

NEUTRON DOSIMETRY WITH SILICON DIODES

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## INTRODUCTION

RECENT DEVELOPMENT OF PIN DIODES WITH IMPROVED CHARACTERISTICS, HAS RENEWED THE INTEREST IN THEIR USE FOR PATIENT DOSE VERIFICATION DURING NEUTRON RADIATION THERAPY. SUCH DIODES ARE AVAILABLE FROM HARSHAW/FILTROL (MODEL DN-156, AT A COST OF \$20 EACH). THE DIODES ARE ALMOST TOTALLY INSENSITIVE TO PHOTON RADIATION AND HAVE CHARACTERISTICS SIMILAR TO TLDs IN THAT THEY STORE THE DOSE IN THE FORM OF RADIATION DAMAGE WHICH CAN BE MEASURED USING A SPECIALLY DESIGNED READER.

## OBJECTIVES

THE PURPOSE OF THIS WORK IS:

1. TO EXPERIMENTALLY MEASURE THE RESPONSE OF SILICON PIN DIODES AS A FUNCTION OF TOTAL ABSORBED DOSE FOR TWO NEUTRON THERAPY BEAMS: THE UNIVERSITY OF CHICAGO (UC) BEAM HAVING AN AVERAGE ENERGY OF ABOUT 8 MeV AND THE MIDWEST INSTITUTE FOR NEUTRON THERAPY (MINT) BEAM AT FERMI NATIONAL LABORATORY WITH AN AVERAGE ENERGY OF ABOUT 25-30 MeV.
2. TO INVESTIGATE THE FADING CHARACTERISTICS AT ROOM TEMPERATURE AS WELL AS THE EFFECT ON THE SENSITIVITY OF ANNEALING THE DIODES.
3. TO INVESTIGATE THE DEPENDENCE OF THE SENSITIVITY TO NEUTRON DOSE AS A FUNCTION OF ACCUMULATED RADIATION-DAMAGE TO THE DIODES. THIS IS IMPORTANT SINCE, UNLIKE TLDs, THE RADIATION-INDUCED DAMAGE CANNOT BE TOTALLY REMOVED.

## MATERIALS AND METHODS

THE PIN DIODES USED CONSIST OF A SILICON CHIP IN WHICH A HEAVILY DOPED P REGION AND A HEAVILY DOPED N REGION ARE SEPARATED BY A LIGHTLY DOPED I (INTRINSIC) REGION. THE PHYSICAL DIMENSIONS OF THE CHIP ARE  $1.5 \text{ mm}^3$  SURROUNDED BY ABOUT 0.8 MM THICK EPOXY TO MAKE A CYLINDER 3 MM DIA. X 3.5 MM LONG. THE DOMINANT MECHANISM FOR PRODUCING RADIATION DAMAGE IS THE PHYSICAL DISPLACEMENT OF SILICON ATOMS FROM THEIR LATTICE SITES WHICH INCREASES THE RESISTIVITY OF THE DIODE. THE CHANGE IN RESISTANCE IS PROPORTIONAL TO THE ABSORBED DOSE. RESISTANCE MEASUREMENTS ARE MADE BY APPLYING A PULSED, CONSTANT CURRENT TO THE DIODE AND READING THE VOLTAGE DROP ACROSS IT. TWO READERS WERE AVAILABLE FOR THIS WORK: ONE DESIGNED AND BUILT AT FERMILAB, THE OTHER A MODEL NC-28 NEUTRON DIODE ANALYZER FROM HARSHAW. BOTH READERS CONSIST OF A PULSED 25 MA CURRENT SOURCE (10 AND 20 MSEC LONG PULSES RESPECTIVELY), A VOLTAGE SAMPLING CIRCUIT, AN ANALOG TO DIGITAL CONVERTER AND A SCALER. THE FERMILAB READER COULD BE USED RELIABLY ONLY UP TO ABOUT 2 VOLTS WHILE THE HARSHAW READER WAS FOUND USEFUL FOR VOLTAGES AS HIGH AS 5 VOLTS. THE READERS WERE INTERCALIBRATED AND COULD BE USED INTERCHANGEABLY.

