RBE of Monoenergetic Fast Neutrons: Cytogenetic Effects in Maize*

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DISCLAIMER

1. INTRODUCTION

Investigations on the relative biological effectiveness (RBE) of densely ionizing radiations (with high LET, rate of linear energy transfer) are of importance in both fundamental and applied radiobiology. In the latter, they serve as a basis in setting permissible exposure levels for types of radiation about which little long range experience is available. Some of the best RBE studies have been done on chromosomal aberrations. The difficulty in determining RBE on the basis of chromosomal exchanges or 2-break aberrations is that the dose-response curves differ for radiations of different LET and dose rate. The dose-squared term tends to predominate with radiations of low LET (such as γ rays and most X rays) and high doses or dose rates; the linear term dominates with high LET tracks in general and at low doses or dose rates. The shape of the curves is thought to reflect the existence of two classes of mechanisms by which chromosome exchanges are produced; exchanges caused by the passage of a single ionizing particle account for the linear component of the dose-response curve, exchanges due to the interaction of effects of two independent ionizing particles are responsible for the dose-squared component. This model has been amply confirmed by time-dose studies. The differences in shape of the dose-response curves indicate thus that with densely ionizing radiations, single particle events dominate the radiation response, while with sparsely ionizing radiations, events based on interaction of two or more particles play the leading role; hence the relative effectiveness of the kinds of radiations can not be the same for the two classes of mechanisms. Now the usual method of assessing RBE is based on comparing the doses which produce matching responses, i.e. equal amounts of effect, but at every response level both single action and interaction mechanisms contribute to the total response; the contribution of interaction mechanisms increasing with dose and dose rate, the more rapidly, the less the LET of radiation. Therefore, the RBE based on the total response will--and does--give values which reflect the various contributions from the two types of mechanisms, and thus changes with response level.

In fundamental radiobiology both the "linear term" and the "square term" RBE values are of interest. In applications to permissible dose levels, the linear terms are of particular interest, since at low doses or low dose rates most effects are likely to be caused by single-event mechanisms. Estimates of linear term RBE's were made by Neary _et al_.[1, 2] for chromosomal aberrations in plants and by Barendsen[3] for human tissue. Neary _et al_. found very high RBE values, in the neighborhood of 100; however, in their material the linear term for γ rays could be estimated only roughly, and therefore the RBE value is rather uncertain.

2. MATERIALS AND METHODS

Plant Material: Maize seeds heterozygous for the yellow-green alleles $\underline{Yg}_2/\underline{yg}_2$ were used in these experiments. This locus is located near the end of the short arm of chromosome IX. Leaves of seedlings grown from $\underline{Yg}_2/\underline{yg}_2$ kernels are of a normal green color. Loss of the locus (deletion) or of function (mutation) for the dominant $\underline{Yg}_2$ allele gives a yellowish green phenotype in leaf cells and cell lineages of the altered genotypes.

The frequency of yellow-green streaks in leaves was used as a measure of the frequency of genetic change or damage which was considered to be due mainly, if not exclusively, to breaks in chromosome IX between the centromere and the $\underline{Yg}_2$ locus, with loss of the $\underline{Yg}_2$-containing segment.[4, 5, 6]

Prior to irradiation the seeds were stored for at least 10 days in a desiccator at 20° C over a saturated aqueous solution of CrO_3 to equilibrate for moisture content in an atmosphere of 35 per cent relative humidity. The relative humidity ranged from 20 to 50 per cent in the laboratory where the seeds were prepared for treatment and in the radiation facilities so that before hydration or sowing, the seeds were kept at all times in an atmosphere of 35 ± 15 per cent relative humidity. The water content of $\underline{Yg}_2/\underline{yg}_2$ maize embryos stored at 35 per cent relative humidity was determined to be 6.7 per cent.

All seeds were sown in pots in moist soil in the greenhouse three days after irradiation, or as noted below to study the effect of post-irradiation storage time. The greenhouse conditions during a 24-hour period were 18 hours of light at approximately 75° F and 6 hours of dark at approximately 70° F. When the third leaf was partly developed, the seedlings were transferred to a controlled environment room with the same photoperiod as above, at a constant light intensity of 1100 foot candles and the temperature was reduced to a constant 65° F. Under these conditions the yellow-green streaks were clearly distinguishable, particularly when leaves were scored as they matured.

Each potted seedling was given a code number and arranged in a completely randomized experimental design. The third, fourth and fifth leaf of each plant was harvested separately and scored, under code number, for frequency of yellow-green streaks. These leaves are in progressively earlier stages of development in the seed embryo at the time of irradiation so that $\underline{yg}_2$ streaks are progressively larger but less frequent in mature leaves 3, 4 and 5, respectively.

