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Research Bulletin 167

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Research Bulletin 167
Agricultural Experiment Station
University of Nebraska College of Agriculture
W. V. Lambert, Director
M. L. Baker, Associate Director
January, 1951 (2500)

The Effects of Thermal-Neutron Irradiation of Maize and Barley Kernels

John W. Schmidt and E. F. Frolik [1]

INTRODUCTION

IT IS THE purpose of this paper to report the effects of thermal-neutron irradiation of maize and barley kernels on subsequent germination, plant establishment, and early plant development. Comparisons are made with equivalent neutron treatments of maize pollen, results of which have been reported in part in previous publications (Frolik and Morris, 1950a and b).

Neutrons are electrostatically neutral and have the characteristic of being nonionizing, *per se*. Indirectly, however, they produce ionizations in one or both of the following ways: (1) through the indirect process of capture by nuclei of various elements, with the direct release of other particles and/or high energy photons, which in turn produce ionizations and/or excitations, and (2) through nuclear reactions which result in the production of unstable isotopes, which in turn give off photon or particulate radiations in the decay process.

The immediate, manifest effect of all known high energy radiations in biologic tissue consists of ionization and excitation. The biological effects which follow consist basically of mutations, including chromosomal aberrations, and chemical changes in other parts of the cell. These fundamental effects may result in impairment of normal functions in or death of cells, of groups of cells, or of the organism as a whole. However, the fundamental biological processes involved are not well understood.

A large amount of research is under way among numerous workers to gain further information on the fundamental aspects of radiation effects on living tissues. The problem is receiving the joint attention of biologists, chemists, and biophysicists. Although much has been done, there is still need for a great deal of additional information on the effects of various radiations on biologic behavior. There is, for example, relatively little information available on the effect of thermal neutrons, particularly with respect to their effect on seeds. Although their effect is complicated by the various possible interactions, thermal neutrons offer a valuable means of adding to the reservoir of information needed to understand and to utilize to a greater extent radiations in biological work.

[1] The work reported herein was done while the senior author was a Predoctorate Fellow in the Biological Sciences, the fellowship being provided by the Atomic Energy Commission and administered by the National Research Council.

MATERIALS AND METHODS

Materials irradiated in the present experiments were barley seed, maize seed, and maize pollen. The barley seed was of a two-row spring variety, Spartan. This seed had been increased from a single plant. The maize seed consisted of F_1 single cross, yellow dent hybrids L289 x I205, N6 x M14, and M14 x N6. Pollen irradiated was that of inbred I205. This was placed on untreated plants of inbred L289 to make seed of the single cross. The pollen irradiations had been made for use in another experiment, and the seed was included in these experiments chiefly as a basis of comparison with pile irradiation of seed.

All of the seed was grown in 1948. The maize and barley crops from which the seed was to be irradiated were grown at Lincoln, Nebraska. The maize crop involving the pollen irradiations was grown at Naperville, Illinois.

The irradiations were made at the Argonne National Laboratory, Chicago, Illinois, as follows: maize pollen, August 16, 1948; barley seed, April 26, 1949; maize seed and a second series of barley seed, May 17, 1949.

The irradiations consisted of exposures for various periods of time in the thermal-neutron column of a heavy water pile. Untreated material and one dosage of X-ray each for seed and pollen were included in the comparisons.

The technique of irradiating the pollen in the nuclear reactor was the same as that employed in other studies made in 1947 and modified in 1948, as previously described by Frolik and Morris (1950a and b).

Air-dry, dormant seed was used for the seed irradiations. The paper-packeted seed samples were also irradiated in the thermal-neutron column of the heavy water pile. The pile was operated at a power of approximately 250 kw. for the seed irradiations as compared with 300 kw. for the tassel samples. However, because it was possible to place the seed samples closer than the tassel samples to the pile proper, the neutron flux of 7×10^{10} neutrons/square centimeter/second was approximately the same in the two series of irradiations.

The method of getting the one X-ray pollen exposure of 1200 roentgens was also the same as previously described by Frolik and Morris (1950b). The seed was X-rayed at various dosages ranging from 5,000 to 25,000 roentgens. The equipment and method of X-raying the seed were the same as for the pollen irradiation, except for the differences in dosage noted above and the fact that the tube was operated at a peak voltage of 250 kv. for the former and 200 kv. for the latter.

The barley seed which had been irradiated on April 26, 1949, was planted in the field at Lincoln on April 28, 1949. Part of the barley seed irradiated on May 17, 1949, was also planted in 1949. That portion of the seed was in turn subdivided into two additional portions, half of it being planted in the field at Lincoln on May 25, and the other half in the field at Ft. Collins, Colorado, within a few days of the Lincoln planting. The remainder of the barley seed irradiated on May 17, 1949, was planted in the greenhouse at Lincoln on April 23, 1950. The irradiated maize seed and the maize seed from the irradiated pollen were also planted in the greenhouse on April 21, 1950. In the latter tests, the barley seed was planted in soil flats, whereas the maize seed was planted in sand in benches. The maize seedlings were fertilized with nitrogen 24 days after planting.

Observations were made on the field plantings to check establishment and subsequent development of all plants that emerged. Detailed studies were made of the greenhouse plantings for a period of 28 days following planting. Data were taken on germination, stand at various dates, growth rate, exposed leaf number, and other morphological characters.

Chemical and spectrographical analyses of maize pollen and of excised maize and barley embryos were made by the Chemistry Division of the Argonne National Laboratory.

EXPERIMENTAL RESULTS

1949 Field Plantings

The original estimates for length of time to irradiate the barley seed in the nuclear reactor were made on the basis of the following information: roughly, one minute of pile exposure had been found to be equivalent to 550 roentgens of X radiation on the basis of a combined average of two dates and several characters in maize pollen irradiations, as reported by Frolik and Morris (1950b). Barley seed is considerably more tolerant than maize pollen to X radiation. Gustafsson and Mac Key (1948) reported that a 10 per cent mature plant stand could be expected from barley seed X-rayed with a dosage of 25,000 roentgens. In contrast with this, Tascher (1945) found that 6,000 r units of X-ray applied to maize pollen constituted a lethal dosage. Maize seed has been found to be even more tolerant than barley seed to X radiation. For example, Collins and Maxwell (1936) found that some mature plants were produced following exposure of maize seed to as much as 40,000 r units of X-ray. Although not entirely applicable, some information was also available on tolerance of barley seed to neutrons of higher energies than those used in the present experiments. A 30 per cent mature plant stand was obtained following a 75-minute exposure of barley seed to fast neutrons (Gustafsson and Mac Key, 1948). The neutrons were obtained from a small cyclotron and had an energy of 6.7 to 7 Mev.

On the basis of the above information, it was estimated that plant establishment should be obtained on at least part of the barley seed exposed for 50 minutes in the nuclear reactor, and that maize seed could withstand an even longer exposure. Subsequent tests, however, showed these calculations were incorrect. No emergence occurred following plantings on April 28, 1949, of barley samples (of 300 kernels each) irradiated for 10, 20, 30, 40, and 50 minutes, respectively, in the nuclear reactor. In contrast with this, plantings made on the same date resulted in normal emergence from control samples and partial emergence from samples X-rayed with dosages up to 25,000 r units.

A further check was made on May 17 by examining the neutron-treated kernels which had been planted on April 28. It was found that most of the kernels had partially germinated. This was true even following the 50-minute exposure. However, the injury accompanying the 50-minute exposure was so severe that only feeble growth occurred. Photographs of representative plants of the control and of the partially germinated kernels of the 10-, 20-, and 30-minute exposures, taken on May 17, i.e., 19 days after planting, are shown in Figure 1.

In the light of experience gained from the irradiations made on April 26, a series of samples of barley and maize seed was irradiated on May 17, 1949. The exposures in the nuclear reactor for this second series were made for periods of 2, 4, and 8 minutes, respectively. An untreated check and irradiation with 7500 r units of X-ray were also included in this series.

