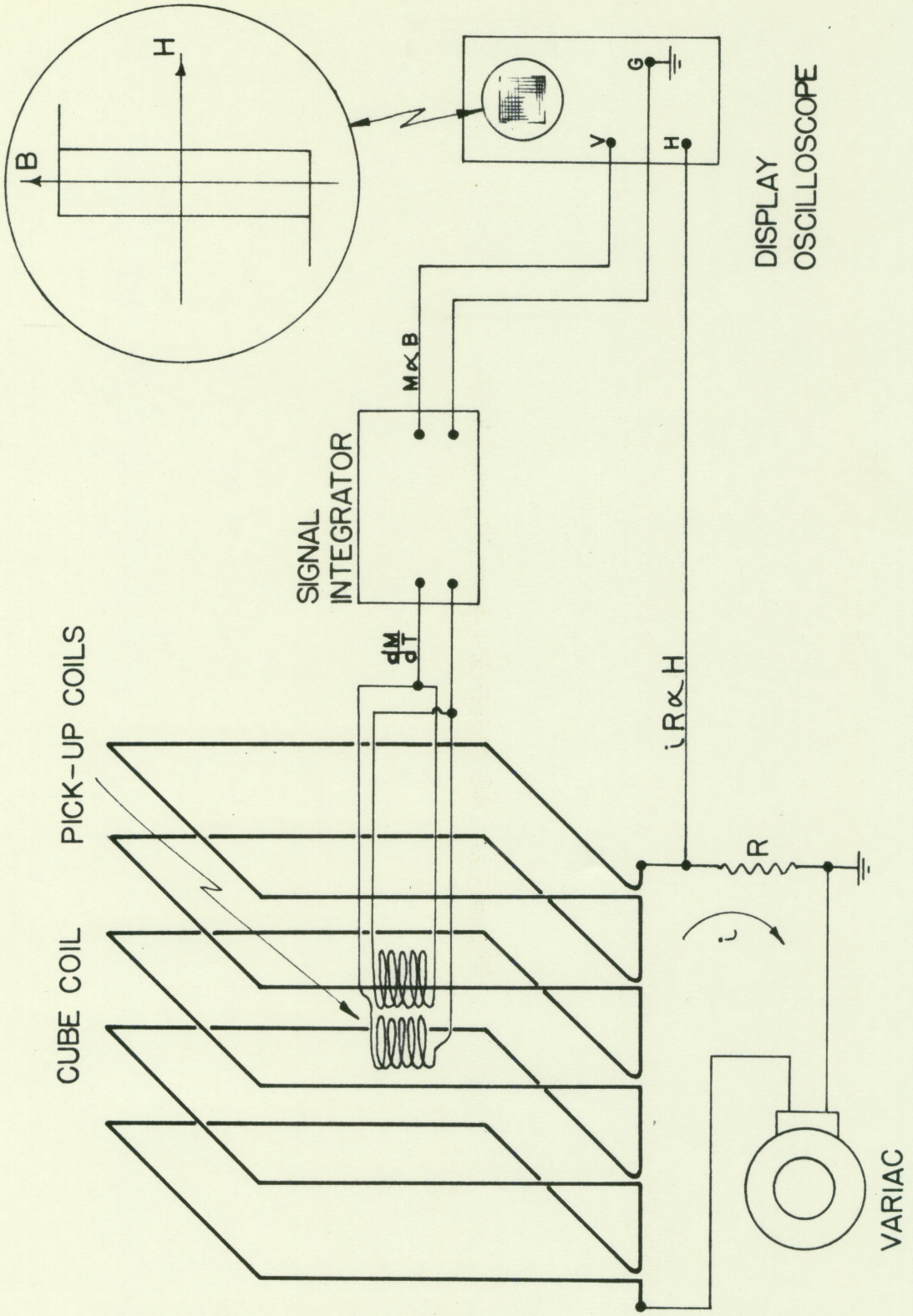
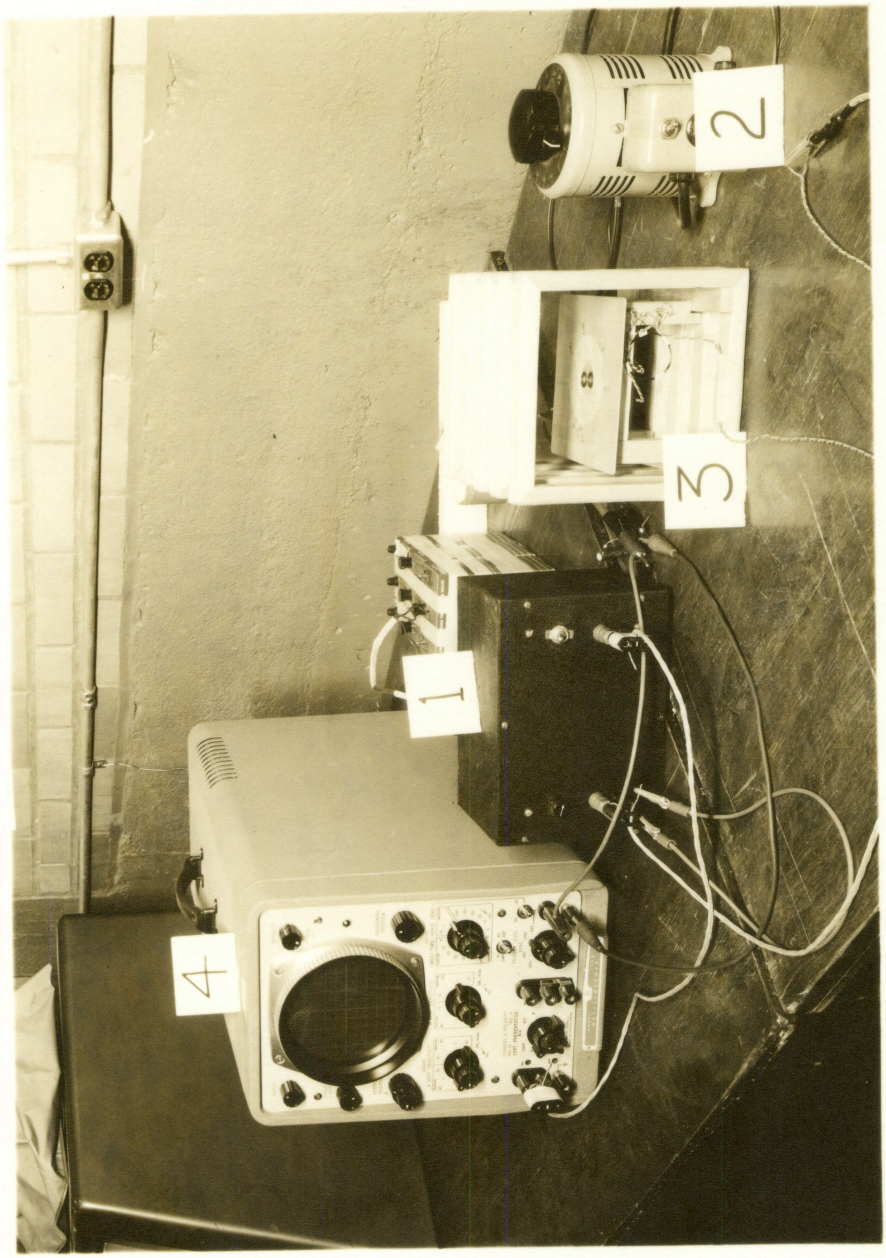

B
H
DISPLAY
OSCILLOSCOPE
G
Y
H
M∝B
SIGNAL
INTEGRATOR
dM/dT
i R∝H
R
i
VARIAC
CUBE COIL
PICK-UP COILS

Figure 9b. The 60-cycle hysteresis apparatus:

1. Signal integrator
2. Variac
3. Cube coil arrangement
4. Display oscilloscope


2
3
1
4

oppositely wound pickup coils, a transistorized signal integrator, a display oscilloscope[1] and appropriate cabling. The signal induced in the two pickup coils is the effect of the time rate of change of the magnetization of the film only. The drive field effect is identical in both pickup coils but opposite in sign and therefore is cancelled. The signal induced in the pickup coils is integrated and amplified giving a signal corresponding to the flux density in the sample and therefore the extent to which it is magnetized. The integrated signal is placed on the vertical plates of an oscilloscope and a signal proportional to the exciting current in the drive coils is placed on the horizontal plates. A plot corresponding to the hysteresis loop of the sample is then obtained.