The atomic composition of treated embryos is important in calculating the absorbed neutron dose since in this energy range 80-95 per cent of the absorbed dose is due to neutron-hydrogen interactions and most of the balance in neutron-oxygen interactions. Analyses of H, O, C and N composition of excised maize embryos were carried out by Schwarzkopf Microanalytical Laboratory (Woodside, New York) with results as shown in Table 1. Since absorbed dose is due almost exclusively to H content, the dosages administered in these experiments were calculated solely on the basis of 8 per cent hydrogen composition.

Fast Neutron Source: The H^3 (p, n) He^3 reaction, originally described by Jarvis,[7] was employed in this experiment. Calculations,[8] which relate energy absorption per neutron in tissue equivalent material to initial neutron energy, were utilized in the construction of an exposure apparatus to produce essentially equal dose rates in five rings designed to intercept neutrons of 0.43, 0.65, 1.00 and 1.80 MeV. Physical design and measurement of first collision dose and mean absorbed dose were as described by Rossi *et al.*[9] Evaluation of spleen and thymus weight loss in mice irradiated at these energies in a similar apparatus was described by Bateman *et al.*[10]

A 3 MeV Van de Graaff generator in the Physics Department of Brookhaven National Laboratory was employed to accelerate 2.8 MeV protons into a tritium impregnated water-cooled titanium target for the experiments reported herein. Figure 1 shows the experimental apparatus; and Table 2 lists its dimensional characteristics. In these experiments, the distance from target midpoint to exposure ring has been decreased to one fourth that used in the mouse studies referred to above. Because of their small size the maize kernels (and more particularly, the embryos) do not subtend a greater angle than mice exposed at four times the distance. At these close distances, variations in neutron flux and energy exist, and the target cannot be considered a point source. Although detailed analysis of neutron energy spectra at each of the five exposure positions of the seeds must be a subject for further study, it was possible to calculate the probable departure from the inverse square relationship of dose rate to distance assumed for point sources. Both the diameter of active target face and the angle relative to the exposure position were taken into account, with results as listed in Table 2. These values are probably small compared to other variations and were therefore not corrected for. A 25 r Victoreen chamber was employed at 0° at a fixed distance from the target to monitor all exposures. In each ring the kerma in tissue (due to protons) per unit reading was obtained by application of the factor of 16.0 to the corresponding values derived in the mouse experiments, as described by Rossi _et al._[10] A maximum of eight kernels could be exposed at one time in Ring A. Each kernel was secured to its pocket by a small pledget of modeling clay behind, and so positioned that the embryo was centered on the "exposure circle" and facing the target. Exposure of the required number of maize kernels was achieved by replication of exposures in close sequence.

3. RESULTS

Unirradiated Controls: In order to establish the "spontaneous" frequency of $\underline{yg}_2$ sectors in unirradiated control leaves, 184 plants were grown in four separate experiments and the $\underline{yg}_2$ sectors were counted in leaves 3, 4 and 5. The average number of sectors per leaf was calculated to be 0.46 for leaf 3, 0.24 for leaf 4 and 0.08 for leaf 5.

X-ray Treatments: For comparison with neutron irradiations, three different exposures of seeds were made with 250 kvp X rays. These were carried out under the following specified conditions.

Experiment	ma	Distance cm	Half-value layer	Dose rate rads/min
Preliminary	30	16	1.5 mm Cu	980
1	30	25	2.0 mm Cu	455
2	30	40	1.0 mm Al	593

Statistical tests applied to the data obtained revealed no relationship between dose rate and frequency of $\underline{yg}_2$ sectors, at least within the range of 455 to 980 rads per minute. The mean LET of 250 kvp X rays in water is 2-3 kev/μ.[11, 12]

Since maize seeds stored at 35 per cent relative humidity are relatively dry biological systems (6.7 per cent moisture content) the possible effect of postirradiation storage time was investigated. In one experiment, seeds were hydrated immediately after X irradiation at 3000, 6000 and 9000 rads, or stored for 1, 3, 7 and 14 days before hydration.

The number of sectors per krad was calculated for each of leaves 3, 4 and 5. The averages for the three doses for the three leaves at the five storage times were as shown below.

Postirradiation storage time in days	No. $\underline{yg}_2$ sectors per leaf per krad
0	0.732
1	0.613
3	0.457
7	0.740
14	0.683

There was no evident effect on frequency of $\underline{yg}_2$ sectors of post X-irradiation storage time. Statistical tests applied to the combined data as well as to those for each radiation level revealed no relationship between storage time and response to X irradiation in this system.

