IRRADIATION DISINFESTATION OF DRIED FRUITS AND NUTS

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and

Economic Research Service

Edited by

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PREFACE

This is a collection of research papers. They are the result of a research project which examined the technical and economic feasibility of irradiation as a means of disinfesting dried fruits and nuts of postharvest insects. The project was overseen by representatives from the United States Department of Agriculture, the United States Department of Energy, the University of California, CH2M HILL, and the dried fruit and nut industry. The actual research was undertaken by the Agricultural Research Service and the Economic Research Service of the United States Department of Agriculture, the University of California, Riverside, and CH2M HILL. The project commenced in the Spring of 1984 and was finished in the Spring of 1986. The papers themselves represent the work of their authors and each paper is itself a complete entity; little effort was made to join them together. Therefore, there are a few redundancies. Much of the success of this project can be attributed to the joint efforts of the private sector. Throughout the project, quarterly meetings of the researchers and industry representatives were held to report and critique the research progress. This provided a stimulating atmosphere and one that permitted no researcher to lag far behind.

GLOSSARY OF TERMS USED IN FOOD IRRADIATION

Accelerator	In food irradiation, a device for producing beams of high-energy electrons.
Curie (Ci)	A basic unit of radioactivity. One curie equals that quantity of any radioactive nuclide having 37 billion disintegrations of atomic nuclei in one second.
Dose	The amount of ionizing radiation absorbed in a specified quantity of material. The units commonly used to measure absorbed dose are the "gray" or the "rad". One gray equals 100 rads.
Dosimetry	The process or technique of measuring dose.
Electron	A negatively charged particle that is a constituent of all atoms.
Electron beam	A narrow stream or a bunched group of electrons moving in the same direction with approximately the same speed.
Electron volt (eV)	A unit of energy. One electron volt is equivalent to the amount of kinetic energy gained by an electron accelerated through an electric potential difference of one volt. One million electron volts (MeV) is equal to 1.6×10^{-13} joules.
Gamma ray	High-frequency, short-wavelength electromagnetic radiation produced when an unstable atomic nucleus spontaneously disintegrates and releases energy to gain stability. The term is sometimes loosely used to include high-energy X-rays.
Gray (Gy)	International System (SI) unit for absorbed dose. One gray is equal to the energy imparted by ionizing radiation to a mass of material corresponding to one joule per kilogram.
Half-life	The average time required for the decay of one-half the atoms of a quantity of radioactive substance.
Induced radioactivity	Radioactivity resulting from certain nuclear radioactivity reactions in which exposure to radiation results in the production of unstable nuclei, which through spontaneous disintegrations give off radiation.

Ion	An atom or molecule which has a net electric charge due to the loss or gain of one or more electrons. The term also refers to isolated electrons or other charged subatomic particles.
Ionization	Any process by which a neutral atom or molecule loses or gains electrons, thereby acquiring a net charge and becoming an ion.
Irradiation	The exposure of material to ionizing radiation.
Isotope	Atoms of the same chemical element having the same atomic number but different atomic weights, or those with nuclei having the same number of protons but different numbers of neutrons.
Radiation	Radiant energy, or the emission and propagation of waves transmitting energy through space or some medium. In food irradiation, the term is limited to gamma rays, X-rays, and electron beams.
Rad	An outdated term which is an acronym for radiation absorbed dose. One rad is equal to 0.01 joules per kilogram, or 0.01 gray.
Radionuclide	An unstable isotope that decays or disintegrates spontaneously, emitting radiation.
X-ray	High-frequency, short-wavelength electromagnetic radiation produced when electrons are accelerated to a high velocity and then impinged on a suitable target material.

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CONCLUSIONS

The purpose of the project was to provide an objective evaluation of the technical and economic potential for using radiation as a process for insect disinfestation of several dried fruits and nuts. It was the general consensus at the beginning of the project that these commodities, being of relatively high value, and not having as critical a time period for treatment as is the case with fresh fruits and vegetables, provided a promising situation for use of radiation technology. To this end the project incorporated studies on insecticidal efficacy, logistics, engineering, economics, and organoleptic studies. The studies were completed in April, 1986 soon after the FDA approved a treatment of 1 kGy as safe for use on foods for human consumption.

Efficacy Studies

The general conclusions are that irradiation will disinfest almonds, walnuts, raisins, and prunes of codling moth, Indianmeal moth, navel orangeworm and driedfruit beetle at a dose of 300 Gy or less, or about one-third the present FDA recommended limit on dose. From an efficacy standpoint, radiation-exposure will eventually kill larvae even though their longevity may be longer as compared to a fumigation treatment. Although average longevity may significantly increase as a result of relatively low doses, feeding is reduced to a great extent. There is no doubt the treatment will prevent reproduction. The extended life span of treated larvae may allow treated commodities to reach the consumer with live insects present.

Possible interactions between controlled atmosphere and radiation were not explored. If the interaction is positive then the severity of either one or both of these treatments could be reduced. Finally, larger scale confirmatory type tests need to be conducted to confirm these studies. An additional potential benefit is irradiation may prove useful as a quarantine treatment for codling moth.

Organoleptic Studies

In addition to tests for efficacy of radiation for insect disinfestation of dried fruit and tree nuts, it was necessary to evaluate the products for potential damage to quality. This work was done for five commodities: walnuts, almonds, pistachios, raisins and prunes. The commodities were irradiated with gamma rays from cesium-137 at different levels from 150 Gy to 900 Gy (15 to 90 krad), and then stored at 90°F for periods up to 90 days.

Irradiated samples were removed periodically from storage and compared by a trained taste panel to control samples maintained under the same conditions. No differences were noted immediately after irradiation. Stored samples irradiated at the highest levels did show variation from controls, but with the exception of walnuts irradiated at 900 Gy, there were no consistent significant differences in flavor. With the exception of the walnuts at highest irradiation levels, all commodities remained acceptable through storage.

It is recommended, if irradiation is used as a means of disinfestation, that it be limited to an average dose of 300-450 Gy. Significant flavor damage seems unlikely at this level, which was shown to be effective for disinfestation.

Economic Engineering Feasibility of Dried Fruits and Nuts

The purpose of this study was to evaluate the economic engineering feasibility of irradiation as a postharvest disinfestation treatment for California almonds, walnuts, raisins and prunes. The study explored ways in which irradiation may be employed for each industry insect control need. The per-ton cost of irradiation was in each case compared with the costs of competing chemical (fumigation, fogging) and physical (modified atmospheres, refrigeration) treatments. Specifically, the study considered practical applications of exothermically-generated low oxygen atmosphere (GLOA), refrigeration, and gamma radiation from cobalt-60 and cesium-137 sources. Relative costs of electron beam (E-beam) and X-ray processing were also investigated. A systems approach was used to evaluate the feasibility of each technology with reference to its place(s) in the processor's complete insect control program. Costs of the alternative insect control programs were compared for hypothetical processing plants, whose insect control needs, product handling schedules, and existing physical plant were constructed to represent typical large and small processors of each of the four commodities.

The study results indicate one or more technically feasible application points for irradiation in the processing of each commodity considered. The most promising points are the disinfestation of newly harvested almonds and walnuts as they are received at large processing plants, and the pre-shipment disinfestation of finished goods at the largest plants. The overriding problem with irradiation is the high fixed cost (greater than $500,000 per year) of owning and operating even the smallest commercial irradiation facilities. Irradiator use corresponding to existing processor insect control needs is, in each case, at too low a volume and/or too seasonal to make current-technology irradiation costs competitive with alternative physical controls such as modified atmospheres. Even if the most efficient size irradiator is operated at full capacity, the cost of irradiation far exceeds the cost of current chemical treatments.

The study indicates that modified atmospheres can provide a basis for postharvest insect control programs which eliminate some or all chemical treatments. Modified atmospheres appear well-suited to the protection of susceptible commodities (chiefly raisins and prunes) from insect infestation and damage during long-term storage. The main disadvantage of modified atmosphere treatments is in the longer treatment time which may be required, particularly at lower temperatures, with the resultant costs to the processor of product hold-up and of building extra facilities to accommodate product which must now occupy the available fumigation space longer. New methods of applying modified atmospheres (elevated temperature treatment, modified atmosphere packaging, in-transit treatment) may be developed which will reduce the product holdup and resultant costs associated with modified atmosphere treatments considered in this report. Unless and until such methods are developed, it will not be possible to entirely eliminate chemical treatments without incurring major costs, which may greatly increase the cost of insect control to the dried fruit and nut processing industries.

INTRODUCTION TO AN IRRADIATION PROJECT

P. V. Vail, J. L. Baritelle and A. A. Rhodes

Background of the Project

The dried fruit and nut industry is large, complex and has many facets. In the United States, the industry is principally located in California. In fact California produces virtually all of the raisin, walnut, almond, and prune crops in the United States, and it also produces a good share of the world's supply of these crops. In 1982 the farm value of these four commodities was nearly a billion dollars. In that same year they represented 825,500 tons of agricultural product (U.S. Department of Agriculture, 1984). These industries employ thousands of individuals not only on the farm but also in the processing plants where they are stored, processed, packaged, and shipped to market. Compared with other types of dried agricultural products, such as grains, dried fruits and nuts are a relatively high value crop. These crops are harvested from August through November with receiving stations handling 26,000 tons per day at the peak of the season. The product is received, processed, and stored in diverse areas throughout the state. Of great concern to the industry is the infestation of the product with several different species of insects. The products may be infested at any time before eventual use by the consumer. In order to prevent damage from these insects and to ensure their protection through the processing and storage channels, the commodities are usually fumigated at least once after harvest with either methyl bromide or phosphine. Depending on the commodity and the type of insect problem, the commodities may be fumigated several times after they are received and while in storage.

Presently methyl bromide and phosphine are the preferred fumigants used by the dried fruit and nut industry (U.S. Department of Agriculture, 1982). These fumigants serve three functions: 1) to control insect populations, 2) to prevent feeding damage, and 3) to meet sanitary requirements by reducing or eliminating live insects. When used properly, these fumigants provide a rapid and complete kill of insects in infested commodities. They are almost universally accepted by the industry because they are easy to use with a high degree of efficacy.

Mortality from methyl bromide fumigation under proper conditions usually occurs within 24 hours. Ordinarily phosphine takes somewhat longer depending on the temperature. Under ideal conditions a phosphine fumigation will take 48 hours, but fumigation times may increase up to 96 hours when temperatures are reduced to 60°F. Large quantities of commodities, up to 4,000 to 5,000 tons, are typically fumigated at one time. Compared with other presently available technologies, these chemical fumigants are inexpensive and of themselves do not require a great deal of capital expenditure. Because of their dependence on these fumigants, the dried fruit and nut industry and the U.S. Department of Agriculture (USDA) have sought to investigate possible alternative treatments. Although never used or registered for dried fruits and nuts, the sudden and recent restrictions placed on the use of ethylene dibromide and its lack of availability to many industries has brought even greater awareness of possible problems to the dried fruit and nut industries. Also, restrictions and tolerances concerning residues has prompted the industry to investigate alternatives. This is particularly the case with methyl bromide whose tolerances could be reduced even further. Such reductions in tolerances could lower domestic and export market shipments. In addition, if separate and low tolerances for organic bromide are imposed, the time required before consumption could be increased significantly. Such things could make the continued use of methyl bromide either impossible or prohibitively expensive. Should this happen, drastic changes in the processing, shipping, and marketing of dried fruits and nuts would have to take place.

History of the Project

Representatives from the USDA, the Department of Energy (DOE) and dried fruit and nut industries, held meetings in 1983 concerning a research project on the use of irradiation as a disinfestation procedure for dried fruits and nuts. An outgrowth of those meetings was a cooperative research project between DOE and USDA which commenced in April 1984. The project was funded for two years.

Objectives of the Study

The overall goal of the study was to investigate the technical and economic potential of using radiation treatment (Moy, 1985; Switzer, 1985) as a substitute for fumigation for the dried fruit and nut industry. It was envisioned that radiation treatment could be used alone or in combination with other alternative treatments. The study was also to provide a comparison of various alternative treatments with irradiation (Soderstrom, 1983). With this information the industries would then be able to make a preliminary and objective appraisal of the feasibility and potential application of irradiation as a commodity treatment to their particular industry. All studies were to be conducted below the FDA guidelines (Young, 1986) of 1,000 Gy (100 krads). In order to achieve these objectives, a number of tasks were developed. These were:

(1) To determine the efficacy of radiation against four important postharvest pests of almonds, raisins, walnuts, and prunes.

(2) To determine postirradiation feeding damage to the commodities under study.

(3) To determine the effects of irradiation on the taste and quality characteristics of the commodities.

(4) To determine with processing plant engineers how the process of irradiation could fit into different types of plant operations.

(5) To examine and compare cost/volume relationships involved in the irradiation process.

(6) To conduct economic, logistical, and engineering studies comparing current industry practices with irradiation.

(7) To determine the cost effectiveness of irradiation when combined with other insect control technologies such as modified atmospheres.

(8) To provide a final report to industry and DOE at the conclusion of the study that would enable them to assess the commercial feasibility of irradiation as a means of disinfesting dried fruits and nuts of insects.

Methodology and Responsibilities

The initial commodities selected for investigation were almonds, raisins, and walnuts. It was felt that these were representative of the industry's products. However, later in the project prunes were also selected to be included in the economic analysis and the organoleptic studies. Also, at a later date, pistachios were included in the organoleptic studies. The research group felt that these five products adequately represented the physical and chemical characteristics of most dried fruits and nuts. The insects investigated were the codling moth (*Cydia pomonella*), navel orangeworm (*Ameylois transitella*), Indianmeal moth (*Plodia interpunctella*), and one species of driedfruit beetle (*Carpophilus hemipterus*). Radiation doses of 0, 150, 300, 600, and 900 Gy and other doses, as required, were to be tested. While there is extensive data available on irradiation biology of all but the driedfruit beetle, little information is available with respect to the insects on or in these specific commodities.

Taste panel data were collected in order to evaluate the effect of radiation on the products tests. Quality was examined immediately after exposure to the irradiation process and after accelerated conditions equivalent to one year's storage.

The economic studies were conducted to determine the cost effectiveness of radiation treatments compared to current fumigation practices and alternative technologies such as modified atmospheres and/or refrigeration. Two scenarios were considered: 1) the use of irradiation while fumigants were still available; and 2) the use of irradiation with fumigants no longer available. In order to adequately reflect the size of industries, an emphasis was placed on both large and small processing plants. Factors such as plant size, site location, processing plant integration, capital costs and operating costs, as well as processing rates were to be considered. Consideration was given to combining irradiation with other control methods. Multiple treatments, although currently not permitted, were to be examined.

The specific areas of research and responsibilities assigned are listed in Table 1 and were as follows:

DOE. The cesium-137 source strengths or loadings required for irradiation of various volumes of dried fruit and nuts were determined by DOE. All irradiation of the commodities was conducted by DOE contract laboratories in Albuquerque, New Mexico, or Richland, Washington. Dosimetry for each commodity was supplied by DOE or one of its contract laboratories.

CH2M HILL. They provided the expertise on plant engineering and irradiation design criterion. This information was used by the USDA-ERS staff to conduct the economic studies.

Dried Fruit and Nut Industry Groups. The Walnut Marketing Board, the Almond Board of California, the California Raisin Advisory Board, and the California Prune Board played a significant and important role in the project. The industries supplied commodities at no cost to the project and paid for the transportation to various radiation and taste panel facilities. These industries also provided important information and economic data concerning plant size, volumes of shippers and any other requested data necessary to complete the economic and engineering studies. Where appropriate, consumer acceptance studies (Anonymous, 1986) would be conducted by the respective industries.

Oregon State University. Taste panel and other organoleptic evaluations of the treated commodities were conducted at Oregon State University in cooperation with the USDA-ARS Western Regional Research Center of Albany, California. ARS contracted with Oregon State University for the work to be completed. Quality changes were noted and monitored.

USDA-ARS. The Horticultural Crops Research Laboratory, Fresno, California served as the primary contractor for the study. They were also responsible for the efficacy studies for all but the codling moth which was the concurrent responsibility of the Yakima Agricultural Research Laboratory of Yakima, Washington. The Western Regional Research Center, Albany, California was responsible for the taste panel and organoleptic studies.

USDA-ERS. The Economic Research Service provided the economic analysis for the project in cooperation with the University of California, Riverside.

University of California, Riverside. Through cooperative agreements, the Department of Entomology supplied the post-doctoral fellow for the efficacy studies and the Department of Economics supplied the post-doctorate fellow for the economic studies.

Budget and Contributions. The financial contributors are listed in Table 2. The Department of Energy provided the majority of the funding and support for the project. The USDA was also a major contributor. The industry groups, in terms of the commodities and freight costs, also made an important contribution. Also, not accounted for in Table 2 is the amount of time contributed by many individuals from both the public and private sector which was very valuable to the project.

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Table 1. List of cooperators and tasks of irradiation project.