The cube coil arrangement, shown in Figure 9, consisted of five equally spaced square coils forming the surface of a cube. The currents in the five coils were proportional to the number of turns[2] in each coil. Spacing between the square coils was 4.5 centimeters while the side of the cube formed was 17.8 centimeters. The coil arrangement gave about 15 oersteds per ampere axially through the center of the cube. The horizontal deflection voltage of the oscilloscope was obtained from a 10-watt, 1-ohm resistor connected in series with the drive field coils. The wire used for the drive coils was 22-gage annealed copper, plain enamel covered.

---

[1] Hewlett Packard Model No. 122A, Serial No. 439.

[2] Drive windings contained 57, 12, 30, 12 and 57 turns respectively.

The pickup windings consisted of two counterwound coils of approximately 1000 turns each. The air mutual coupling between the drive coils and the pickup coils was adjusted to zero by a small "tickler" coil connected to one of the pickup coils. The wire used for the pickup coils was 38-gage annealed copper, plain enamel covered.

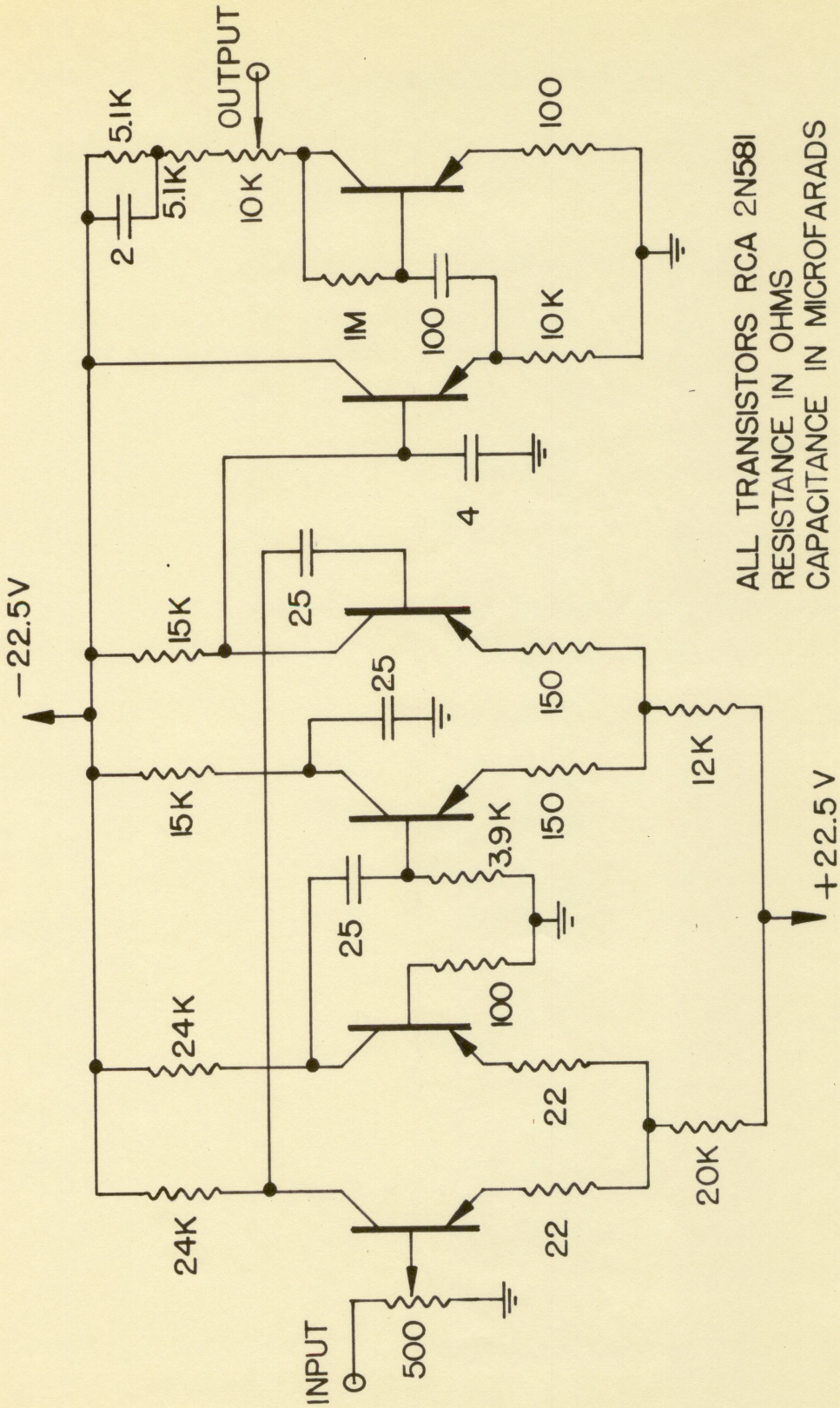
The transistorized signal integrator, schematically shown in Figure 10, was composed of six RCA 2N581 transistors. Two differential amplifiers employed four transistors while an emitter follower and integrating circuit employed the remaining two transistors. With an overall gain of 60 db at 60 cycles the signal integrator amplified and integrated the time rate of change of the magnetization of the films giving an output signal corresponding to the state of magnetization of the films. The signal strength was on the order of 150 millivolts. The signal integrator received its supply voltages from three Eveready 45 volt batteries[1]. The batteries were connected in parallel providing ground potential, 22.5 volts and -22.5 volts for a reasonable operating period.

Magnet resistance telephone wire manufactured by Consolidated Corporation was used to connect the signal from the pickup coils to the input of the signal integrator and the output of the signal integrator to the vertical plates of the oscilloscope. Electrical connectors were General Radio types 274-MB and 274-DB (single and double plug). All other hookup wire consisted of 18-AWG test-prod wire.

---

[1] No. 762-S and NEDA No. 709.

Figure 10. Transistorized signal integrator - schematic.


OUTPUT
5.1K
5.1K
2
10K
100
1M
100
10K
4
−22.5V
15K
25
25
150
12K
15K
3.9K
150
25
100
24K
22
20K
24K
22
INPUT
500
+22.5 V
ALL TRANSISTORS RCA 2N581
RESISTANCE IN OHMS
CAPACITANCE IN MICROFARADS

Transistor curve characteristics were studied through the use of the Electrical Engineering Department transistor curve tracer[1].

Experimental Method

Pictures were taken of the 60-cycle hysteresis loop before and after irradiation. All measurements were made in the Reactor Building, Chemical Engineering-West. Circuitry used remained the same for all measurements. The transistors were analyzed before and after irradiation at the Electrical Engineering Building. All samples required approximately a week for decay before Health Physics allowed handling.

Samples were irradiated in the Nuclear Engineering Department UTR-10 reactor operating at full power, 10 KW; each irradiation period lasted for one-half hour. The temperature of all samples was kept at 85° F.

The Cobalt-60 source was used only for thin film irradiation. Samples were analyzed, taken to the Cobalt-60 source, irradiated for approximately eight days and returned for analysis.

Thin films received a total integrated neuron flux of approximately 2.88×10^{14}nvt thermal, 1×10^{14}nvt epicadmium (Appendix A) and 1.34×10^{7} RADS electromagnetic.

Transistors received a total integrated flux of approximately 1.55×10^{14}nvt thermal and 5.95×10^{13} epicadmium.

The usual way to describe a neutron flux or field is to define the intensity of the flux consisting of neutrons having energies greater than

---

[1]Type 575, Serial No. 00274, manufacturer, Tektronix, Inc.

a certain value:

fast neutrons, $\bar{E} > 0.5$ Mev

slow neutrons, $\bar{E} = 0.025$ ev

epithermal, $\bar{E} > 0.025$ ev

epicadmium, $\bar{E} > 0.4$ ev

Thermal and epicadmium energies will be used in this report. Some of the epicadmium flux contains neutrons with energies in the fast flux range, but the proportions are not known.

Gamma flux can be described in roentgens per hour (R/hr) or in terms of the energy absorption (ergs/gm) of one roentgen in a material, where the absorption of one roentgen in air is equal to 83.3 ergs per gram and in carbon, 87.7 ergs per gram. Roentgens per hour will be used in this report.

