STORED-PRODUCT

# Irradiation of *Maconellicoccus hirsutus* (Homoptera: Pseudococcidae) for Phytosanitation of Agricultural Commodities

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**ABSTRACT** Studies on the tolerance of pink hibiscus mealybug, *Maconellicoccus hirsutus* (Green), to ionizing irradiation were undertaken to determine the dose needed to disinfest commodities of this pest. Overall, radiotolerance of *M. hirsutus* was found to increase with maturity. Target doses of 50 Gy reduced eclosion of eggs to <50%, but doses as great as 750 Gy did not eliminate hatching during the study. At 100 Gy, *M. hirsutus* eggs, crawlers, and nymphs were controlled, because progeny were not produced despite crawlers and nymphs living for much longer periods than unexposed individuals. Fecundity of treated crawlers and nymphs was greatly impacted by treatment of 100 Gy; crawlers developing into adults produced no eggs, and 10 adults of 3,983 treated nymphs (0.25%) produced 309 eggs. Few adult females exposed as nymphs deposited eggs because male nymphs died during development, which left the females unfertilized. By comparison, 89% of female nymphs treated at 100 Gy and mated as adults with nonirradiated males produced a total of 1,447 eggs (19 eggs per female). Evidence from this study suggests *M. hirsutus* reproduces sexually, not parthenogenetically. Adults, the most resistant stage, exposed to target doses of 100 Gy produced eggs that were 1.2% viable, from which a small portion of individuals successfully completed development and produced progeny. A target dose of 250 Gy was sufficient to control adult *M. hirsutus* because, at that dose, none of the eggs produced by 3,093 irradiated adults eclosed. The minimum dose needed to ensure quarantine security is between 100 and 250 Gy.

**KEY WORDS** *Maconellicoccus hirsutus*, pink hibiscus mealybug, irradiation, quarantine security

COMMERCIAL INTEREST IN IONIZING irradiation treatment of agricultural commodities for phytosanitary purposes has been growing worldwide. Over 40 countries have approved irradiation treatment of one or more foods (Loaharanu 1999). In 1986 and 1991, task forces from the International Consultative Group on Food Irradiation (ICGFI) recommended generic doses of 150 Gy for fruit flies and 300 Gy for other arthropod pests for quarantine treatments (Loaharanu 1999). However, these doses are not accepted by the United States Department of Agriculture (USDA), Animal and Plant Health Inspection Service (APHIS), which in 1996, issued a notice of policy that irradiation as a phytosanitary treatment would be considered on a case-by-case basis after pest risk analysis and the evaluation of efficacy data (APHIS 1996). APHIS currently allows Hawaii to export eight tropical fruits, provided they are treated with a 250-Gy dose to control fruit flies and are free of other pests (APHIS 1997). APHIS has proposed regulations for treatment of imported fruits and vegetables encompassing 11 tephritid species and the mango weevil, *Cryptorhynchus mangiferae* (Fabricius), regardless of host or country of origin (APHIS 2000). Because APHIS has not yet recommended generic phytosanitary doses, efficacy studies are needed for specific quarantine pest species to allow their inclusion in phytosanitary regulations and facilitate movement of irradiated commodities in the continental United States.

The pink hibiscus mealybug, *Maconellicoccus hirsutus* (Green), is a USDA, APHIS quarantine pest that would poses a threat to many agricultural and ornamental plants in portions of the continental United States should it be introduced. *M. hirsutus* has a recorded host range of >300 plants and widespread distribution in many tropical and subtropical regions of the world, including the Caribbean and Pacific (USDA 1998). In Hawaii, *M. hirsutus* is already established and infests tropical fruits for export such as atemoya (*Annona squamosa* L. x *A. cherimola* Mill.), rambutan (*Nepthelium lappaceum* L.), durian (*Durio zibethinus* Murr.), longan (*Dimocarpus longan* (Lour.) Steud.), and sapodilla (*Manilkara zapota* L.) (Follett 1999).