SIXTY PIN DIODES WERE PURCHASED IN A SINGLE BATCH. FORTY-FIVE OF THESE (6 GROUPS OF 3 FOR THE UC BEAM AND 9 GROUPS OF 3 FOR THE MINT BEAM) WERE EXPOSED TO GRADED DOSES OF NEUTRONS AT BOTH FACILITIES. VOLTAGE MEASUREMENTS WERE MADE PRECEEDING ( $V_{\text{PRE}}$ ) AND AT SEVERAL TIME-INTERVALS FOLLOWING THE IRRADIATIONS ( $V_{\text{POST}}$ ). THIS WAS DONE IN ORDER TO INVESTIGATE THE FADING CHARACTERISTICS AT ROOM TEMPERATURE.

UNLESS OTHERWISE INDICATED, THE RESULTS FROM THE READINGS AT 24 HOURS POST IRRADIATIONS WERE USED FOR THE DATA ANALYSIS PRESENTED HERE.

TWO WEEKS AFTER THE FIRST IRRADIATION, EACH DIODE WAS EXPOSED TO A DOSE OF 60 cGy AT THE CORRESPONDING FACILITY AND READINGS WERE TAKEN AT 3 AND 24 HOURS FOLLOWING IRRADIATION. THIS WAS DONE IN ORDER TO INVESTIGATE THE CHANGE IN SENSITIVITY WITH ACCUMULATED DOSE. FINALLY THE SET OF DIODES USED AT THE UNIVERSITY OF CHICAGO WERE ANNEALED AT 180°C FOR TWO HOURS AND THEN THE RESPONSE TO 60 RADS OF NEUTRONS WAS MEASURED AGAIN. THIS PROCEDURE IS BASED ON EXPERIENCE GAINED IN PREVIOUS WORK.

TO DETERMINE AN UPPER LIMIT FOR THE SENSITIVITY TO PHOTON RADIATION, A GROUP OF 4 DIODES WAS EXPOSED SEQUENTIALLY TO GRADED DOSES OF 4 MV PHOTONS FROM 10 TO 500 Gy. IN A SEPARATE EXPERIMENT A DIFFERENT SET OF, 4 DIODES WAS GIVEN A TOTAL DOSE OF 800 cGy OF NEUTRONS AT THE UC FACILITY IN A NUMBER OF EXPOSURES IN ORDER TO INVESTIGATE THE DEPENDENCE OF THE NEUTRON SENSITIVITY ON THE HISTORY OF ACCUMULATING RADIATION DAMAGE (SINGLE VS MULTIPLE EXPOSURES). THIS IS IMPORTANT SINCE THE BULK OF DATA WAS OBTAINED BY GIVING THE TOTAL DOSE IN A SINGLE EXPOSURE.

## RESULTS

FIGURE 1 DISPLAYS THE DISTRIBUTION OF RELATIVE SENSITIVITIES OF THE 60 DIODES ACQUIRED FOR THIS EXPERIMENT. NOTE THAT, ALTHOUGH THIS IS A GROUP PRESELECTED BY THE MANUFACTURER, THE SPREAD IN SENSITIVITIES IS  $\pm 9\%$  AND THE DISTRIBUTION IS CLOSE TO FLAT. FOR THESE REASONS, EACH DIODE WAS CODED AND ITS IDENTITY MAINTAINED THROUGHOUT THE MEASUREMENTS. HERE 1.0 CORRESPONDS TO 2.8 mV/cGy FOR THE UC NEUTRON BEAM.

FIGURE 2 SHOWS THE NORMALIZED VOLTAGE DIFFERENCE READ AT INCREASING TIMES AFTER IRRADIATION FROM 0 TO 30 DAYS. WE SEE THAT, FOLLOWING AN INITIAL STEEP DROP, THE FADING IS SLOW AND LEVELS OFF AFTER ABOUT 3 WEEKS. THE FADING CHARACTERISTICS WERE FOUND TO DEPEND SLIGHTLY ON THE ACCUMULATED DOSE BUT NOT ON BEAM ENERGY.

IN FIGURE 3 WE HAVE PLOTTED THE VOLTAGE DROP ACROSS THE PIN DIODES FOLLOWING EXPOSURES TO THE NEUTRON BEAMS AT THE FERMILAB (MINT) AND THE UNIVERSITY OF CHICAGO (UC) FACILITIES. HERE WE SHOW THE DIFFERENCE OF THE VOLTAGE READING 24 HOURS AFTER IRRADIATION ( $V_{\text{POST}}$ ) TO THAT PRIOR TO IRRADIATION ( $V_{\text{PRE}}$ ) VERSUS THE ABSORBED NEUTRON DOSE. EACH POINT IS THE AVERAGE OF READINGS FROM 3 DIODES EXPOSED SIMULTANEOUSLY. THE TOTAL DOSE INDICATED ON THE ABSCISSA WAS DELIVERED IN A SINGLE FRACTION. THE LINES ARE THE RESULT OF A LINEAR LEAST-SQUARES FIT TO ALL DATA POINTS. TO THE EXTENT THAT A STRAIGHT LINE CAN BE USED TO REPRESENT THE OVERALL SENSITIVITY, THE SLOPES YIELD 2.5 mV/cGy FOR THE MINT AND 4.0 mV/cGy FOR THE UC NEUTRON BEAMS.