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1. United States Department of Agriculture

   Agricultural Research Service

   a. Horticultural Crops Research Laboratory, Fresno, California — primary contractor; conduct efficacy studies against Indianmeal moth, navel orangeworm and driedfruit beetles infesting walnuts, raisins and almonds.

   b. Western Regional Reseach Center, Albany, California — direct organoleptic and taste panel studies.

   c. Yakima Agricultural Research Laboratory, Yakima, Washington — conduct efficacy studies against codling moth infesting walnuts.

   Economic Research Service, Riverside, California — conduct economic feasibility studies.

2. CH2M HILL, Albuquerque, New Mexico and Sacramento, California — provide expertise for engineering and input to the economic study.

3. Sandia National Laboratories, Albuquerque, New Mexico — provide radiation expertise and facilities.

4. Oregon State University, Corvallis, Oregon — conduct taste panel tests through a cooperative agreement with ARS.

5. University of California, Riverside, California

   a. Department of Entomology — supply post-doctoral fellow for efficacy studies.

   b. Department of Economics — supply post-doctoral fellow for economic studies.

6. Dried fruit and nut industry groups — provide experise, commodites and their shipping costs.

   a. Walnut Marketing Board

   b. Almond Board of California

   c. California Raisin Advisory Board

   d. California Prune Board

7. United States Department of Energy, Albuquerque, New Mexico — determine cesium-137 source strengths or loadings and dosimetry for each commodity.

Table 2. Source of funds for irradiation project.

U.S. Department of Energy

U.S. Department of Agriculture

- Agricultural Research Service
  - Fresno, California
  - Albany, California
  - Yakima, Washingto

- Economic Research Service
  - Riverside, California

Industry Contributions (California)

- Walnut Marketing Board
- Almond Board of California
- California Raisin Advisory Board
- California Prune Board

OVERVIEW OF FOOD IRRADIATION TECHNOLOGY

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Radiation Processing/General

Ionizing radiation sources, or those radiation sources which emit gamma rays, X-rays, or high-energy electrons, have become a valuable tool in many industrial processes. Markovic (1985) estimates that more than 130 industrial gamma irradiators are currently operating in 41 countries, and that the total number of electron beam machines is approaching 400 worldwide.

Radiation processing is used to help produce products such as automobile tires, computer parts, telephone cables, plastics and films for packaging, and to sterilize disposable medical products. Table 1 identifies those radiation processing applications which have been in industrial operation for many years around the world (established technologies); those that have reached the pilot or semi-industrial levels, but have not yet become fully commercialized (emerging technologies); and those that are in the research development stage (development technologies). Food irradiation is an emerging technology that utilizes ionizing radiation to help reduce food losses after harvest.

Commercialization of Food Irradiation

Food irradiation is not a miracle technique or a panacea. However, when certain feasibility conditions are met, food irradiation may be used to supplement, or act as a substitute for, conventional food preservation treatments. A list of commercial food irradiation facilities, either completed, under construction, or planned, is shown in Table 2.

In recent years, there has been renewed interested in food irradiation in the United States. Part of the motivation for this recent flurry of interest has been the 1984 ban of ethylene dibromide (EDB) and potential restrictions on other chemicals used as fumigants for disinfestation of spices, grains, nuts, packaging materials, and fruits. Additional motivations for the renewed interest include: (1) the potential for replacing or reducing the amounts of preservatives used, such as nitrite, (2) the reduction of food spoilage, particularly in developing countries, (3) the ability to control trichinosis from pork, (4) the reduction in enteric pathogenic organisms such as _Salmonellae_ and _Campylobacter_ in poultry, (5) decreased rehydration times in dried vegetables, (6) increased juice extraction from fruits, (7) delay of ripening in some tropical fruits such as bananas and papayas, (8) delay of senescence in some fruits, and (9) increased shelf life.

Safety Issues

Research

The first study of irradiated food was conducted at the request of the U.S. Army by the Massachusetts Institute of Technology in the early 1940s. Since that time, numerous studies by the United States, India, Japan, the Netherlands, and over 20 other countries, have been conducted to prove the wholesomeness of food treated by ionizing energy. After decades of studies and scientific peer reviews using the most modern methods of toxicology, no evidence has been found that food irradiation has any adverse effects on the consumer.

Regulations and Guidelines

Implementation of irradiation as a new technology requires approval from various levels and branches of government. The regulations impact facility design, construction, licensing, operation, product handling, and worker safety. The regulations are often significantly influenced by guidelines or standards proposed by nonpolitical expert committees.

International activities. Lending impetus on an international scale for food irradiation approval is the support of prestigious international organizations: the Joint Expert Committee on Food Irradiation (JECFI), and the Codex Alimentarius Commission.

After a review of all relevant food safety research, the JECFI (1981), under sponsorship of the Food and Agriculture Organization (FAO) of the United Nations and the World Health Organization (WHO) together with members of the International Atomic Energy Agency (IAEA), concluded that there is no toxicological hazard caused by irradiating any food for preservation up to a medium-level dose of 10 kilogray (1,000 kilorad).

In mid-1983, the Codex Alimentarius Commission adopted the International General Standard for Irradiated Foods [Reference No. Codex Stan 106-1983] and the Recommended International Code of Practice for the Operation of Radiation Facilities Used for Treatment of Foods [Reference No. CAC/RCP 19-1979 (Rev. 1)]. The General Standard approves irradiation up to 10 kilogray (1,000 kilorad), cites approved energy levels, and indicates that irradiation is a process and not an additive. Both the General Standard and the the Code of Practice have been distributed to the Member States for acceptance.

The international thrust in food irradiation has helped to motivate action on the national level. At present, over 25 countries have approved approximately 50 irradiated food items.

U.S. activities. The Food Additives Amendment of 1958, an amendment to the Federal Food, Drug and Cosmetic Act of 1938, specifically included the irradiation process with the definition of a food additive. As a result, a tremendous amount of testing was required which made it very time consuming and costly for the private sector to obtain approval for the use of irradiation. The amendment also mandated that the U.S. Food and Drug Administration

(FDA) evaluate the safety of food irradiation and regulate the process to ensure that any commercial irradiation process operated within safe limits. In the decade following 1958, the FDA approved gamma radiation for control of insect infestation of wheat and wheat products (August, 1963), and for sprout inhibition of white potatoes (October, 1964). Irradiation of these products was never used commercially in the United States, however, because it was more expensive than using chemicals for the same purpose, and market conditions did not demand it.

In 1968, the FDA rejected a petition for irradiated ham and rescinded the earlier approval for radiation preservation of canned bacon because of concerns raised about certain experimental protocol as applied to wholesomeness testing. These setbacks, combined with the long-term difficulties of feeding trials, caused an abrupt halt in much of the irradiation research and development being done in the U.S. private sector. Although research continued in many other countries, it was not until more recently that there has been a renewed interest in food irradiation in the U.S. This is due in large part to indications by the FDA of a willingness to reconsider their position on irradiating food. Since 1980, the following food irradiation notices or approvals have been published in the Federal Register (FR):

(1) March 27, 1981 (46 FR 18992) - FDA published an "Advance Notice of Proposed Procedures for the Regulation of Irradiated Foods for Human Consumption" which (a) allowed petitions to use low doses up to 1 kilogray (100 kilorad) on any product that demonstrates the intended technical effect but without submitting safety data, (b) published guidelines for

petitions seeking approval at a dose exceeding 1 kilogray (100 kilorad), and (c) adopted a policy that a food class comprising only a minor portion of the daily diet and irradiated at a high dose of 50 kilogray (5,000 kilorad) or less may be considered safe for human consumption based upon minimal biological testing.

(2) July 5, 1983 (48 FR 30613) - FDA approved irradiation to reduce or control microbial infestation in garlic powder, onion powder, and 36 dried spices. The absorbed dose was not to exceed 10 kilogray (1,000 kilorad). This rule was reissued with slight modifications on June 19, 1984 (49 FR 24988), and April 18, 1985 (50 FR 15415).

(3) June 10, 1985 (50 FR 24190) - FDA approved irradiation of dry or dehydrated enzyme preparations, used as food processing aids, with doses up to 10 kilogray (1,000 kilorad).

(4) July 22, 1985 (50 FR 29658) - FDA approved irradiation of fresh pork for control of Trichinella spiralis, a parasite (worm) which causes trichinosis, with a minimum dose of 0.3 kilogray (30 kilorad) and a maximum dose of 1 kilogray (100 kilorad).

(5) April 18, 1986 (51 FR 13376) - FDA approved irradiation up to a maximum dose of 1 kilogray (100 kilorad) to inhibit the growth and maturation of fresh foods and to disinfest food of anthropod insects. The FDA also approved irradiation up to a maximum dose of 30 kilogray (3,000 kilorad) to disinfect dry or dehydrated aromatic vegetable substances of microorganisms. The regulation does not permit multiple irradiations of food.

Current regulations in the United States specify maximum dose levels at 1 kilogray (100 kilorad) for most foods. This is a factor of 10 lower than the JECFI- and Codex-recommended maximum dose level of 10 kilogray (1,000 kilorad). However, these low dose levels are sufficient for control of insects and parasites. Medium- and high-dose levels would be required for extension of shelf life or for complete sterilization. The FDA will need to obtain and analyze more data before providing a final ruling on the dose levels above 1 kilogray (100 kilorad).

Regulations governing radiation protection and safety for radioisotope facilities are promulgated by the U.S. Nuclear Regulatory Commission (NRC) and its 27 Agreement States. These regulations, which address both radiation safety (e.g., source integrity, design and operation of safety systems, and training of personnel) and licensing of facilities, are found primarily in the Standards for Protection Against Radiation [10 CFR PART 20] and Rules of General Applicability to Domestic Licensing of Byproduct Material [10 CFR PART 30]. In the U.S., there are approximately 40 licenced commercial irradiators, most of which are primarily oriented toward medical product sterilization. Since radiation processing is not a new technology, the established licensing and regulatory structure of the NRC has already had many years of experience with operating facilities. However, the NRC does not try to continually update and modify its regulatory base to cover each new facility design. It is the responsibility of the facility owner to demonstrate to the satisfaction of the NRC that any new equipment or design concept meets the standards set by the current regulations (Cunningham, 1984).

In addition to the NRC's regulations, other organizations are preparing guidelines to help facilitate the introduction of food irradiation facilities on a commercial scale. Design and operational standards are being prepared by Subcommittee N43-3 of the American National Standards Institute (ANSI). Dosimetry standards for U.S. food irradiation are currently being developed by Task Group E10.07.04 (Radiation Dosimetry for Food Processing) of the American Society for Testing and Materials (ASTM).

Product Response

Activation

It is widely accepted by scientists that the energy levels of gamma rays from cobalt-60 and cesium-137 are below the threshold values for activation, meaning that it is impossible to induce radioactivity in a substance using these isotopes. It is also well established by sensitive detection methods that irradiation with machine-generated radiation sources, within the energy levels dictated by the regulations, produces no measurable induced radioactivity.

Temperature Response

Relatively little energy in the form of ionizing radiation is required to obtain desired biological effects in food. Therefore, radiation treatments of food, to doses needed for food preservation, deposit only a small amount of heat and cause only a very slight increase in temperature of the food. For this reason, the term "cold" process is often used in describing the treatments.

Biological Effects

Two basic processes occur when ionizing radiation such as gamma rays or electrons interact with matter. The primary, or direct process, causes the formation of ions, excited molecules or molecular fragments. The secondary, or indirect process, involves the interaction of products formed in the primary process, and can lead to the formation of compounds different from those originally present. Thus the biological effects of radiation are due to chemical changes in the material, much as with any other energy process. The damage caused by radiation in insects or living organisms is primarily associated with the impairment of metabolic reactions. For irradiation to be useful as a disinfestation technique, the biological effects of radiation must be more significant for the pest than for the commodity. This is determined on a commodity-by-commodity basis.

The biological effect of radiation on an organism depends on the genetic/biological complexity of that organism. The following groups of organisms are listed in descending order of complexity, and therefore descending order of sensitivity to lethal radiation:

(1) Higher animals
(2) Insects
(3) Fungi, molds, non-sporulating bacteria
(4) Sporulating bacteria
(5) Viruses

Long-chain compounds, such as polymers, are relatively easily affected by irradiation. Enzymes and low molecular weight toxins, however, are inhibited only at very high doses, and inorganic compounds are virtually unaffected.

Applications

The degree of preservation depends on the absorbed dose of ionizing radiation. Some examples are shown in Table 3.

Dose Distribution

The dose profile of gamma or X-ray radiation that is absorbed in any homogeneous material decreases exponentially as a function of distance into that material. For electron beam radiation, the dose profile gradually rises to some intermediate depth and then falls off rapidly to zero.

The purpose of irradiation is to achieve a desired product response to some absorbed dose. The minimum dose is the dose required to obtain the desired technical effect, such as disinfestation or sprout inhibition. The maximum dose is that dose above which undesirable side reactions in the product may occur, such as changes in texture, color, or in flavor. The minimum and maximum dose may also be limited by government regulation. It is essential to obtain a dose that falls within the acceptable maximum and minimum dose range for a particular food. For thin foods, single-side irradiation may be acceptable; however, most products are irradiated from both sides. Since the ionizing effect of the radiation is additive, the combined dose from both sides must fall within the product's desired maximum-to-minimum ratio.

The maximum-to-minimum absorbed dose ratio tolerated by the product, and the dose actually absorbed throughout the product during exposure to radiation, will determine the source configuration, conveyor speed, conveyor configuration, and the system control sequence. The dose requirements also determine whether the product must be treated individually, or can be boxed, bagged, or palleted.

Radiation Sources

Government regulations permit the treatment of foods using the following radiation sources:

(1) Gamma rays from sealed units of the isotopes cesium-137 or cobalt-60.

(2) Electrons generated from machine sources operated at energy levels not to exceed 10 million electron volts (MeV).

(3) X-rays generated from machine sources operated at energy levels not to exceed 5 MeV.

Isotopes

Production and double-encapsulation of cobalt-60 and cesium-137 entails long and exacting manufacturing processes. The fabrication process is covered by extensive quality control measures to ensure that the final product meets all of the engineering and safety specifications.

Table 4 lists some of the salient characteristics of cobalt-60 and cesium-137 source capsules.

Cobalt-60. The isotope, cobalt-60, is manmade. It is not produced as a fission byproduct of nuclear fuel, such as cesium-137. It is produced via a neutron capture reaction that is initiated by placing the stable isotope cobalt-59 into a nuclear reactor.

Cobalt-60 is widely used in commercial gamma irradiation facilities. The 1983 installed commercial base of cobalt-60 in the U.S. was approximately 33 megacuries* (MCi) (over 40 percent of the world base). The primary manufacturer of cobalt-60, supplying over 80 percent of the world installed base of the isotope, is the Atomic Energy of Canada Limited (AECL), a Canadian Crown corporation. Domestic sources of supply of cobalt-60 are the Idaho National Engineering Laboratory (INEL) and the Oak Ridge National Laboratory (ORNL). However, their production capacity is much smaller than AECL.

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*Curie (abbreviated Ci) is a unit of radioactivity defined as the quantity of a radioactive nuclide which has 37 billion disintegrations per second. The prefix "mega" denotes one million.

Due to the large demand for cobalt-60 sources, AECL was on a cobalt-60 allocation system. They are now in a "post-allocation" period where they are trying to fill some back orders and are beginning to fill new orders as well. The future supply of cobalt-60 will depend on the growth of old and new market opportunities for cobalt-60 as traded off against additional production capacity continually being developed by AECL.

Cesium-137. Radioactive cesium-137 is produced as a fission product in nuclear reactor fuel. After the cesium-137 is removed from the fission waste, it is encapsulated at the Waste Encapsulation and Storage Facility (WESF) at Hanford, Washington. Approximately 70 MCi of the cesium at Hanford have been encapsulated. It is advertised for use by the U.S. Department of Energy (DOE) through their Civilian Byproducts Utilization Program (CBUP).

It is a well-known principle of physics that a curie of cesium-137 is not equivalent to a curie of cobalt-60 with respect to absorbed dose in a product. Taking into account the amount of gamma energy released during each radioactive decay of the nucleus, as well as the amount of gamma energy absorbed within the capsule, it is estimated that seven (7) curies of cesium-137 (in the WESF capsule) provide an absorbed dose rate which is equivalent to one curie of cobalt-60.

Market demand for cesium-137 was very modest until 1984, when a sharp increase in interest occurred. The DOE received requests for the capsules which exceeded the limited supply, and the DOE must now make allocations (DOE, 1985). The shortfall may continue to exist through the next decade because

Hanford, by itself, cannot supply enough cesium to make up the near-term identified needs.

Machine-Generated Radiation Sources

Electron beam. As a general rule, electron beam accelerators (Ramler, 1982) show technical and economic viability in applications characterized by (1) relatively large bulk product throughputs which are conveyed through the beam in stream form, (2) low-density products with relatively thin cross sections, and (3) products requiring only surface or subsurface treatment.