Eggs of *M. hirsutus* are laid in white cottony ovisacs; fecundity varies among host plants, with as many as 700 eggs per ovisac from mealybugs reared on pumpkins (Kairo 1998). *M. hirsutus* develop from egg to

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adult in ≈25 d for males and 26 d for females reared at 24–28°C (Mani 1986) and develop in up to 35 d under different environmental conditions (Hall 1921). Males have four nymphal stages and females have three. Male pupae develop into adults having a pair of wings, whereas females remain wingless. Differences between the sexes are observable by the end of the second instar (Mani 1989). *M. hirsutus* and other mealybugs can be found in cracks, crevices, and other protected areas of a host. This behavior can reduce efficacy of some postharvest treatments and make inspection difficult. For example, insecticidal coatings and hot water treatment have reduced efficacy in treatment against mealybugs infesting limes because of the protection provided by the fruit's calyx (Gould and McGuire 2000). Additionally, *M. hirsutus* ovisacs can provide protection from chemicals and insulation from heat. Irradiation is a promising treatment because overall efficacy against many types of insects on several host plants has been well documented (Hallman 1998).

Research on the tolerance of mealybugs to irradiation is very limited, and no studies have been conducted with *M. hirsutus.* Dohino and Masaki (1995) found that egg and nymph stages of the Comstock mealybug, *Pseudococcus comstocki* (Kuwana), are sterilized at doses ≥200 Gy, whereas adults require between 200 and 400 Gy. While their study of Comstock mealybug likely provides some insight into general tolerance to ionizing radiation, wide variations in susceptibility have been observed among related insects, suggesting a separate evaluation for each species is necessary (Hallman 1998). The objective of this study was to examine the effects of irradiation on different stages of *M. hirsutus* and identify an efficacious dose against this pest.

## Materials and Methods

**Insect Rearing.** A large laboratory colony of *M. hirsutus* was initiated by collecting *M. hirsutus* eggs and crawlers from infested hibiscus plants in Honolulu, HI. The colony was originally reared on Japanese pumpkins, *Cucurbita moschata* (Duchesne), and later was reared on fresh green beans, *Phaseolus vulgaris* (L.) "Hawaiian Wonder," to facilitate irradiation research. Mass rearing was accomplished by maintaining colonies of insects in 360-ml unwaxed paper bowls (12FCS Tapa Hawaii; Sweetheart Paper Products Co., Chelsea, MA) with plastic lids. Fresh beans were added to the bowls every 7–14 d depending on the stage and number of *M. hirsutus* in the colony. Mealybugs were either brushed onto new beans or allowed to move to the fresh bean independently. Bowls containing the colonies were held in a dark growth chamber (Biotronette; Lab-line, Melrose Park, IL) at 22°C. *M. hirsutus* of known age were obtained for testing by hand collecting ovisacs, and as eggs eclosed, crawlers were collected daily on fresh beans. For all tests, crawlers were <6 d old (day after eclosing); nymphs were 12–18 d old; and adults were 26–40 d old.

**Treatment Facility.** All irradiation treatments were conducted at the University of Hawaii at Manoa, HI, Research Irradiator (HRI) in Honolulu, HI. The HRI has a $^{60}$cobalt source of gamma radiation located inside a stainless-steel tank filled with water, which provides shielding of the source. Doses of irradiation were applied by placing samples inside an 18 by 53 by 58 cm treatment chamber and lowering the chamber near the source for a predetermined length of time based on the dose rate. The dose rate during testing ranged from 5.3 to 4.4 Gy/min. Samples to be irradiated were confined to the center of the chamber to optimize the dose uniformity ratio (max/min ≈ 1.3) based on a recent dose mapping study of HRI by Follett and Lower (2000). Gafchromic film dosimeters (ISP Technologies, Wayne, NJ) that had been previously calibrated with alanine dosimeter standards quantified by the National Physical Laboratory, Middlesex, United Kingdom, were used to verify accuracy of the treatments. Twenty-four hours after irradiation, films were read with a spectrophotometer (model 550; Perkin-Elmer, Foster City, CA) at 500-nm absorbance.