HARSHAW'S DATA SHEET FOR THE DN-156 DIODES SHOWS A SLOPE OF 5 mV/cGy FOR REACTOR PRODUCED NEUTRONS. THESE RESULTS IMPLY THAT THERE IS A TREND OF INCREASED SENSITIVITY WITH DECREASING MEAN NEUTRON ENERGY.

TO INVESTIGATE THE RESPONSE TO PHOTONS WE EXPOSED 4 DIODES SEQUENTIALLY TO INCREASING DOSES OF A 4 MV BEAM FROM 10 TO 500 GY. THERE WAS NO DETECTABLE SIGNAL BELOW 15 GY AND THE LINEAR FIT TO THE DATA ABOVE 100 GY YIELDED A PHOTON SENSITIVITY OF 0.1 mV/GY DOWN BY MORE THAN A FACTOR OF 1,000 FROM THAT TO NEUTRONS.

IN FIGURE 4 WE PRESENT THE SENSITIVITY IN mV/cGy FOR PIN DIODES WHEN EXPOSED TO 60 RADS OF NEUTRON DOSE AFTER RECEIVING A TOTAL DOSE AS INDICATED ALONG THE ABSCISSA. THE SOLID LINES DRAWN THROUGH THE SOLID CIRCLES REPRESENT THE SENSITIVITY AS A FUNCTION OF ACCUMULATED DOSE DELIVERED IN ONE SINGLE EXPOSURE. EACH DATA POINT IS THE AVERAGE OF THE READING FROM 3 DIODES EXPOSED SIMULTANEOUSLY. ONE CAN SEE THAT THE GENERAL TREND IS SIMILAR FOR THE UC AND MINT BEAMS BUT THAT THERE IS AN OVERALL ENERGY DEPENDENCE AS MEASURED BY THE SLOPES IN FIGURE 3. THE DATA REPRESENTED BY X'S, WITH THE DOTTED LINE DRAWN THROUGH THEM, SHOW THE SENSITIVITY OF PIN DIODES AFTER ACCUMULATING A TOTAL DOSE AS INDICATED ON THE ABSCISSA BUT IN MULTIPLE EXPOSURES. THE DATA HERE WERE COLLECTED FOR THE SAME 4 DIODES AND AVERAGED AT EACH POINT. NOTE THAT, ALTHOUGH THE GENERAL TREND OF THE SENSITIVITY CURVES IS SIMILAR, THERE IS A DEPENDENCE ON THE IRRADIATION HISTORY OF THE DIODES (SINGLE VERSUS MULTIPLE EXPOSURES).

WE FURTHER INVESTIGATED THE EFFECT ON THE FORWARD RESISTANCE IF THE DIODES ARE ANNEALED AFTER IRRADIATION. FIGURE 5 SHOWS THE READING OF THE VOLTAGE ACROSS A NUMBER OF DIODES AS A FUNCTION OF ABSORBED DOSE, BEFORE AND AFTER ANNEALING FOR 2 HOURS AT  $180^{\circ}$  cGY. SOME RECOVERY IS OBSERVED. THE DOTTED LINE SHOWS THE BEHAVIOR OF A HYPOTHETICAL DIODE WHICH WOULD HAVE HAD A READING OF 3.4 VOLTS POST IRRADIATION AFTER A DELIVERY OF 600 cGY AND THEN, AFTER ANNEALING, THAT SAME DIODE WOULD READ 2.3 VOLTS WHICH CORRESPONDS TO A PRE-ANNEALING RESISTANCE ASSOCIATED WITH AN ABSORBED DOSE OF 260 cGY. WE CALL THIS THE "RESIDUAL" DOSE WHILE THE 600 cGY IS THE "TOTAL" DOSE.