The main purpose of the X-ray treatments was to establish a dose-response curve. Seeds were irradiated at doses of from 1500 to 15,600 rads. The results are shown in Table 3 and Figure 2. The data for each of the leaves fitted the linear regression model, $Y = K + \alpha D$, where Y is the number of $\underline{yg}_2$ sectors per leaf, K the control value (or spontaneous $\underline{yg}_2$ frequency), α is the slope, and D the dose in rads.

$$\text{Leaf 3} \quad Y = -1.047 + 0.0011\, D$$

$$\text{Leaf 4} \quad Y = -1.266 + 0.0008\, D$$

$$\text{Leaf 5} \quad Y = 0.061 + 0.0001\, D$$

The additional reduction in the error sums of squares due to fitting a quadratic regression model, $Y = K + \alpha D + \beta D^2$, rather than the linear, was not significant for the curves of leaves 3 and 4, but was significant at the 5 per cent level for leaf 5. The best interpretation appears to be that the dose-response curve is accounted for largely by a straight-line relationship of $\underline{yg}_2$ sector frequency to X-ray dose. The loss of $\underline{Yg}_2$ is a single hit response throughout the range of 1500 to 15,600 rads of X irradiation. At the highest dose some difficulty was experienced in scoring $\underline{yg}_2$ sectors in leaf 3 owing to a generally mottled appearance resulting from the irradiation. Higher doses would, therefore, be expected to cause cell lethality and the dose range used in these experiments approaches the limits of usefulness of this system.

Neutron Treatments: In each of the two neutron experiments analyzed in this paper, two dosage levels were employed; 54.2 and 116.0 rads in Experiment 1, 32.8 and 65.6 rads in Experiment 2. At these levels the numbers of sectors produced by neutrons per leaf were bracketed by the results in the X-ray experiments and the higher doses approached saturation levels as indicated, e.g. in Experiment 2, where a 2-fold dosage increase caused the response to increase by a factor of 1.7.

In Experiment 1, 16 seeds were exposed to neutrons at each of the five energies: 0.43, 0.65, 1.00, 1.50 and 1.80 MeV. These energies of fast neutrons have been calculated to produce tracks in this material with dose average energy LET values of 72, 67, 58, 47.5 and 42.5 kev/μ, respectively. In Experiment 2, 80 seeds were exposed to only 1.00 and 1.50 MeV neutrons. This experiment also included a test of the effect of postirradiation storage time, as described under the X-ray experiments. As expected, no storage effect was observed and the data were handled without regard for this variable.

The average dose rate in the two neutron experiments was 6.5 rads per minute and, since the neutron RBE's were of the order of 70 (as shown later in this paper), a comparable biologically effective dose rate for X rays would be approximately 480 rads per minute, which is within the range that was used.

The results of the neutron experiments are summarized in Table 4. Regression lines were fitted to the overall data from Experiment 1 and Experiment 2 for each of the three leaves. In each, the regression was linear (highly significant in 5 of the 6 lines, and significant at the 5 per cent level in 1); and the additional reduction in the error sum of squares due to fitting the second degree polynomial was nonsignificant. These lines are:

<u>Experiment 1</u>

Leaf 3 $Y = 0.730 + 0.0898\ D$
Leaf 4 $Y = 0.883 + 0.0410\ D$
Leaf 5 $Y = 0.262 + 0.0141\ D$

<u>Experiment 2</u>

Leaf 3 $Y = 0.594 + 0.0640\ D$
Leaf 4 $Y = 0.394 + 0.0420\ D$
Leaf 5 $Y = 0.063 + 0.0129\ D$

The data from Experiment 1 show, in general, a higher number of <u>yg_2</u> sectors per krad with a decrease in energy. In order to test the significance of these apparent differences, an analysis of variance was carried out using the 5 MeV values as treatments and the 3 leaves at 2 doses per leaf as replicates. Large differences among leaves were independent of energy. Differences among energies were highly significant (1 per cent level). Partitioning the treatment sum of squares into the linear, quadratic, etc.

components revealed that the linear component was highly significant (1 per cent) and accounted for most of the variation among energies.

An additional test was made to determine if the differences are significant between mean number of sectors per krad for each energy. These values are:

Energy (MeV)	0.43	0.65	1.00	1.50	1.80
mean sect/krad	69.09	56.19	52.39	48.11	47.17

The ranked means of the 5 energies correspond to the ranked MeV's themselves. Applying Student-Newman Keuls' multiple range test[13] to the treatments (energies), showed that 0.43 was significantly different from 0.65 but that 0.65, 1.00, 1.50 and 1.80 formed a fairly homogeneous subset. It was concluded that the linear relationship between energy and sectors per krad is well supported, the difference between 0.43 and the higher energy means is significant, and further data would be needed to establish significant differences between the sectors per krad at the other energy values.

<u>RBE Values</u>: Since both the X-ray and monoenergetic fast neutron dose-response curves in this material are linear, and the X-ray response brackets that of the neutrons, a constant RBE value can be considered to hold throughout the range. This value can best be determined as the ratio of the slope (α) of each neutron energy curve to that of the X-ray curve, i.e. a comparison of the increment in $\underline{yg}_2$ sector frequency per rad of neutrons with X rays.