**Irradiation of *M. hirsutus.*** All stages of *M. hirsutus* were treated at target doses of 0, 100, 250, 500, or 750 Gy; in addition, eggs were treated at 50 Gy. A total of 12 replicates were treated for each stage and dose over the period of the study with each stage receiving treatment on three separate dates (four replicates of each dose per date). Mean (±SE) numbers of treated *M. hirsutus* were 492.0 (42.3), 343.9 (22.0), 347.9 (23.3), and 242.9 (13.3) for eggs, crawlers, nymphs, and adults, respectively. Crawlers, nymphs, and adults were treated while infesting their bean host inside the same 360-ml paper bowls used for rearing. Each bowl was placed in a plastic bag sealed with masking tape. Because of the space limitation in the center of the chamber, no more than three columns of four bowls were treated at any one time. Eggs in complete ovisacs were placed on filter paper in 100 by 15 mm plastic petri dishes (Fisher, Pittsburgh, PA). Dishes were sealed with parafilm and irradiated. To prevent the possibility of post-treatment ovipositioning, adult females within the ovisacs were killed before treatment by probing with needles. Soon after treatment, crawler, nymph, and adult stages were placed inside new paper bowls with fresh nonirradiated beans. For eggs, the filter paper containing them was lifted from the petri dish and placed inside a paper bowl with a fresh nonirradiated bean for crawlers to settle on. *M. hirsutus* were maintained as described in the insect rearing section for ≤17 wk. To prevent possible cross-contamination of treatments, each paper bowl was isolated atop an inverted 250-ml beaker inside a 25-cm-diameter plastic dish filled with 500 ml of soapy water (1% detergent solution). Eggs were counted and evaluated for hatch and survival of emerged crawlers. Crawlers, nymphs, and adults were each evaluated for survival, fecundity, egg hatch, and progeny survival. Mortality was determined by absence of movement when probed with a needle. Evaluations were conducted once per week until all insects had died or the progeny of a treated *M. hirsutus* had suc-

**Table 1. Mean eclosion (±SE) of irradiated *M. hirsutus* eggs, longevity of individuals, and total progeny production**

| Treatment (Gy) | *N* treated | Percent eclosion | Longevity until 100% mortality (wk) | Total progeny produced |
|---|---|---|---|---|
| 0 | 9,012 | 96.5a (0.6) | 12.8a (0.4) | 37,944 |
| 50 | 7,417 | 45.4b (3.9) | 14.0a (1.1) | 3,928 |
| 100 | 8,296 | 13.7c (4.1) | 8.3b (1.9) | 0 |
| 250 | 7,968 | 8.3c (3.8) | 0.8c (0.6) | 0 |
| 500 | 8,288 | 1.0d (0.5) | 0.3c (0.3) | 0 |
| 750 | 8,100 | 0.6d (0.4) | 0.3c (0.3) | 0 |

Means in a column followed by different letters are significantly different by Tukey's multiple comparison procedure ($P < 0.05$).

**Table 2. Regression analyses relating time (=*X*) to logit-transformed survivorship of *M. hirsutus* after eclosion (=*Y*) as affected by the dosage of irradiation applied to eggs (±SE)**

| Treatment (Gy) | Obs. | *Y*-intercept | Slope | Resid. MS error | $R^2$ |
|---|---|---|---|---|---|
| 0 | 132 | 5.48 (0.30) | −0.751a (0.04) | 2.01 | 74.8 |
| 50 | 128 | −0.09 (0.17) | −0.192b (0.02) | 0.74 | 43.6 |
| 100 | 90 | −0.90 (0.34) | −0.236b (0.04) | 2.27 | 31.3 |
| 250 | — | — | — | — | — |
| 500 | — | — | — | — | — |
| 750 | — | — | — | — | — |

Slopes followed by different letters are significantly different by Tukey's multiple comparison procedure ($P < 0.05$).

cessfully developed and produced a second generation.

A mating study was also conducted to examine the fecundity of irradiated female nymphs. Late-stage nymphs were irradiated and allowed to develop to adults. Four replicates of 15–25 female nymphs per paper bowl were treated at 0 and 100 Gy as described above. Two weeks after treatment, 10–15 nonirradiated males were introduced to each paper bowl containing irradiated females. *M. hirsutus* were evaluated for fecundity, eclosed eggs, and survival of progeny.

**Data Analysis.** Survivorship data of crawlers, nymphs, adults, or of the progeny from eggs after irradiation were logit transformed to allow a linear plotting of the sigmoid curve relationship (Colton 1974). Simple regression analysis was then performed with terms $Y = \ln$ (proportion survival/1 − proportion survival) and $X$ = week. Differences in survivorship among stages and within stages at different doses were determined by multiple comparisons of slope values or elevations using an analog of Tukey's multiple comparison procedure after analysis of covariance (ANCOVA); an analog of the *t*-test was used to determine differences in survival of progeny that hatched from irradiated adults because only the two lower doses produced progeny (Zar 1999). Additionally, longevity after exposure among the different stages was analyzed by Tukey's multiple comparison procedure.