The plantings from the second series of irradiations were made in part at Lincoln on May 25, 1949. Although this date is considerably later than the normal planting time for barley at this location, subsequent performance was reasonably indicative of the severity of the various treatments. There was no emergence following 8 minutes of seed exposure in the nuclear reactor, and a high percentage of emergence following 4 minutes and 2 minutes of neutron treatment, the X radiation, and no irradiation. However, the seedlings from the seed exposed to 4 minutes of neutron treatment died shortly after reaching the one- or two-leaf stage. Plantings from the other treatments continued to grow in what appeared to be a normal manner. Owing apparently to the late date of planting, none of the plants produced heads.

The duplicate planting made at Ft. Collins, Colorado, in 1949, where conditions are more favorable than at Lincoln for planting at these late dates, gave results which in general were similar to those observed at Lincoln. Here, as at Lincoln, no emergence occurred following 8 minutes of neutron exposure. A few plants of the 4-minute

FIGURE 1.—The effect of extended thermal-neutron irradiation of barley kernels on subsequent development. Photographed 19 days after planting. Treatments, top to bottom: 0-, 10-, 20-, and 30-minute exposures in the nuclear reactor.

neutron-irradiated seed survived the seedling stage but were extremely stunted. Plants from seed which had been exposed for 2 minutes in the nuclear reactor were also extremely stunted and failed to head. In contrast with this, plants from untreated seed and from the 7500 r unit X-rayed seed produced heads.

1950 Greenhouse Plantings

The following data relate entirely to the plantings made of the maize and barley seed irradiated on May 17, 1949, and the seed obtained following pollination with maize pollen irradiated on August 16, 1948. The plantings were made in the greenhouse at Lincoln on April 21 and 23, 1950.

Barley seedling observations

Data on the mean height of plants and mean number of exposed leaves per plant 7, 14, 21, and 28 days following planting of the barley seed are given in Table 1 and presented graphically in Figure 2.

Seedling plants from all irradiated lots of seed, including X-rayed seed, were significantly shorter in height (leaves held erect for meas-

TABLE 1.—Mean height of plants and mean number of exposed leaves per plant of barley 7, 14, 21, and 28 days following planting of seed exposed for 0, 2, 4, and 8 minutes to thermal neutrons and to 7500 roentgens of X-ray, respectively.

Treatment of seed	No. of plants*	Mean height of plants, cm.**	Mean no. exposed leaves per plant
		7 days after planting	
None	37	11.3 ± 0.41	————
X-ray, 7500 r units	39	9.5 ± 0.38	————
Nuclear reactor, 2-min. exposure	36	5.0 ± 0.30	————
Nuclear reactor, 4-min. exposure	33	2.6 ± 0.24	————
Nuclear reactor, 8-min. exposure	1	0.4 ——	————
		14 days after planting	
None	37	20.3 ± 0.76	2.8 ± 0.07
X-ray, 7500 r units	39	16.3 ± 0.53	3.0 ± 0.03
Nuclear reactor, 2-min. exposure	36	7.6 ± 0.44	3.6 ± 0.13
Nuclear reactor, 4-min. exposure	29	3.3 ± 0.24	2.5 ± 0.16
Nuclear reactor, 8-min. exposure	2	0.8 ——	(coleoptile only)
		21 days after planting	
None	37	21.7 ± 0.64	4.4 ± 0.12
X-ray, 7500 r units	39	19.6 ± 0.48	4.6 ± 0.08
Nuclear reactor, 2-min. exposure	36	13.6 ± 0.71	5.3 ± 0.20
Nuclear reactor, 4-min. exposure	25	4.6 ± 0.41	4.7 ± 0.35
Nuclear reactor, 8-min. exposure	0	————	————
		28 days after planting	
None	37	23.3 ± 0.70	6.3 ± 0.12
X-ray, 7500 r units	39	21.2 ± 0.49	6.4 ± 0.08
Nuclear reactor, 2-min. exposure	34	17.1 ± 0.53	7.5 ± 0.38
Nuclear reactor, 4-min. exposure	21	7.4 ± 0.95	6.4 ± 1.73
Nuclear reactor, 8-min. exposure	0	————	————

* 50 seeds planted for each treatment.
** Leaves held erect for measurement.

urement) on each of the four dates of measurement than the control plants. At 7 days and 14 days after planting, mean height of plants following the X radiation was approximately two times that following 2 minutes of pile irradiation, and approximately four times that following 4 minutes of pile irradiation. Differences in height for the various treatments six days after planting are shown in Figure 3.

The plants from seed which had been irradiated in the pile for 2 minutes had a higher mean number of exposed leaves than plants from control seed at 14, 21, and 28 days after planting, respectively. Similar differences were noted for many individual plants from the 4-minute pile-irradiated seed. This higher number was offset, however, by other seedlings which were so stunted that they did not advance beyond the one- or two-leaf stage. The result was that the mean number of exposed leaves per plant following 4 minutes of pile irradiation did not differ significantly from the control.

The effects of the various treatments on maximum stands and on stands 28 days after planting are summarized in Table 2. Maximum stand or emergence was 4 per cent for the 8-minute neutron treatment compared with 74 per cent for control. On the other hand, per-

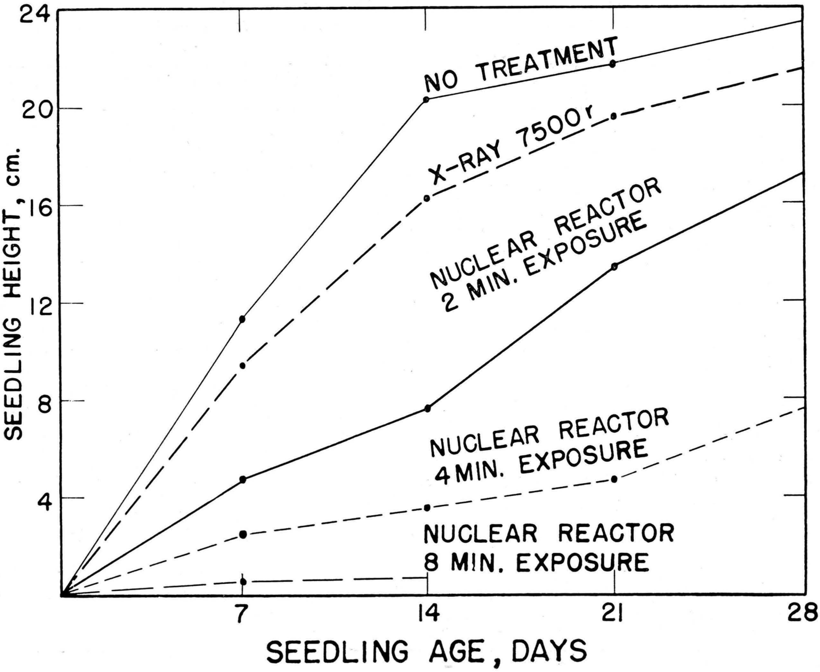

FIGURE 2.—The effect of exposing barley seed to 0, 2, 4, and 8 minutes of thermal-neutron irradiation on subsequent seedling height at successive seven-day intervals following planting compared with no treatment and a 7500 r X radiation effect. (Based on Table 1.)

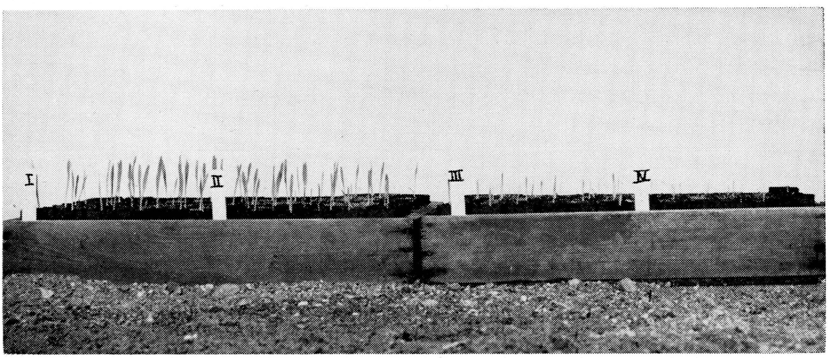

FIGURE 3.—Thermal-neutron tolerance of barley kernels as indicated by seedling growth six days after planting. I, No treatment; II, 7500 r X radiation; III, 2-minute exposure to thermal neutrons; and IV, 4-minute exposure to thermal neutrons.

