ACHIEVEMENTS AND LIMITATIONS OF IONIZING RADIATION FOR STORED-PRODUCT INSECT CONTROL

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ABSTRACT: Extensive tests conducted by many workers throughout the world have proved that doses of gamma irradiation below 50 krad control insects in stored products. Practical methods of using gamma radiation with most products have been developed.

Combinations of infrared or microwave heating with gamma radiation gave excellent results controlling stored-product insects in wheat. Infrared heating of gamma irradiated grain seems more promising because it is easier to handle and costs less.

No resistance developed in any of four species of insects exposed to substerilizing levels of irradiation for 30 generations. Also, two malathion-resistant strains of Indian meal moth, *Plodia interpunctella* (Hubner), showed normal susceptibility to gamma irradiation.

Results with electron irradiation agree closely with those for gamma irradiation. Disinfestation with ionizing radiation is technically feasible, but the method is not used commercially for economic reasons. Some studies indicate that irradiation disinfestation has a favorable cost relationship to fumigation. These studies were based on the assumption that all the product to be handled by a facility will be treated and that the product will be available on a continuous uniform flow basis for treatment. Neither of these assumptions is correct: fumigation of commodities is usually highly selective and is used only when needed, and most products move through collection or shipping points with great fluctuations in volume. Another disadvantage that must be considered is the initial high cost of an irradiator, with most of the cost for several years of disinfestation paid at the beginning of the operation.

INTRODUCTION: The technology of grain and grain product disinfestation by the use of ionizing radiation has been shown to be feasible. The economics of grain irradiation have been studied sufficiently to show that on the basis of per unit volume cost grain irradiation is competitive with fumigation. Yet more than 60 years after the first attempt to control insects in a stored agricultural commodity and despite over 20 years of intensive research [1,2], there has been only limited implementation, and no competitive commercial use is made of the process. Even though both the United States and Canada have approved the use of irradiation for control of insects in wheat, and both export large quantities of wheat, neither uses irradiation for insect control in wheat. With the worldwide concern that pesticide residues in foodstuffs may be hazardous, why is a process that offers a residue-free method of insect control in grain and grain products at a cost that appears competitive not in general use?

To view the entire problem in its proper perspective, one must determine the current status of the technology and the advantages and limitations of radiation disinfestation of stored products. Most of the information that follows is based on the use of gamma radiation obtained from ^{60}Co, but I feel that the conclusions apply to other forms of ionizing radiation as well.

CURRENT STATUS OF STORED-PRODUCT IRRADIATION: When the Agricultural Research Service of the U. S. Department of Agriculture undertook research in the early 1960's to determine the feasibility of controlling stored-product insects in bulk grain and packaged commodities, basic studies of the effects of irradiation and large-scale testing for control application were both anticipated [3]. However, a major problem in disinfestation of stored commodities by any method is the large number of insect species that may be present. Therefore, an effective dose of irradiation must sterilize or kill the most resistant of the species present. At the same time, the lowest effective dose should be chosen because of economic savings.

Thus, one of the major efforts at the Stored-Product Insects Research and Development Laboratory, Savannah, Georgia, has been the determination of the minimum doses of irradiation needed to kill each metamorphic stage or to sterilize the adults of 30 species of insects that infest stored commodities. The tests were performed in a systematic manner so as to permit valid comparisons of sensitivity between species. Lack of time prohibits any extensive analysis of the resulting data. However, differences between species of Coleoptera were substantial: the most resistant beetles were 6 to 7 times more resistant than the most sensitive species; the bruchids appeared the most sensitive, but curculionids were almost equally sensitive. The cucujids and most of the tenebrionids were intermediate in sensitivity; and the anobids, dermestids, and ptinids were increasingly resistant. At present, our data indicate that *Palorus subdepressus* (Wollaston), a tenebrionid, may be the most resistant to irradiation of all stored-product Coleoptera; both males and females have reproduced after exposure to 30 krad.

In general, the females of the species were more sensitive to sterilizing effects of irradiation than were the males of the same species. However, in some situations, a dose high enough to sterilize the females could be selected, even if viable males persisted. Also, the dose required to produce 100% mortality in the several metamorphic stages depended almost entirely on age at the time of treatment and this extreme variability greatly limited the usefulness of mortality as a means of establishing the relative sensitivity of species.