The slopes of dose-response curves for X irradiation and for the two neutron experiments (doses combined) are listed in Table 5. The calculated RBE values ($\alpha N/\alpha X$) for each leaf at each neutron energy are shown in

Table 6. The average RBE value for neutrons of all the energies tested in Experiment 1 is 78.2; the range from 42.5 (1.50 MeV, leaf 4) to 135.2 (0.43 MeV, leaf 5). Among neutron energies the RBE values, averaged over leaves, varied from 99.8 for 0.43 MeV to 68.7 for 1.80 MeV. RBE values for the combined treatments at energies of 1.00 and 1.50 MeV in Experiment 1 are shown in Table 6 for comparison with Experiment 2. Although the RBE values for these two neutron energies combined do not differ appreciably between experiments, in the first experiment the lower energy was more efficient and in the second this was reversed indicating the difficulty in distinguishing differences in efficiency between these two neutron energy treatments. Figure 3 shows these results graphically, for leaf 5 only, in comparison with the X-ray dose-response curve. The graph shows that to produce an endpoint of one sector in leaf 5, between 60 (Experiment 1) and 72.5 (Experiment 2) rads of neutrons of energies 1.0 and 1.5 MeV are required, compared to 6750 rads of 250 kvp X rays. The corresponding RBE values are 112 and 93, respectively, which can be compared with RBE's of 90.4 and 92.4, respectively, calculated from the slopes (Table 6, leaf 5).

The differences in RBE values among leaves are conspicuous and consistent. Leaf 5 gives invariably the largest RBE values, leaf 4 (with one exception) the lowest. These leaves are in different stages of development at the time of irradiation, undergo different numbers of mitoses after irradiation to reach maturity, and produce yg_2 sectors of markedly different size. Efforts are currently being made to place the mutation frequency on a per-krad-per-cell basis and to assess the factors that contribute to the quantitative difference in irradiation response in the different leaves.

4. DISCUSSION

It is generally held that a major part of the biological damage caused by radiation results from injury to the chromosomes, particularly to their breakage and the subsequent loss of genetic information. Breakage-deletion events have generally been observed less frequently than breakage followed by rearranged rejoining, so that there is a paucity of data by which to compare the effects of different radiations in inducing chromosomal breakage and loss *per se*. The scoring of yg_2 sectors in the Yg_2/yg_2 system used in these experiments is considered to be a direct quantitative means of estimating the frequency of simple deletions in one arm of one chromosome. Confirmatory evidence for this interpretation is the linear dose-response curve found with low as well as with high LET radiations in this material.

The results reported here support those of Neary *et al*.[1, 2] and lead to the conclusion that neutrons in the energy range of about .5 to 2 MeV are more highly efficient in breaking plant chromosomes, relative to X rays, than had been indicated prior to experiments in which the influence of the dose-squared term was minimized. Davies and Bateman[14] find a mean maximum RBE value of about 40 for 0.65 MeV neutrons compared to 250 kvp X rays in causing somatic mutations in stamen hairs of *Tradescantia*. With regard to minimum permissable doses of high LET radiations for man, it is important that tests comparable to those reported for plant chromosomes be made with human tissues.

The relation observed between RBE and energy of fast neutrons which, in these experiments, reached a maximum at MeV of 0.43 and dose average LET of 72 is similar to the results of Bateman *et al*.[10] on mice (maximum RBE at dose average LET of 72), Barendsen *et al.*[3] on human cells (maximum RBE at dose average LET of 85), and Conger *et al.*[15] on chromosomes of the plant *Tradescantia* (maximum RBE at dose average LET of 50 to 70). The highest RBE values reported for these animal and plant materials are of the order of 10 and the low LET responses are curvilinear. It is not known whether the two-hit component of these animal survival curves and plant chromosome exchanges is causally related, but in each it contributes to the lower RBE estimates in these systems compared to the yg_2 system reported here.

The fact that in these maize studies the RBE is highest with the highest energy average LET (72 kev/μ) indicates that the two factors involved in producing a chromosomal loss (yg_2 sector), namely the number of traversals of the short arm of chromosome IX by a proton track and the probability of a traversal causing a break, are maximized at this energy (0.43 MeV). It is probable that still higher RBE's might be obtained at average energy LET's above 72, but ultimately the RBE would be expected to decline when an ion density is reached at which the decrease in number of traversals of the chromosome (shorter tracks) becomes more than is compensated for by the increased probability of a break, given a traversal.[15, 16]

5. SUMMARY

The maize material used in these experiments has the advantage for RBE studies of yielding a basically first order dose-response curve ($Y = \alpha + \beta D$) with low (X rays) as well as with high (fast neutron) LET radiations. The frequency of yellow-green (yg_2) sectors in leaves 3, 4 and 5 of young plants grown from irradiated Yg_2/yg_2 seeds served as a quantitative measure of response. The mutant sectors are believed to be

due mostly to simple chromosome breakage and deletion. An exposure apparatus was used which produced essentially equal dose rates in five rings of seeds placed so as to intercept neutrons of 0.43, 0.65, 1.00, 1.50 and 1.80 MeV. Dose average LET values for these energies are 72, 67, 58, 57.5 and 42.5 kev/μ, respectively.