TABLE 2.—Maximum stand and number of plants on the 28th day after planting barley seed exposed to 0, 2, 4, and 8 minutes of thermal neutrons and to 7500 roentgens of X-ray, respectively.

Treatment	No. kernels planted	Stand			
		Maximum		28 days after planting	
		No.	%	No.	%
None	50	37	74	37	74
X-ray, 7500 r units	50	39	78	39	78
Nuclear reactor, 2-min. exposure	50	36	72	34	68
Nuclear reactor, 4-min. exposure	50	34	68	21	42
Nuclear reactor, 8-min. exposure	50	2	4	0	0

centage emergence for none of the other treatments differed significantly from control.

All seeds that failed to produce plants were dug to determine the nature and extent of possible growth. Of the 50 kernels planted for each treatment, the following number in each series showed no growth: untreated lot, 5; X-ray, 4; 2-minute neutron exposure, 4; 4-minute neutron exposure, 9; and 8-minute neutron exposure, 12. Some of these differences approached significance. For the kernels which had made limited growth, some root development with no visible shoot development was more common than the reverse situation. The fact that roots had developed to a greater extent than shoots suggests the possibility that root primordia are more tolerant to irradiations than the shoot primordia. Determination of the relative extent of injury in the two primordial regions will require cytological analysis.

Stands remained at the maximum (28 days following planting) for control and X-rayed seed. However, delayed death resulted in a small reduction in stand for the 2-minute neutron treatment and in a much larger reduction for the 4-minute neutron treatment. Delayed death accounted for a loss of 13 of the 34 plants which had emerged following the 4-minute pile irradiation, and a few additional plants probably would not have matured.

The morphological effects observed on barley seedlings grown from seed exposed in the nuclear reactor are summarized as follows: (1) The first two leaves were very much mottled. (2) The next few leaves were narrower than those of the control plants, but they showed no chimeras of any kind up to 28 days following planting (later one plant had white-striped tillers). (3) Plant height was significantly below that of control plants. (4) Leaf number was increased significantly. (5) Delayed death occurred to some extent following 2 minutes of exposure and occurred extensively following 4 minutes of exposure. (6) Virtually no emergence occurred following 8 minutes of exposure.

The only observable effects of the 7500 r units of X radiation were a slight mottling of the first two leaves and a slightly shorter plant height than in the control.

Maize seedling observations

Mean seedling heights and mean numbers of exposed leaves per seedling for the maize plantings are presented in Table 3.

The mean height of plants on each of the four dates of measurement for each seed treatment was lower than for the control. This was likewise true for seed with the irradiated-pollen parent, except that little effect on growth was noted for the 1-minute pile-irradiated lot. In the L289 x I205 series, which included both seed and pollen irradiations, mean seedling height on each of the four dates of measurement was slightly lower for the 1200 roentgen pollen-irradiated series than for the 7500 roentgen seed-irradiated series.

Although a 1-minute neutron treatment of seed was not included in these tests, it appears by interpolation that such a treatment would have been approximately equal in effect on seedling height to 7500 roentgens of X radiation of seed. This is true for all three hybrids and for all dates of measurement. From the seedling height data of the L289 x I205 hybrid, it appears that the effect of 1200 roentgens of X radiation of pollen was equal to somewhere between 1 and 2 minutes of neutron exposure of pollen, as shown in Figure 4.

The similarities in height between progeny of the seed-irradiated series and of the pollen-irradiated series with the same neutron exposure are striking. However, the low standard errors for the former are indicative of the uniform effect of seed irradiation in contrast with the wide variation of effects observed with pollen irradiation.

An increase in exposed leaf number was associated with the longer nuclear reactor exposures of the maize seed. No significant difference was observed between plants of the 2-minute exposure and the control. However, a marked increase was noted for the 4-minute exposures over control, and for the 8-minute over the 4-minute exposures. On the other hand, the exposed leaf number per plant for the nuclear-reactor-exposed pollen series was slightly lower than that for the control.

The effects of the various treatments on maximum stands and stands 28 days after planting are reported in Table 4. It will be noted that maximum stands were unaffected by the various pile irradiations or X radiation of the seed. In contrast with this, an increase in length of time of pollen irradiation in the nuclear reactor was associated with a decrease in percentage maximum stand, beginning with the 2-minute treatment. A stand of only 16.7 per cent was obtained for the 8-minute irradiation of the pollen.

TABLE 3.—Mean height of maize plants at 7, 14, 21, and 28 days and mean number of exposed leaves per plant at 28 days following planting of irradiated seed and seed obtained from irradiated pollen.

Treatment	Plant age								
	7 days		14 days		21 days		28 days		
	No. plants*	Mean height, cm.**	No. plants	Mean height, cm.	No. plants	Mean height, cm.	No. plants	Mean height, cm.	Mean no. exposed leaves per plant
L289 x I205									
None	60	5.3 ± 0.16	60	19.7 ± 0.23	60	28.4 ± 0.44	60	37.1 ± 0.45	4.9 ± 0.04
X-ray, 7500 r, seed	60	5.1 ± 0.10	60	18.8 ± 0.18	60	25.6 ± 0.31	60	34.7 ± 0.27	4.6 ± 0.06
X-ray, 1200 r, pollen	53	4.8 ± 0.22	54	17.5 ± 0.58	54	24.8 ± 0.68	54	32.2 ± 0.89	4.4 ± 0.11
1-min. exposure, pollen	60	5.3 ± 0.13	60	20.6 ± 0.21	60	26.8 ± 0.28	60	37.4 ± 0.36	4.0 ± 0.02
2-min. exposure, seed	60	4.2 ± 0.09	60	15.5 ± 0.19	59	22.9 ± 0.25	59	30.1 ± 0.29	5.0 ± 0.04
2-min. exposure, pollen	51	4.8 ± 0.23	51	17.2 ± 0.52	51	23.8 ± 0.66	51	30.3 ± 0.88	4.5 ± 0.09
4-min. exposure, seed	59	3.8 ± 0.08	60	12.9 ± 0.17	60	20.7 ± 0.27	60	27.3 ± 0.39	5.4 ± 0.07
4-min. exposure, pollen	34	5.0 ± 0.34	35	16.0 ± 0.84	35	21.5 ± 1.02	35	27.6 ± 1.33	4.5 ± 0.13
8-min. exposure, seed	59	2.8 ± 0.08	59	5.6 ± 0.17	58	9.7 ± 0.36	42***	14.3 ± 0.71	6.3 ± 0.13
8-min. exposure, pollen	8	2.6 ± 0.57	10	10.3 ± 1.65	10	14.5 ± 2.32	10	20.3 ± 3.26	4.0 ± 0.56
N6 x M14									
None	20	5.2 ± 0.15	20	17.9 ± 0.36	20	27.5 ± 0.45	20	37.2 ± 0.58	5.0 ± 0.00
X-ray, 7500 r, seed	20	4.2 ± 0.12	20	16.3 ± 0.21	20	26.4 ± 0.38	20	36.5 ± 0.48	5.0 ± 0.05
2-min. exposure, seed	19	3.5 ± 0.26	19	13.9 ± 0.33	19	22.7 ± 0.34	19	32.6 ± 0.57	4.8 ± 0.11
4-min. exposure, seed	20	3.1 ± 0.13	20	12.2 ± 0.26	20	18.0 ± 0.25	20	25.7 ± 0.54	6.0 ± 0.00
8-min. exposure, seed	18	2.6 ± 0.14	18	7.3 ± 0.28	18	11.8 ± 0.49	18***	18.8 ± 0.98	7.2 ± 0.18
M14 x N6									
None (N6 x M14)	20	5.4 ± 0.16	20	18.0 ± 0.40	20	27.3 ± 0.43	20	37.3 ± 0.66	5.0 ± 0.00
X-ray, 7500 r, seed	20	4.1 ± 0.16	20	15.5 ± 0.31	20	22.9 ± 0.50	20	32.1 ± 0.65	4.8 ± 0.10
2-min. exposure, seed	19	3.1 ± 0.13	19	13.3 ± 0.22	19	20.4 ± 0.44	19	30.3 ± 0.72	4.9 ± 0.07
4-min. exposure, seed	20	2.9 ± 0.13	20	11.0 ± 0.34	20	16.1 ± 0.29	20	23.0 ± 0.48	5.6 ± 0.11
8-min. exposure, seed	19	1.7 ± 0.09	19	5.3 ± 0.37	19	8.5 ± 0.76	17***	15.5 ± 1.29	7.5 ± 0.34

* 60 seeds planted for each treatment.
** Leaves held erect for measurement.
*** Includes some plants partly green.