RESULTS

Thin Magnetic Films

Thin magnetic films received no nuclear radiation damage with respect to the 60-cycle hysteresis loop. Neutron flux levels experienced by the thin films were computed to be at 8.6×10^{10} n/cm^2-sec thermal and 3.3×10^{10} n/cm^2-sec epicadmium (Appendix A). Total integrated flux levels seen by the films did not exceed 2.88×10^{14}nvt thermal and 1×10^{14}nvt epicadmium. Total gamma radiation dosage received by the thin films was estimated at 1.34×10^7 RADS.

The resultant photographs taken at pre-irradiation and post-irradiation times of samples utilizing the rabbit tube experiment facility are shown in Figures 11 and 12. Neutron flux levels in the rabbit tube were approximately 7.4×10^{10} n/cm^2-sec thermal and 2.25×10^{10} n/cm^2-sec epicadmium. Total integrated flux received by these samples was 1.33×10^{14}nvt thermal and 4.05×10^{13}nvt epicadmium.

The resultant photographs taken of films irradiated in the inner thermal column test void are shown in Figures 13, 14 and 15. Neutron flux levels in the thermal column void were computed to be 8.6×10^{10} n/cm^2-sec thermal and 3.3×10^{10} n/cm^2-sec peicadmium. Total integrated flux received by these samples was 1.55×10^{14}nvt thermal and 5.95×10^{13}nvt epicadmium.

Resultant photographs for thin films irradiated by the Cobalt-60 source are shown in Figures 16 and 17. Total photon dosage received by

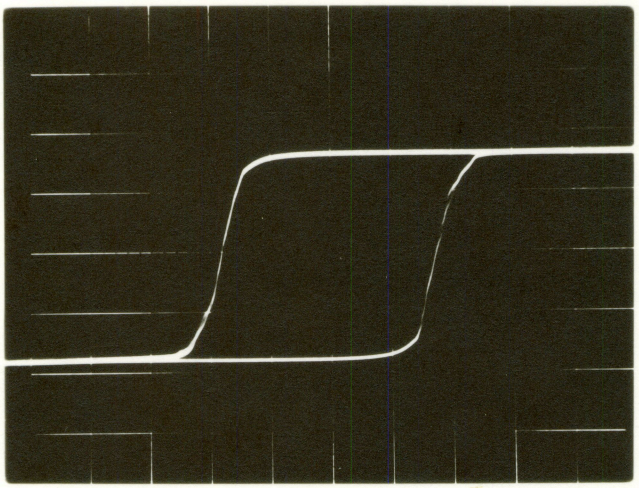
Before irradiation

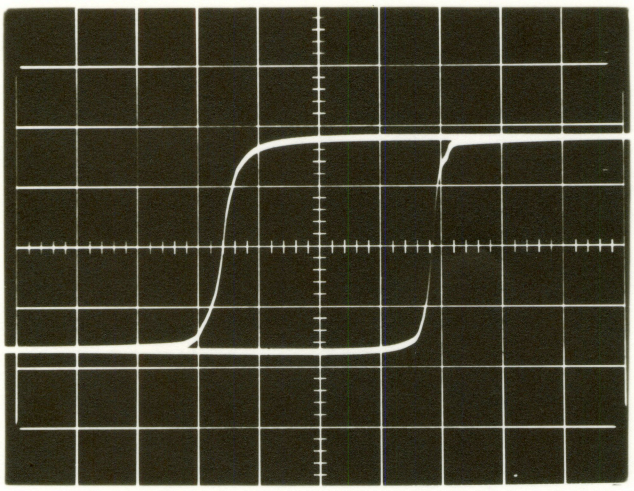
After irradiation

1.33×10^{14} nvt thermal

4.05×10^{13} nvt epicadmium

Figure 11. Thin film No. RT1.





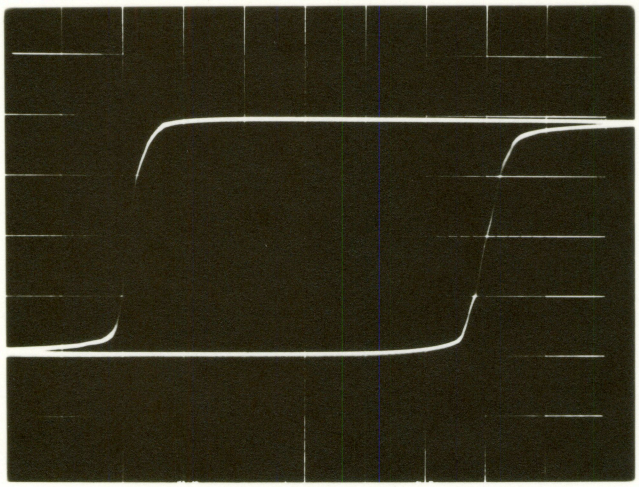
Before irradiation

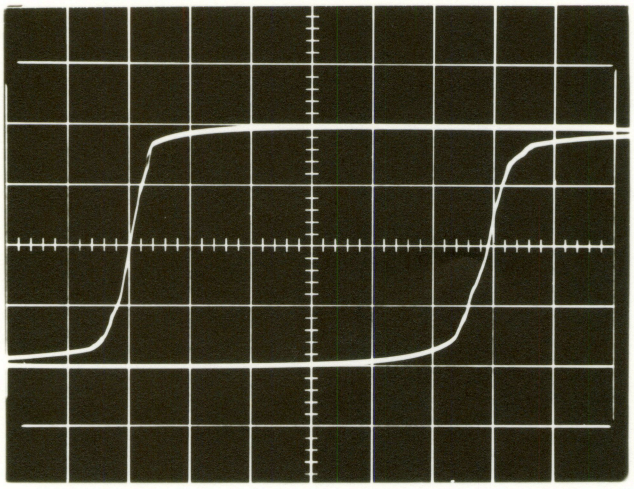
After irradiation

1.33×10^{14} nvt thermal

4.05×10^{13} nvt epicadmium

Figure 12. Thin film No. RT2,





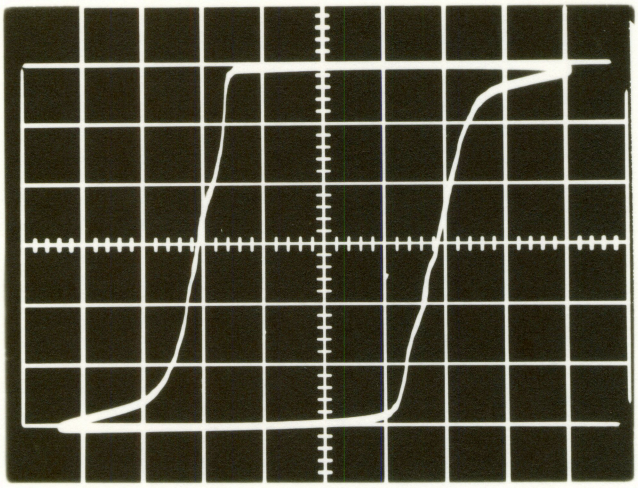
Before irradiation

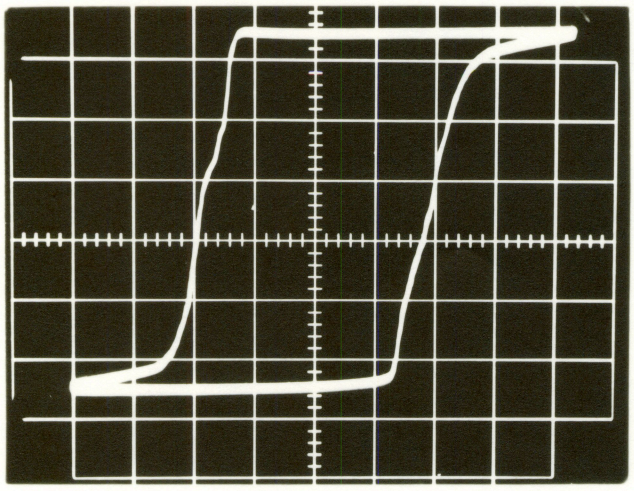
After irradiation

1.55×10^{14}nvt thermal

5.95×10^{13}nvt epicadmium

Figure 13. Thin film No. TC1.