IN ORDER TO INVESTIGATE THE SENSITIVITY OF DIODES THAT HAVE BEEN ANNEALED, WE EXPOSED GROUPS OF 3 DIODES TO GRADED DOSES, ANNEALED THEM FOR 2 HOURS AT  $180^{\circ}$  cGY AND THEN MEASURED THEIR SENSITIVITY BY EXPOSING THEM TO 60 cGY. THESE NEW SENSITIVITIES ARE PLOTTED IN FIGURE 4 AS OPEN CIRCLES VERSUS THE "RESIDUAL" DOSE INFERRED FROM THE CURVES IN FIGURE 5. IT IS REASSURING TO NOTE THAT THESE POINTS FALL RIGHT ALONG THE SOLID LINE THAT REPRESENTS THE SENSITIVITY OF NON-ANNEALED DIODES. THIS SHOWS THAT ANNEALED DIODES HAVE THE SAME SENSITIVITY AS NON-ANNEALED ONES IF "RESIDUAL" INSTEAD OF "TOTAL" DOSE IS USED TO DESCRIBE THEIR ACCUMULATED RADIATION DAMAGE.

## SUMMARY AND CONCLUSIONS

WE HAVE INVESTIGATED THE RESPONSE OF PIN DIODES TO NEUTRON ABSORBED DOSE AS A FUNCTION OF BEAM ENERGY AND MODE OF DOSE DELIVERY (SINGLE VS MULTIPLE EXPOSURES). WE HAVE STUDIED THE FADING AT ROOM TEMPERATURE AS WELL AS THE EFFECT OF ANNEALING AT 180°C FOR TWO HOURS. WE FIND THAT:

1. THE AVERAGE SENSITIVITY DEPENDS ON THE NEUTRON AVERAGE ENERGY. IT INCREASES BY A FACTOR OF 2 BY GOING FROM THE MINT BEAM ( $E_{AVE}$  25-30 MeV) TO REACTOR PRODUCED NEUTRONS ( $E_{AVE}$  1-2 MeV)
2. AT ROOM TEMPERATURE, THERE IS A RAPID DROP IN THE FORWARD RESISTANCE OF THE DIODES IMMEDIATELY AFTER IRRADIATION. FADING RESULTS IN A DECREASE OF THE FORWARD RESISTANCE OF THE DIODES TO 75% OF THEIR INITIAL VALUE AFTER ABOUT 3 WEEKS.
3. THERE IS SOME DEPENDENCE ( $\sim 10\%$ ) OF THE NEUTRON SENSITIVITY ON THE IRRADIATION HISTORY OF THE DIODE (SINGLE VS MULTIPLE EXPOSURES).
4. ANNEALING AT 180°C FOR 2 HRS RESULTS IN THE RECOVERY OF SLIGHTLY MORE THAN  $\frac{1}{2}$  THE RADIATION DAMAGE WITHOUT CHANGE IN SENSITIVITY.
5. PIN DIODES CAN BE USED FOR NEUTRON DOSIMETRY WITH PRECISION OF  $\pm 3\%$  IF THE IDENTITY OF EACH DIODE IS MAINTAINED PROVIDED AND THE CALIBRATION IS UPDATED AS A FUNCTION OF ACCUMULATED DOSE.