Unlike gammas from isotopes, electrons in the energy range from 0.2 to 10 MeV have limited penetration and cannot be used to process densely packaged or relatively large-sized products, including some medical devices and many packaged foods. Penetration of the electrons is roughly proportional to the energy of the electron, and inversely proportional to the density of the product. If irradiating a product from one side only, an electron beam energy of 10 MeV (maximum permitted in the FDA regulations) would provide 3.6 centimeters (1.4 inches) of penetration in water, and 9 centimeters (3.5 inches) of penetration in a product with a 0.4 bulk specific gravity. (Note: the bulk specific gravity for dried fruits and nuts ranges from 0.3 to 0.5.) For two-sided irradiation, the penetration increases to 8 centimeters (3.1 inches) in water, and 20 centimeters (7.9 inches) in a product of 0.4 bulk specific gravity.

The source of electrons in an accelerator is usually a diode- or triode-type structure, with a tungsten or tantalum emitting surface. The intensity of emission is controlled by temperature, a control grid, or an accelerating potential. In addition, the emission may be either continuous or pulsed beam.

The fundamental principle used in increasing the energy of a free electron, which has an electric charge of -1, is to accelerate the electrons in a vacuum with either a nonvarying potential (DC) or radio-frequency (RF) electric field. The vacuum is necessary to keep the electrons from colliding with air molecules. In the simplest case, the electric field is created by applying a high voltage across a gap between two electrodes, and the electrons are accelerated toward the positive electrode. With current technology, the maximum potential that can be sustained across a single pair of electrodes is on the order of 0.3 MeV. Increasing the voltage further causes arcing between the electrodes or breakdown of the insulators. With multigap accelerator tubes, much higher voltages can be reached (up to 30 MeV in some research accelerators). However, economic and other practical considerations have limited the voltage rating for large DC industrial accelerators to approximately 4 MeV.

Electron energies higher then several MeV are attained using the microwave linear accelerator, or linac. The principle of the linac is to increase the energy of the electron in a sequence of small increments rather than all at once. Thus, the linac has many small accelerator stages arranged in-line which gradually increase the energy level of the electron. The acceleration is achieved at each stage of the linac using a programmed RF electric field.

An oscillator connected to each set of electrodes sets up an alternating field in each RF cavity. Successive stages are synchronized so that the polarity of the alternating field is correctly oriented to accelerate the electron as it enters the cavity. Timing is a critical parameter in the acceleration and spatial formation of an electron beam. Upon leaving the accelerator section, the electron beam is focused to a predetermined position on the target by a scanning magnet.

High energy electron beams for radiation processing have been demonstrated for some industrial processes. Industrial electron accelerators can now provide average beam powers up to 1,000 kilowatt* (kW) at electron energies of 0.3 MeV, and 150 kW in the 1.5 to 4.5 MeV range, but only 20 kW between 5 and 12 MeV. Table 5 lists some of the potential suppliers of electron beam accelerators. Accelerator systems operating at higher power levels between 5 and 12 MeV are desirable for some applications. Although some development and commercial testing would be required, much of the basic technology needed to design and fabricate the higher power systems is available.

X-ray. When electrons from an electron beam machine impinge on a metal plate, such as tungsten, the electron energy is converted into X-rays and heat. For an initial electron energy of 5 MeV, a broad spectrum of X-ray photon energies is produced with a maximum at 5 MeV (Farrell et al., 1983).

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*Watt (abbreviated W) is a unit of power equal to one joule per second. The prefix "kilo" denotes one thousand. Power is equal to the current (in units of amperes) times the potential difference (in units of volts).

The advantage of X-rays is that their product penetration is equivalent to that of gammas. Also, since X-rays are preferentially emitted in the forward direction, the geometrical efficiency is slightly greater than for the isotopes, which emit gammas equally in all directions (isotropic emitters). The primary disadvantage of X-rays is that they are produced relatively inefficiently: only about 8 percent of the electron beam power is converted to X-ray power. The low conversion efficiency significantly increases the power cost of an X-ray machine over that of an accelerator operating strictly in the electron mode. Thus, whether or not an X-ray source is particularly applicable for an industrial process becomes fundamentally a question of economics. No industrial electron beam accelerators in the U.S. are currently operating for a significant portion of the time in the X-ray mode.

Summary Comments on Sources

Each type of source has unique advantages and disadvantages which must be weighed in choosing a specific source for a given application. Table 6 summarizes some of the salient information regarding each source.

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Table 1. Radiation processing applications (extracted from Markovic, 1985).

Established technologies	Emerging technologies	Development technologies
Sterilization of medical supplies	Food irradiation	Biomass conversion (e.g., agricultural waste to sugar and alcohol)
Crosslinking (e.g., wires, tires, plastics, foams)	Irradiation of laboratory and farm animal feed	Immobilization of bio-active materials in the production of anti-bodies and drugs
Curing of coatings or laminates (e.g., video tapes, paper, and wood panels)	Irradiation of sewage sludge for fertilizer or animal feed supplement	Radiation vulcanization of natural latex rubber
Grafting and other processes (e.g., membranes, frying pans, wood products)	Irradiation of stack gases to remove sulfur and nitrogen oxides	Synthesis of biologically compatible polymers which contact human tissues

Table 2. Commercial activities in food irradiation as of January 1985.[a]

Country	Commercial irradiator location	Status	Products treated
Bangladesh	Multipurpose irradiator Dhaka	Planned	Potatoes, onions, fish
Belgium	MEDIRIS facilities Fleurus	Completed	Spices, animal feed
Brazil	Embrarad[b]	Completed	
Bulgaria	Sofia	Unknown	
Chile	Multipurpose irradiator Santiago	Completed	Onions
	Fruit irradiator	Planned	Grapes (?)
France	Pallet irradiator (2 million Ci ^{60}Co) Marseille	Completion in 1986	Dried food products, spices
	CGR-MeV accelerator (10 MeV)	Completion in 1986	Frozen, deboned poultry
German Democratic Republic	^{60}Co irradiator	Completed	Onions
Ghana	Multipurpose irradiator	Planned	Cocoa beans, maize
Hungary	Onion irradiator	Completed	Onions
	AGROSTER Joint Co. Budapest	Planned	Spices, onions, potatoes, corks, seeds
Israel	Mobile gamma irradiator Tel Aviv	Completed	Garlic, onions, potatoes

Table 2. Continued.

Country	Commercial irradiator location	Status	Products treated
Israel (cont.)	Electron accelerator	Completed in 1985	Animal feed
Italy	Commercial vegetable irradiator, Fucino	Under construction	Potatoes, onions, garlic
Japan	Shihoro potato irradiator, Shihoro, Hokkaido	Completed	Potatoes
Republic of Korea	Multipurpose irradiator	Planned	
Mexico	Multipurpose irradiator	Planned	Fruits (disinfestation)
Netherlands	Pilot plant for food irradiation, Wageningen	Completed	Frozen chicken, frog legs, organic dyes, spices
	Gammaster - 2 Ede	Completed	Spices, shrimp, dry ingredients
	Gammaster - 1[b]	Completed	Animal feed
Nigeria	Multipurpose irradiator	Planned	Yams, onions, maize
Pakistan	Multipurpose irradiator	Planned	Potatoes, dried fruits
Poland	Vegetable irradiator	Planned	Potatoes, onions, mushrooms
Sri Lanka	Multipurpose irradiator Colombo	Planned	---

Table 2. Continued.

Country	Commercial irradiator location	Status	Products treated
South Africa	Fruit and vegetable irradiator, Tzaneen	Completed	Mangoes, strawberries, potatoes, onions
	Iso-Ster (Pty.), Ltd.[b] Kempton Park	Completed	Fruits, vegetables, coconut powder
	Multipurpose irradiator Atomic Energy Board Pretoria	Completed	Fruits, vegetables, chicken
Taiwan	Multipurpose irradiator	Completed	Vegetables
Thailand	Multipurpose irradiator Bangkok	Planned	Food in general
United States	Isomedix, Inc. Parsippany, NJ	Completed	Spices, seasonings, other foods
	Neutron Products, Inc. Dickerson, MD	Completed	Spices, seasonings
	Radiation Technology, Inc. Rockaway, New Jersey	Completed	Spices, seasonings
U.S.S.R	Two 20 kW EhLV-2 accelerators Odessa	Completed	Grain (disinfestation)

[a] Most of the information in this table was provided by Van Kooij (1985).

[b] Mainly used for sterilizing medical supplies.

Table 3. Applications in food irradiation.

Dose level	Uses	Examples of food commodities
Low-- Up to 1 kilogray (100 kilorad)	Sprout inhibition	Potatoes, onions, garlic
	Insect disinfestation nuts, vegetables	Grains, flour, fruits,
	Delays ripening	Papayas, mangoes, bananas
	Delays senescence	Sweet cherries, apricots, papayas
	Parasite inactivation	Pork, other meats
Medium-- Up to 10 kilogray (1,000 kilorad)	Extends storage life by reducing microbial load	Meat, fish, poultry, tomatoes, strawberries, figs
	Delays cap opening	Mushrooms
	Elimination of non-spore pathogens	Poultry, shrimp, frog legs, cocoa
	Decontamination	Spices and other dried ingredients
High-- Up to 50 kilogray (5,000 kilorad)	Sterilization for long-term shelf stability	Meat, poultry and other products

Table 4. Isotope characteristics.

	Cobalt-60 (AECL)	Cesium-137 (WESF)
Gammas per decay	2.0	0.85
Energy (MeV) per gamma	1.33,1.17	0.66
Energy (MeV) per decay	2.5	0.56
Half-life (yr)	5.27	30.17
Source replenishment (%/yr)	12.32	2.27
Capsule dimensions		
Length (in)	17.8	20.775
Outside diameter (in)	0.44	2.625
Self-absorption factor	0.09	0.33
Specific activity (kCi/capsule)	6.0	50.0

Table 5. Potential suppliers of electron beam accelerators.

Electron Accelerator	Beam Energy (MeV)	Average Beam Power (kW)	Comments
Direct Current (0.3 MeV)			Continuous beam
Nissin-High Voltage (Japan)	≤3	≤100	Multiple sales
Radiation Dynamics (U.S.)	≤4.5	≤150	Multiple sales; first unit operational about 1980
Microwave Linear			Pulsed beam
CGR-MeV (France)	6	7	CARIC facilities in France; used for medical product sterilization
	10	5-10	Chicken deboning plant in France; operational in 1986
	10	20	New linac planned for the CARIC facilities
Duer (Polymer Physik/FRG)	0.7-2	20	Wire and tubing factories in the USSR
Haimson Research (U.S.)	10-16	10	Research facilities in the U.K. and Denmark; operational about 1975
Radiation Dynamics (U.K.)	10	25	Prototype built
Siemens Medical Lab (U.S.) (formerly Applied Radiation Corporation)	12	10	Two machines in California; operational about 1975
Varian (U.S.)	10	10	Facility in Denmark; operational about 1970
Other potential suppliers:			
Beta Development			
Brobeck			
RPC			
Induction Linear			
LLL (U.S.)	1-10	≤1,000	Modular components tested
Continuous Wave Linear			
AECL (U.S./Canada)	5-10	500	Conceptual design stage

Table 6. Comparison of radiation sources.

	Commercial irradiation	
Radiation sources	Advantages	Disadvantages
Isotopes	No repair needed; continuous gamma output; product flexibility; source reliability and flexibility	Constant shielding required; gamma emission is isotropic
- Cesium-137	Produced domestically	Supply is severely limited due to U.S. Government policy on reprocessing of commercial spent fuel
- Cobalt-60	Widely used; many years of experience	Primarily foreign supply only, very minor U.S. supply
Machine-generated	Radiation emission stops when machine is turned off; conveyor simplicity	Some development still required based on utilization scenario
- Electron beam	Capable of high throughputs	Package size is restricted
- X-ray	Geometry efficiency is slightly greater than with isotopes; product flexibility	Power cost is high (power conversion efficiency is low)

IRRADIATOR DESIGN AND SELECTION

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System Component Design

Although detailed design can be somewhat complicated, a food irradiation system is very simple in concept. The principal components for an isotopic irradiator (see Figure 1) or a facility with a machine-generated radiation source include:

(1) The radiation source.

(2) A conveyor system to bring the product into the ionizing radiation chamber and back out again.

(3) Radiation shielding.

(4) System controls to operate and manage a safe process.

The radiation sources have already been briefly discussed in a previous section. The other irradiator components are addressed below.

Conveyor System

The conveyor system is simply a mechanical trolley or rail system designed to transfer the product between storage/loading areas and the irradiation chamber. The conveyor also holds the product in a desired configuration or alignment and exposes it to the source for a specified time period. Because the radiation will degrade organic materials, caution must be exercised in selecting lubricants and conveyor materials.

Shielding

Shielding (Jaeger et al., 1970) is required to protect operating personnel from inadvertent exposure to excessive radiation levels. The shielding consists of radiation-attenuating barriers interposed between the sealed radiation sources and human access areas.

The thickness of the barrier increases with the energy of the radiation. For a commercial-sized cesium-137 irradiator, adequate protection can be provided by roughly 1.5 meters (5 feet) of concrete, or 20 centimeters (8 inches) of lead. For a cobalt-60 irradiator, with gamma energies double those of cesium-137, the shielding required for the same amount of attenuation increases to 2 meters (6.5 feet) of concrete, or 38 centimeters (15 inches) of lead. For 5 to 10 MeV machine sources, the shield wall directly in front of the source is 3 meters (10 feet) to 3.8 meters (12.5 feet) of concrete. The other walls in the facility would be somewhat less.

The shielding design must allow for replenishment of the radionuclide source as it decays, for maintenance access to the irradiation zone, and for normal flow of the irradiated product. In most commercially available isotope systems, the radiation source is stored in a clear-water pool (around 6 meters, or 20 feet deep) to make the irradiation chamber accessible for maintenance and source replacement. Dry-storage options for these same functions also have considerable merit. Of course, machine sources have the obvious advantage from a radiological safety standpoint that they can be simply turned off when not in use and do not require a shielded storage position.

The product is typically conveyed from the storage/loading areas to the irradiation chamber through a shielded maze or labyrinth. To prevent the transmission of high-energy gamma rays or X-rays along the conveyor path when the source is exposed or operating, the labyrinth must change directions to provide at least three reflections of radiation between the source and the entrance-exit. Sufficient shielding must be present along the conveyor path to absorb the scattered radiation.

Safety and Control Systems

The control system for an irradiator is designed to monitor the product's progression through the irradiation cycle, to control the conveyor operation, to control the radiation source emission/shielding, and to control the internal environment. To preclude the possibility of operator exposure to radiation, sophisticated interlock systems are used. Standard practice calls for double interlock systems (mechanical and electrical) to ensure that the safety of the operator will not be jeopardized by the failure of a protective device.

Design Parameters

Communication between irradiator supplier and customer/owner is essential in order to design and construct a facility which fits the needs of the customer. The customer should clearly define his goals and then work with the supplier to understand the technical and economic tradeoffs which affect the selection process. The suppliers ultimate recommendation for a particular design will be based in part on the following information from the customer.

(1) Minimum dose needed to attain the desired technical effect or benefit in the commodity. Since product throughput is proportional to the minimum dose, this dose limit should be set as low as possible.

(2) Maximum dose above which the irradiated commodity exhibits side-effects (e.g., phytotoxic or organoleptic effects) which make the commodity undesirable for marketing.

(3) Product package dimension and any special product handling requirements. If many different sized packages are to be irradiated, then considerations of conveyor loading efficiency will need to be balanced off against versatility.

(4) Product bulk density.

(5) Peak throughput rate requirements for the irradiator. Since the amount of radiation source required depends directly on the peak throughput rate, it may be to the advantage of the customer to smooth out the throughput fluctuations as much as possible. Otherwise, the irradiator may be significantly underutilized.

(6) Plant operation schedule, specifically the hours of operation per day, week, and year. For isotopic sources which continually decay, it is usually recommended that the irradiator be run on a continual basis.

(7) Anticipated future growth in production or product handling requirements.

(8) Ancillary support facilities and degree of integration of the irradiator into existing structures, or into the process flow. Support facilities might include an equipment room, warehouse, dosimetry laboratory, office space, or loading docks.

An irradiator supplier or designer starts with the above set of parameters and attempts to optimize a design, both economically and technically. Critical decisions are then made with regard to the type and strength of radiation source, the geometric configuration of the source and target, and the type of conveyor and product handling system.

General Design Considerations

The primary objectives in a facility design are to:

(1) Minimize the capital, operational, and maintenance costs.

(2) Minimize the dose distribution ratio (maximum dose divided by minimum dose).

(3) Maximize the product throughput.

(4) Maximize the geometrical efficiency.

(5) Maximize the flexibility or versatility of the system to obtain a range of possible operating conditions.

Not all of these objectives can be fully realized in a design. Some of them are mutually exclusive, and will require that tradeoffs or compromises be incorporated. To what degree the objectives can be met will depend on the specific irradiation application and the preferences of the facility management.