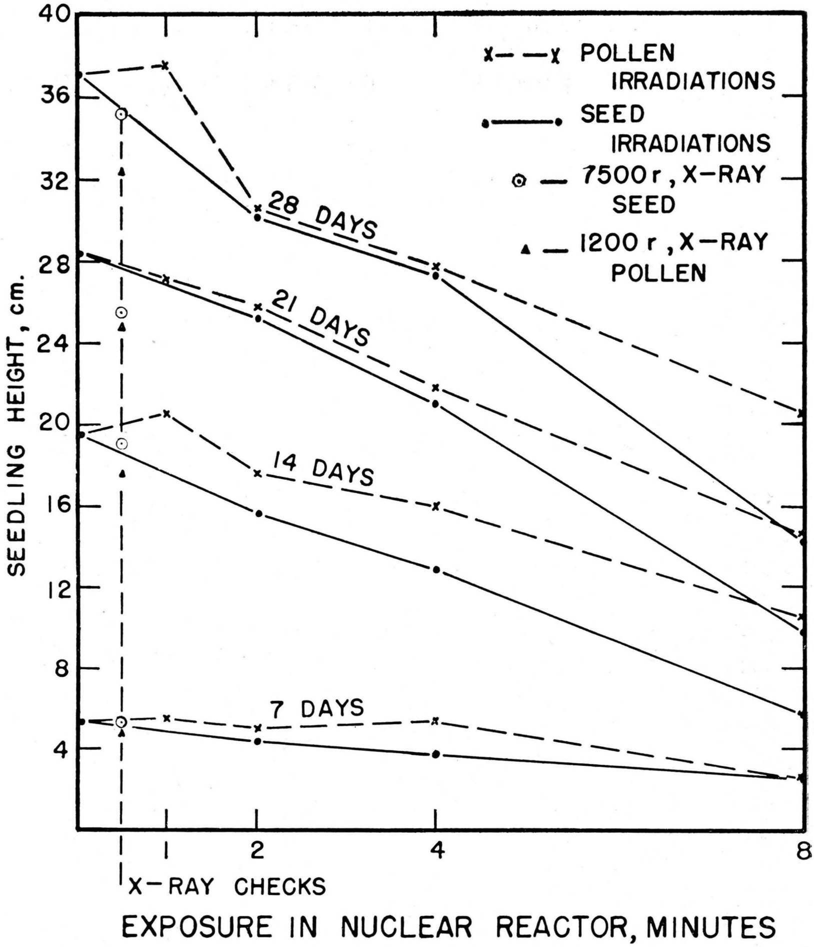

FIGURE 4.—Effects of exposing single-cross hybrid maize seed or inbred maize pollen to thermal-neutron irradiation and to X radiation on subsequent height of seedlings grown from the irradiated L289 X I205 seed and seed obtained from the pollination of untreated L289 plants with irradiated I205 pollen. (Based on Table 3.)

Delayed death occurred in the L289 x I205 lot following 8 minutes of seed treatment in the nuclear reactor. The stand dropped from a maximum of 98.3 per cent to 63.3 per cent on the 28th day. There was no evidence of delayed death in the pollen treated series.

One of the most striking effects following seed exposure in the nuclear reactor was the narrowness and upright position of the leaves.

TABLE 4.—Maximum stand and number of plants on the 28th day after planting hybrid maize seed irradiated or seed obtained from pollen irradiated for various periods with thermal neutrons or with X radiation.

Treatment	No. kernels planted	Stand			
		Maximum		28 days after planting*	
		No.	%	No.	%
N6 x M14 (Seed)					
None	20	20	100.0	20	100.0
X-ray, 7500 r units	20	20	100.0	20	100.0
Nuclear reactor, 2-min. exposure	20	19	95.0	19	95.0
Nuclear reactor, 4-min. exposure	20	20	100.0	20	100.0
Nuclear reactor, 8-min. exposure	20	18	90.0	17	85.0
M14 x N6 (Seed)					
None (N6 x M14)	20	20	100.0	20	100.0
X-ray, 7500 r units	20	20	100.0	20	100.0
Nuclear reactor, 2-min. exposure	20	19	95.0	19	95.0
Nuclear reactor, 4-min. exposure	20	20	100.0	20	100.0
Nuclear reactor, 8-min. exposure	20	19	95.0	16	80.0
L289 x I205 (Seed)					
None	60	60	100.0	60	100.0
X-ray, 7500 r units	60	60	100.0	60	100.0
Nuclear reactor, 2-min. exposure	60	60	100.0	59	98.3
Nuclear reactor, 4-min. exposure	60	60	100.0	60	100.0
Nuclear reactor, 8-min. exposure	60	59	98.3	38	63.3
L289 x I205 (Pollen)					
X-ray, 1200 r units	60	54	90.0	54	90.0
Nuclear reactor, 1-min. exposure	60	60	100.0	60	100.0
Nuclear reactor, 2-min. exposure	60	51	85.0	51	85.0
Nuclear reactor, 4-min. exposure	60	35	58.3	35	58.3
Nuclear reactor, 8-min. exposure	60	10	16.7	10	16.7

* Plants definitely dying not included.

As shown in Table 5, there was a significant decrease in leaf width (at the 2 per cent level of probability) with each increase of pile exposure. Plants from X-rayed seed likewise had leaves significantly narrower than plants from untreated seed, but they were significantly wider than those from seed exposed for 2 minutes in the nuclear reactor. These differences were clearly visible at the conclusion of the experiment (Figures 5 and 6).

TABLE 5.—Mean width of the second leaf of 21-day-old plants of a maize hybrid, L289 x I205, grown from seed irradiated with 0, 2, 4, and 8 minutes of thermal neutrons and with 7500 roentgens of X-ray, respectively.

Treatment	No. plants	Mean width of second leaf, cm.*
None	20	1.4 ± 0.02
X-ray, 7500 r units, seed	20	1.3 ± 0.01
Nuclear reactor, 2-min. exposure, seed	19	1.1 ± 0.03
Nuclear reactor, 4-min. exposure, seed	20	1.0 ± 0.02
Nuclear reactor, 8-min. exposure, seed	17	0.8 ± 0.02

* All differ at 2% level.