Two experiments were performed at dosages that gave responses which were linear, below saturation levels, and overlapping in range for X rays and neutrons. These ranges in dosages were 32.8 to 126.4 rads of neutrons and 1500 to 15,600 rads of 250 kvp X rays.

RBE values, calculated from relative slopes (α) of linear regression lines for N and X, ranged from 42 to 135 (average 78) in Experiment 1 and from 48 to 106 (average 68) in Experiment 2. Monoenergetic fast neutrons of 0.43 MeV were the most efficient in producing $\underline{yg}_2$ sectors as shown by the yield of sectors per krad and highest RBE values.

The RBE values obtained in these experiments are higher than commonly reported and in the neighborhood of those found by Neary *et al.*[1, 2] for plant chromosomes when the dose-squared term of low LET radiation response is minimized. With regard to minimum permissible levels of radiation these results suggest the alternatives that either chromosome breaks in plants have a much higher RBE than comparable reactions in man and need not be considered; or that the problem of chromosome damage *per se* in human tissues be reexamined after exposure to high LET radiations and/or low LET radiations at low doses or dose rates.

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TABLE 1. Atomic Composition of

Excised Maize Embryos ($\underline{Yg_2}/\underline{yg_2}$) Equilibrated at 35%

Relative Humidity over a Saturated Aqueous Solution of CrO_3

Element	Per cent composition by weight
H	8.10
O (nonresidual)	31.14
C	51.26
N	4.58
Ash	3.60
Total	98.68

TABLE 2. Maize Exposure Cage Data

Ring	Neutron energy in MeV	Distance to target in cm	Angle to forward beam in degrees	Calculated error due to $1/r^2$ assumption	Kerma rate in tissue at location of seeds ergs/gm/min
A	0.43	2.50	130°	+0.2%	720
B	0.65	2.73	100°	-0.9%	660
C	1.00	2.58	75°	-1.0%	640
D	1.50	3.30	45°	+0.5%	630
E	1.80	4.98	20°	+0.9%	640

TABLE 3. Frequency of yg_2 Sectors per Leaf in Maize Plants Grown from X-irradiated Yg_2/yg_2 Seeds

Dose in rads	Dose rate rads/min	No. plants	Average no. yg_2 sectors per leaf: Leaf 3	Leaf 4	Leaf 5
1500	455	16	1.35	0.20	0.05
1590	980	16	2.40	0.40	0.00
2000	980	16	1.10	0.32	0.11
3000	455	16	1.67	1.09	0.17
3000	593	80	2.79	1.89	0.45
4000	980	16	1.94	1.82	0.59
4500	455	15	4.14	1.29	1.05
6000	980	16	3.47	2.29	0.99
6000	455	16	3.85	4.03	0.98
6000	593	80	5.86	5.01	1.63
7500	455	15	7.01	3.29	1.19
7650	980	16	10.04	5.43	0.73
9000	455	16	7.10	4.20	1.42
9000	593	80	8.66	7.02	2.44
15600	980	16	16.92	11.89	1.62

TABLE 4. Effect of Exposure to Monoenergetic Fast Neutrons on Frequency of *yg*$_2$ Sectors in Maize Leaves

MeV	Dose average LET	No. seeds	Dose rate rads/min	Dose rads	Leaf 3 Sect/leaf	Leaf 3 Sect/krad	Leaf 4 Sect/leaf	Leaf 4 Sect/krad	Leaf 5 Sect/leaf	Leaf 5 Sect/krad
EXPERIMENT 1										
Low Dose Level										
0.43	72	13	7.2	59.2	7.69	122.13	5.08	81.76	1.85	29.90
0.65	67	15	6.6	54.4	5.80	98.16	3.80	65.44	1.07	18.20
1.00	58	16	6.4	52.8	5.62	97.73	2.81	48.67	1.13	19.89
1.50	47.5	14	6.3	52.0	4.93	85.96	2.86	50.38	1.00	17.69
1.80	42.5	16	6.4	52.8	5.12	88.26	3.13	54.73	0.63	10.42
mean				54.2	5.83	98.45	3.54	60.20	1.14	19.22
High Dose Level										
0.43	72	16	7.2	126.4	14.44	110.60	6.69	51.03	2.50	19.14
0.65	67	15	6.6	116.0	9.60	78.79	7.20	60.00	2.00	16.55
1.00	58	15	6.4	113.6	10.73	90.40	5.07	42.52	1.80	15.14
1.50	47.5	16	6.3	111.2	10.31	88.58	4.06	34.35	1.38	11.69
1.80	42.5	13	6.4	112.8	9.77	82.54	4.15	34.66	1.46	12.23
mean				116.0	10.97	90.18	5.43	44.51	1.83	14.95
EXPERIMENT 2										
Low Dose Level										
1.00	58	60	6.4	32.8	3.07	79.57	1.83	48.48	0.63	16.77
1.50	47.5	60	6.3	32.8	2.65	66.77	2.02	54.27	0.31	7.01
mean				32.8	2.86	73.17	1.93	51.38	0.47	11.89
High Dose Level										
1.00	58	60	6.4	65.6	4.74	65.24	2.76	38.41	0.79	10.82
1.50	47.5	60	6.3	65.6	4.84	66.7	3.38	47.86	1.05	14.79
mean				65.6	4.79	66.00	3.07	43.14	0.92	12.80