The dose distribution ratio in a product is a function of several parameters: target dimensions, bulk density of the target, atomic number of the material, energy of the ionizing radiation, and the source-to-target geometry. Of these, the target dimensions and the source-to-target geometry are the two parameters most amenable to change and optimization in the design process.

The overall dose uniformity profile in a product is three dimensional. It is a composite of the dose distribution through the depth of a product (direction perpendicular to the source plane), and lateral dose distributions through the length and width of the product (directions parallel to the source plane). The depth dose distribution can be made more uniform by 1) decreasing the product depth, 2) increasing the distance between the source and the target, and 3) irradiating from two sides instead of one. The lateral dose distributions can be made more uniform by making the radiation field impinging on the surface of the product as uniform as possible. For machine-generated radiation sources, lateral dose profiles are not a significant problem if correct beam handling techniques are used. For isotopes, lateral dose distributions can be improved by 1) strategically rearranging the sealed sources on the source holder so that more source is near the low dose target points, and less source is near the high dose target points, 2) allowing the source holder to overlap the target in the lateral direction, and 3) conveying the target past the source in one or both lateral directions at a constant rate of speed, or with a "stop-dwell" motion. These single or multiple direction conveyors provide good dose uniformity along any line in the target that is parallel to its direction of motion (Rizzo, 1968).

The geometrical efficiency is defined as the fraction of ionizing energy actually emitted from the source and available for irradiation which is absorbed in the product to obtain the minimum dose. It is a strong function of the source-to-target geometry. Typical efficiencies to be expected in irradiation of packaged product is 0.05 to 0.35 for isotope, 0.20 to 0.45 for X-ray, and 0.30 to 0.55 for electron beam. The efficiencies for machine sources are higher than for isotope because of the capability for some preferential focusing of the radiation. Since isotope emission is in all directions and gamma rays are so penetrating, the technique for increasing the efficiency in isotopic irradiators is to simply surround the sources with as much product as possible or practical using modern conveyor systems. Thus some conveyor systems have the capability of indexing product packages in multiple directions, with multiple passes on each side of the source.

Maximizing the geometrical efficiency will maximize product throughput for a given source strength. It is a good goal if only one or two commodities are run through the irradiator. If many different products are to be irradiated, maximizing the efficiency can mean significant delay in product changeover and decreased flexibility in handling products of different dimensions.

Designs have been investigated in bulk grain irradiation where gravity-fed grain moves in plug flow downward past and around encapsulated sources. A substantial fraction of the space around the capsules is filled with product which enhances the efficiency. Geometrical efficiencies as high as those for electron beam can be obtained by irradiating the bulk product with isotope in this way.

Examples of Irradiators

Isotopic Irradiators

Radioisotopes are the most prevalent radiation source in the world today in food irradiation applications. For the purpose of discussion, the irradiators have been categorized as bulk, box, or carrier irradiators.

Bulk. A pilot plant was constructed in 1977-78 at the Sandia National Laboratories to irradiate bulk product (McKeon et al., 1983). An isometric drawing of a proposed commercial upgrade to the pilot plant is shown in Figure 2. A major component of the pilot plant is a bucket conveyor, with each bucket having a 0.0425 cubic meter (1.5 cubic feet) capacity. The conveyor includes a collapsing-chain feature that brings the buckets together for greatest efficiency in loading and absorbing radiation. The speed of the conveyor is adjustable to provide control of the radiation dose. The efficiency of the system is approximately 16 percent.

The pilot facility utilizes approximately 1 MCi of cesium-137. The source capsules are loaded into the irradiator by placing them into a 20-foot-deep source storage area filled with water. Following loading, concrete covers are placed over the source storage area and the water is drained. A large lead shutter is then retracted to allow movement of the source plaque from the storage area to the radiation area. An elaborate system of mechanical and electrical interlocks is provided to ensure that no radiation escapes the facility and to prevent inadvertent exposure of operating personnel.

A different bulk irradiator was constructed by the U.S. Atomic Energy Commission in 1966 and was made available to the U.S. Department of Agriculture for the study of bulk grain irradiation (AEC, 1965, and Tilton and Brower, 1971). In this system, the grain is placed into a hopper where it is picked up by a bucket elevator and carried vertically to the top of the irradiator. The bucket elevator discharges to an input screw which carries the grain along the top of the irradiator to the grain bin inlet. The input to the grain bin is offset to reduce radiation streaming through the concrete shield.

During irradiation the grain continuously flows past the source rod configuration, housed in a shielded radiation bin, and is eventually discharged out of the bottom. The rate of flow, and consequently the dose rate, is controlled by a metering valve located below the bin. As it travels down the bin, the grain moves in a plug flow* pattern. This is controlled through the use of a vibrating bin activator located at the bottom of the bin.

Although it was never experimentally verified, the estimated efficiency for the irradiation was 50 percent. Other intriguing designs for bulk grain irradiators with high efficiencies were conceptualized and discussed by Cornwell (1966).

Box. The box irradiator is relatively common in the industry (Cuda, 1984; Varaklis, 1983). Individual units of packaged product are conveyed into and out of the irradiation chamber with a multitude of different conveyor systems.

An example of this type of plant is the Marine Products Development Irradiator (MPDI) in Gloucester, Massachusetts (Miller and Herbert, 1964). The

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*Plug flow is characterized by orderly flow of material through the irradiator, with no portion of the material overtaking or mixing with any other portion ahead or behind it. The residence time in the irradiator is the same for all portions of the material.

MPDI is used for finned fish, such as haddock, and for shellfish, such as clams. The system is basically designed to handle a 14-kilogram (30-pound) fillet tin.

In the normal operation of the MPDI, the tins of fillets are placed on a high-speed mechanical conveyor which carries them into the gamma cell through a vertical labyrinth which goes under the floor. Figure 3 is a diagram of the conveyor arrangement. Inside the cell the packages are transferred to a slow-moving conveyor which carries them past the radiation source. The source is in the form of a horizontal plaque because the packages must be kept in a horizontal position since their covers are loose-fitting.

The conveyors operate on a start-stop basis to permit loading and unloading, and transfer between the fast and slow conveyors. Each package makes a round trip under and over the source on one side of the source centerline. It then comes out of the cell, is shifted to the other side by the operator, then goes back into the cell for a second round trip. Two packages are carried side by side on a single carrier, or basket, which is part of the conveyor. The packages follow each other closely in the direction of travel, to minimize loss of radiation. The slow conveyor is loaded with packages for a distance of 2.7 meters (9 feet), compared with a source length of 1.2 meters (4 feet). In the other direction, a double row of packages is 56 centimeters (22 inches) wide compared to the source width of 28 centimeters (11 inches). Thus there is package overlap in both lateral directions which provides an efficiency of 24 percent for MPDI.

Box irradiators can have varying degrees of complexity in their conveyor systems. The simplest conveyor mode is the batch system where boxes of commodity are manually placed around the source while the source is in the storage position. A more complex conveyor would be a fully automatic system where product boxes are placed in lightweight metal boxes and indexed around the source by pneumatic cylinders. The boxes slide from position to position on stainless steel trays and roller conveyors.

The efficiency of the box irradiators is increased in relation to the amount of product in the irradiation chamber. Some box irradiators not only index their product around the source in both lateral directions (directions parallel to the plane of the source), but also may have the product 4 or 5 layers deep (in the direction perpendicular to the source plaque) on each side of the source. These multidirection, multipass systems can realistically increase efficiencies up to 35 percent.

Carrier. Large carriers or totes on overhead conveyor systems are commonly used to transfer groups of boxes or pallets through the irradiation chamber. Isometric drawings of tote and pallet irradiators are shown in Figures 4 and 5, respectively. The carriers may actually convey two pallet loads, one above the other, to help increase the efficiency (McKinnon and Chu, 1985).

The advantages of a carrier system over a multidirection, multipass conveyor systems are that 1) the system is not as labor intensive with regard to product handling, 2) packaging and processing flexibility is not as limited,

3) the system requires smaller periods of time for product changeover, and 4) the maintenance requirements will probably not be as high. The disadvantages of a carrier system are 1) a smaller overall geometrical efficiency, and 2) a poorer dose distribution ratio since the product is thicker. Actual operating experience with a pallet irradiator is discussed by Leemhorst (1984).

Machine-Generated Radiation Sources

Figure 6 shows a typical layout for an electron beam facility (Gallien et al., 1985). The accelerator can be positioned either horizontally or vertically in the facility.

The accelerator section of the machine is often located in a room separate from the irradiation chamber. If the accelerator section is in the irradiation chamber, additional space is needed for it which increases the concrete costs. Although some shielding or limited access provisions must be made for field emissions or straying beam currents in the accelerator section, the shielding requirements are not nearly as severe as those for the targeting area in the irradiation chamber.

An accelerator power source is usually characterized by high voltage and high capacity. Utility requirements, specifically with regard to grounding, need to therefore be considered.

As with isotope facilities, mechanical and electrical interlocks must be provided to ensure safety for operating personnel. If the interlocks are violated, alarms should be activated, and the machine should be automatically shut off. The interlocks should also ensure that access to the irradiation chamber is delayed for a suitable period to permit the ventilation system to dilute the ozone and nitrogen oxides concentration in the beam area.

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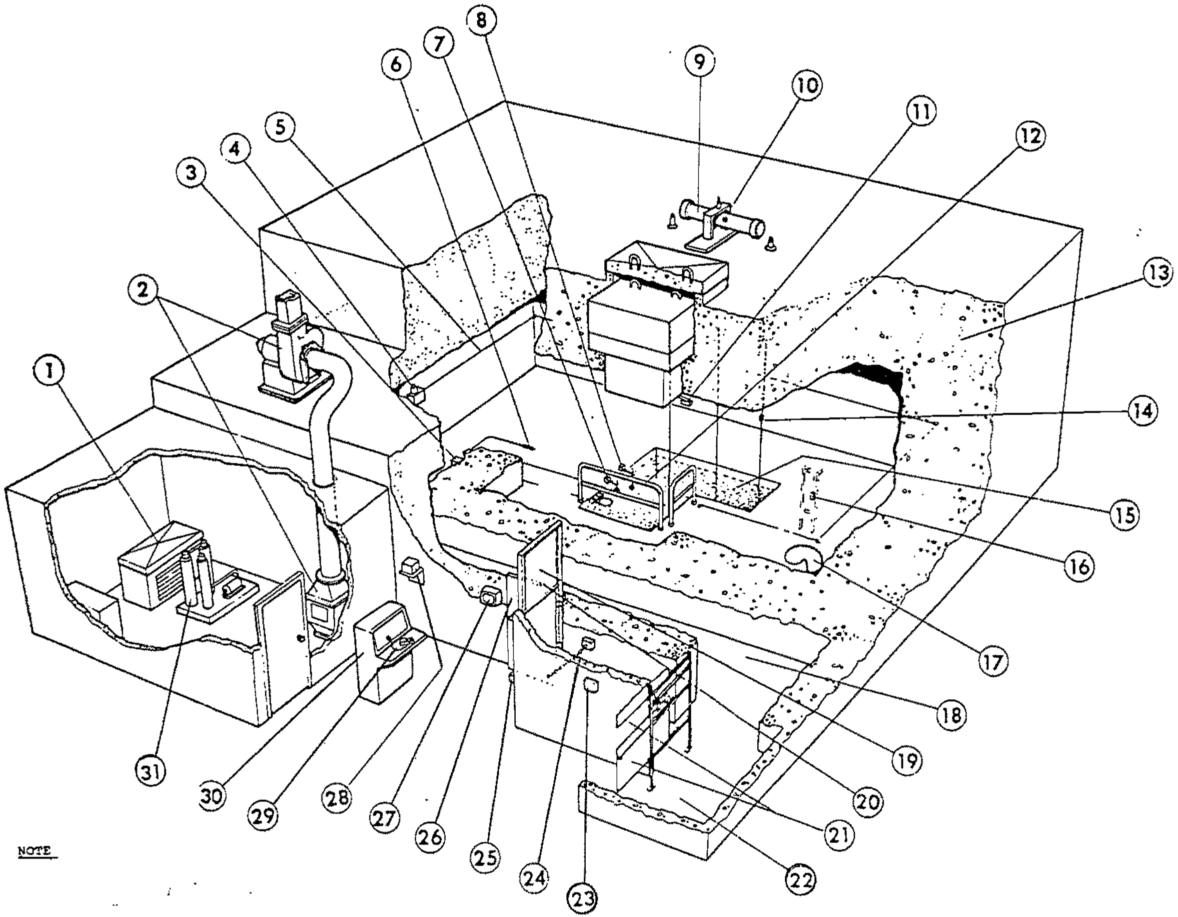


KEY

1. Water Cooler
2. Radiation Room Ventilation System
3. Radiation Room Monitor Probe
4. Safety Delay Timer Alarms
5. Emergency Stop Device
6. Heat and Smoke Sensors
7. Water Level Control—Normal
8. Water Level Control—Abnormal (Low)
9. Source Hoist
10. 'Source Down' Switch
11. Roof Plug Interlock Switch(s)
12. Pool Guard
13. Radiation Room Shield—Concrete
14. 'Source Up' Switch
15. Source Storage Pool
16. Safety Delay Timer Keyswitch
17. Exhaust Air Intake
18. Personnel and Product Entry/Exit Maze
19. Radiation Warning Light
20. 'Source Moving' Light
21. Product Entry/Exit Barrier Doors
22. Product Entry/Exit Maze
23. Product Exit Monitor
24. Source Hoist Power Disconnect
25. Check Source Location
26. Personnel Access DoorWith Interlocks
27. Radiation Room Monitor with Alarms
28. Seismic Detector
29. Master Key Attached to Portable Survey Meter
30. Control Console
31. Water Conditioner

NOTE

FOR EASE IN PRESENTATION, CERTAIN IRRADIATOR COMPONENTS AND SAFETY FEATURES HAVE BEEN OMITTED FROM THIS ILLUSTRATION e.g. PRODUCT PASS MECHANISM AND RADIATION SOURCE.

Figure 1. Typical components for an isotopic irradiator (American National Standard N43.10, 1984).