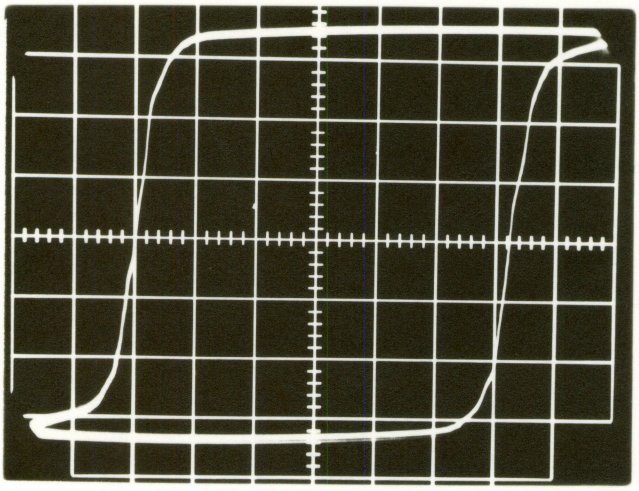
Before irradiation

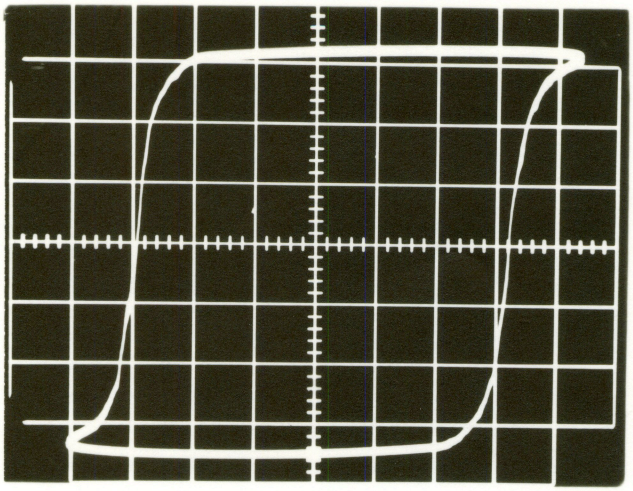
After irradiation

2.88×10^{14}nvt thermal

1×10^{14}nvt epicadmium

Figure 14. Thin film No. TC2.





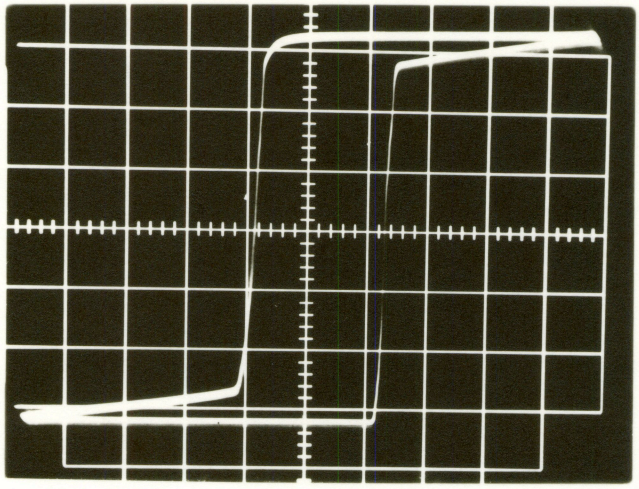
Before irradiation

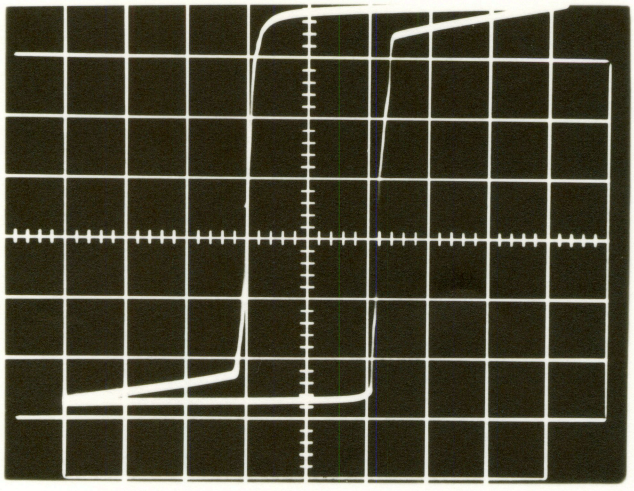
After irradiation

2.88×10^{14} nvt thermal

1×10^{14} epicadmium

Figure 15. Thin film No. TC3.



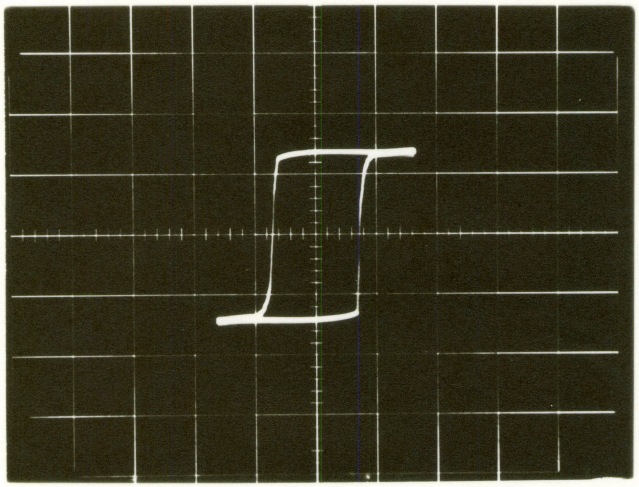


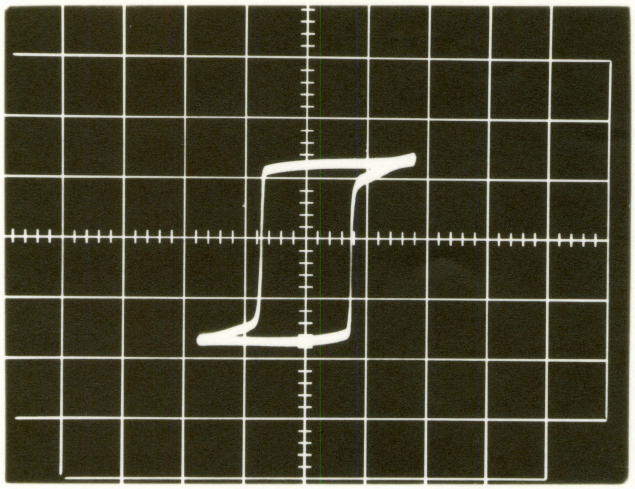
Before irradiation

After irradiation

1.34×10^7 RADS.

Figure 16. Thin film No. C01.



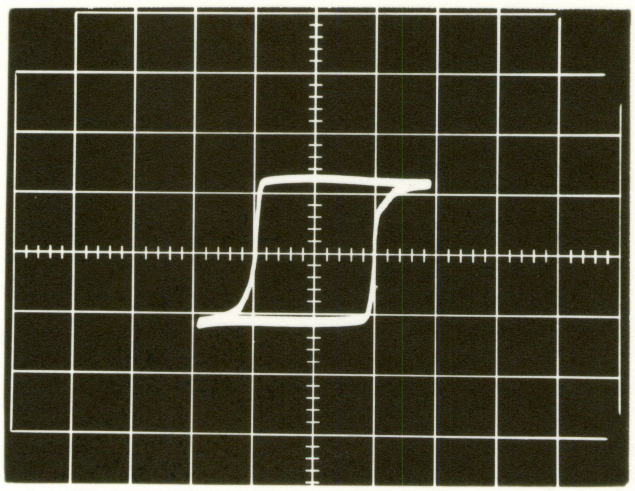


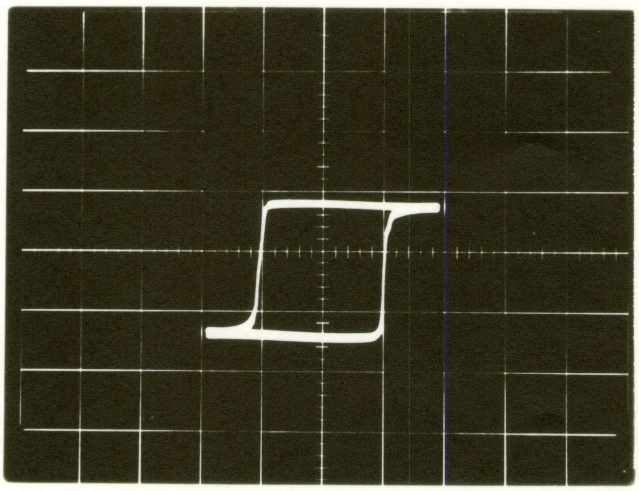
Before irradiation

After irradiation

1.34×10^7 RADS.