TABLE 5. Slopes (α) of Linear Dose-Response Curves for X- and Neutron Irradiated Maize

Irradiation	Slope of linear dose-response curve Leaf 3	Leaf 4	Leaf 5
X rays	0.0011	0.0008	0.0001
Neutrons			
Experiment 1			
MeV			
0.43	0.1104	0.0504	0.0189
0.65	0.0784	0.0599	0.0165
1.00	0.0902	0.0424	0.0150
1.50	0.0886	0.0340	0.0116
1.80	0.0824	0.0343	0.0123
mean	0.0898	0.0410	0.0141
mean (1.00 + 1.50)	0.0820	0.0369	0.0126
Experiment 2			
1.00	0.0652	0.0384	0.0108
1.50	0.0668	0.0479	0.0148
mean (1.00 + 1.50)	0.0650	0.0420	0.0129

TABLE 6. RBE Values, Neutrons/ X rays, Calculated as the Ratio of the Slopes of the Linear Dose-Response Curve

MeV	RBE values: Leaf 3	Leaf 4	Leaf 5	Mean
Experiment 1				
0.43	101.2	63.0	135.2	99.8
0.65	71.9	74.9	118.0	88.3
1.00	82.8	53.0	107.4	81.1
1.50	81.3	42.5	82.6	68.8
1.80	75.6	42.8	87.6	68.7
mean	82.4	51.2	100.9	78.2
mean (1.00 + 1.50)	75.2	46.1	90.4	70.5
Experiment 2				
1.00	59.9	48.0	77.3	61.7
1.50	61.2	59.8	105.6	75.6
mean (1.00 + 1.50)	60.6	52.4	92.4	68.5

FIGURE LEGENDS

Figure 1. Diagrammatic representation of experimental apparatus for exposing maize seeds to monoenergetic fast neutrons.

Figure 2. Linear dose-response curves for number of $\underline{yg}_2$ sectors scored on leaves 3, 4, 5 of maize plants following X irradiation of $\underline{Yg}_2/\underline{yg}_2$ seeds.

Figure 3. Dose-response curves for number of $\underline{yg}_2$ sectors produced on leaf 5 following neutron irradiation at 1.00 and 1.50 MeV (combined) in Experiments 1 and 2 (separately) compared with the X-ray dose-response curve.