The Lepidoptera as a group were more resistant to irradiation than were the Coleoptera, especially if the dose for sterilization was the basis for comparison. For example, even 100 krad may not sterilize some moth species, but fertility and fecundity were low after this dose. *Cadra cautella* (Walker) appeared to be somewhat more sensitive than *Sitotroga cerealella* (Olivier) or *Plodia interpunctella* (Hubner), but other phycitids had sensitivities similar to that of *Cadra*. The grain mite, *Acarus siro* L., was intermediate in sensitivity between the Coleoptera and the Lepidoptera.

The dose of irradiation selected for control of stored-product insects can therefore be much lower if only the more sensitive beetle species are present; it must be much higher if some of the most resistant beetles, mites, or moths are present. However, when commodities are infested with many species, a dose of 50 krad will control even the most resistant beetle species and the immature stages of moths. Some adult moths might remain fertile, but the few progeny would be sterile because of inherited genetic damage.

Description of bulk-grain irradiator - The bulk-grain and packaged-product irradiator built by the U. S. Atomic Energy Commission and made available to the U. S. Department of Agriculture is located at the Stored-Product Insects Research and Development Laboratory at Savannah, Georgia. The irradiator is composed of three essentially separate systems: (1) A ^{60}Co source and source-handling system, (2) a grain-handling and treatment system, and (3) a packaged-product irradiation system.

The ^{60}Co source and source-handling system (source array) is composed of 13 ^{60}Co assemblies that had an original total strength of 26,565 Ci. Each assembly is 1.5 m long and contains lengths of doubly encapsulated ^{60}Co bars, but the specific activity of each assembly varies: the highest activity occurs around the periphery of the source array and the lowest activity in the center. This configuration insures fairly uniform radiation over the entire area of the source array. When the irradiator is not in use, the source array is stored in a steel-jacketed lead cask located in the concrete cell wall.

The grain-handling and treatment system is used for bulk grain. The grain flows slowly into the concrete cell, through the source plane in the spaces between the source rod tubes, surrounds the source that minimizes the loss of energy, and flows continuously past the source tubes. The rate of flow, and thus the dose, is controlled by a metering valve located below the bin and can be varied from 1 to 5 t per h. At the outlet, the grain enters an airstream that moves it through a tube extending through the cell wall to railroad cars, trucks, or adjacent storage bins.

The packaged-product irradiation system is a separate system except for the source. The source array is moved into a position that allows treatment of packaged products moving through the cell on aluminum carriers, and the dose is regulated by adjusting an automatic timer that controls the speed at which the carriers move. The loading of the carrier and the dose thus determine the amount of packaged material that can be processed by the package irradiator, but the average is about 1 t per h. A much more complete description of the irradiator with a discussion of desirable modifications has been published [4].

Bulk-grain irradiation - In the 1960's, the technology necessary to build bulk-grain irradiators capable of handling large quantities of grain was available, but the doses necessary to control insects in a commercial-scale irradiator had not been determined. Therefore, the bulk-grain irradiator was used to test two doses (a low dose that averaged 27.4 krad and a high dose that averaged 41.2 krad) for control of insects in nine 13.6-t lots of wheat that was heavily infested with rice weevils, *Sitophilus oryzae* (L.); lesser grain borers, *Rhyzopertha dominica* (F.); and flat grain beetles, *Cryptolestes spp*. (Smaller numbers of other species were present.)

Since much higher levels of irradiation than those used are required to produce immediate mortality in adult insects, the post-treatment samples were expected to contain live adults. For this reason, the observed scarcity of live insects at the time of the post-treatment counts was attributed to mechanical killing rather than to irradiation. However, in the control bins the populations of immature insects returned to pretreatment levels within 6 months after treatment. The populations in bins treated with either 27 or 41 krad did not show any significant recovery.

The effectiveness of the treatments was best demonstrated by the total lack of emergence of rice weevils and lesser grain borers in samples taken immediately after treatment. However, laboratory tests with these and other species had shown that both levels of irradiation should have prevented the insect populations from surviving. Thus the presence of live, fertile insects in treated grain drawn at 1, 3, and 6 months and the lack of insects in incubated samples collected immediately after treatment suggested that reinfestation of the grain by untreated insects had probably occurred.