Figure 17. Thin film No. CO2.





these films was estimated[1] to be 1.34×10^7 RADS.

No change in coercive force or "squareness" of the hysteresis loops was noted.

Upon close examination, some loops appear to have changed a small amount with respect to their squareness (Figure 11, sample RT1). It is believed that this is due to the geometry of the films with respect to the pickup coils. Any slight shift, translation or rotation, of the films in their post-irradiation position with respect to their pre-irradiation position would result in this difference.

Transistors

Transistors received considerable radiation damage with respect to their collector current versus collector voltage curve characteristics. The resultant photographs taken at pre-irradiation and post-irradiation times of the samples utilizing the thermal column void are shown in Figures 18, 19 and 20. Neutron flux levels experienced by the transistors were 8.6×10^{10} n/cm^2-sec thermal and 3.3×10^{10} n/cm^2-sec epicadmium. Total integrated flux received by these samples was 1.55×10^{14}nvt thermal and 5.95×10^{13}nvt epicadmium.

Damage to transistors: parameter changes

Two transistor parameters were observed for changes (Appendix B). They were the base to collector gain β or h_{fe} (sometimes called the common emitter forward current transfer ratio) and h_{oe}, the output

[1]Courtesy of Dr. Joseph Picken.

Before irradiation

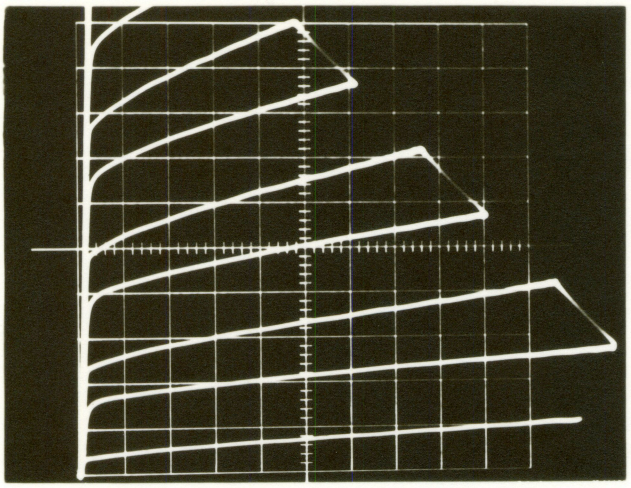
5 days after irradiation

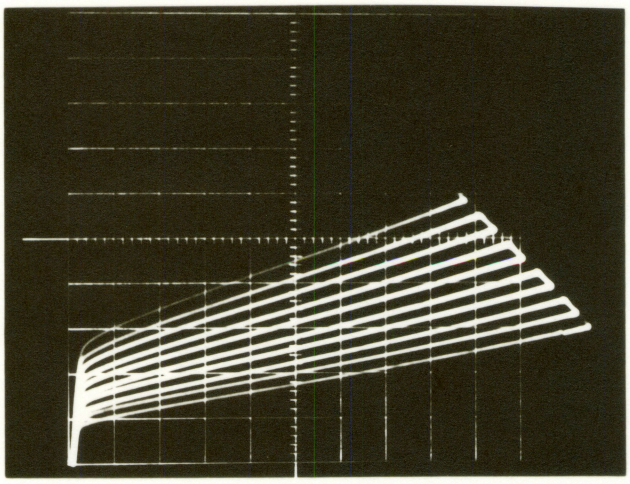
1.55×10^{14}nvt thermal

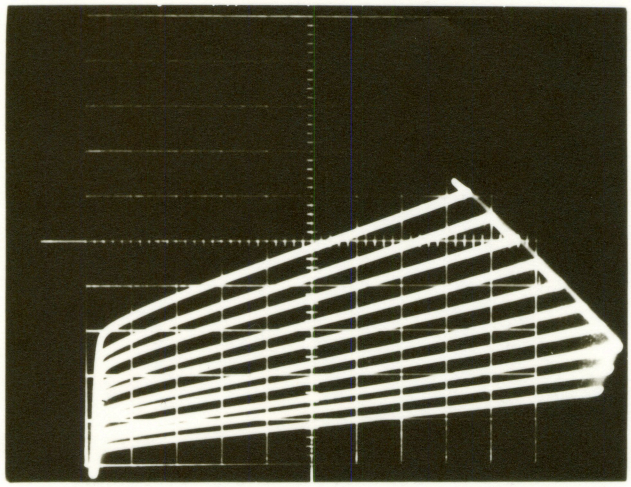
5.95×10^{13}nvt epicadmium

3 months after irradiation

Figure 18. Transistor No. 3TC.







Before irradiation

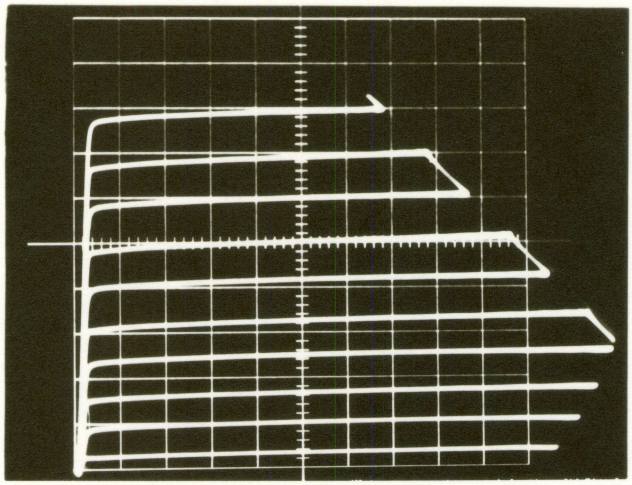
5 days after irradiation

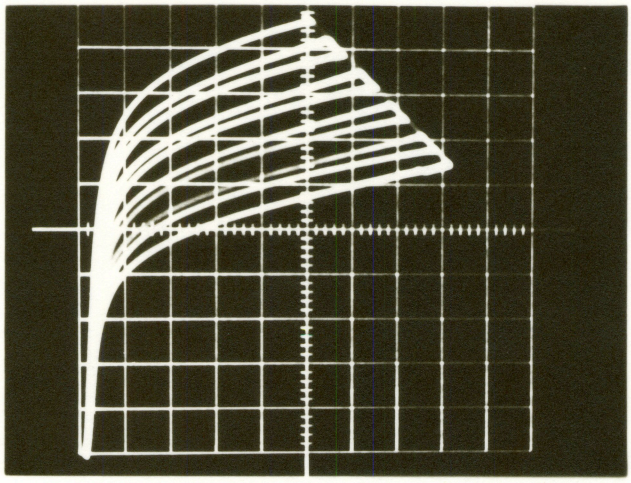
1.55×10^{14}nvt thermal

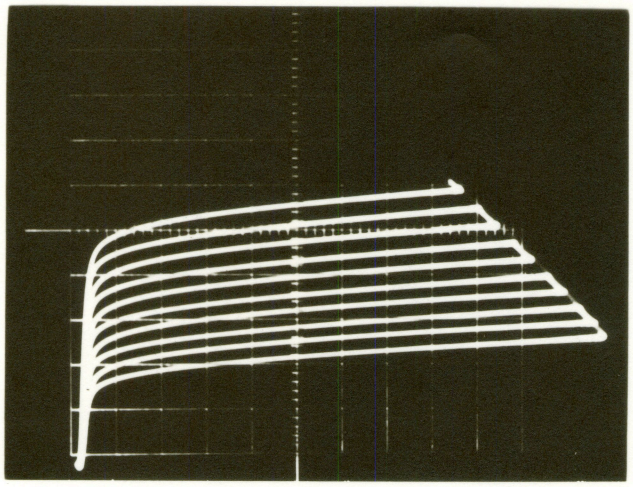
5.95×10^{13}nvt epicadmium

3 months after irradiation

Figure 19. Transistor No. 4TC.