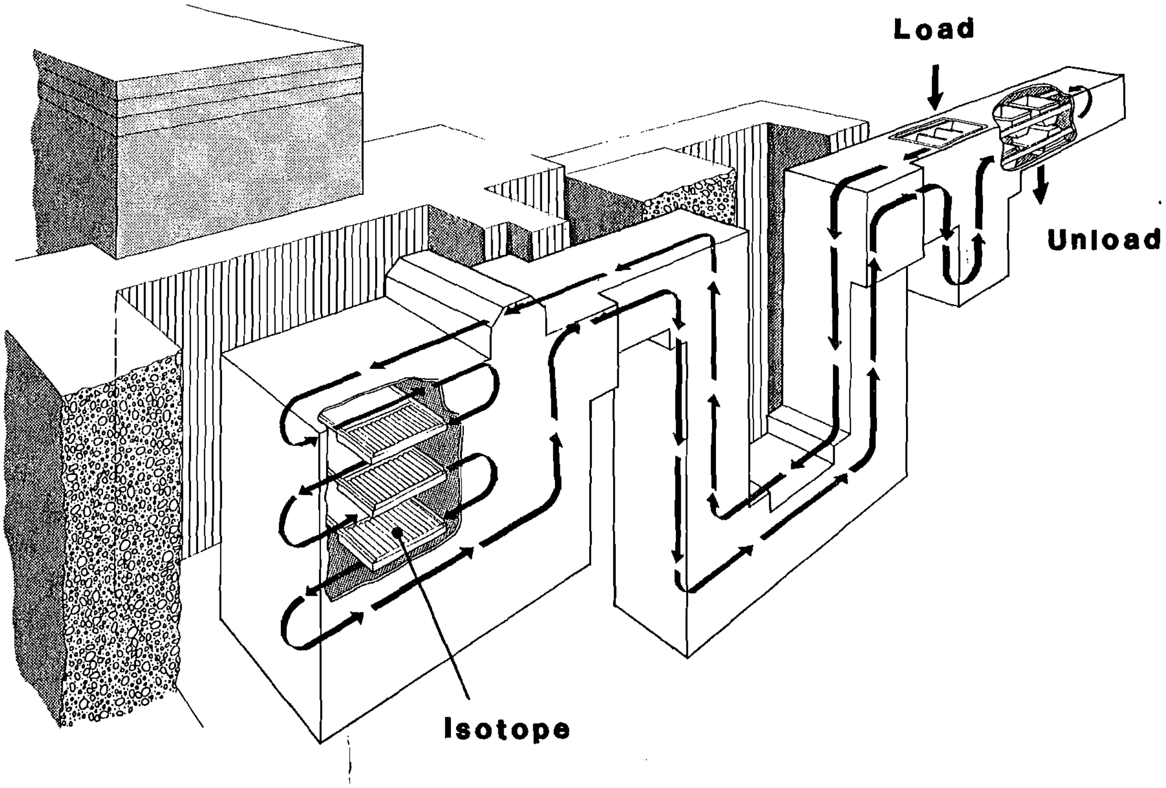
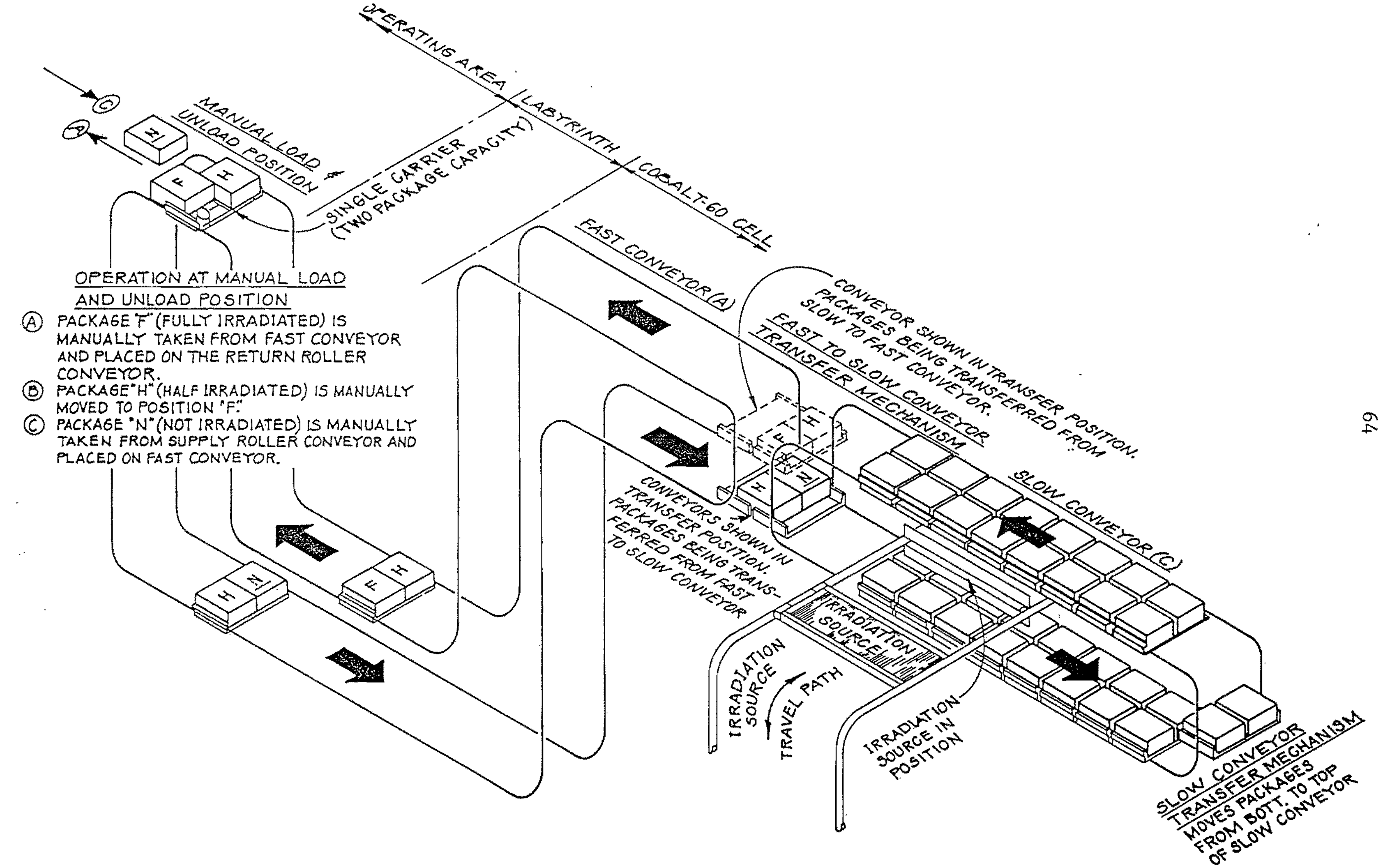


Figure 2. Cut-away isometric drawing of a bulk product irradiation plant.



OPERATION AT MANUAL LOAD AND UNLOAD POSITION

Ⓐ PACKAGE "F" (FULLY IRRADIATED) IS MANUALLY TAKEN FROM FAST CONVEYOR AND PLACED ON THE RETURN ROLLER CONVEYOR.

Ⓑ PACKAGE "H" (HALF IRRADIATED) IS MANUALLY MOVED TO POSITION "F".

Ⓒ PACKAGE "N" (NOT IRRADIATED) IS MANUALLY TAKEN FROM SUPPLY ROLLER CONVEYOR AND PLACED ON FAST CONVEYOR.

Figure 3. Schematic of the conveyor system for the Marine Products Development Irradiator (Miller and Herbert, 1964).

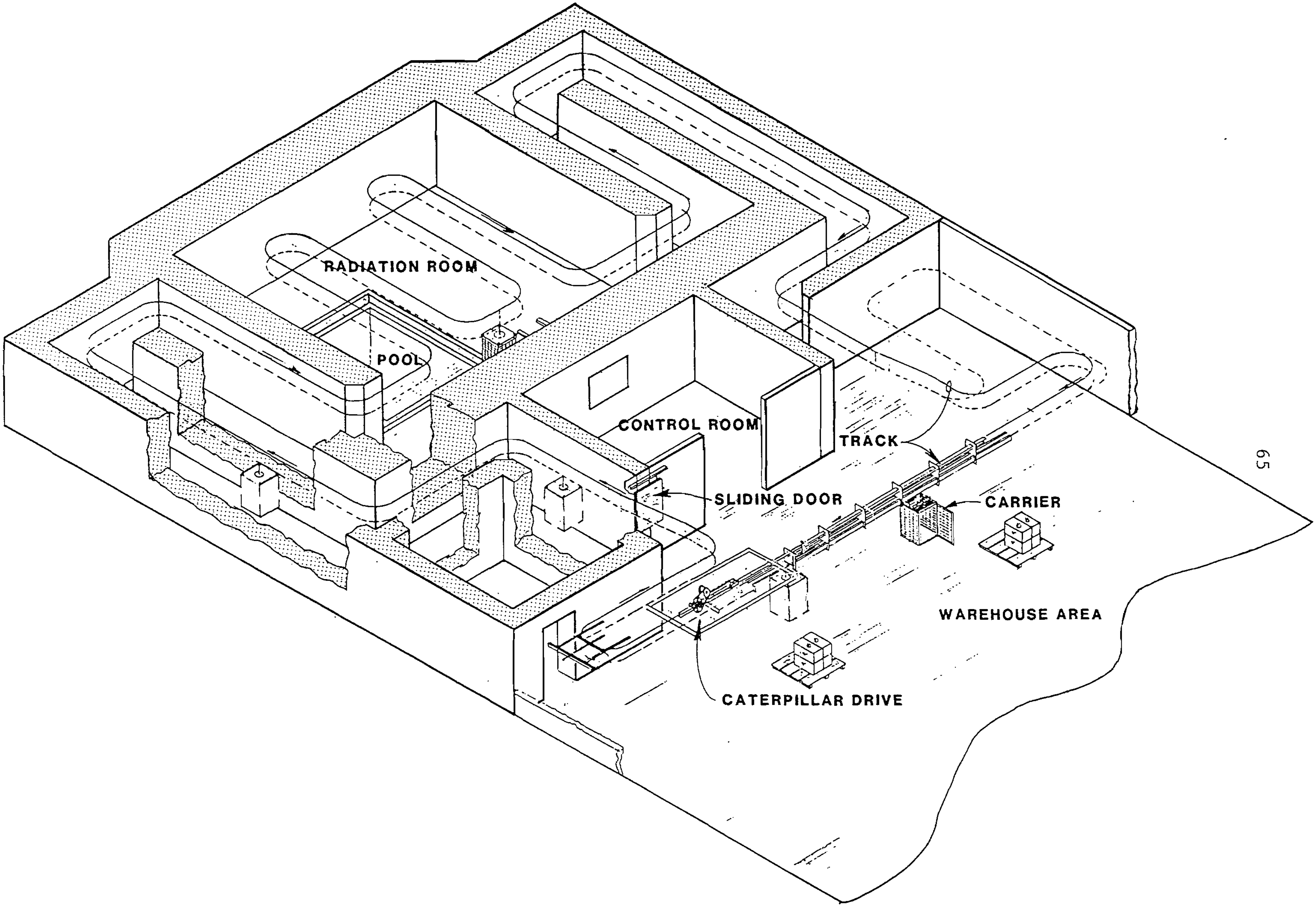


Figure 4. Cut-away isometric drawing of a tote irradiator.

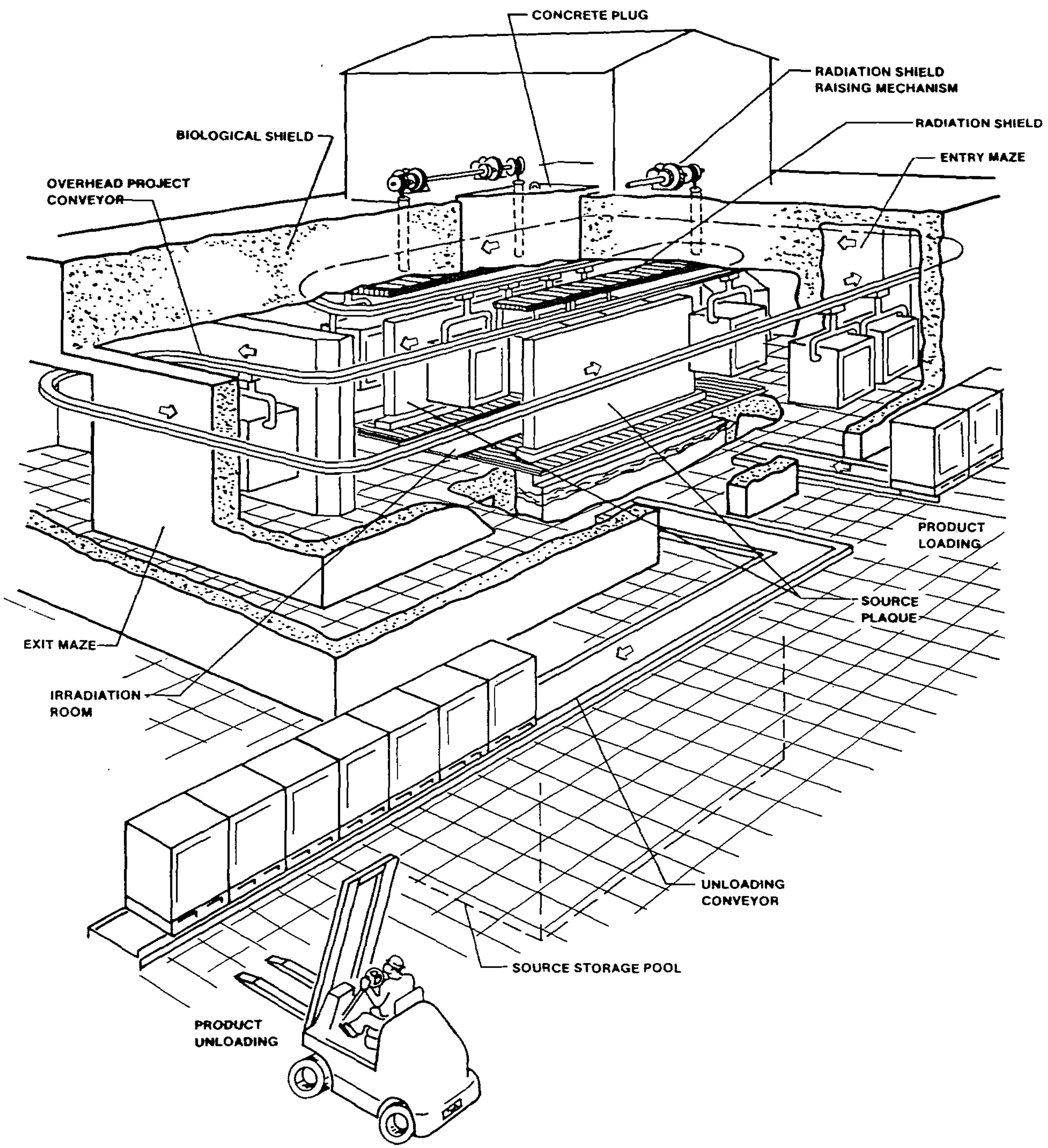


Figure 5. Cut-away isometric drawing of a pallet irradiator.

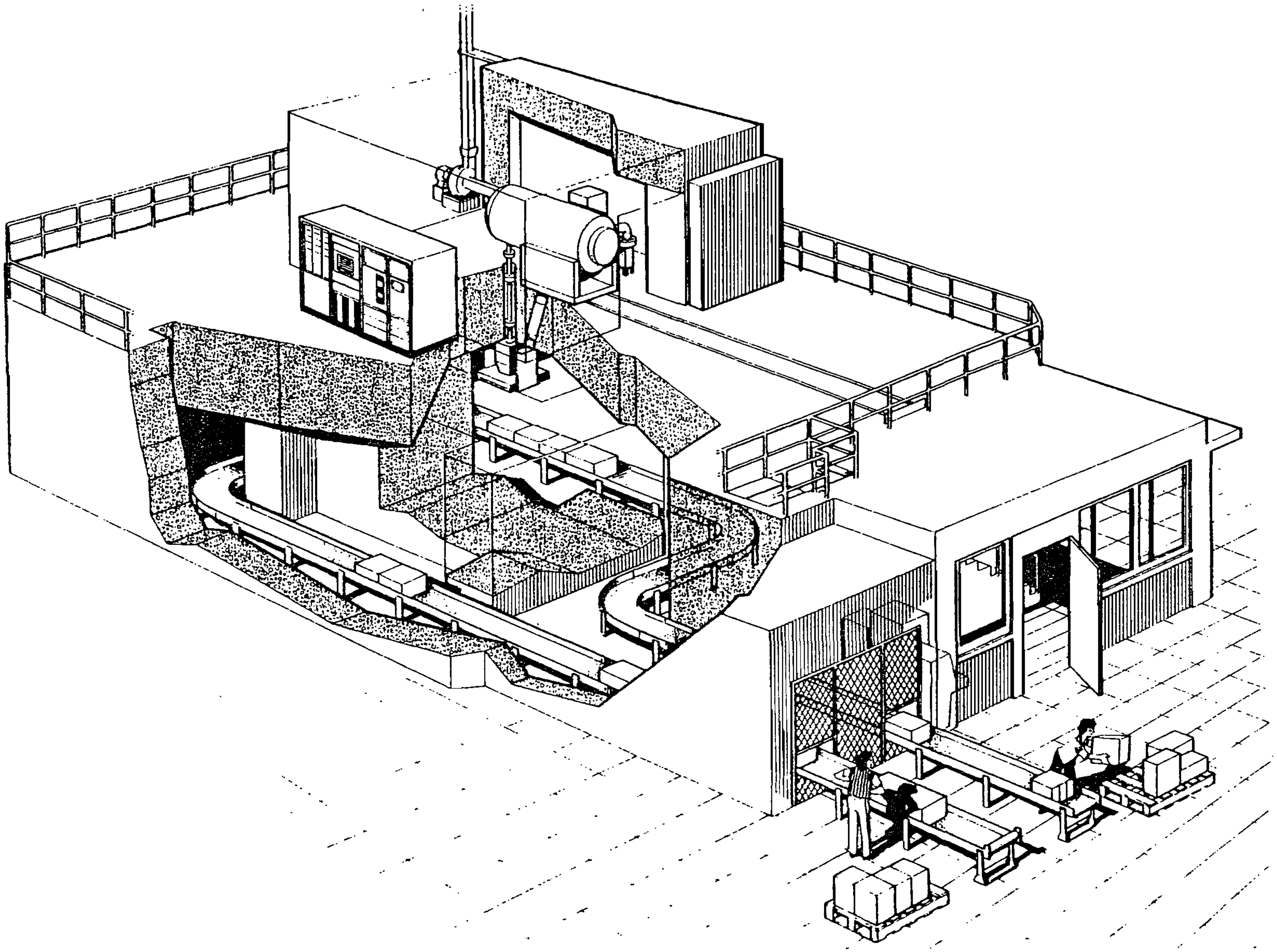


Figure 6. Typical electron beam facility (courtesy of GCR-MeV).

EFFICACY OF GAMMA RADIATION TREATMENTS FOR INSECT DISINFESTATION OF SELECTED DRIED FRUITS AND NUTS

by

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Introduction

Our primary research objective was to develop efficacy data on radiation treatments against Indianmeal moth, Plodia interpunctella (Hübner), navel orangeworm, Amyelois transitella (Walker) and driedfruit beetle, Carpophilus hemipterus (L.). Earlier work done on these and other species indicated that control could be obtained by treatment at doses not exceeding the FDA limit of 1 kGy (100 krad). While considerable information exists on the radiation doses required to prevent reproduction in numerous insect species, data on larval mortality and feeding behavior after irradiation are limited. In particular, the effectiveness of radiation in reducing commodity damage from feeding larvae is poorly understood. Our research was therefore directed at determining the dose required to prevent reproduction and minimize feeding damage.