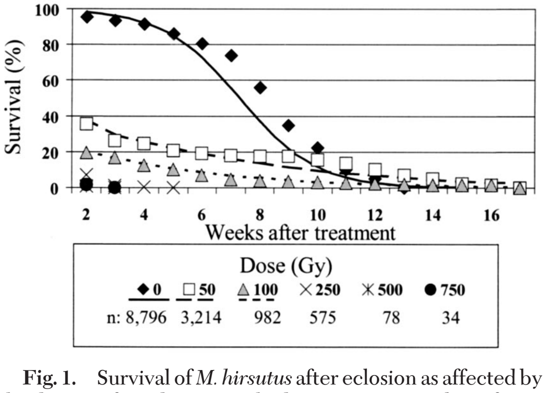


**Fig. 1.** Survival of *M. hirsutus* after eclosion as affected by the dosage of irradiation applied to eggs. $n$ = number of eggs eclosing after treatment. Statistical details for predicted lines are presented in Table 2.

Eclosion of eggs of *M. hirsutus* 2 wk after exposure, expressed as percentages, were arcsine (sqrt p) transformed to normalize data, subjected to analysis of variance (ANOVA), and means were separated by Tukey's multiple comparison procedure. Data from the mating study (percentages of females to oviposit, eggs eclosed, and total number of eggs produced) were subjected to *t*-tests, with the percentage data arcsine transformed before testing. Analyses were performed using Minitab statistical software (Minitab 1997).

## Results

**Dosimetry.** During the study, the maximum:minimum dose ratio was 1.33 for all applied doses. At 250 Gy, the mean absorbed dose was 252 ± 9.3 Gy, with minimum and maximum absorbed doses of 218 and 289 Gy, respectively.

**Eggs.** As treatment doses increased, fewer eggs hatched ($F = 164.4$; df = 5, 66; $P < 0.0005$; Table 1). A target dose of 50 Gy reduced hatching by 50% compared with nonirradiated eggs, whereas 250-Gy treatment further decreased hatching to 8%, and ≤1% of eggs treated at 500 or 750 Gy hatched. Survival of crawlers that emerged was also shortened as doses increased ($F = 45.1$; df = 2, 344; $P < 0.0005$; Fig. 1; Table 2); only those treated at ≤100 Gy lived long enough for regression analysis. Crawlers that emerged from eggs exposed to ≥100 Gy did not reproduce. By 5 wk after treatment, all individuals that emerged from eggs treated with ≥250 Gy were dead. Individuals from one replicate treated at 100 Gy developed into adult females and lived for 17 wk after treatment but did not produce offspring. Only eggs treated at 50 Gy were capable of producing fertile adults; however, their fecundity was ≈75% lower than adults from nonirradiated eggs.

**Crawlers.** Increasing irradiation doses accelerated mortality; however, some crawlers treated with 100 Gy lived longer than untreated individuals ($F = 76.40$; df = 4, 289; $P < 0.0005$; Fig. 2; Table 3). For insects treated with a target dose of 250 Gy, mean longevity until 100% mortality was 6.1 wk, with a replicate persisting until 8 wk after treatment. In the 100-Gy treatment, ≈5% of the exposed crawlers lived for 14 wk, with a mean longevity until 100% mortality among