Before irradiation

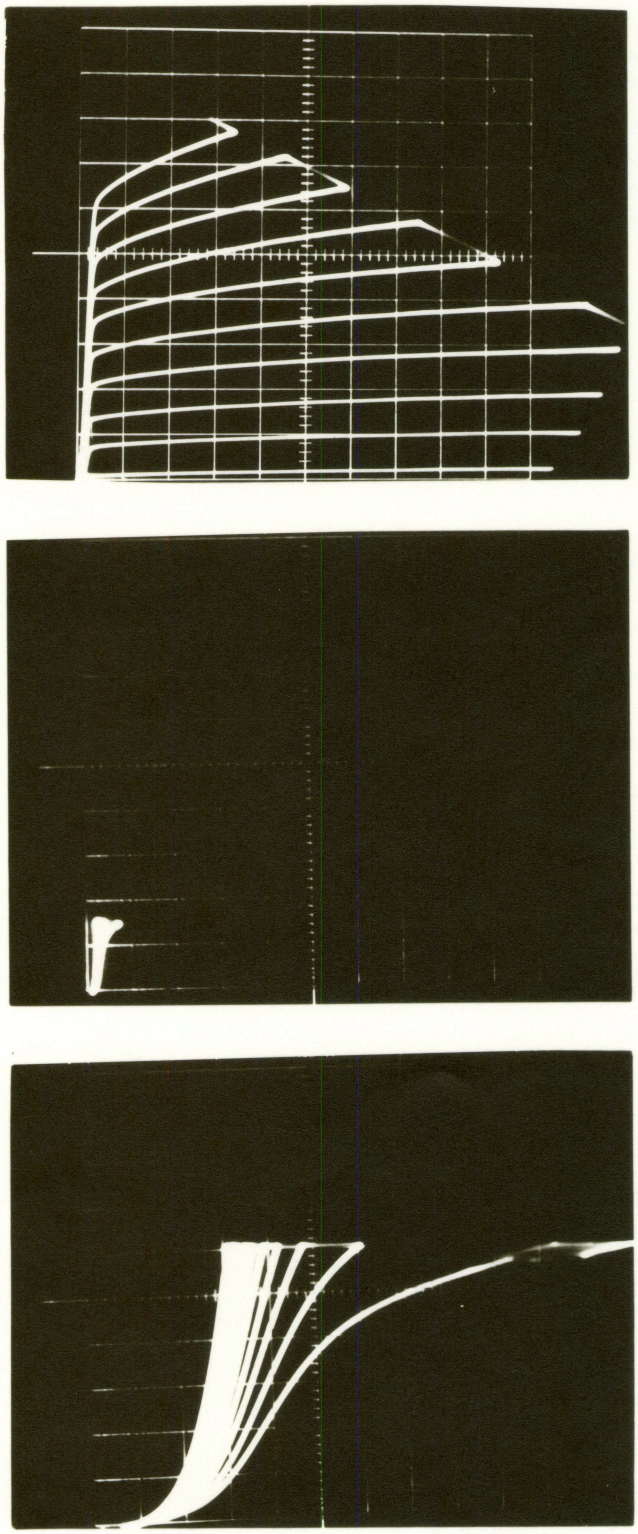
After irradiation

1.55×10^{14}nvt thermal

5.95×10^{13}nvt epicadmium

Same trace - more vertical and horizontal sensitivity

Figure 20. Transistor 5TC.



admittance. The following changes were noted:

Transistor no. 3TC (Figure 18) before irradiation:

h_{fe} = 32

h_{oe} = 3.08 millimhos

5 days after irradiation:

h_{fe} = 8; magnitude of change: 4 to 1

h_{oe} = 3.64 millimhos; magnitude of change: 1 to 1.18

3 months after irradiation:

h_{fe} = 12; magnitude of change: 2.67 to 1

h_{oe} = 3.33 millimhos; magnitude of change: 1 to 1.08

Transistor no. 4TC (Figure 19) before irradiation:

h_{fe} = 20

h_{oe} = 1.0 millimhos

5 days after irradiation:

h_{fe} = 6; magnitude of change: 3.33 to 1

h_{oe} = 5.72 millimhos; magnitude of change: 1 to 5.72

3 months after irradiation:

h_{fe} = 7; magnitude of change: 2.86 to 1

h_{oe} = 1.43 millimhos; magnitude of change: 1 to 1.43

Transistor no. 5TC (Figure 20):

For all practical purposes this transistor was completely damaged.

DISCUSSION

Thin Films

It is believed that the thin films used in this study would have experienced radiation damage similar to that shown for toroids of similar ferromagnetic material given an integrated neutron flux of sufficient magnitude and energy. Since the thin films depend on an atomic ordering of the constituent atoms for their square loop characteristics, atomic displacements produced by impinging neutrons could cause the degree of order to be altered and therefore the magnetic properties. No reference work is available showing results of the irradiation of thin films with respect to their 60-cycle hysteresis loop.

It seems feasible from work of Salkovitz (1960) that thin magnetic films or any ordered ferromagnetic alloy displaying an uniaxial axis of anisotropy could be made completely radiation resistant by merely placing the thin films in a saturating magnetic field (parallel to the easy axis of magnetization) during periods of high radiation intensities. Not only could thin films maintain their atomic ordering in this way but damaged or partially ordered films could be restored to an ordered condition again. If an airborne computer was to operate continually in a damaging radiation environment one might equip the computer with two identical magnetic film memories. While one memory was storing information and receiving its "daily" integrated dosages the other would exist in a "healing" magnetic field. Rate of "healing" or return of atomic ordering in the films incorporated in the memory experiencing

down-time should be the same as the rate of damage in the operating memory. If the two memory units could "exchange positions", so to speak, the healed memory could continue storing the information while the new damaged memory was being restored. This operation could proceed indefinitely.

Films versus Transistors

In reviewing Figures 11 through 20 it is easy to conclude that collector current versus collector voltage characteristics of a transistor are more sensitive to radiation than 60-cycle loop characteristics of a thin film. With increased technology in the applications of thin films to electronic devices it would be logical to expect thin films to replace transistors in radiation environments wherever possible.

Transistors

Transistors used in this study were RCA germanium alloy-junction, PNP. Transistors no. 3TC, Figure 18, and no. 4TC, Figure 19 were both type 2N581 and transistor no. 5TC, Figure 20 was type 2N643. Both 2N581 types suffered serious damage to about the same degree. Transistor no. 3TC showed a 4 to 1 change in base to collector gain and a 1 to 1.18 change in output admittance with respect to before irradiation and 5 days after irradiation. Three months after irradiation the transistor had regained some of its original properties and showed a 2.67 to 1 change in base to collector gain and a 1 to 1.08 change in output admittance. Transistor no. 5TC was for all practical purposes, completely damaged.

A decrease in current gain can be attributed to the deterioration of the minority carrier lifetime (Rohrback, 1961). After long exposure to radiation n-type germanium is converted to p-type; that is, the n-type material decreases in conductivity until a minimum value is reached and the material is changed to p-type. P-type germanium decreases in conductivity until it reaches the same limiting value as the converted n-type.

With suitable allowances for the decrease in current gain and other changes, transistors of this type should be generally operable after exposure to doses of 10^{12}nvt epicadmium.

SUMMARY AND CONCLUSIONS

Thin magnetic films composed of approximately 80 percent Ni and 20 percent Fe were irradiated in the Iowa State University UTR-10 reactor and by the Veterinary Research Institute Cobalt-60 source. Integrated flux levels encountered by the films were 2.88 x 10^{14}nvt thermal and 1.0 x 10^{14}nvt epicadmium and a known photon dosage of 1.34 x 10^{7} RADS. No radiation dosage was noted with respect to the 60-cycle hysteresis loop.

Transistors composed of germanium alloy junction types were irradiated in the UTR-10 reactor. Considerable damage resulted. A decrease in current gain and an increase in output admittance was noted. Integrated neutron fluxes experienced by the transistors were 1.55 x 10^{14}nvt thermal and 5.95 x 10^{13}nvt epicadmium. It is believed that transistors of this type should be generally operable after exposure to doses of 10^{12}nvt thermal and epicadmium.