The insects chosen for this study represent a wide range of habits and responses to radiation, and so our research objectives varied accordingly.

The Indianmeal moth is a pest of world-wide importance, capable of infesting a variety of stored products. Infestations may occur at any time so that any stage of the insect may be present in the commodities. Information on the radiation effects on both feeding behavior of irradiated larvae and reproduction of irradiated adults and pupae were necessary for the purposes of this project. On the other hand, most navel orangeworm infestations of commodities occur in the field and are carried into storage, where adults do not normally reproduce. Since radiation would only be useful in cleaning-up larval infestations on incoming produce, the effects of radiation on larval mortality and feeding behavior were of prime consideration. With the driedfruit beetle, both larval and adult stages feed, and so radiation effects on adult longevity and feeding behavior, in addition to reproduction were examined. Since eggs are the most radiosensitive stage in any insect, when effective control of more advanced stages is obtained, the egg stage should also be controlled. Because of this and the logistical problems involved, the effect of radiation on the egg stage of the above insects was not studied.

Literature Review

Indianmeal Moth

The effects of radiation on the Indianmeal moth (IMM) have been extensively studied. The possibility of developing a sterile insect release program, using radiation-sterilized IMM, along with the use of direct radiation treatments for commodity disinfestations has been investigated.

Radiation effects on the reproductive capacity of IMM irradiated as pupae and adults were observed by Cogburn et al. (1966) and Brower (1975, 1976). Radioresistance was shown to increase with the age of irradiated pupae and males were less affected than females. Relatively high doses (greater than 500 Gy) were needed to significantly reduce adult emergence from pupae 2.5 to 5 days old. Complete sterility of older female pupae was obtained at 350 Gy, while male pupae were only 60% sterile at 500 Gy. Progeny numbers of irradiated males mated with untreated females was reduced by 90% at 350 Gy and 95% at 550 Gy. When IMM adults were irradiated, no progeny were produced by males treated with 500 Gy, or by females treated with 450 Gy.

The inheritance of radiation induced sterility by the progeny of partially sterile IMM irradiated as pupae was determined by Cogburn et al. (1966) and Brower (1976). F_1 progeny of irradiated male pupae showed a high degree of sterility when compared to progeny of irradiated females. Also female F_1 progeny were less likely to inherit sterility from irradiated parents. The progeny of irradiated adults were also noted to inherit sterility (Brower, 1979, 1981). Again, female IMM were less likely than males to pass on radiation-induced sterility to their progeny, or inherit sterility from irradiated parents. In both irradiated parents and adults, the highest degree of sterility was obtained in F_1 incrosses.

Less information is available concerning the effects of radiation on the larval stage of the IMM. Generally, lepidopterous larvae are more radiosensitive than pupae or adults. Cogburn et al. (1966) showed that the percentage of successful pupation of irradiated last instar larvae decreased with increasing dose. No irradiated larvae were able to complete development and emerge as adults, even at doses as low as 132 Gy. Diapausing IMM larvae were prevented from pupating at 200 Gy, but while nearly all mature non-diapausing larvae successfully pupated at this dose, none were able to emerge as adults (Brower, 1980). Ashraf et al. (1971) reported a similar pattern of pupation and adult emergence, and also noted that feeding in irradiated larvae was reduced or abandoned even though the larvae often lived for long periods of time after treatment.

Generally, the egg stage is most susceptible to radiation-induced damage, due to the presence of mitotic activity in embryonic tissues (Tilton and Brower, 1983). Cogburn et al. (1966) reduced egg hatch by 45.8% with a treatment of 250 Gy, and all resulting larvae died shortly after hatching. Age of eggs was determined to be an important factor (Brower, 1974) with older eggs more radioresistant.

Disinfestation of IMM populations in a number of dried fruit and nut commodities has been investigated (Brower and Tilton, 1970, 1971, 1972). In all cases, the target stages irradiated were eggs, young larvae and ovipositing adults. Suggested doses for practical levels of control were 200 or 250 Gy. For complete control and elimination of feeding damage, 400 Gy was recommended. Doses near 500 Gy were predicted to control mixed stages of the IMM in cornmeal when complete mortality by one month after treatment was required, but 200 Gy was recommended if delayed mortality was acceptable (Tilton et al., 1978).

Navel Orangeworm

Previous radiation studies on the navel orangeworm (NOW) were primarily to develop a sterile insect release program. Consequently, most data available deal with the effect of radiation on NOW reproduction. Husseiny and Madsen (1964) did the most comprehensive study on irradiated NOW. A dose of 120 Gy completely prevented hatch of irradiated eggs and emergence of normal adults from mature irradiated larvae. Pupae treated at 1.6 kGy or above were unable to emerge as adults. Adults emerging from pupae treated with 500 Gy or above produced no viable eggs. The lowest dose causing complete sterility of irradiated adult NOW was 540 Gy.

Driedfruit Beetle

While considerable work has been done on irradiation of stored product beetles, little information exists on radiation effects on nitidulids. Papadopoulou (1964) reported that 88 and 95% of driedfruit beetle eggs failed to hatch when treated at 250 and 500 Gy, respectively. The time required for 50% of DFB larvae to die after irradiation at 1 kGy was 3 days. Fifty percent mortality was reached 3 days after treatment in adults irradiated at 1.5 kGy. Reproduction was prevented from adults irradiated at 1 kGy.

Eggs and larvae of the corn sap beetle (*Carpophilus dimidiatus*) failed to produce adults when irradiated at doses as low as 50 Gy (Brower et al., 1973). One kGy was required to completely prevent adult emergence from irradiated pupae, but adult longevity was significantly reduced at lower doses.

Longevity of irradiated adults was also reduced. Since the corn sap beetle was considered relatively radiosensitive, any dose providing adequate control of other species would also control the corn sap beetle.

Irradiation and Transportation

Irradiation facilities for the project, provided by the Department of Energy, were located at the Sandia National Laboratories in Albuquerque, New Mexico. The first irradiator used was the Sandia Irradiator for Dried Sewage Solids (SIDSS) which employed a bucket conveyor to move material past an underground cesium-137 source. When SIDSS became unavailable, work was transferred to the Gamma Irradiator Facility (GIF), a cesium-137 chamber irradiator. For all radiation trials, doses were monitored by strategically placing thermo-luminescent dosimeters (TLD) within the test material. After treatment, the TLDs were analyzed by the Sandia Dosimetry Laboratory, to determine the actual dose received by the test material.

The representative commodities chosen for the project were raisins, walnuts and almonds. Commodity samples for use in radiation trials were provided by the corresponding marketing boards. Test insects were from stock cultures kept at the Horticultural Crops Research Laboratory, Fresno, California. After irradiation, material was returned to the Fresno laboratory for evaluation. Air freight transportation of test material to and from the irradiation facilities in Albuquerque was also provided by the marketing boards. Plastic, insulated ice chests were used as shipping containers. Test material was generally sent the day before a scheduled radiation treatment and returned the evening of or the morning after treatment. In all cases, control insects were also shipped but left untreated.

Indianmeal Moth Pupae and Adults

Since doses needed to prevent adult emergence of lepidopterous pupae or cause immediate mortality in adult moths are generally too high for practical consideration and those stages cause no feeding damage, the primary objective in studies with IMM pupae and adults was to prevent their reproduction. In addition, the physical effect of the commodities on the response of irradiated pupae was determined.

For the IMM pupal experiments, mature IMM larvae reared on standard bran diet were placed in pint mason jars containing 125 g of commodity. The larvae were held at 27°C for 8 days and allowed to cocoon and pupate within the commodity. The jars were then shipped to Albuquerque for irradiation at 150, 300, 600 and 900 Gy, and returned to Fresno immediately after treatment.

Test jars were held at 27°C and checked daily for any adult emergence. Emerging adults were paired up in one of three mating combinations: incrosses of irradiated females with irradiated males (I ♀ x I ♂), outcrossed irradiated females with untreated, normal males (I ♀ x N ♂) and outcrossed irradiated males with normal females (N ♀ x I ♂). Paired adults were allowed to mate and oviposit in plastic pint cartons containing bran diet. The resulting F_1 progeny were reared in the cartons at 27°C. Emerging F_1 adults were collected and paired up in mating combinations similar to the previous generation. The resulting progeny numbers were determined by collecting the emerging F_2 adults. Two such pupal experiments were conducted.

Virgin IMM adults for irradiation were obtained by removing cocoons from colony pupation rolls and placing them in individual stoppered test tubes. After adult emergence, the moths were sexed and sent to Albuquerque for irradiation at 150, 300, 600 and 900 Gy. Adults were returned to Fresno immediately after treatment and paired in mating combinations as described above. The reproductive potential of the resulting F_1 progeny was similarly determined.

Tables 1 and 2 show percent emergence of adults from irradiated pupae in the two tests. Little or no emergence occurred from pupae treated with 900 Gy. Those adults that did emerge were deformed and died almost immediately after emergence. Emergence was reduced significantly from the controls at the 600 Gy level, and the resulting adults were weak, deformed and unable to mate. Little or no reduction in adult emergence was found in the 150 and 300 Gy levels.

The average adult progeny numbers produced by IMM irradiated as pupae are given in Table 3. Reproductive studies were limited to the 150 and 300 Gy treatment levels because of the lack of undeformed adults at higher levels. Progeny numbers were greatly reduced from controls in the incrosses and outcrossed female combinations at 150 Gy. No progeny were produced in these combinations at 300 Gy. A slight reduction occurred in the outcrossed male combination at 150 Gy, with a more significant decrease at 300 Gy.

The different commodities had no consistent effect on the response of IMM to radiation. No significant difference was found in adult emergence or progeny numbers from the different commodities.

The effect on the reproductive potential of the F_1 progeny of irradiated pupae is given in Table 4. Since irradiated females were sterile at 300 Gy and produced few progeny at 150 Gy, only progeny from outcrossed males were used in the first test. In the second test, progeny of incrosses and outcrossed females at the 150 Gy level were also used for mating studies.

At the 150 Gy level, the highest overall reduction in F_1 reproductive capacity occurred when both parents were irradiated. F_1 progeny of outcrossed irradiated males produced fewer offspring than F_1 progeny of outcrossed irradiated females. The reproductive capacity of female F_1 progeny was consistently less affected than their male counterparts.

The reproductive capacity of F_1 progeny of outcrossed males was greatly reduced at 300 Gy. Again, female progeny were slightly less affected than males, but even so, reproductive capacity was reduced by 93% or more in all mating combinations.

Adult progeny numbers of irradiated adult IMM and their corresponding reduction from control progeny numbers are given in Table 5. No progeny were produced by adults irradiated at either 600 or 900 Gy. At 300 Gy, incrosses were completely sterile and outcrossed female progeny numbers were reduced by 99.9%. Male reproductive capacity was also greatly affected, with a reduction of 92.4%. Female reproductive capacity was reduced by more than 90% at 150 Gy, while that of males was reduced only 45.6%.

The effect on the reproductive capacity of the F_1 generation is given in Table 6. The results are very similar to those obtained from irradiated pupae. F_1 progeny of irradiated females are less affected than progeny of irradiated males, and F_1 females are more productive than their male siblings. Regardless of parental origin, F_1 incrosses were completely sterile. The highest overall reduction was found in F_1 progeny of adult males irradiated at 300 Gy.

Indianmeal Moth and Navel Orangeworm Larvae

In contrast to pupae and adults, lepidopterous larvae cause direct damage to infested commodities. Consequently, sterility or reduced reproductive potential may not be a suitable criterion for evaluating the effectiveness of radiation treatments against IMM and NOW larvae. For this reason, larval studies were designed to determine the length of time to mortality for irradiated larvae and the effect of radiation on larval feeding behavior and development.

Larvae for the radiation studies were reared from the neonate stage in 2 ml plastic analytical beakers containing 1 ml of artificial codling moth diet. To determine the length of time to mortality after irradiation, 6- and 11-day-old IMM and 7-, 12- and 15-day-old NOW larvae were irradiated at 150, 300, 450 and 600 Gy. Test larvae were held at 27°C until mortality or pupation and subsequent adult emergence.

The effect on larval feeding behavior and development was examined using 6-day-old IMM and NOW larvae irradiated at 300 and 450 Gy. Immediately after treatment larvae were transferred to beakers with fresh diet where they were allowed to feed for several days before a second transfer to fresh diet. The amount of diet consumed in both sets of beakers was visually rated as an indication of larval feeding activity. Larval development was monitored by periodically weighing individual larvae.

The effect on larval damage to the commodity was determined by irradiating IMM and NOW larvae at 300 and 450 Gy in 1 oz cups filled with bran diet. Immediately after treatment, the larvae were transferred to pint mason jars containing 125 g of the appropriate commodity. The larvae were allowed to feed and develop on the commodity. After adult emergence, the commodities were inspected and rated for damage.

Figures 1 and 2 show percent larval mortality over time for 6- and 11-day-old IMM respectively. In both cases, control mortality was very low, while most treated larvae died before pupation. Thirteen percent of the 11-day-old larvae treated at 150 Gy successfully pupated, but none completed development to emerge as adults. Thus, even 150 Gy is sufficient to prevent adult emergence and reproduction.

Mortality in irradiated 6-day-old larvae began almost immediately after treatment. Complete mortality for the 600, 450, 300 and 150 Gy treated larvae occurred at 14, 19, 30 and 42 days post-treatment, respectively. Mortality in control larvae was 4%, while 90% had pupated by 24 days post-treatment.

Compared to that of younger larvae, mortality in 11-day-old larvae was delayed and did not begin until 19 days post-treatment. In contrast, 90% of the control larvae had successfully pupated by 14 days post-treatment. Maximum mortality for the 600, 450, 300 and 150 Gy-treated larvae was reached at 36, 44, 46 and 50 days post-treatment, respectively. Although older larvae die before or shortly after pupation, radiation does extend their lifespan considerably past the normal. While the lifespan of younger larvae is not necessarily extended after irradiation it does take as long as 2 weeks after treatment, even at the highest dose, for complete mortality to occur.

The results from the NOW studies were similar. Figures 3, 4 and 5 give percent larval mortality for 7-, 12- and 15-day-old NOW larvae. Control mortality for NOW was much higher than for IMM, due to the diet drying out. As in the IMM, mortality began earlier in the younger irradiated larvae. The older the larvae, the more time was required for complete mortality to occur.

Maximum control pupation for 7-day-old NOW larvae occurred 19 days post-treatment. Complete mortality ranged from 15 days post-treatment for 600 Gy to 38 days post-treatment for 150 Gy. The lifespan of younger NOW larvae was not abnormally extended after irradiation.

Complete mortality in the older, 12-day-old NOW larvae took from 27 to 54 days post-treatment, depending upon the dose. Maximum control pupation was reached 21 days post-treatment. In this case, only the lower doses seem to extend the larval stage.

For the oldest NOW larvae, maximum control pupation occurred 15 days post-treatment while complete mortality of irradiated larvae emerged from 38 to 56 days. As with the IMM, radiation at all doses extended the lifespan of nearly mature larvae.

Larval development, measured as weight gain, was inhibited by radiation. Figure 6 gives the mean weights of 6-day-old IMM larvae. Control mean weight increases very rapidly and then drops with the onset of pupation. Mean weight of irradiated larvae increases during the first 6 days post-treatment and then levels off. The peak weight for larvae treated at 300 Gy was 52% of the peak weight for controls, while 450 Gy treated larvae weighed 32% of the controls.

The effect is even more noticeable in 6-day-old NOW larvae (Figure 7). When compared to the mean weight of control larvae the peak weight of larvae treated at 300 and 450 Gy was only 11 and 8% that of the controls, respectively. While it appears that NOW larvae are more radiosensitive than IMM, it is not possible to directly compare the results of this test. Radiosensitivity depends to some extent on the developmental stage irradiated. Thus, the relative radioresistence of the IMM larvae was probably due to their being in a more developmentally advanced stage. In any event, radiation does slow and eventually stop larval development.

A decrease in weight gain suggests that radiation interferes with normal larval feeding. When the extent of post-treatment feeding on artificial diet is examined (Table 7), this is found to be true. By 6 days post-treatment, 93.8% of NOW control larvae displayed moderate or extensive feeding activity, as opposed to 26.6 and 5.4% shown by larvae irradiated at 300 and 450 Gy. Most treated NOW larvae were capable of only slight feeding. IMM showed similar results, with 83.8% of control larvae exhibiting moderate feeding and few treated larvae capable of more than slight feeding.

The reduction in larval feeding continued between 6 and 10 days post-treatment. Again, 94% of NOW control larvae displayed moderate or extensive feeding activity, while all treated larvae showed slight or no feeding. No moderate or extensive feeding was exhibited by any IMM larvae, including the controls. But while the reduction in feeding activity in irradiated larvae can be attributed to the treatment, in control larvae it was a result of nearly 90% pupation.