Obviously, insects in bulk grain need not be killed immediately. Control can be obtained with lower, more economical doses if the resident populations are sterilized rather than killed. But when that is the case, these sterile insects continue to feed and further damage the commodity. We therefore examined the feeding of insects treated with a sterilizing dose. The test showed that wheat consumption by irradiated *Sitophilus oryzae* and *Rhyzopertha dominica* during a 5-week period was reduced 90 and 97%, respectively. Also, Rogers and Hilchey [5] reported that *Tribolium castaneum* (Herbst) treated with high-speed electrons fed at a reduced rate. Cornwell [6] found that *Sitophilus granarius* (L.) treated with 16 krad of gamma irradiation consumed only half as much food as did untreated adults. Watters and MacQueen [7] found that four stored-product insect species could still damage wheat 14 weeks after irradiation with 6.25 krad but that the amount of damage was greatly reduced. This cessation of feeding after exposure to these smaller doses of gamma irradiation appeared to result primarily from damage to the midgut of irradiated insects. For example, the levels required to sterilize both *Tenebrio molitor* (L.) and *Plodia interpunctella* produced considerable damage in the midgut [3].

Nevertheless, the presence of live, but sterile insects can only be considered a disadvantage. The possibility of supplemental treatments to increase the initial mortality were therefore investigated. Such treatments might also reduce the cost of disinfestation by irradiation and make the process more competitive with current control measures.

Since treatments with infrared (i.r.) and microwave (m.v.) irradiation were most likely to provide stresses that would be complementary to that produced by gamma irradiation, m.v. and i.r. irradiation were tried both before and after gamma irradiation of *Sitotroga cerealella*, *Rhyzopertha dominica*, and *Sitophilus oryzae* in wheat.

Each type of treatment alone was found to produce some mortality. The expected percentage mortality for the combined treatments was therefore calculated by using these mortalities. However, actual mortality for the combinations was always greater than that calculated, an average of 16% and 11% for the i.r. and m.v. treatments, respectively; indeed, differences of as much as 24% were obtained. Also, the results showed that the sequence of the treatments did not alter the percentage of mortality.

The dose of gamma irradiation can then be greatly reduced without sacrificing a high level of mortality if a supplemental treatment is used, and most such supplemental treatments would greatly reduce the cost of the irradiation. For example, if natural gas-fired i.r. heaters are used, the cost of the combined treatment might be less than the cost of gamma irradiation alone. Also, the quantity of grain treated by the irradiator would be increased proportionately.

Other tests were made to determine whether irradiation is compatible with currently used chemical methods of control. Since malathion is commonly used to protect grain from insects, tests were made to determine whether gamma irradiation adversely affected the residues of malathion. Neither the toxicity nor the degradation of malathion on wheat or on kraft paper was affected by doses of as much as 4,300,000 rad. However, irradiated *Tribolium castaneum* were slightly more susceptible to malathion after they were treated with a dose of 10 krad or more. Also, the combination of treatments produced more and earlier mortality than did irradiation alone.

In addition, fumigation with methyl bromide and treatment with gamma irradiation were found to be compatible if the interval between treatments was short and complementary if the interval was longer. For example, mortality from the combination was greater than from either treatment alone if 1 week or more was left between treatments. Thus, disinfestation by irradiation also appears compatible with currently used methods of chemical control and might actually be increased by the combination.

Irradiation of packaged commodities - Small-scale tests with wheat, rice, and corn confirmed that insect populations are eliminated by doses of 45 krad gamma irradiation though some insect populations occasionally persisted after treatment with 25 krad. Also, we found that the commodity (i.e., the diet) altered the effects of irradiation on *Sitophilus oryzae* though the differences were minor. Shipp [8] had similar results with *Sitophilus granarius* and *Tribolium confusum* Jacquelin du Val. He too concluded that the differences were real but that the effectiveness of the disinfestation was unlikely to be affected.

Other tests were made with three varieties of inshell and shelled peanuts (groundnuts), three kinds of tree nuts, and four kinds of dried fruits infested with known numbers of laboratory-reared insects [3]. The samples were treated with 10, 20, or 40 krad gamma irradiation and inspected periodically for feeding damage and numbers of live insects. *Tribolium castaneum* and *Oryzaephilus surinamensis* (L.) were controlled in all commodities by a dose of 20 krad but not by 10 krad; and eggs, young larvae, and adults of *Plodia interpunctella* were controlled by 40 krad but not 20 krad. Thus a practical level of insect control in bulk dried fruit and nuts could probably be achieved by treatment with 25 krad, but in packaged products 40 krad would probably be needed to prevent all signs of feeding damage.