It seems feasible from work of Salkovitz (1960) that thin magnetic films or any ordered ferromagnetic alloy displaying an uniaxial axis of anisotropy could be made completely radiation resistant by placing the thin films or other in a saturating magnetic field during periods of high radiation intensities. Not only could thin films maintain their atomic ordering in this way but damaged or partially ordered films could be restored to an ordered condition again.

BIBLIOGRAPHY

Aronin, L. R.
1954 Radiation damage effects on order-disorder in nickel-manganese alloys.
J. Appl. Phys. 25:344-349.

Beetz, W.
1860 Ueber die inneren Vorgange, welche die Magnetisirun bedingen.
Annalen der Physik und Chemie 111:107-121.

Blois, M. S., Jr.
1955 Preparation of thin magnetic films, and their properties.
J. Appl. Phys. 26:975-980.

Daughton, J. M., Smay, T. A., Read, A. A. and Pohm, A. V.
1961 Magnetic film devices using passive loading.
J. Appl. Phys. Suppl., 32:36S-37S.

Dienes, G. J. and Damask, A. C.
1958 Radiation enhanced diffusion in solids.
J. Appl. Phys. 29:1713-1721.

Gianola, U. F.
1960 Possibilities of all-magnetic logic.
J. Appl. Phys. Suppl., 32:27S-34S.

Henry, W. E. and Salkovitz, E. I.
1959 Reduction of saturation magnetization of -Fe_2O_3 and Fe_3O_4 by pile irradiation.
J. Appl. Phys. Suppl., 30:286S-287S.

Kaya, S.
1953 Uniaxial anisotropy of a permalloy crystal.
Rev. Mod. Phys. 25:49-55.

Laferski, J. J.
1958 Analysis of the effect of nuclear radiation on transistors.
J. Appl. Phys. 29:35-40.

Neel, L. M.
1954 Anisotropie magnetique superficelle et surstructures d'orientation.
Le Journal De Physique 15:225-239.

Pohm, A. V., Read, A. A., Stewart, R. M., Jr. and Schauer, R. F.
1959 High frequency magnetic film parametrons for computer logic.
Proc. Natl. Electronics Conf. 15:202-214.

Pohm, A. V., Read, A. A., Stewart, R. M., Jr. and Schauer, R. F.
1960 Operation of magnetic film parametrons in the 100 to 500 mc region.
J. Appl. Phys. Suppl., 31:119S-120S.

Read, A. A. and Pohm, A. V.
1959 Magnetic film parametric amplifiers.
Proc. Natl. Electronics Conf. 15:65-78.

Read, A. A. and Samuels, R. L.
1960 Thin ferromagnetic film balanced modulators.
Paper presented at 1960 Winter Convention on Military Electronics, Los Angeles, Calif., Feb. 3-5, 1960. (Mimeographed). Dept. of Electrical Engineering, Iowa State Univ. of Science and Technology, Ames, Iowa.
(Reviews published in Electronics 33:78-80. Feb. 26, 1960; Electronics Design 8:8. Mar. 2, 1960.

Rohrback, E. J.
1961 Nuclear radiation effects on electronic components and materials. In Airborne Instruments Laboratory. Topics in electronics. Vol. 2 pp 1-21. Deer Park, Long Island, N. Y.

Rubens, S. M.
1945 Cube-surface coil for producing a uniform magnetic field.
Rev. Scientific Instr. 16:243-245.

Salkovitz, E. I.
1960 Irradiation effects in magnetic materials.
J. Metals 12:622-625.

Salkovitz, E. I., Bailey, G. C. and Schindler, A. I.
1958 Effect of neutron irradiation on the Curie temperature of a variety of ferrites.
J. Appl. Phys. 29:1747-1748.

Salkovitz, E. I., Schindler, A. I., Sakiotis, N. G. and Ansell, G. S.
1960 Solid state physics in electronics and telecommunications.
In International Union of Pure and Applied Physics. Solid state physics in electronics and telecommunications. Vol. 2. pp 808-815.

Samuels, R. L.
1960 Thin ferromagnetic film balanced modulators. Unpublished M.S. thesis. Library, Iowa State Univ. of Science and Technology, Ames, Iowa.

Sanders, R. M.
1961 Stable-oscillation conditions for the magnetic film parametron. J. Appl. Phys. 32:478-482.

Schauer, R. F., Stewart, R. M., Jr., Pohm, A. V. and Read, A. A.
1960 Some applications of magnetic film parametrons as logical devices.
Institute Radio Engineers Trans. on Computer. EC9 Electronic computer :315-320.

Schindler, A. I., Salkovitz, E. I. and Ansell, G. S.
1959 Effect of neutron irradiation on the magnetic properties and degree of order of magnetic metal alloys.
J. Appl. Phys. Suppl. 30:282S-283S.

ACKNOWLEDGMENTS

I wish to express sincere appreciation to Dr. Glenn Murphy for his guidance and encouragement.

I would also like to acknowledge the help of those in the Electrical Engineering Department and the Veterinary Research Institute. Drs. A. A. Read and A. V. Pohm deserve many thanks for their efforts toward my behalf in regards to the 60-cycle hysteresis apparatus and knowledge of the thin films. Many thanks also to Dr. Joseph Picken for the use of his Cobalt-60 source and for the calibration curve he so graciously made determining total gamma dosage.

APPENDIX A

Determination of Thermal and Epicadmium Neutron Fluxes in the Thermal Column and Rabbit Tube; Experimental Facilities, UTR-10 Reactor

Start-up and shut-down corrections

For thermal column irradiation it is necessary to place a sample in the thermal column before reactor start-up. This is because of the closure shield that must be opened for access to the void facility. A start-up and shut-down correction might be necessary for flux calculations depending upon total time of irradiation. These corrections were investigated and it was found that if ignored a six percent error would be introduced to a calculation of neutron flux for a 10 minute irradiation time and a two percent error for a 30 minute irradiation time. That is to say, a sample being irradiated for 10 minutes sees about six percent of its integrated flux during start-up and shut-down and about two percent of its integrated flux for a 30 minute irradiation time. These errors were computed for a 39 second start-up period and a shim rod scram shut-down. These errors will be neglected in this report.

Procedure

Two gold foils were exposed in the "standard pile" at Argonne National Laboratory in a known thermal neutron flux (Experiment 26, NE 541). The activity of these foils was measured with the gas flow counting set-up (Iowa State University Nuclear Engineering Department) using a reproducible geometry in respect to the foils and counter. By

combining information on number of counts collected, foil weight, exposure time, counting time, time between removal from pile and counter, cadmium ratios and thermal neutron flux, a calibration factor, K, could be determined.

Knowing this calibration factor two gold foils, one bare and one cadmium covered, were irradiated in the same position at different times. This was done separately for the thermal column and rabbit tube facilities.

Results: thermal column

Run 1.

Uranium standard average activity:

24,217 c/m

Background average activity:

15 c/m

Bare gold foil no. 3, wt.= 0.0644 gm., average activity 10 minutes after scram:

31.207 c/m

Indium standard foil no. 50, wt.= 0.0833 gm., absorber no. 13 (173.5 mg/cm^2) average normalized activity at time of scram:

205 c/m

Run 2.