Commodity damage due to larval feeding was also reduced after treatment. Tables 8, 9 and 10 summarize the results of damage evaluations of NOW and IMM infested almonds, walnuts and raisins, respectively. In all cases, significantly more of the commodity escaped or received only negligible damage when infested with irradiated larvae than with untreated insects. Also, commodities infested with untreated larvae showed significantly more moderate damage than did those infested with irradiated larvae. It should be noted that the infestation levels used in these experiments are very high, with 40 to 50 larvae present in 125 g of commodity. Damage from irradiated larvae should be far less noticeable at infestation levels normally found in commercial processing systems.

No adult moths were recovered from any of the commodities infested with irradiated larvae. Adult emergence from nuts containing untreated larvae ranged from 62.5 to 90.8%. Emergence of IMM adults from raisins infested with untreated larvae was only 33.2%, suggesting that raisins are a poor diet for IMM development.

Post-infestation weights of nuts infested with untreated NOW were significantly lower than those infested with irradiated NOW. Larvae of the IMM, being smaller than NOW larvae, consume less of the commodity, thus significant weight differences were harder to detect. Almonds infested with untreated IMM showed significantly lower post-infestation weights than almonds with irradiated IMM, but weight of walnuts with untreated IMM were not significantly different from those infested with IMM irradiated at 450 Gy. No significant differences in weight were detected in any of the IMM-infested raisins.

Driedfruit Beetle

Since both larvae and adult driedfruit beetles feed, and the average adult lifespan is 3 to 4 months, the criteria for determining efficacy cannot be limited to adult sterility and reduction of larval feeding. The lifespan of irradiated adults must be shortened and their feeding also reduced.

Larval infestations of raisins were obtained by adding large numbers of adult beetles to pint jars containing 125 g of moist raisins. The beetles were allowed to oviposit in the jars for 3 days and then removed. The jars were shipped to Albuquerque and irradiated at 150, 300, 600 and 900 Gy. Three different age groups of larvae were treated.

Test jars were held after treatment at 27°C. When larvae were judged to be near maturity, the jar lids were replaced with course screen and the jars inverted over cartons containing moist sand. The sand was examined periodically for mature larvae, pupae and adults.

Even-aged DFB pupae were obtained by extracting prepupae from the sand substrate of rearing jars. Newly emerged pupae were collected periodically over a span of 3 days and held at 10°C until a sufficient number were obtained. The pupae were then segregated by sex and placed in moist vermiculite in 2 ml vials for transport and irradiation at 300 and 450 Gy. All pupae were held at 27°C for adult emergence.

Pupae extracted from rearing jars were segregated by sex and held until adult emergence. The resulting virgin adults were shipped and irradiated in plastic vials at 300 and 450 Gy. After treatment, groups of males and females from each treatment level were placed in pint rearing jars containing moist, sterile sand and banana slices. The jars were checked periodically for adult mortality and progeny development.

No irradiated larvae of any age survived to the adult stage (Table 11). Of the larvae irradiated when 7 to 10 days old, most survived to the mature wandering stage and were recovered in the sand beneath the test jars. When compared with controls, a significantly greater number of irradiated larvae were found dead shortly after their emergence from the raisins (19 to 21 days after commodity infestation). Very few larvae irradiated when 4 to 7 days old survived to the wandering stage, and all had died 19 to 21 days after infestation. No irradiated larvae treated when 1 to 4 days old were found in the sand. For DFB, even the lowest dose was enough to prevent adult emergence from the most resistant, older larvae.

Pupae of the DFB proved considerably more radiosensitive than the IMM. Pupal mortality was 91.5 and 98% for 300 and 450 Gy, respectively, with pupal sex having no observable effect on mortality (Table 12). Adults emerging from irradiated pupae died shortly (within 48 hrs) after emergence. The results from the adult irradiation were difficult to interpret, due to erratic control mortality. Within one week after treatment, all treated adults were dead, while control mortality was less than 50%. No progeny were detected in the rearing jars containing irradiated adults. Untreated control adults produced large numbers of healthy progeny.

Conclusions

Our results corroborate those of earlier studies and show that gamma radiation treatments for insect disinfestation of dried fruits and nuts are efficacious, although certain limitations of the method must be accepted. The most practical dose for providing a sufficient level of control of the three insects considered in this study is 300 Gy. This dose would be considered the minimum dose required within the commodity for adequate control. Since most engineering designs specify a 1.5:1 or 2:1 maximum:minimum dose ratio, the applied dose would be between 450 and 600 Gy.

Because of the possible presence within treated commodities of any stage of the Indianmeal moth, the effect of radiation on all stages must be considered. The number of progeny of female IMM irradiated as pupae or adults can be reduced by 99 to 100% with a 300 Gy dose, but adult emergence and longevity are not significantly reduced. One possible disadvantage could then be consumer reaction to the presence of living, though sterile adults within the commodity. Adult IMM are not long-lived, and most moths would not survive after normal processing and shipping times.

A treatment dose of 300 Gy effectively halts reproduction in female IMM irradiated as pupae or adults, but only partially sterilizes similarly treated males. Partial male sterility should not be considered a disadvantage. Since irradiated males would have to mate with unirradiated females to produce progeny and any such females migrating into the treated product would probably have already mated with unirradiated males, the presence of only partially sterile males after treatment does not present a threat of reinfestation to the product.

Incomplete male sterility may actually be advantageous by slowing reinfestation from outside sources. Should any untreated virgin females invade the treated product and mate with an irradiated male, their progeny would be almost completely sterile, even when mating with untreated adults. Thus the presence of partially-sterile males may form a reproductive barrier to invasion of the commodity, slowing reinfestation. However, radiation sometimes reduces competitiveness in male moths, so the actual impact on the invading population may be negligible.

The delay in mortality of irradiated NOW and IMM larvae as compared to fumigation may prove a more serious disadvantage. Complete mortality may take nearly two months to occur, depending upon larval age, so that even though larval development and feeding damage are substantially reduced, the presence of living larvae within commodities may elicit negative consumer response. To some extent, the severity of the problem is lessened by the fact that larvae become sluggish shortly after treatment and often take on a shrivelled appearance.

As was expected, all stages of the DFB proved to be relatively radiosensitive, with 300 Gy preventing reproduction of pupae and adults and development of larvae. Complete mortality of irradiated adults and pupae occurred within one week after treatment. While exact measurements of larval longevity after treatment were not made, visual examination of treated raisins yielded no noticeable living larvae by two weeks after irradiation, with the youngest larvae dying even sooner. Thus, for the DFB, radiation as a control method does not have the same disadvantages found with lepidopterous larvae.

Even after taking into account the disadvantages noted above, our study indicates that gamma radiation treatments of 300 Gy would provide control comparable to that obtained with existing methyl bromide treatments. Additional studies need to be conducted before adopting this technology as a control procedure. Since the product may be treated when coming directly from the field or cold storage, the effects of temperature extremes on efficacy must be determined. Radiation may be used in conjunction with modified atmospheres, and so any antagonistic or synergistic effects from the combination of these two methods must be investigated. Pilot scale studies must also be done to corroborate laboratory findings with field data.

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Table 1. Percent adult emergence from IMM irradiated as pupae in commodities: Test I.

Dose (Gy)	Raisins		Almonds		Walnuts		Combined	
	♀	♂	♀	♂	♀	♂	♀	♂
0	98 a	96 a	88 a	91 a	93 a	95 a	93 a	94 a
150	98 a	96 a	85 a	92 a	95 a	89 ab	93 a	93 a
300	94 a	92 a	86 a	79 b	95 a	84 bc	92 a	85 b
600	73 b	67 b	74 b	52 c	69 b	75 c	72 b	65 c
900	0 c	0 c	0 c	0 c	0 c	0 d	0 c	0 d

Data subjected to arcsine transformation. ANOVA and DMRT done at the 5% level of significance. Same letters after column means indicate no significant difference.

Table 2. Percent adult emergence from IMM irradiated as pupae in commodities: Test II.

Dose (Gy)	Raisins		Almonds		Walnuts		Combined	
	♀	♂	♀	♂	♀	♂	♀	♂
0	91 a	96 a	83 a	80 a	94 a	90 a	90 a	89 a
150	94 a	94 a	81 a	84 a	89ab	92 a	89 a	90 a
300	86 a	90 a	83 a	85 a	81 b	82 b	84 a	86 a
600	70 b	60 b	55 b	50 b	46 c	56 b	57 b	56 b
900	0 c	8 c	18 c	0 c	0 d	0 c	6 c	3 c

Data subjected to arcsine transformation. ANOVA and DMRT done at the 5% level of significance. Same letters after column means indicate no significant difference.

Table 3. Adult progeny numbers of IMM irradiated as pupae in commodities.

Dose (Gy)	Mating combinations	Raisins		Almonds		Walnuts		Combined	
		Test I	Test II	Test I	Test II	Test I	Test II	Test I	Test II
0	N ♀ x N ♂	270.0 a	202.4 a	229.6 a	200.1 a	225.0 a	198.3 a	241.5 a	200.3 a
150	I ♀ x I ♂	0 c	2.3 c	0.2 b	1.2 c	0.6 b	3.0 d	0.3 c	1.3 d
	I ♀ x N ♂	1.2 c	3.0 c	0.4 b	1.7 c	0.2 b	0.6 d	0.6 c	1.8 d
	N ♀ x I ♂	160.4 b	179.2 a	205.8 a	133.8 b	225.0 a	154.9 b	197.1 b	156.0 b
300	I ♀ x I ♂	0 c	0 c	0 b	0 c	0 b	0 d	0 c	0 d
	I ♀ x N ♂	0 c	0 c	0 b	0 c	0 b	0 d	0 c	0 d
	N ♀ x I ♂	17.2 c	58.7 b	34.0 b	30.2 c	17.4 b	56.4 c	22.9 c	48.4 c

ANOVA and DMRT done at the 5% level of significance. Same letters after column means indicate no significant difference.

Table 4. Progeny numbers and percent reduction of F_1 offspring of IMM irradiated as pupae.

Dose (Gy)	Parental	Mating combination	Test I		Test II	
			$\bar{X}$ progeny numbers	% reduction from control	$\bar{X}$ progeny numbers	% reduction from control
0	control	N♀ x N♂	280.6 a	-	332.6 a	-
150	I♀ x I♂	F_1♀ x F♂	-	-	1.5 b	99.5
		F_1♀ x N♂	-	-	84.0 ab	74.7
		N♀ x F♂	-	-	22.0 b	93.4
	I♀ x N♂	F_1♀ x F_1♂	-	-	35.3 b	89.4
		F_1♀ x N♂	-	-	176.7 ab	46.9
		N♀ x F_1♂	-	-	107.5 ab	67.7
	N♀ x I♂	F_1♀ x F_1♂	3.9 c	98.6	10.7 b	96.8
		F_1♀ x N♂	118.3 b	57.8	164.7 ab	50.5
		N♀ x F_1♂	38.8 c	86.2	58.0 b	82.6
300	N♀ x I♂	F_1♀ x F_1♂	16.8	94.0	0 b	100
		F_1♀ x N♂	18.2 c	93.5	5.0 b	98.5
		N♀ x F_1♂	7.3 c	97.4	0 b	100

ANOVA and DMRT done at the 5% level of significance. Column means followed by the same letter are statistically similar.

Table 5. Mean progeny numbers of irradiated adult IMM.

Mating combination	$\bar{X}$ progeny numbers	% reduction from control
Control	279.8 a	-
150 Gy I♀ x I♂	8.6 de	96.9
150 Gy I♀ x N♂	25.9 c	90.7
150 Gy N♀ x I♂	152.3 b	45.6
300 Gy I♀ x I♂	0 e	100
300 Gy I♀ x N♂	0.4 e	99.9
300 Gy N♀ x I♂	21.3 cd	92.4
600 Gy I♀ x I♂	0 e	100
600 Gy I♀ x N♂	0 e	100
600 Gy N♀ x I♂	0 e	100
900 Gy I♀ x I♂	0 e	100
900 Gy I♀ x N♂	0 e	100
900 Gy N♀ x I♂	0 e	100

ANOVA and DMRT done at 5% level. Column means followed by the same letter are statistically similar.

Table 6. Progeny numbers and percent reduction of F_1 offspring of IMM irradiated as adults.

Dose (Gy)	Parental	Mating combination	$\bar{X}$ progeny numbers	% reduction
0	Control	N ♀ x N ♂	198.0 a	-
150	I♀ x I♂	F_1 ♀ x F_1♂	0 d	100
		F_1 ♀ x N ♂	39.4 cd	80.1
		N ♀ x F_1♂	4.8 d	97.6
	I♀ x N♂	F_1 ♀ x F_1♂	82.3 bc	58.4
		F_1 ♀ x N ♂	125.2 b	36.8
		N ♀ x F_1 ♂	115.1 b	41.9
	N♀ x I♂	F_1 ♀ x F_1 ♂	0 d	100
		F_1 ♀ x N ♂	28.0 cd	85.9
		N ♀ x F_1 ♂	1.0 d	99.5
300	N♀ x I♂	F_1 ♀ x F_1 ♂	0 d	100
		F_1 ♀ x N♂	5.4 d	97.3
		N♀ x F_1 ♂	1.4 d	99.3

ANOVA and DMRT done at the 5% level of significance. Column means followed by the same letter are statistically similar.

Table 7. Extent of feeding on artificial diet by NOW and IMM larvae after irradiation.

Days post treatment	Dose (Gy)	NOW					IMM				
		0	Trace-10%	10-50%	> 50%	Pupae	0	Trace-10%	10-50%	>50%	Pupae
1-6	0	0	6.2 a	76.5 a	17.3 a	0	1 a	15.2 a	83.8 a	0	3.0
	300	0	73.4 b	25.4 b	1.2 b	0	7.2 b	87.2 b	5.6 b	0	0
	450	0	94.6 c	5.4 c	0 c	0	7.1 b	92.9 b	0 c	0	0
6-10	0	0 a	6.0 a	78.4 a	15.6 a	3.8	71.8 a	28.2 a	0	0	89.9
	300	23.4 b	76.6 b	0 b	0 b	0	50.0 a	50.0 b	0	0	0
	450	14.8 c	85.2 b	0 b	0 b	0	69.0 b	31.0 a	0	0	0

Means subjected to arcsine transformation. ANOVA and DMRT done at the 5% levels of significance. Column means followed by the same letter are statistically similar.

Table 8. Percent damaged nuts in almonds infested with irradiated NOW and IMM larvae.

Test Insect	Dose (Gy)	Extent of damage				Weight of commodity (g)
		Negligible	Slight	Moderate	Extensive	
NOW	0	19.6 a	13.3 ab	65.4 a	1.7 a	114.5 a
	300	63.8 b	11.7 b	24.5 b	0 b	120.0 b
	450	71.7 b	15.5 a	12.8 c	0 b	119.9 b
IMM	0	25.3 a	32.4 a	42.3 a	0	118.3 a
	300	57.3 b	17.1 c	25.6 b	0	119.7 b
	450	60.3 b	24.1 b	15.6 c	0	119.9 b

Initial commodity weight = 125 g. Data subjected to arcsine transformation. ANOVA and DMRT done at the 5% level of significance. Column means followed by the same letter are statistically similar.

Table 9. Percent damaged nuts in walnuts infested with irradiated NOW and IMM larvae.

Test Insect	Dose (Gy)	Extent of damage				Weight of commodity (g)
		Negligible	Slight	Moderate	Extensive	
NOW	0	0.8 a	3.0 a	87.5 a	8.8 a	111.7 a
	300	70.6 b	16.2 c	12.5 b	0.7 b	122.1 b
	450	89.6 c	7.2 b	3.2 c	0 b	121.4 b
IMM	0	32.8 a	10.8 a	56.4 a	0 a	119.7 a
	300	85.6 b	6.4 a	8.0 b	0 a	122.7 b
	450	91.0 b	5.6 a	3.4 c	0 a	120.0 a

Initial commodity weight = 125 g. Data subjected to arcsine transformation. ANOVA and DMRT done at the 5% level of significance. Column means followed by the same letter are statistically similar.

Table 10. Percent damaged raisins infested with irradiated IMM.

Dose (Gy)	Extent of damage				Weight of commodity (g)
	Negligible	Slight	Moderate	Extensive	
0	7.2 a	26.8 a	63.2 a	2.8 a	113.2 a
300	21.1 b	41.6 b	37.2 b	0.1 b	115.2 a
450	22.0 b	36.0 b	42.0 b	0 b	114.2 a

Initial commodity weight = 125 g. Data subjected to arcsine transformation. ANOVA and DMRT done at the 5% level of significance. Column means followed by the same letter are statistically similar.

Table 11. Survival of DFB larvae irradiated in raisins at 3 different ages.