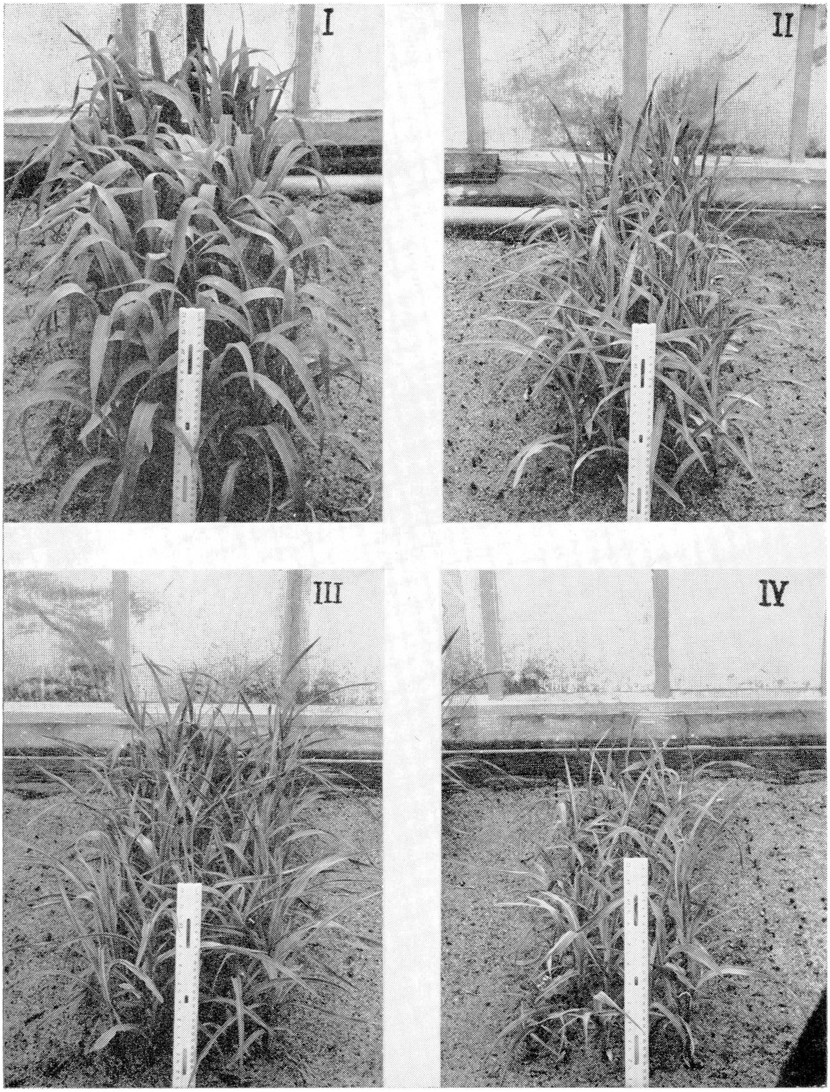

FIGURE 5.—Thermal-neutron tolerance of maize kernels as indicated by plant height and leaf width of 34-day-old seedlings. I, No treatment; II, 2-minute; III, 4-minute; and IV, 8-minute exposures of seed to thermal neutrons.

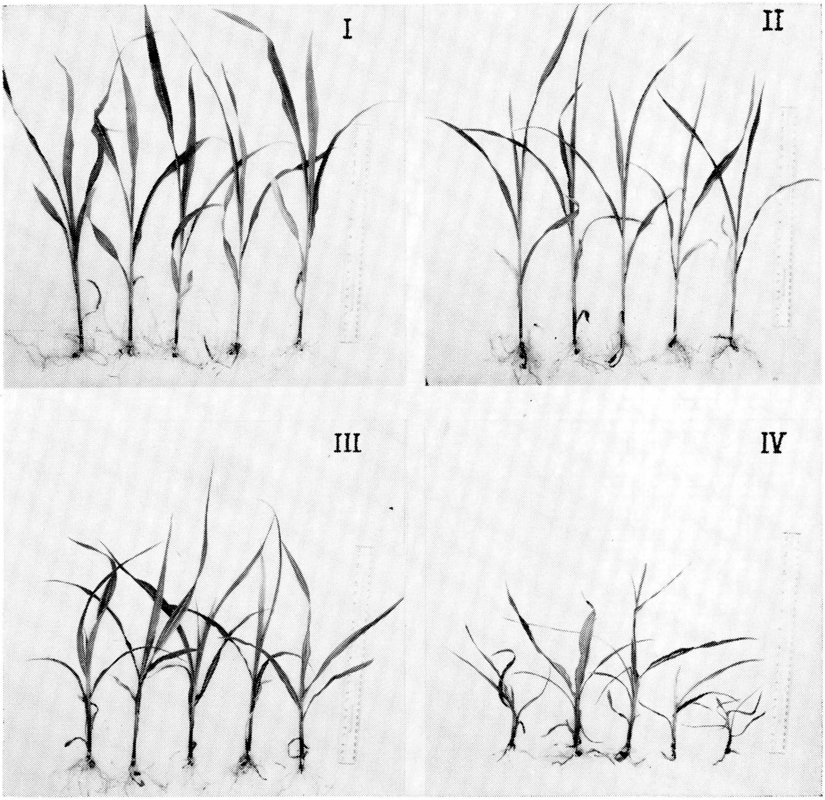

FIGURE 6.—Representative 34-day-old maize seedlings selected from plats shown in Figure 5, reflecting the effect of irradiating maize kernels with thermal neutrons. I, No treatment; II, 2-minute; III, 4-minute; and IV, 8-minute exposures to thermal-neutron irradiation.

In addition to the effects on leaves for pile-irradiated seed noted above, other effects included mottling, formation of chimeras, slashed leaves, and one-sided development. The chimeras increased in size and frequency with increase in the length of exposure. The slashed effect was probably due to killed areas. Singularly, plants from treated seed were also darker bluish-green in color, despite mottling, than plants from untreated seed.

For the 2-minute pile-irradiated seed, approximately 15 per cent of the plants had one or more leaves showing light green striping. Eight per cent of the plants had slashed leaves.

The percentage of plants with light green striping on the leaves increased to approximately 40 per cent for the 4-minute pile exposure.

In addition, one plant had a cream-colored stripe and another had a red stripe. In this lot, nearly 22 per cent of the plants had one or more slashed leaves.

In the 8-minute exposure lot, approximately 42 per cent of the surviving plants had the light green striping on leaves. Also, 10 per cent of the plants had white stripes, 16 per cent had wrinkled leaves, and approximately 31 per cent had peculiarly slashed leaves. The most common effect in this series, however, was the one-sided leaf development, resulting in much twisting and curling of the leaves.

The only apparent effects resulting from the 7500 r unit dosage of X radiation were very slight mottling and depression in growth. There were no leaf anomalies or sectors evident in this series.

The effects of exposing maize seed for 2, 4, and 8 minutes, respectively, in the nuclear reactor on subsequent development of seedling plants may be summarized as follows: (1) The first two leaves were heavily mottled and somewhat shorter and narrower than the corresponding leaves in the control. (2) The third, fourth, and fifth leaves were much narrower than corresponding leaves in the control. In going from the third to the fifth leaf, the mottling became increasingly confined to a pattern of streaks and a correspondingly smaller area in the upper portion of the leaf. In the 8-minute treatment these leaves were mostly one-sided, i.e., only the midrib and one side of the leaf had developed. (3) Striping occurred on some of the plants, beginning with the fifth leaf and continuing in the leaves above. (4) In plants where a narrowing of the lower leaves occurred, the leaves beginning with the sixth one and continuing above were usually normal in this respect. However, in some cases the anomaly persisted in leaves above the fifth one. (5) Many of the abnormalities occurred as mirror images of each other in adjacent leaves.

Barley and Maize Plants Grown to Maturity

All of the surviving barley seedlings and representative lots of the surviving maize seedlings were transplanted to the field shortly after the final seedling data had been recorded. Transplanting at the relatively advanced stage of development precluded fully normal field development. Nevertheless, certain general observations on growth to maturity are of interest.

Up to the time of flowering, only two of the barley plants in the field showed any visible effects of irradiation. One of these plants, which had appeared to be normal in the seedling stage, failed to head. It was still green at the time the remaining plants were harvested. The other plant produced chlorophyll-deficient tillers which failed to head.

Main spikes of all barley plants from the 2- and 4-minute thermal-neutron-exposed seed produced very few kernels. Percentage kernel production was somewhat higher but still far below normal in the tiller heads of these same plants. Seed set in both the main and tiller spikes of the untreated checks was close to normal.