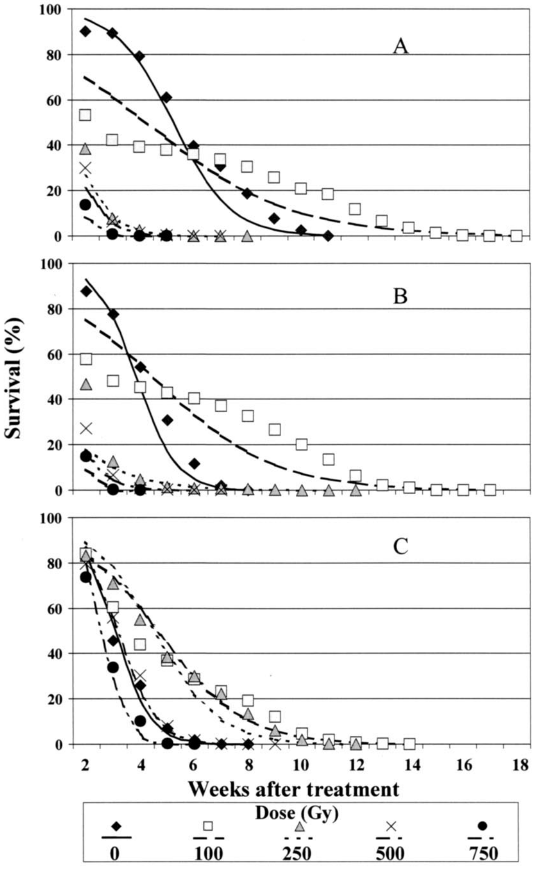


**Fig. 2.** Survival of *M. hirsutus* after exposure as affected by the dosage of irradiation applied to (A) crawlers, (B) nymphs, and (C) adults. Statistical details for predicted lines are presented in Table 3.

replicates of 16.4 wk (18 wk max), whereas all *M. hirsutus* with no irradiation had produced offspring and died by 11 wk after treatment. *M. hirsutus* irradiated as crawlers produced no eggs at the doses tested.

**Nymphs.** Some nymphs treated with 100 Gy had greater survival than untreated individuals, but as doses increased, survival was reduced ($F = 67.2$; df = 4, 395; $P < 0.0005$; Fig. 2; Table 3). While all nonirradiated nymphs developed to adults, reproduced, and died by 8 wk after treatment, 100% mortality among replicates was achieved in 15.3 wk (17 wk max) in the 100-Gy treatment, and in 7.6 wk (12 wk max) at 250 Gy. Unlike crawlers, several treated nymphs that developed to adults laid a few eggs. One of 4,878 in the 250-Gy treatment produced 30 eggs, none of which hatched. Ten of 3,983 in the 100-Gy treatment produced 309 eggs, 5 of which hatched; 3 of the crawlers died soon after emergence, and the other 2 crawlers lived for 1 wk (data not shown). By comparison, 4,138 untreated insects produced 31,330 eggs, of which 96% eclosed.

**Adults.** Two weeks after treatment, 76% of the individuals treated with 750 Gy remained alive, whereas survival among other doses ranged from 82 to 86.7% (data not shown). Despite delayed onset of mortality, the survival rate of adults decreased as doses increased ($F = 99.8$; df = 4, 438; $P < 0.0005$; Fig. 2; Table 3), with slopes ranging from −0.6 at 100 Gy to −2.2 at 750 Gy. Only adults treated with a target dose of 750 Gy had decreased survival compared with untreated adults. While all nonirradiated adults had died by 6.7 wk (9 wk max) after treatment, individuals exposed to 100 and 250 Gy survived up to 13.2 and 10.3 wk (14 and 11 wk max) after treatment, respectively. Adult females produced eggs at all doses evaluated, but the quantity

**Table 3. Regression analyses relating time (=$X$) to logit-transformed survivorship of *M. hirsutus* after exposure (=$Y$) as affected by the dosage of irradiation applied to crawlers, nymphs, or adults (±SE)**

| Stage and dose (Gy) | Obs. | $Y$-intercept | Slope | Resid. MS error | $R^2$ | Longevity until 100% mortality (wk) |
|---|---|---|---|---|---|---|
| Crawler | | | | | | |
| 0 | 74 | 4.96 (0.37) | −0.943b (0.05) | 1.61 | 0.81 | 10.3b (0.3) |
| 100 | 123 | 1.60 (0.20) | −0.376a (0.02) | 0.92 | 0.76 | 16.4a (0.5) |
| 250 | 41 | 1.54 (0.37) | −1.28c (0.08) | 0.73 | 0.86 | 6.1c (0.4) |
| 500 | 37 | 1.48 (0.42) | −1.40cd (0.10) | 0.78 | 0.85 | 5.6c (0.3) |
| 750 | 24 | 1.86 (0.66) | −2.11d (0.21) | 0.82 | 0.83 | 4.0d (0.2) |
| Nymph | | | | | | |
| 0 | 79 | 5.32 (0.25) | −1.38c (0.05) | 0.66 | 0.91 | 7.8b (0.1) |
| 100 | 170 | 2.01 (0.20) | −0.451a (0.02) | 1.26 | 0.74 | 15.3a (0.3) |
| 250 | 79 | −0.22 (0.40) | −0.653b (0.06) | 2.00 | 0.57 | 7.6b (0.7) |
| 500 | 47 | 0.970 (0.56) | −1.33c (0.14) | 1.85 | 0.65 | 4.9c (0.3) |
| 750 | 30 | 3.17 (0.78) | −2.73d (0.27) | 1.20 | 0.79 | 3.4d (0.1) |
| Adult | | | | | | |
| 0 | 68 | 4.84 (0.37) | −1.57c (0.08) | 1.26 | 0.86 | 6.7c (0.3) |
| 100 | 145 | 2.91 (0.18) | −0.628a (0.02) | 0.83 | 0.86 | 13.2a (0.3) |
| 250 | 111 | 3.81 (0.25) | −0.845b (0.04) | 1.13 | 0.83 | 10.3b (0.4) |
| 500 | 75 | 4.52 (0.29) | −1.43c (0.06) | 0.93 | 0.89 | 7.3c (0.3) |
| 750 | 49 | 5.81 (0.59) | −2.24d (0.16) | 1.88 | 0.82 | 5.1d (0.2) |