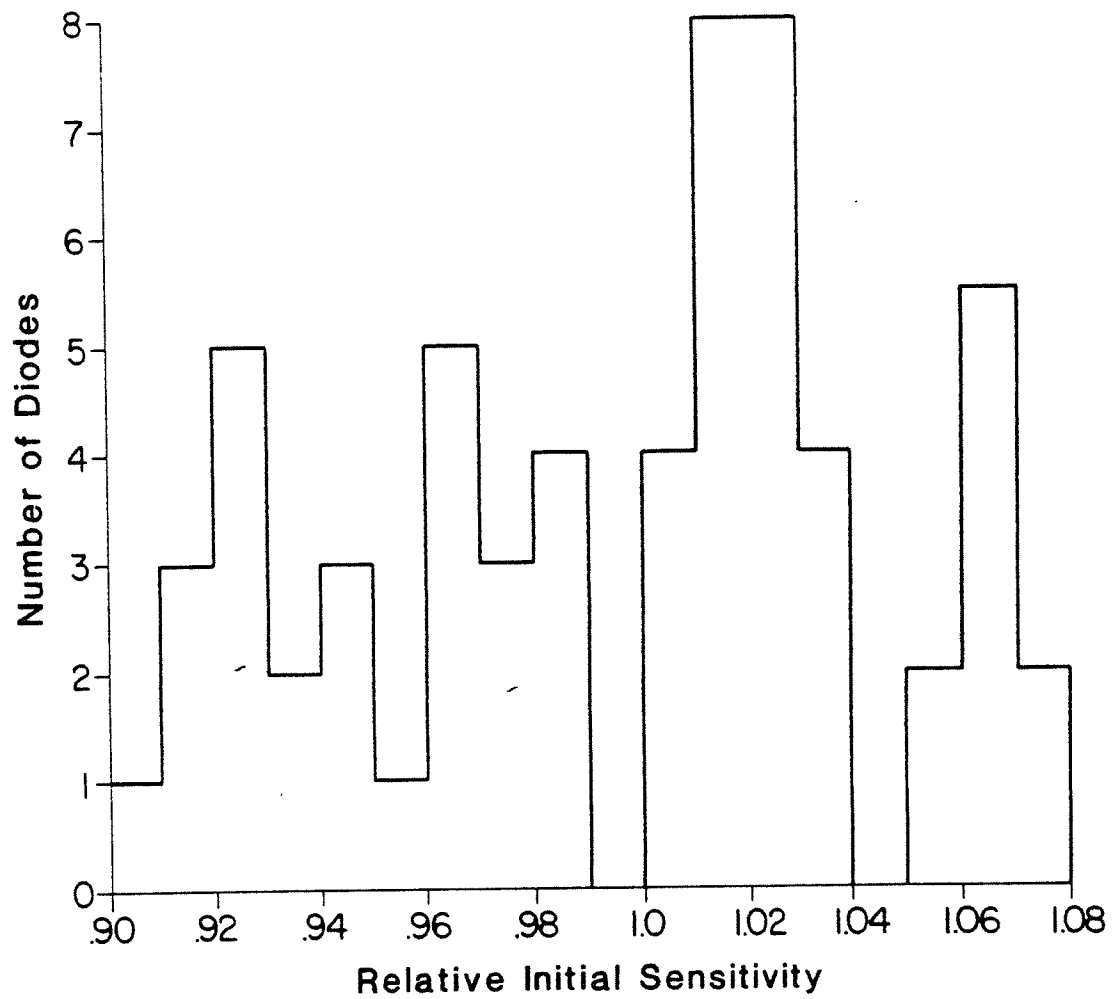