The striping noted in the maize seedlings in the greenhouse persisted until maturity in a few plants. The tillers on one maize plant were entirely devoid of chlorophyll.

A random examination was made of tassels on the maize plants grown from the 2- and 4-minute thermal-neutron-exposed seed to determine degree of pollen abortion. The tassels had normal pollen throughout, partial pollen abortion throughout, or they were normal except for sectors with partial pollen abortion. Ears from the main stalks were also examined for sterility. The percentage of ears showing sterility and the percentage of sterility for affected ears increased with increase in length of time of exposure of the parent seed to neutrons. In spite of this general relationship, two apparently normal ears were produced on plants from seed exposed for 8 minutes to thermal neutrons. No sectors were apparent in the ears.

DISCUSSION

A comparison of the data relating to the simultaneously irradiated maize and barley seed indicates that the thermal-neutron tolerance of dormant barley seed is less than 50 per cent of that of dormant single-cross hybrid maize seed when compared on the basis of subsequent seedling height, increase in average leaf number per plant, and delayed death. In the production of morphological anomalies and chimeras, the two crops reacted differently—the barley plants showed very little effect while virtually every maize plant of the 8-minute neutron treatment exhibited one or more defects.

The difference in susceptibility between maize and barley seed is not entirely unexpected. Smith (1946) reported that X radiation of maize seed with 30,000 r units resulted in a germination of 70 per cent of the control and a seedling height, after 19 days, of 42 per cent of the control, whereas the somewhat smaller dose of 27,000 r units, when applied to barley seed, resulted in a germination of 31 per cent of the control and a seedling height of 8 per cent of the control. At exposures of 38,000 r units and 40,000 r units for barley and maize seed, respectively, germination for the barley dropped to 3 per cent of the control, while the germination percentage of the maize seed had not changed. Gustafsson and Mac Key (1948) also reported that for barley seed 30,000 r units is probably the upper limit of X-ray tolerance, since with 25,000 r units they obtained a mature plant stand of only 10 per cent of the control. With maize, Collins and

Maxwell (1936) found that delayed death occurred following X radiation of maize seed with 40,000 r units. Germination was unimpaired following irradiation with 100,000 r units, but all plants from this seed died in the seedling stage. Results obtained in the present studies are in agreement with these earlier reports in that an X radiation of 7500 r units was more severe on barley seed than on maize seed.

The relative tolerance of barley and maize seed to thermal-neutron irradiation is, therefore, comparable to the relative tolerance of these crop seeds to X radiation. The failure of the barley seedlings grown from thermal-neutron-irradiated seed to show many morphological irradiation effects has also been generally reported for barley seedlings grown from X-rayed seed. In contrast, Gustafsson and Mac Key (1948) reported many mutant effects in barley seedlings grown from fast-neutron-irradiated seed.

The effects noted in the maize seedlings grown from the thermal-neutron-irradiated seed were comparable to those reported by Randolph (1950) for the maize seedlings grown from the seed exposed at the 1946 Bikini atomic bomb detonation (Test Able). Randolph indicated that the effects noted, except for frequency, were similar to those obtained following 15,000 r units of X radiation.

The difference in susceptibility between maize pollen and both barley and maize seed to equal dosages of thermal-neutron irradiation, when compared on the basis of susceptibility to X radiation, constituted the most striking observation in these experiments.

This difference, determined, for example, on the basis of subsequent seedling height, may be framed from the experimental results as follows: (1) In the pollen lots, 600 r units of X radiation were approximately equal to the 1-minute thermal-neutron exposure in seedling growth depression; (2) in the seed lots of both barley and maize, the effect of 7500 r units of X radiation was determined by interpolation to be approximately equal in effect to a 1-minute thermal-neutron exposure. Therefore, on the basis of X-ray comparisons, an equal thermal-neutron exposure was 12 times more effective on the seeds than would be expected on the basis of X-ray effects. However, Frolik and Morris (1950b) reported that the effectiveness of pollen exposures in the nuclear reactor at the same power and for the same durations varied rather widely on different days of exposure. Using four kernel characters as a measure of comparison, they found that on August 16, 1948, the irradiation date of the pollen used in the present experiments, approximately 3 minutes of pile irradiation of the pollen was necessary to equal the effect produced by 1200 r units of X radiation of pollen, whereas on August 19, 1948, only about 1 to 1½ minutes of exposure was needed to equal the same

X-ray effects. If it is assumed that the pollen irradiations represent an effect of only half of the average expected from a given period of exposure, the effectiveness of the thermal-neutron irradiation of the seed would still be six times that expected on the basis of the pollen data. Admittedly, the effects of seed irradiations may also have been either lighter or heavier than would be obtained as an average of a series of tests.

In order to account for the apparently greater efficiency of the thermal-neutron irradiation over X radiation on the seeds, the radiations to which the pile-irradiated pollen and seed lots were exposed and the properties of these radiations are considered. The possible radiations from the pile proper were (1) gamma ray contamination, (2) fast, intermediate, or slow neutrons, and (3) thermal neutrons.

The amount of gamma ray contamination at the position where the the materials were exposed is unknown. Since no shielding was employed, the ionization due to gamma ray contamination could have been considerable. However, since gamma rays are presumed to give results very similar to X-rays, the gamma rays present could hardly account for the much greater efficiency of pile irradiation on seed than on pollen on the basis of X-ray comparisons. This is further substantiated by the following reports. From their observations of seed set on ears pollinated by pollen irradiated with thermal neutrons, Frolik and Morris (1950a) reported that for maize pollen 16 minutes of exposure in the nuclear reactor constituted a near lethal dose as determined by subsequent seed set. Tascher (1945) reported that a dosage of 1200 r units of X-ray constituted "near the maximum permitting of fertilization in corn" and that 6000 r units constituted a killing dosage. A comparison of these reports suggests that the gamma ray contamination present in the 16 minutes of pile exposure could only produce the lethal effect that would be expected from 6000 r units of X radiation. The seed data, however, indicate that on that basis the effect due to gamma ray contamination during even the 8-minute seed exposure would have been negligible.

In regard to fast, intermediate, and slow neutrons, it is assumed that the heavy water moderator was sufficiently effective so that neutrons of only thermal energy were present at the place of irradiation.

The differential effectiveness of nuclear reactor exposures on pollen and seed must then be due to the thermal neutrons. The effect of thermal-neutron irradiation is indirect and consists of neutron capture by atomic nuclei, followed by immediate emission of ionizing particles or photons, and in some cases by subsequent radioactivity. Since the capture probability of nuclei of different elements for thermal neutrons varies greatly, the chemical *composition of the tissue* exposed is of paramount importance in determining the degree of ionization produced.

The chemical compositions as determined by spectrochemical or chemical analyses of tissues comparable to those irradiated are presented in Tables 6 and 7. Analyses were not performed for the elements hydrogen, carbon, oxygen, and chlorine, but the probable percentages of these four elements were either obtained from published sources or calculated from such sources.

TABLE 6.—Spectrochemical analysis of ash of maize pollen, excised maize embryos, and excised barley embryos.

Concentration of elements	Maize pollen	Maize embryo	Barley embryo
Strong	Ca, K, Mg, P, Si	K, P	P
Moderate	Al, Fe, Na	Mg	K, Mg
Weak	As, Ba, Cu, Hg, Li, Mn, Pb, Ti, Zn	As, Ca, Hg, Si, Zn	As, Ca, Hg, Zn
Very weak	Ag, Be, Bi, Co, Cr, Ni, Sb, Sn, Zr	Ag, Al, Ba, Be, Bi, Co, Cr, Cu, Fe, Li, Mn, Na, Ni, Pb, Sb, Sn, Ti, Zr	Ag, Al, Ba, Be, Bi, Co, Cr, Cu, Fe, Li, Mn, Na, Ni, Pb, Sb, Sn, Ti, Zr

Elements are important in thermal neutron capture either because of their very high concentration or their high capture cross sections or both. The analyses and subsequent calculations showed that only hydrogen and nitrogen, primarily because of their high concentration, and boron, primarily because of its high capture cross section, contributed materially to the total ionization produced immediately following neutron capture.