Uranium standard average activity:

24,082 c/m

Background average activity:

19 c/m

Cadmium covered gold foil no. 2, wt. = 0.0650 gm.,

average activity 10 minutes after scram:

7,145 c/m

Indium standard no. 50, wt. = 0.0833 gm., absorber no. 13

(173.5 mg/cm^2) average normalized activity at scram:

170 c/m

Flux calculation:

$$\Phi_{tot} = \frac{A\ sat}{wt\ (gm)} \cdot \frac{1}{K} \qquad K = 2.27$$

$$As = \frac{e^{\lambda t}\ A_t}{1-e^{-\lambda T}} \qquad t = \text{time between scram and counting}$$

$$\frac{31,207}{(1.79 \times 10^{-4})(10)} \qquad T = \text{time in reactor}$$

$$1.74 \times 10^7\ c/m$$

$$\Phi_{tot} = \frac{1.74 \times 10^7}{(0.0644)(2.27)} = 1.19 \times 10^8\ \frac{n}{cm^2\text{-}sec} \qquad 10\ watts$$

$$\Phi_{tot}\ (10KW) = 1.19 \times 10^{11}\ \frac{n}{cm^2\text{-}sec}$$

$$CR = \frac{bare\ activity}{cd.\ covered\ activity} = 3.64$$

$$\Phi_{thermal} = \frac{(CR-1)}{CR} \Phi_{tot}$$

$$= \frac{3.64-1}{3.64} \; 1.19 \times 10^{11} = 8.6 \times 10^{10}$$

$$\Phi_{th} = 8.6 \times 10^{10} \; \frac{n}{cm^2\text{-sec}} \quad \text{thermal}$$

$$\Phi_{epicadmium} \; 3.3 \times 10^{10} \; \frac{n}{cm^2\text{-sec}} \quad \text{epicadmium}$$

Results: rabbit tube

using the same procedure for the rabbit tube

$$\Phi_{tot} = 9.65 \times 10^{10} \; \frac{n}{cm^2\text{-sec}}$$

$$\Phi_{thermal} = 7.40 \times 10^{10} \; \frac{n}{cm^2\text{-sec}} \quad \text{thermal}$$

$$\Phi_{epicadmium} = 2.25 \times 10^{10} \; \frac{n}{cm^2\text{-sec}} \quad \text{epicadmium}$$

CR = 4.3

APPENDIX B

Calculation of Transistor Parameters Before and After Irradiation

The following two transistor parameters will be calculated:

1. β or h_{fe}, the base to collector current gain or the common emitter forward current transfer ratio.
2. h_{oe}, the output admittance.

The base to collector gain can be determined by measuring the change in collector current produced by a change in base current at a specified collector voltage (Figure B -1).

The output admittance is determined by measuring the change in collector current produced by a change in collector voltage at a specified value of base current (Figure B -2).

Transistor No. 3TC: before irradiation

Settings on transistor curve display:

Vertical:

Collector ma = 0.02 ma/div.

Horizontal:

Collector volts = 1.0 v/div.

Step selector:

ma/div = 0.001 ma/div.

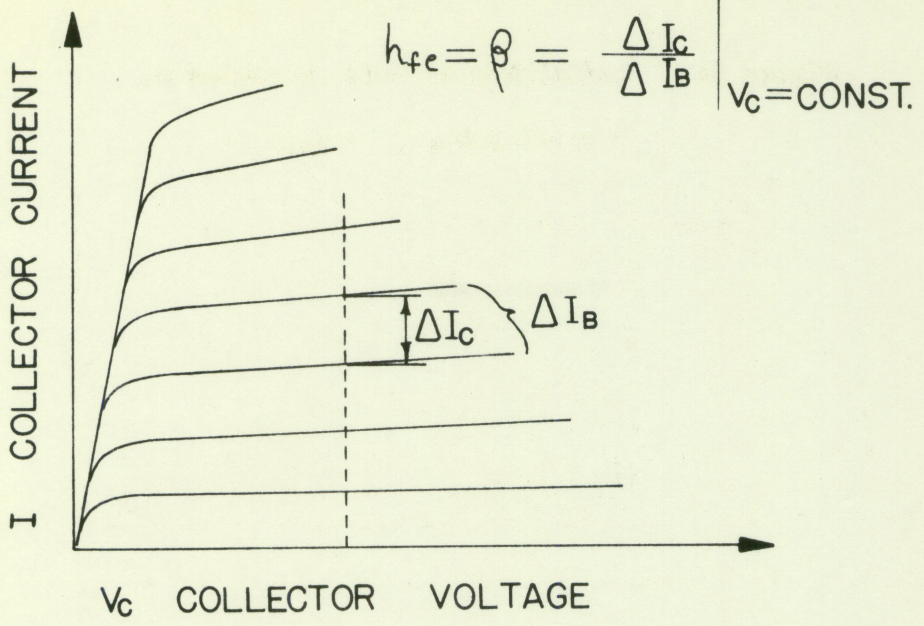
$$h_{fe} = \left.\frac{\Delta I_c}{\Delta I_b}\right|_{V_c = \text{const}} = \frac{0.032}{0.001} = 32$$

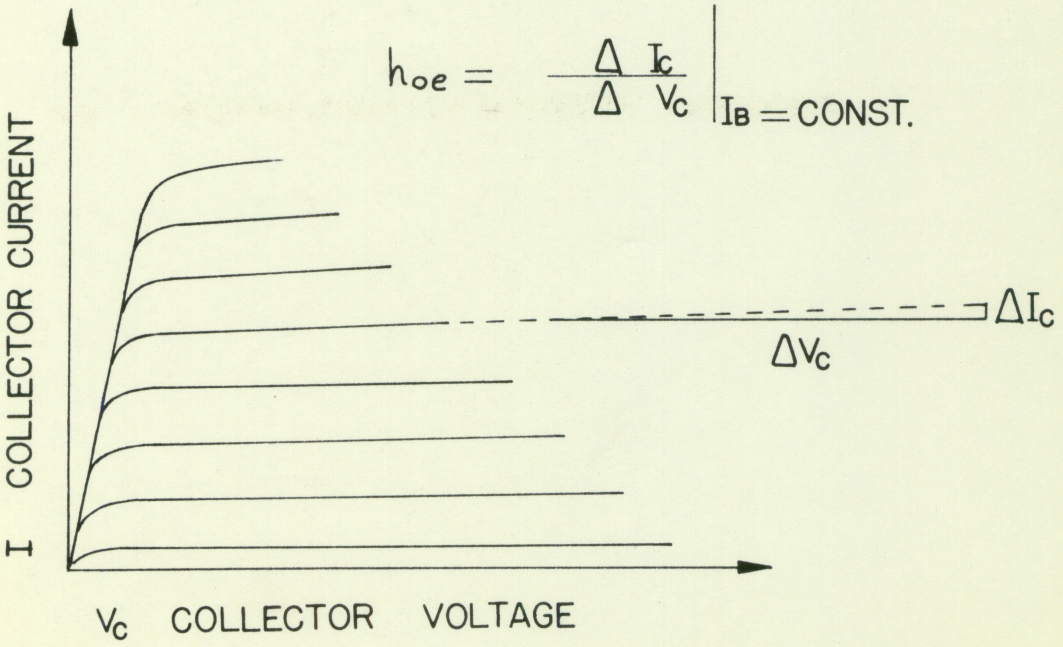
$$h_{oe} = \left.\frac{\Delta I_c}{\Delta V_c}\right|_{I_b = \text{const}} = \frac{0.02}{6.50} = 3.08 \times 10^{-3}$$

$$= 3.08 \text{ millimhos}$$

Figure B-1: Definition of base to collector current gain, $\beta = h_{fe}$.

Figure B-2: Definition of output admittance, h_{oe}.


$h_{fe} = \beta = \frac{\Delta I_C}{\Delta I_B}\Big|_{V_C = \text{CONST.}}$
I COLLECTOR CURRENT
ΔI_C
ΔI_B
V_C COLLECTOR VOLTAGE


$h_{oe} = \frac{\Delta I_C}{\Delta V_C}\Big|_{I_B = \text{CONST.}}$
I COLLECTOR CURRENT
ΔI_C
ΔV_C
V_C COLLECTOR VOLTAGE

Transistor No. 3TC: 5 days after irradiation

$$h_{fe} = \frac{0.008}{0.001} = 8$$

$$h_{oe} = \frac{0.02}{5.50} = 3.64 \text{ millimhos}$$

Transistor No. 3TC: 3 months after irradiation

$$h_{fe} = \frac{0.012}{0.001} = 12$$

$$h_{oe} = \frac{0.02}{6.00} = 3.3 \text{ millimhos}$$

Transistor No. 4TC: before irradiation

Settings on transistor curve display: same as above.

$$h_{fe} = \frac{0.02}{0.001} = 20$$

$$h_{oe} = \frac{0.004}{4.00} = 1.0 \text{ millimhos}$$

Transistor No. 4TC: 5 days after irradiation

$$h_{fe} = \frac{0.006}{0.001} = 6$$

$$h_{oe} = \frac{0.02}{3.50} = 5.72 \text{ millimhos}$$

Transistor No. 4TC: 3 months after irradiation

$$h_{fe} = \frac{0.007}{0.001} = 7$$

$$h_{oe} = \frac{0.01}{7.00} = 1.43 \text{ millimhos}$$