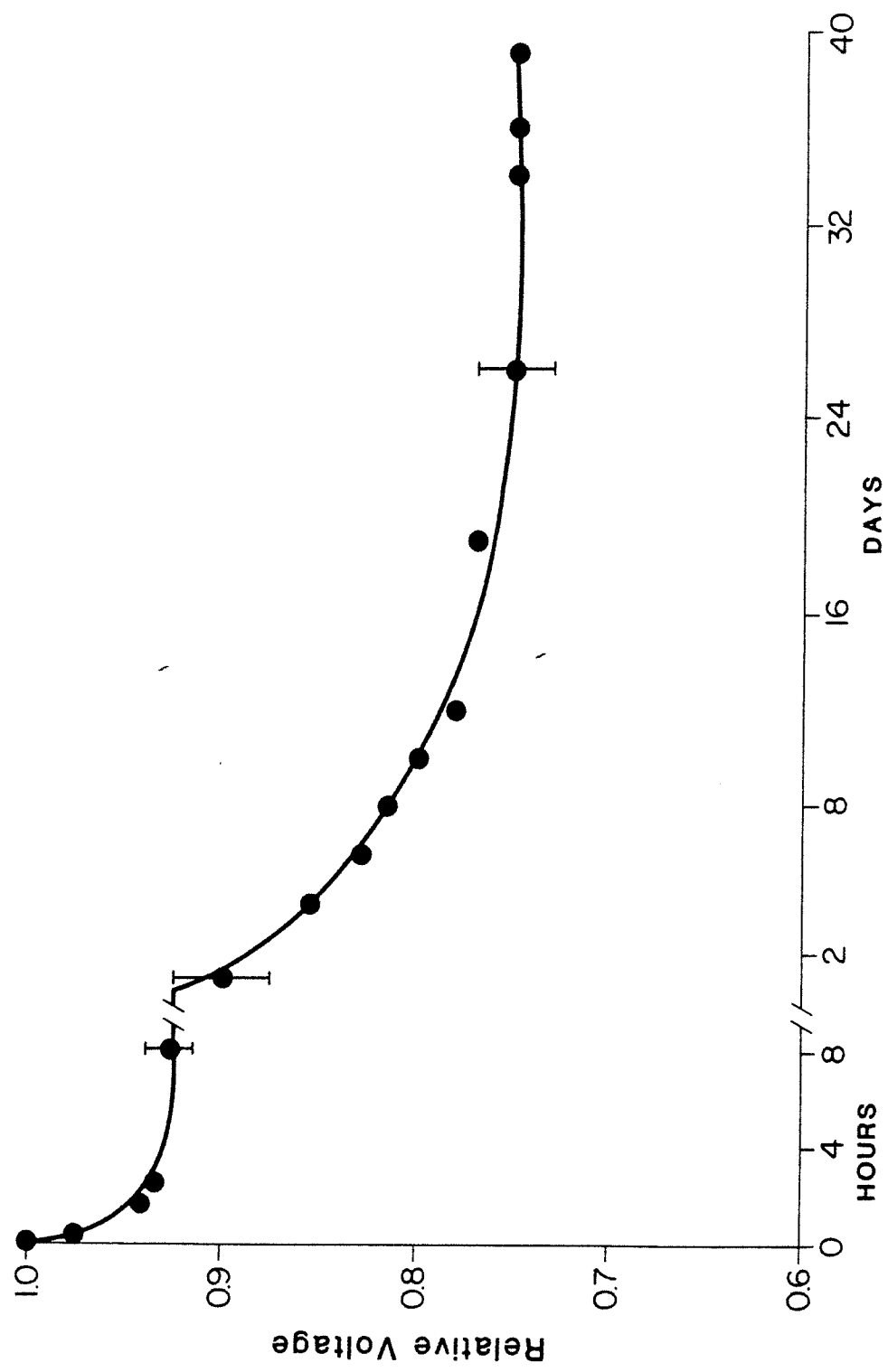