The capture and emission reactions of the three elements are as follows:

$$
\begin{aligned}
{}_0n^1 + {}_1H^1 &\longrightarrow [{}_1H^2] \longrightarrow {}_1H^2 + \gamma\ (2.23\ \text{Mev}) \\
{}_0n^1 + {}_5B^{10} &\longrightarrow [{}_5B^{11}] \longrightarrow {}_3Li^7 + \alpha\ (2.40\ \text{Mev}) \\
{}_0n^1 + {}_7N^{14} &\longrightarrow [{}_7N^{15}] \longrightarrow {}_6C^{14} + p\ (0.6\ \text{Mev})
\end{aligned}
$$

The alpha particles and protons produce ionization by direct action of their electric fields on electrons. On the other hand, most of the ionization resulting from gamma rays is produced by the electrons ejected following gamma ray absorption.

The contribution of the three elements to the radiation effect varies both quantitatively and qualitatively, since the emissions are of different types. It is generally believed that damage to biological material from radiation is largely due to production of ion pairs and further depends, to a large extent (Aebersold and Lawrence, 1942),

TABLE 7.—Components of total rep per minute of ionization absorbed in maize pollen, maize embryo, and barley embryo tissue partitioned among the capture reactions of hydrogen, boron, and nitrogen. Thermal-neutron flux 7 x 10 [10] neutrons per square centimeter per second. Calculations based on the method used by Conger and Giles (1950).

Element	Atomic weight	Per cent of wet weight*	No. of atoms per cc. $X10^{-24}$	Capture cross section $X10^{24}cm^2$	Capture radiation emitted and energy		Fraction of energy absorbed in tissue	Rep/min. absorbed in tissue	Per cent of total rep/min.
					Type	Energy (Mev)			
				Maize pollen**					
H	1.008	8.5	0.0508	0.32	γ	2.23	0.0021	6.13	6.49
B	10.82	0.000,081,5	0.000,000,045	715.0	α	2.40	1.0	6.21	6.58
N	14.008	2.333	0.0010	1.7	p	0.6	1.0	82.07	86.93
							Total........	94.41	
				Maize embryo					
H	1.008	8.0	0.0478	0.32	γ	2.23	0.0016	4.39	2.00
B	10.82	0.000,519	0.000,000,289	715.0	α	2.40	1.0	39.90	18.16
N	14.008	4.975	0.002,138	1.7	p	0.6	1.0	175.46	79.84
							Total........	219.75	
				Barley embryo					
H	1.008	8.0	0.0478	0.32	γ	2.23	0.0013	3.75	1.76
B	10.82	0.000,164	0.000,000,091	715.0	α	2.40	1.0	12.56	6.18
N	14.008	5.305	0.002,28	1.7	p	0.6	1.0	187.12	92.06
							Total	203.25	

* B and N analyses by Chemistry Division, Argonne National Laboratory, Chicago, Illinois. H calculated from data presented by Anderson and Kulp (1923) for maize pollen and by Winton and Winton (1932) for maize and barley kernels.

** Composite sample collected in the greenhouse at Lincoln, Nebraska, in 1950.

on the density with which ion pairs are produced, which, in turn, is a function of the magnitude of charge and the speed or range of the ionizing particle. Data presented by Locher (1936) and Lea (1946) indicate that production of ion pairs per micron length for alpha particles, protons, and electrons of equal energy is greatest for alpha particles, and smallest for electrons. Greatest biological damage per reaction, both chromosomal and physiological, would therefore be expected for the boron reaction. The density of the ionizations produced by the recoil nuclei would be even greater, but the path or track would be extremely short.

The total amount of ionization (assuming for the purpose of calculation that all energy is given to the emission) produced in the tissue as a result of thermal neutron capture reactions may be conveniently partitioned among hydrogen, boron, and nitrogen by using the formulations used by Conger and Giles (1950). The calculation of the roentgen-equivalent-physical (rep) of ionization energy per unit volume of tissue per unit time, since 1 roentgen is equal to 5.22 x 10^{13} ev, is as follows:

$$\text{rep/min.} = \frac{\begin{pmatrix}\text{Flux}\\ \text{per}\\ \text{min.}\end{pmatrix}\begin{pmatrix}\text{No. of atoms}\\ \text{per cc.}\\ \times\ 10^{-24}\end{pmatrix}\begin{pmatrix}\text{Capture cross}\\ \text{section in}\\ \text{“barns”} \times 10^{24}\end{pmatrix}\begin{pmatrix}\text{Radiation}\\ \text{energy}\\ \text{emitted}\\ \text{in Mev}\end{pmatrix}\begin{pmatrix}\text{Fraction of}\\ \text{energy}\\ \text{absorbed}\\ \text{in tissue}\end{pmatrix}}{5.22 \times 10^{13}\ \text{ev}}$$

where the number of atoms per cubic centimeter of the element under consideration is given by the following calculation:

$$\frac{\%\ \text{of wet weight} \times 0.602 \times 10^{24}}{100 \times \text{atomic weight}},\ \text{density of 1}$$

All of the energy of the emitted short range 2.4 Mev alpha and 0.6 Mev proton particles was expended in the tissues under consideration. However, only a small fraction of the 2.23 Mev gamma rays emitted by the hydrogen nuclei was expended in this manner. This fraction absorbed in the tissue under consideration depends on gamma ray absorption coefficient (u) in the tissue, and the thickness (t) of the traversed tissue. A further geometric correction (G) may be necessary since the gamma rays can originate anywhere in the tissue. In the maize and barley embryos no geometric correction was deemed advisable, but in the maize pollen a geometric correction of 0.75 as suggested by Conger and Giles (1950) was employed. The fraction of the emitted energy absorbed by the tissue is equal to $1 - e^{-utG}$.

The pollen sample used for chemical analysis, Tables 6 and 7, may not have been truly representative of that actually irradiated since it was a greenhouse composite collected at Lincoln. However, the nitrogen content obtained was in fairly close agreement with that generally reported, and the boron content of the soil in which the plants were growing was not known to be deficient.

Calculation of the rep per minute of ionization absorbed in the tissue due to the capture reactions (assuming for the purpose of calculation that all of the energy of the neutron was imparted to the emitted particle or photon) showed that the nitrogen reaction accounted for approximately 80 to 92 per cent of the ionization, the boron reaction for approximately 6 to 18 per cent, and the hydrogen reaction for approximately 2 to 6 per cent. A slight increase in boron concentration, however, raised its contribution to the total rep per minute tremendously because of its high capture cross section. This is evident in the maize embryo, Table 7. Conger (1950) has shown that boron-enriched *Tradescantia* buds were four to five times as sensitive to thermal neutrons as unenriched buds.

The radioactivity from unstable isotopes produced as a result of thermal neutron capture also contributed to ionization. The seed samples were too radioactive immediately following irradiation to be handled safely with bare hands. The degree of radioactivity dropped off sharply within a period of 12 hours but was not checked subsequently. Probably one of the sources of this radioactivity was chlorine^{38}. According to Seaborg and Perlman (1948) Cl^{38} has a half-life of 37 or 38.5 minutes and gives off beta particles and gamma rays. Also present, but probably not detected, was C^{14}. It is a beta emitter with a half-life of 4700 to 6400 years (Seaborg and Perlman, 1948). Even though the seeds were held for a period of approximately ten months from time of irradiation to planting, this source of radioactivity is considered unimportant in its contribution to total effect produced because of the low intensity and the type of ionization. Other elements present in very small quantities (Table 7) also contributed to the total radioactivity.

Any calculation of the biological efficiency of thermal neutrons from the data of Table 7 is of little value since the inherent gamma ray contamination is unknown. A comparison of the total rep/min. of ionization in the maize and barley embryos gives no clue as to the greater susceptibility of barley seed to thermal-neutron irradiation. It merely confirms the fact that for equivalent radiation dosages, barley seed is more susceptible than maize seed.