The packaged-product irradiation facility was also used to treat infested wheat flour and infested cornmeal (maize). Each commodity was treated in 5-gallon (18.9-liter) metal cans containing 14.5 kg of commodity and also in multiwall kraft paper bags containing either 100 (45.3 kg.) or 50 pounds (22.7 kg) of flour or meal. Doses ranged from about 15 to 45 krad. In some of the tests, infestations were introduced before irradiation. A total of five tests was made with wheat flour and three with cornmeal. The insect species tested included *Tribolium castaneum*, *Plodia interpunctella*, *Cadra cautella*, *Lasioderma serricorne* (F.), and *Rhyzopertha dominica*.

Normally the only stages of insects likely to be present in freshly milled farinaceous material are eggs and very young larvae. Our tests showed that these stages were killed at the doses used. However, commodities that contained mature larvae, pupae, and adults usually contained live insects at 1 month after treatment, and in one test, they were present at 2 months after treatment. Live insects were not present 3 months after irradiation [9,10].

Safety of irradiated commodities - After extensive tests had demonstrated the safety for consumption of irradiated wheat and wheat flour, ionizing radiation in the range of 20-50 krad was approved as an insect control method for these commodities in the United States [4]. However, the extensive, and therefore expensive, tests needed before this method of treatment is approved for other stored products have not been made, serious limitation to the immediate use of irradiation.

Also, no deleterious effects of large doses of gamma irradiation have been determined on the fertility, fecundity, or survival of insects reared for many generations on treated wheat, wheat flour, raisins, or tree nuts. Indeed, most earlier work on this aspect of irradiation treatment is in general agreement in this regard.

Insect resistance - The development of resistance to insecticides by species of stored-product insect pests is an increasingly serious problem. Also, cross resistance in resistant populations can make new insecticides obsolete almost as soon as they are introduced. Thus disinfestation by irradiation has a large advantage over currently used chemical control because insecticide resistance is unrelated to radiosensitivity. Disinfestation of grain or other stored commodities by irradiation might thus be economical in areas where there are insecticide-resistant insect populations.

As mentioned earlier, insects can be sterilized with doses of irradiation that are lower than those needed to produce quick mortality, and these lower doses make disinfestation by irradiation less costly. However, the use of these lower doses might mean that a small proportion of the insects are exposed to a substerilizing dosage. Thus it was important to know whether substerilizing doses applied to several successive generations could cause insects to develop irradiation-resistant strains.

Few workers have studied the possibility of inducing resistance to irradiation in insects. However, Cornwell and Morris [11] found no increase in the resistance in F_1 and F_2 *Sitophilus granarius* from an irradiated parent population. Indeed, the F_2 generation appeared to be slightly more susceptible than a strain with no past history of irradiation treatment. Also, extensive tests have been made at the Savannah laboratory with four diverse species of stored-product insects that were irradiated for as many as 30 successive generations with substerilizing doses. These strains were analyzed periodically for changes in longevity, fertility, fecundity, and resistance to acute exposures. No evidence of any pronounced increase in resistance to irradiation was found in any species, even after the prolonged periods of selection [3]. However, the population "fitness" of the selected strains tended to be reduced as indicated by higher percentages of sterility, lower fecundities, and decreased lifespans. The possibility of accidental exposure of some insect to substerilizing doses during commercial disinfestation thus does not appear apt to cause the development of irradiation-resistant populations.

CONCLUSIONS: To restate the question raised at the beginning of this talk--Why is a residue-free insect control method that has so much to offer not in general use? The reasons appear to be wholly economic. Although some engineering studies indicate that on a per ton basis irradiation disinfestation has a favorable cost relationship to fumigation, these studies were based on the assumptions that all the product to be handled by a facility will be treated and that the product will be continuously and uniformly available for treatment. Neither of these assumptions is correct. Fumigation of commodities is usually done only when necessary, and the balance of most products that move through collection or shipping points fluctuate greatly. Another disadvantage is the initial, high cost of the irradiator, which means that most of the costs for several years of disinfestation must be paid at the beginning of the operation.

At the time the research program began at Savannah in the early 1960's, industry felt that a serious problem existed in relation to infestation of wheat flour. Therefore, an integral part of the research program was aimed at developing radiation techniques for wheat flour; however, by the time the irradiation facility was completed and pertinent tests had been conducted, the problem had nearly ceased to exist. The construction of new and better facilities, utilization of effective pesticides, increased sanitation, improved screening, and other physical controls have all helped to alleviate the problem.

An advanced technology of stored-product disinfestation by irradiation exists and will be used if needed and if the process offers an economic advantage.

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