FIGURE 1



Time At Room Temperature After Irradiation

FIGURE 2

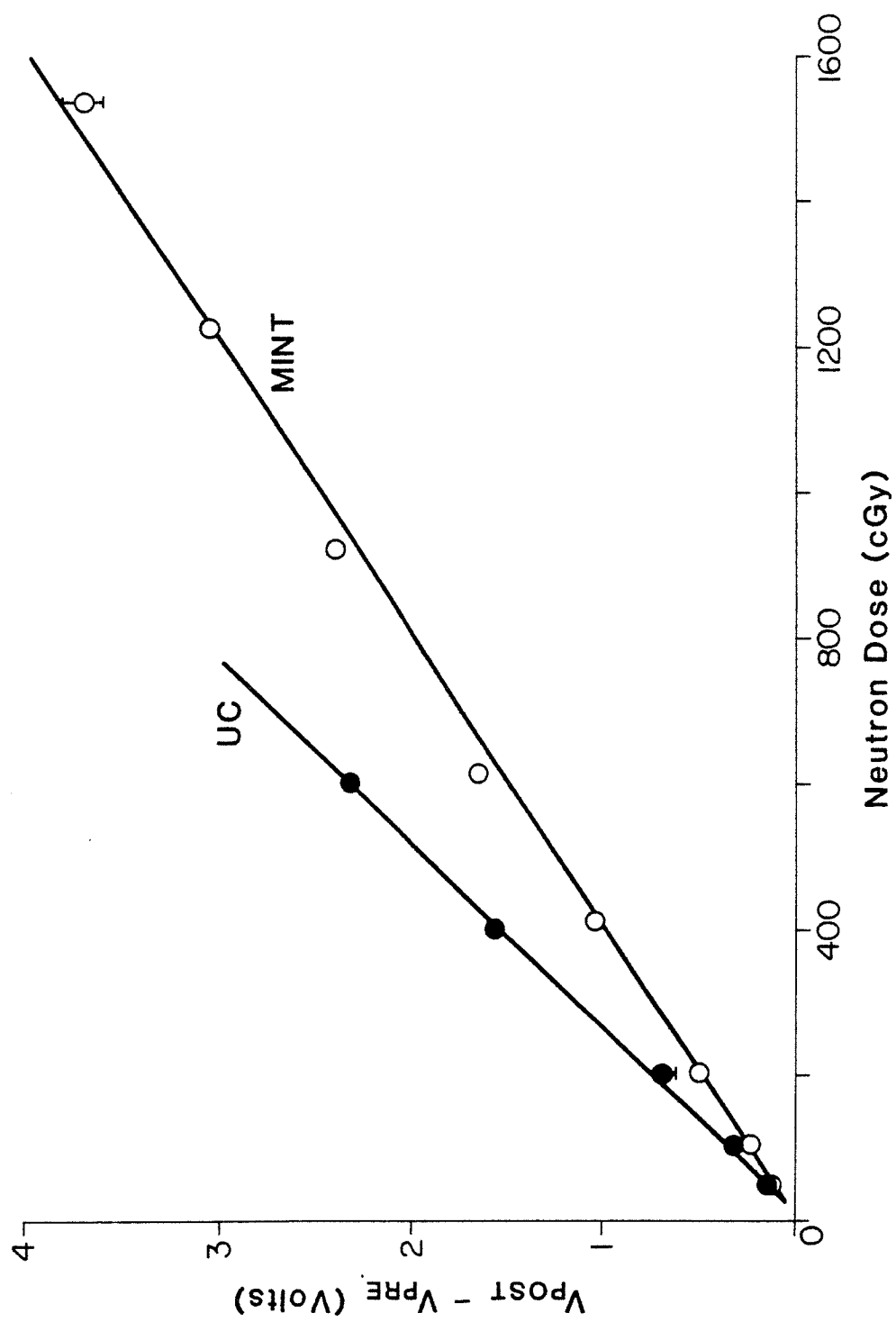