Means or slopes in a column within developmental stages that have different letters are significantly different by Tukey's multiple comparison procedure ($P < 0.05$).

**Table 4. Mean fecundity (±SE) of irradiated *M. hirsutus* adults, degree of egg hatch, and longevity of individuals**

| Dose (Gy) | No. females | No. eggs | Percent hatch | Longevity until 100% mortality (wk) |
|---|---|---|---|---|
| 0 | 2,480 | 46,200 | 97.2a (0.4) | 15.5a (0.4) |
| 100 | 2,498 | 25,788 | 1.2b (0.3)[a] | 8.2b (1.2)[b] |
| 250 | 3,093 | 13,824 | 0.0 (0.0) | — |
| 500 | 3,254 | 8,820 | 0.0 (0.0) | — |
| 750 | 3,247 | 7,025 | 0.0 (0.0) | — |

Means in a column followed by different letters are significantly different by *t*-test ($P < 0.05$).
[a] $t = 170.8$, df = 22, $P < 0.00005$.
[b] $t = 6.04$, df = 22, $P < 0.00005$.

**Table 5. Regression analyses relating time (=*X*) to logit-transformed survivorship of *M. hirsutus* progeny after eclosion (=*Y*) as affected by the dosage of irradiation applied to mothers prior to ovipositing (±SE)**

| Dose (Gy) | Obs. | *Y*-intercept | Slope | Resid. MS error | $R^2$ |
|---|---|---|---|---|---|
| 0 | 158 | 4.13 (0.27) | −0.507a (0.03) | 1.90 | 0.67 |
| 100 | 62 | 4.27 (0.99) | −0.957b (0.16)[a] | 10.1 | 0.36 |
| 250 | — | — | — | — | — |
| 500 | — | — | — | — | — |
| 750 | — | — | — | — | — |

Slopes in a column followed by different letters are significantly different by a *t*-test analog for comparison of slopes ($P < 0.05$).
[a] $t = 3.95$, df = 216, $P < 0.001$.

oviposited decreased by >85% as doses increased and ranged from 46,200 eggs at 0 Gy to 7,025 eggs at 750 Gy (Table 4). Hatch of the eggs was reduced to 1.2% with irradiation of 100 Gy and was absent in treatments ≥250 Gy. Although progeny from adults exposed to 100 Gy had much lower survival rates (Fig. 3; Table 5), a subsequent generation of 170 individuals was produced in one of the replicates and sterile eggs were oviposited in another. Thus 100 Gy, which controlled all other stages, was not a sufficient dose to control *M. hirsutus* adults. Increased tolerance of adults was found at all the doses. At 250 Gy, crawlers had the greatest rate of mortality ($b = -1.28$) compared with nymphs ($b = -0.653$) and adults ($b = -0.845$; $F = 13.4$; df = 2, 225; $P < 0.0005$; Table 3). Adults were more tolerant than nymphs because their greater initial survival after treatment resulted in a plot with greater elevation than that of the nymphs. At 500- and 750-Gy doses, adults had greater survival initially and in the weeks after treatment ($F = 147.7$; df = 2, 155; $P < 0.0005$ and $F = 118.1$; df = 2, 99; $P < 0.0005$, respectively).

**Mating Study.** Eighty-nine percent of females irradiated at a target dose of 100 Gy as nymphs and mated as adults with nonirradiated males produced 1,447 eggs, of which 12.8% hatched, whereas nontreated females produced 3,437 eggs, of which 97.3% hatched (Table 6). However, the percentage of treated females that oviposited was greater than within the life-stage dose–response tests, where 3,983 treated nymphs had no subsequent mating with nonirradiated males and <0.25% oviposited.