A comparison of the total rep/min. of ionization for the maize pollen, assuming that the chemical composition is representative, with that of either maize or barley embryos is of considerable interest and may account for the greater effectiveness of thermal neutrons on the barley and maize seed than on the maize pollen on the basis of X-ray comparisons. The total rep/min. of ionization for the pollen is somewhat less than half of that calculated for maize embryo tissue. This *per se* would not account for the greater effectiveness of 6 to 12 times reported above for equivalent thermal-neutron exposures of maize seed as compared with maize pollen. A possible explanation is that the effect on biological tissue with increasing rep/min. of ionization due to neutron capture is not a linear but rather an exponential relationship. Confirmation of this must await further experimentation since the present experiment cannot provide an answer to that problem.

In the calculations above, all of the emission energy has been assumed to have been imparted to the particle or photon emitted. A certain amount of this, however, is expended in the recoil of the emitting compound nucleus. The large biological efficiency of neutron irradiation is often ascribed to the very dense ionizations produced by these recoil nuclei. A further effect which may be of great importance is the effect that transmutation of an element may have upon the molecule of which it is a part. Certainly in the case of the nitrogen of the chromosomal nucleic acids such an effect could be of considerable importance. The possibility of biological effects resulting directly from transmutation of nitrogen to carbon has been suggested by Conger and Giles (1950). More recently, Hershey *et al.* (1951) have presented data from which they conclude that killing of bacteriophage by assimilated P^{32} is a direct result of the nuclear reaction and rarely a result of the beta radiation given off in the decay of the phosphorous to sulfur. Further work will be necessary to establish whether or not transmutation of, for example, nitrogen to carbon or boron to lithium in higher plants may through its effect on disrupting the molecule cause biological changes. Certainly such an effect cannot be ruled out as a possibility at this time. The corollary to the occurrence of such a phenomenon is that thermal-neutron and X or gamma irradiation of various plants and parts of plants may result in qualitative as well as quantitative differences other than those well recognized as being due to differences in specific ionization.

The results of this experiment add more evidence to the belief that certain biological materials are more susceptible to irradiation than others, regardless of the type of radiation. This is shown by a comparison of the X-ray and thermal-neutron effects observed on maize and barley seeds. In the case of the maize pollen and maize seed comparison, however, the suggestion by Locher (1936) that biological damage can be regulated at will by nutrient-enriching processes with certain elements is underscored.

SUMMARY

Studies were conducted to determine the comparative effects of thermal-neutron and X radiation of barley and maize seed and of maize pollen (placed on untreated female flowers) on subsequent seedling development.

Thermal-neutron irradiations of barley seed were made for periods of 2, 4, 8, 10, 20, 30, 40, and 50 minutes, respectively. The flux was 7×10^{10} neutrons/square centimeter/second. Even the heaviest treatment failed to kill the seed outright. However, there was no emergence of plants where treatment exceeded 8 minutes of exposure. For the 8-minute pile-irradiated lot the emergence was 4 per cent compared with 74 per cent for control. Percentage emergence for the 2- and 4-minute irradiated lots did not differ significantly from control. Delayed death resulted in a loss of 2 of the 36 plants for the 2-minute neutron treatment, 13 of the 34 plants for the 4-minute lot, and only two plants for the 8-minute lot.

The morphological effects of thermal-neutron irradiation of barley seed for the 2- and 4-minute periods on subsequent seedling development were as follows: (1) Seedling height was significantly lower than for control. (2) The first two leaves were very much mottled. (3) The next few leaves were narrower than those of the control plants. (4) The exposed leaf number was significantly higher than for control.

All of the surviving barley seedlings were transplanted to the field. Only two of the plants showed any visible effects of pile irradiation up to the time of flowering. Percentage kernel production on plants from neutron-irradiated seed was very low in the main spikes and somewhat higher but still far below normal in tiller spikes. Seed set in both the main and tiller spikes of the untreated checks was close to normal.

In preliminary tests, partial stands were secured from barley seed X-rayed with dosages ranging up to 25,000 roentgens. In the main test comparisons, X-raying of seed with a dosage of 7500 roentgens resulted only in the following visible effects on seedlings: (1) a slight mottling of the first two leaves, and (2) plant height slightly below that of control.

In the maize studies, seeds of F_1 single-cross yellow dent hybrids L289 x I205, N6 x M14, and M14 x N6 were given the following treatments: none, 2, 4, and 8 minutes of thermal neutrons with a flux of 7×10^{10} neutrons/square centimeter/second; and 7500 roentgens of X-ray, respectively. Comparisons were made with seed produced by pollinating untreated L289 with I205 pollen irradiated with 1, 2, 4, and 8 minutes of the same thermal-neutron flux as above, with 1200 roentgens of X-ray, and with no treatment, respectively.

Mean height of maize seedlings was lower for irradiated seed than for control. In general, the longer the exposure had been to thermal neutrons, the more severe the effect on the seedlings. There was a striking similarity in mean height of progeny of the seed-irradiated series and of the pollen-irradiated series with the same neutron exposure. However, the standard error was much lower for the former than for the latter. In the L289 x I205 series, mean seedling height was slightly lower for the 1200-roentgen X-rayed pollen series than for 7500-roentgen X-rayed seed series. It appeared that on the basis of this character, 1200 roentgens of X-ray were equal in effect to 1 to 2 minutes of neutrons in pollen irradiation, and that 7500 roentgens of X-ray were equal in effect to 1 minute of neutrons in seed irradiation.

Percentage maximum stand was unaffected by any of the maize seed irradiations, but beginning with the 2-minute exposure there was an inverse relationship between length of pollen exposure to thermal neutrons and maximum stand. The only clear-cut case of delayed death occurred in the 8-minute neutron-exposed L289 x I205 seed series where the stand dropped from a maximum of 98.3 per cent to 63.3 per cent on the 28th day.

Mean exposed leaf number increased with increase in length of maize seed exposure to thermal neutrons, beginning with the 4-minute exposure. A slightly lower leaf number was found in the neutron-irradiated pollen series than in control. Other seedling effects of neutron irradiation of maize seeds were as follows: (1) The first two leaves were heavily mottled and somewhat shorter and narrower than those of control. (2) In going from the third to the fifth leaves the mottling became confined to streaks in the upper portions of the leaves. These leaves were much narrower than those of control. (3) Striping, beginning with the fifth leaf, occurred in some of the plants. (4) In most plants where narrowing of the leaves was present, leaves beginning with the sixth one were normal. (5) Many of the abnormalities occurred as mirror images of each other in adjoining leaves.

The only visible effects of the X radiation of maize seed consisted of slight mottling and narrowing of leaves and depression of growth.

The striping noted in maize seedlings persisted until maturity in a few plants. In the plants of the neutron-irradiated-seed series, partial pollen sterility occurred in entire tassels or in sectors of tassels. Percentage of plants with sterility in the ears and percentage of sterility for affected ears increased with increase in length of exposure to thermal neutrons.

Total ionization produced immediately following neutron capture in the pile irradiations was attributed principally to nitrogen with the emission of protons, to boron with the emission of alpha particles, and to hydrogen with the emission of gamma rays. The rep per minute absorbed in embryos was approximately twice that in the pollen. This was due principally to the higher nitrogen content and to a lesser extent to the higher boron content in the former than in the latter. The radioactivity from unstable isotopes produced as a result of thermal neutron capture also contributed to ionization.

On the basis of X-ray comparison, the thermal neutrons were at least six times as effective when used on seed as when used on pollen. The difference is reduced but still present when allowance is made for the difference in ionization in the two plant parts. It is suggested that the biological effect may be due in part to the disruption in molecules caused by the transmutation of nitrogen to carbon and/or of boron to lithium as well as to the extremely dense ionization resulting from the recoiling nuclei.

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