FIGURE 3

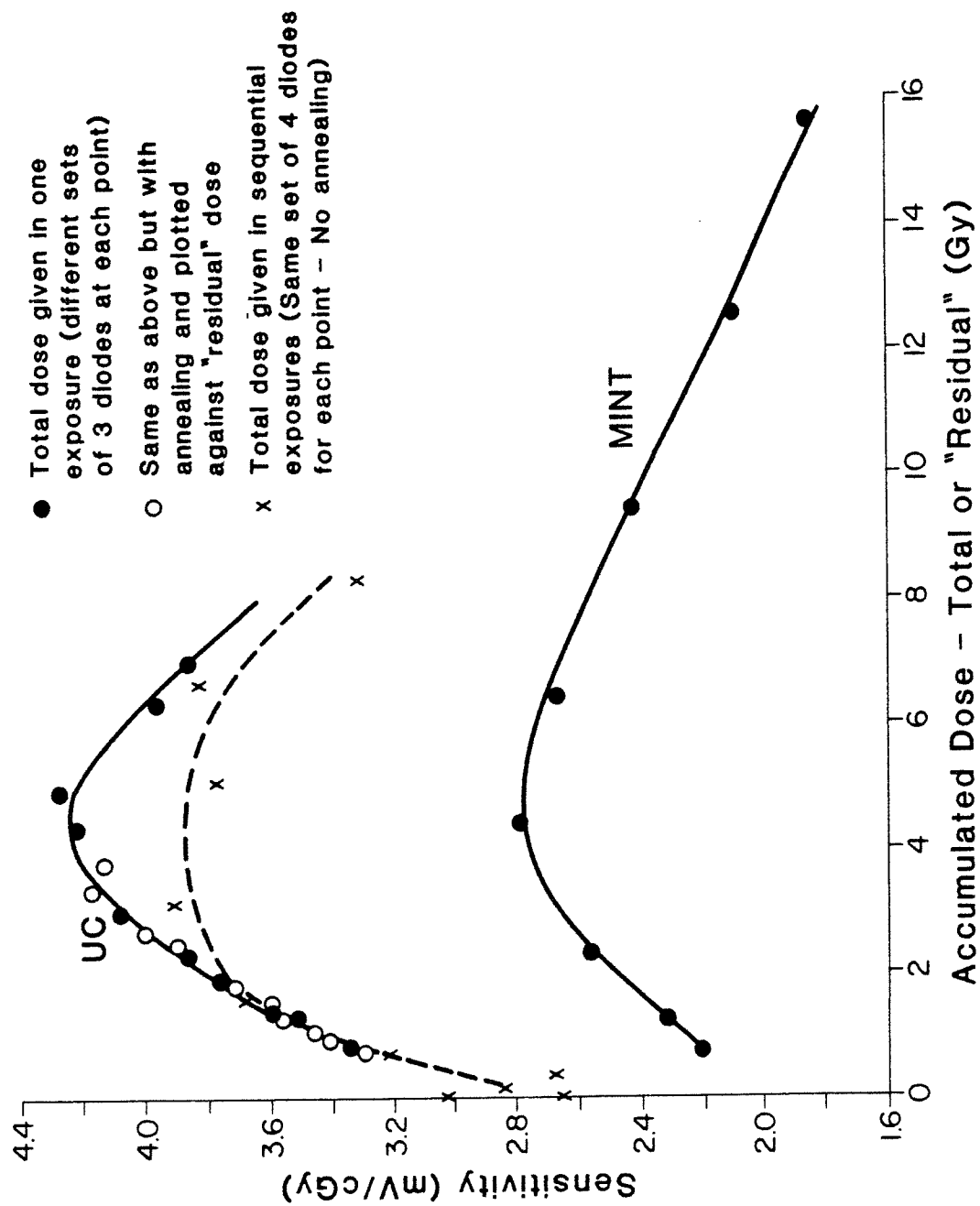


FIGURE 4

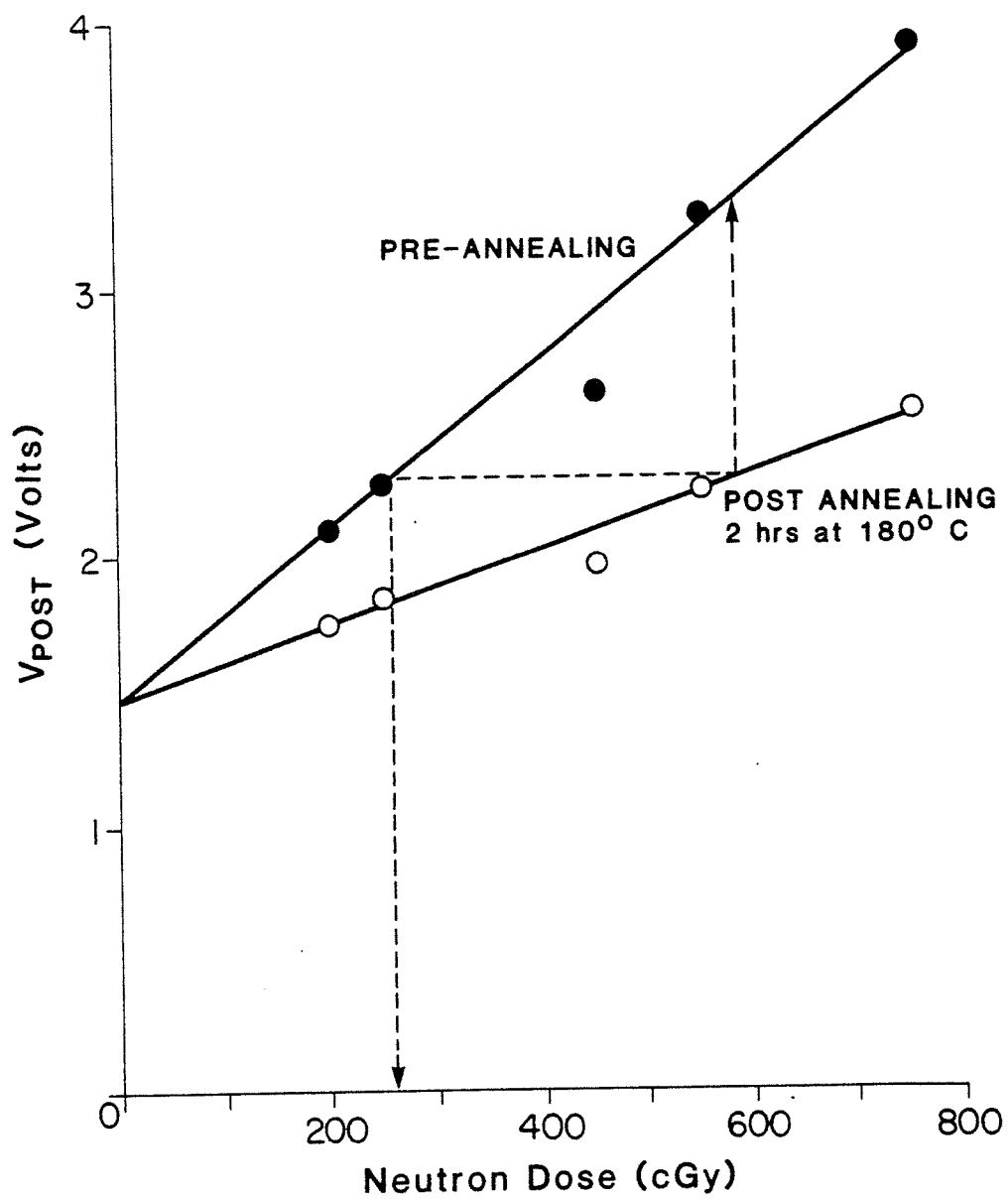


FIGURE 5