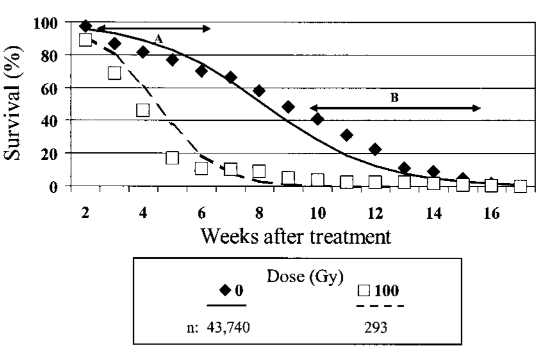


**Fig. 3.** Survival of *M. hirsutus* progeny after eclosion as affected by the dosage of irradiation applied to mothers before ovipositing. (A) Period progeny eclosed from eggs. (B) Period progeny oviposited and the second-generation eclosed from their eggs. Individuals in the 250- to 750-Gy treatments laid only nonviable eggs. Statistical details for predicted lines are presented in Table 5.

## Discussion

In this study, male nymphs were highly susceptible to irradiation. At 100 Gy, no males developed through pupation, whereas many females developed to adults. The increased susceptibility of male nymphs is likely caused by their metamorphosis during prepupal and pupal stages, which requires radical cell division and differentiation similar to that of an embryo (Tilton and Brower 1983). Oviposition by females irradiated at 100 Gy as nymphs occurred when the females were allowed to mate with nonirradiated males. However, when nymphs of both sexes were treated together at 100 Gy and allowed to develop, females developed to adults but failed to oviposit in the absence of males and mating opportunities. Both of the above results support the paper of Ghose (1972) that reported the sexual reproduction of *M. hirsutus.* Although other literature on *M. hirsutus* reproductive biology has reported parthenogenetic reproduction or a combination of sexual and parthenogenetic reproduction (Singh and Ghosh 1970 and Mani 1986, respectively), this study did not observe indications of parthenoge-

**Table 6. Effect of mating adult female *M. hirsutus* (irradiated as nymphs) with nonirradiated males on ovipositing, fecundity, and egg hatch (±SE)**

| Treatment (Gy) | No. of nonirradiated males introduced | No. of females mated | Percent females ovipositing | Total no. eggs | Percent hatch |
|---|---|---|---|---|---|
| 0 | 40 | 60 | 97.6a (1.4) | 3,437a | 97.3a (0.3) |
| 100 | 56 | 85 | 89.6b (1.3)[a] | 1,447b[b] | 12.8b (11.8)[c] |

Values within a column followed by different letters are significantly different using a *t*-test.
[a] $t = 3.14$, df = 6, $P = 0.02$.
[b] $t = 4.35$, df = 6, $P = 0.0048$.
[c] $t = 6.73$, df = 6, $P = 0.0005$.

netic reproduction by *M. hirsutus,* which would have resulted in oviposited eggs by female adults without mating.

Tolerance of irradiation by *M. hirsutus* tended to increase as maturity increased, and adults were the most radiotolerant stage of *M. hirsutus.* Eggs, crawlers, and nymphs were controlled with doses ≥100 Gy, whereas adults produced some viable progeny at 100 Gy. Studies have often found insect radiotolerance increases with age and maturity (Hallman 1998). Tilton and Brower (1983) suggested that cells of more developed stages such as adults are not more resistant than cells of other stages, but that the damage is latent and becomes visible only through increased mitotic activity or proliferation of cells. Because adults were the most radiotolerant of all life stages examined and are capable of infesting commodities, a phytosanitary dose needed for *M. hirsutus* must be sufficient to control adults. The objective of irradiation quarantine treatments against adult insects is usually female sterility (Hallman 1998). A 250-Gy treatment in this study produced complete sterility in 13,824 eggs oviposited by 3,093 treated adults. Although irradiation treatment at a minimum absorbed dose of 250 Gy will effectively disinfest commodities of *M. hirsutus,* the minimum effective dose for quarantine security lies between 100 and 250 Gy. Future research could focus on this range to determine the lowest possible dose needed for phytosanitation. Commodities can receive up to three times the minimum absorbed dose during commercial irradiation treatment, and determining the lowest effective dose may increase the potential number of tolerant commodities (Hallman 1998).

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