MAIZE EXPOSURE CAGE

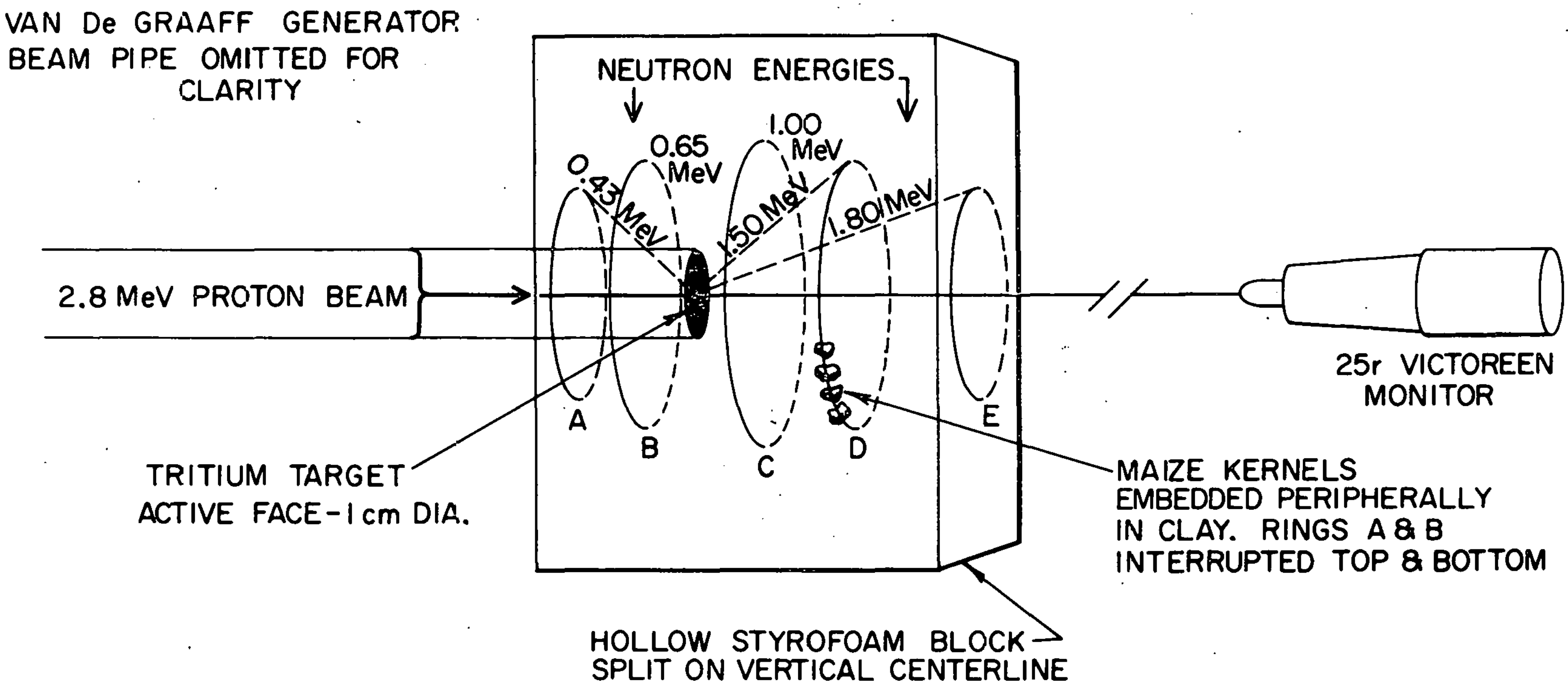
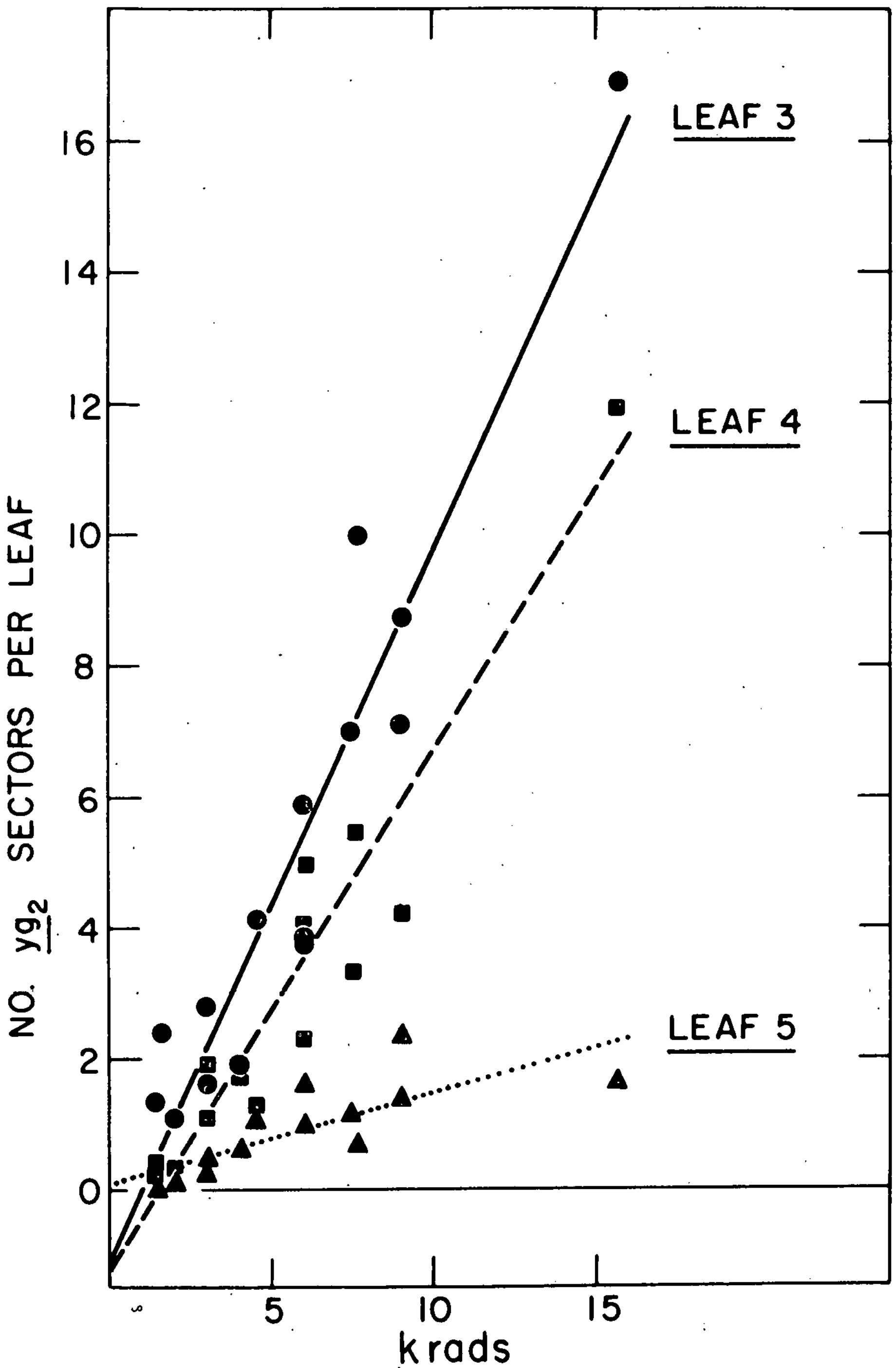
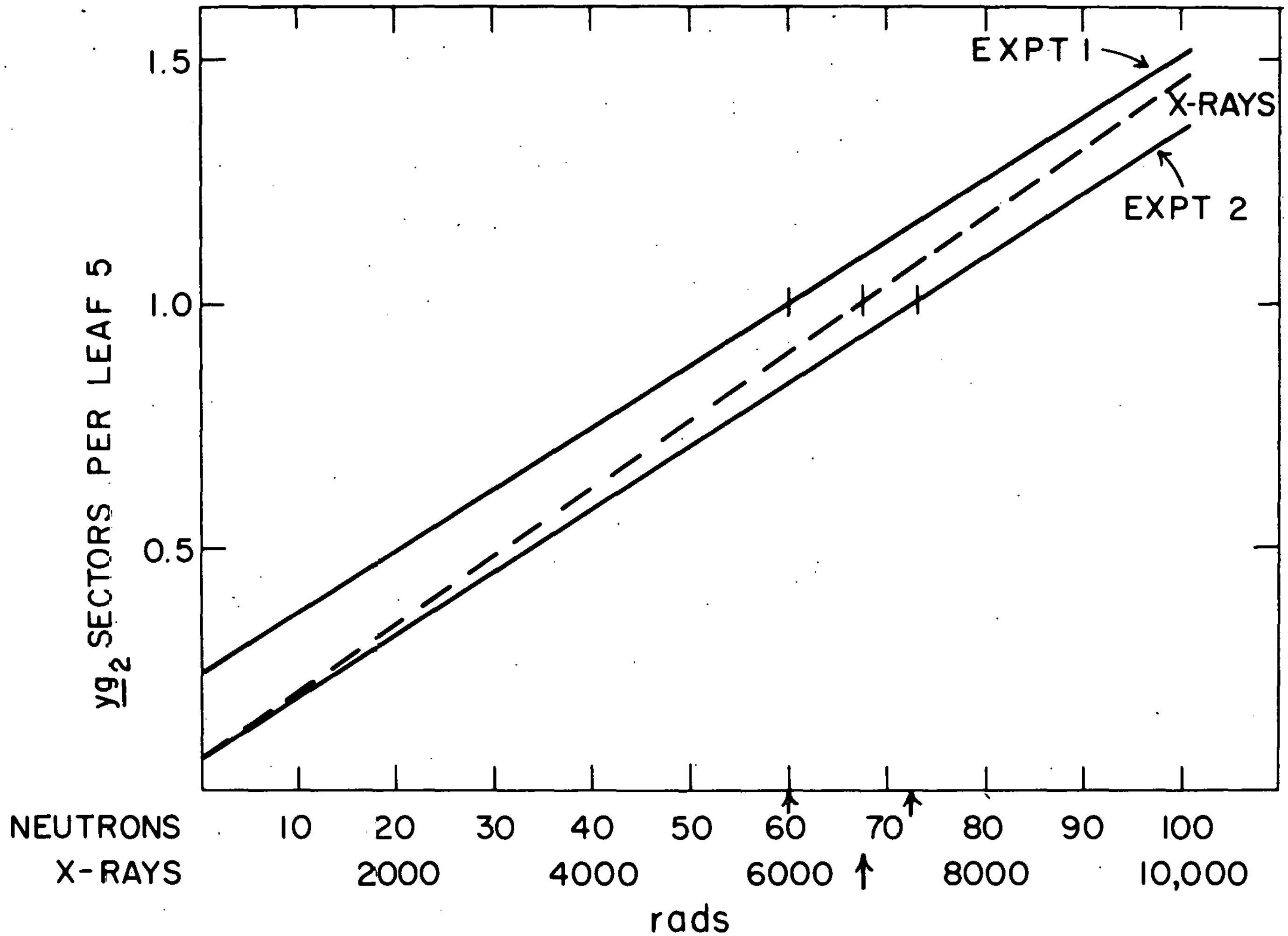


FIGURE 1



LEAF 3
LEAF 4
LEAF 5
NO. yg2 SECTORS PER LEAF
0
2
4
6
8
10
12
14
16
5
10
15
k rads

FIGURE 2



EXPT 1
X-RAYS
EXPT 2
1.5
1.0
0.5
yg_2 SECTORS PER LEAF 5
NEUTRONS 10 20 30 40 50 60 70 80 90 100
X-RAYS 2000 4000 6000 8000 10,000
rads

FIGURE 3