Age class	Dose (Gy)	$\bar{X}$ No. DFB recovered 19-21 days after infestation		Total DFB surviving to adult stage
		Total living DFB	Total dead DFB	
A	0	40.8 a	0.2 a	39.0
(7-10 days)	150	27.4 b	18.2 b	0
	300	21.4 b	43.8 c	0
	600	1.4 c	45.8 c	0
	900	0 c	34.4 c	0
B	0	29.0	0.2	27.8
(4-7 days)	150	0	2.6	0
	300	0	4.0	0
	600	0	0	0
	900	0	0	0
C	0	44.6	2.0	42.6
(1-4 days)	150	0	0	0
	300	0	0	0
	600	0	0	0
	900	0	0	0

ANOVA and DMRT done at the 5% level of significance. Column means followed by the same letter are statistically similar.

Table 12. Percent mortality of DFB irradiated as pupae.

Dose (Gy)	% pupal mortality	% pupal mortality
0	19.5 a	20.1 a
300	91.5 b	91.5 b
450	98.0 b	98.0 b

Data subjected to arcsine transformation. ANOVA and DMRT done at 5% level of significance. Column means followed by the same letter are statistically similar.

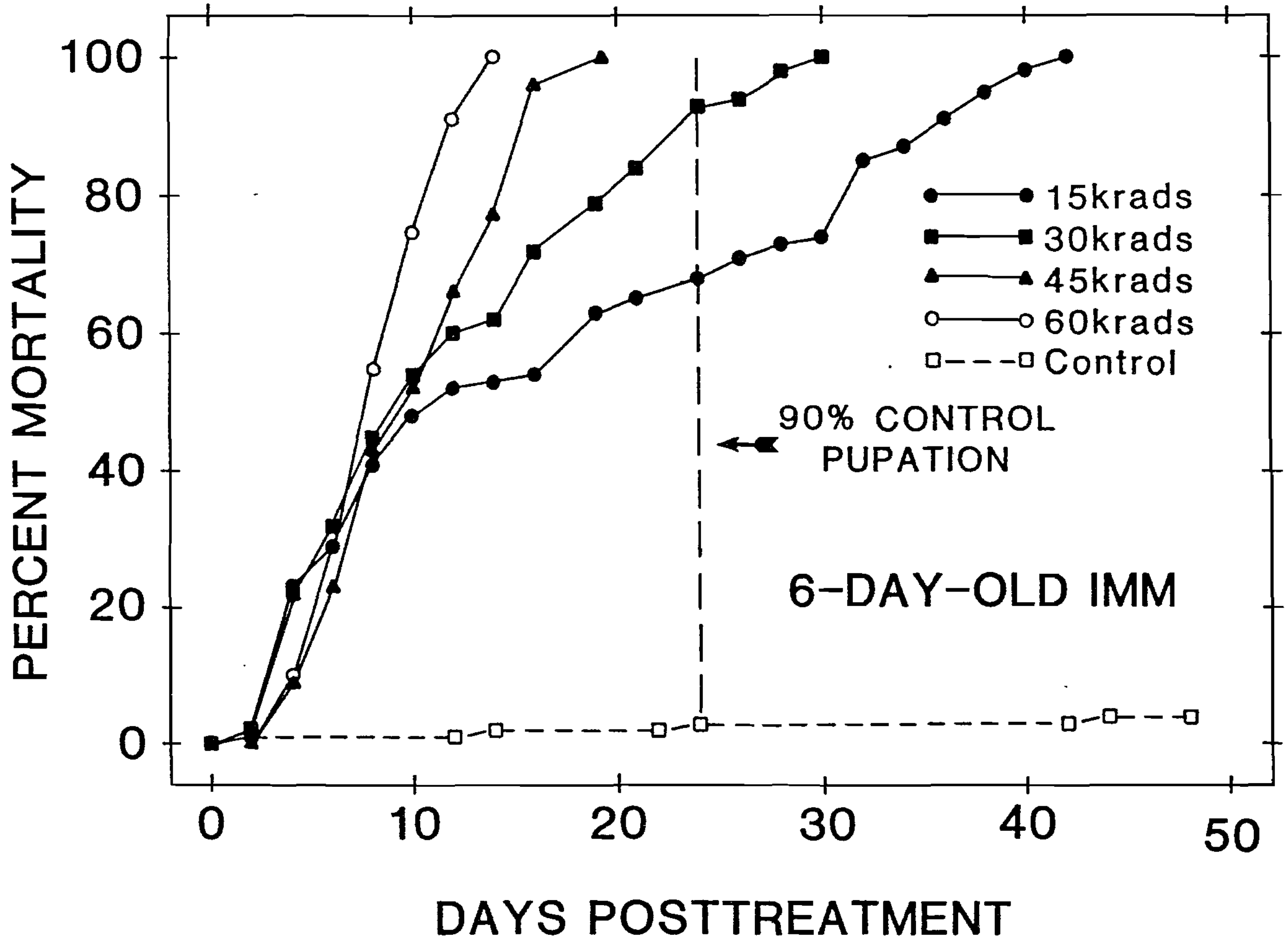

Fig. 1. Posttreatment mortality of 6-day-old IMM larvae irradiated at 150, 300, 450 and 600 Gy (15, 30, 45 and 60 krad) (n = 100).

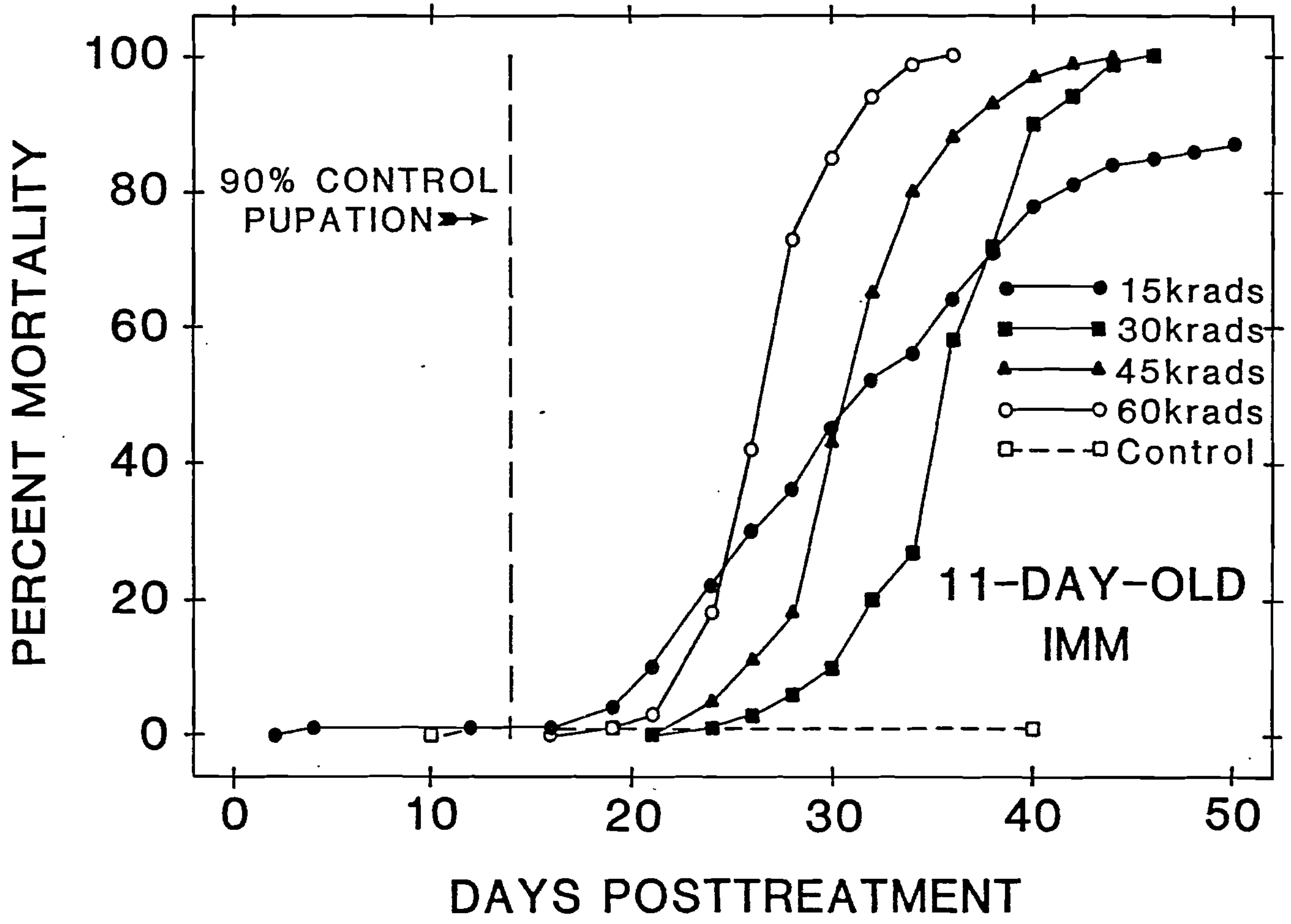

Figure 2. Posttreatment mortality of 11-day-old IMM larvae irradiated at 150, 300, 450 and 600 Gy (15, 30, 45 and 60 krad) (n = 100).

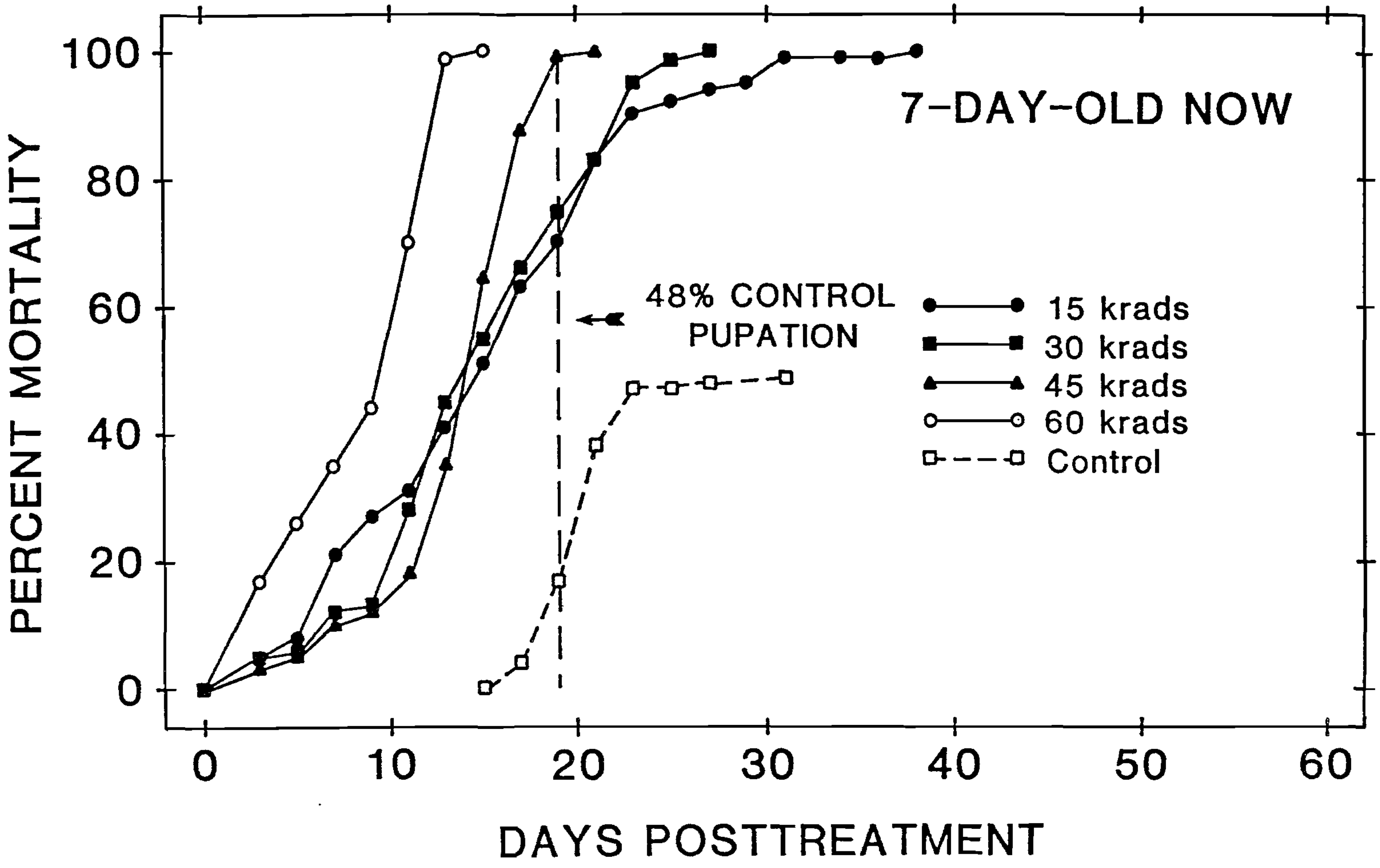

Figure 3. Posttreatment mortality of 7-day-old NOW larvae irradiated at 150, 300, 450 and 600 Gy (15, 30, 45 and 60 krad) (n = 100).

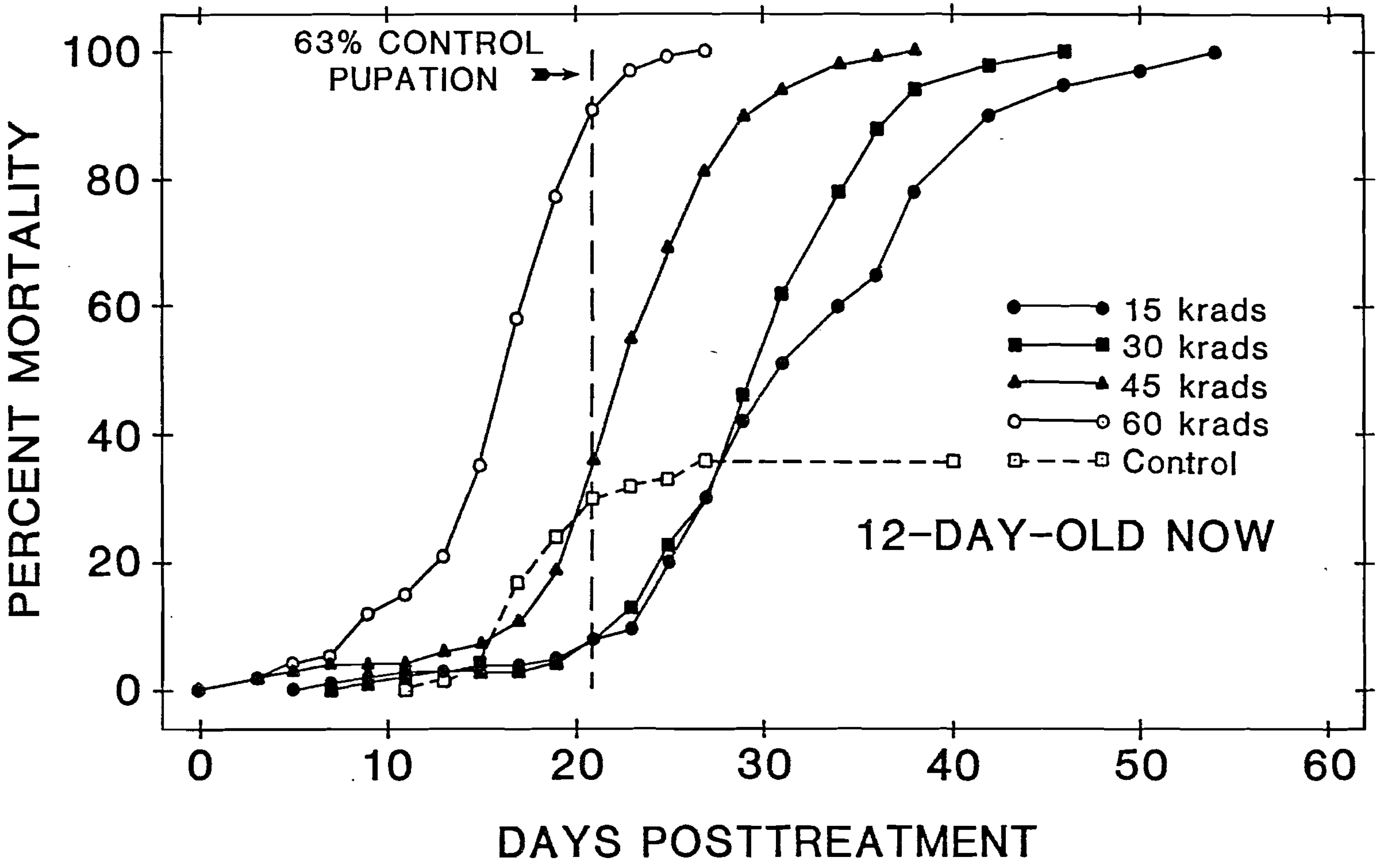

Figure 4. Posttreatment mortality of 12-day-old NOW larvae irradiated at 150, 300, 450 and 600 Gy (15, 30, 45 and 60 krad) (n = 100).

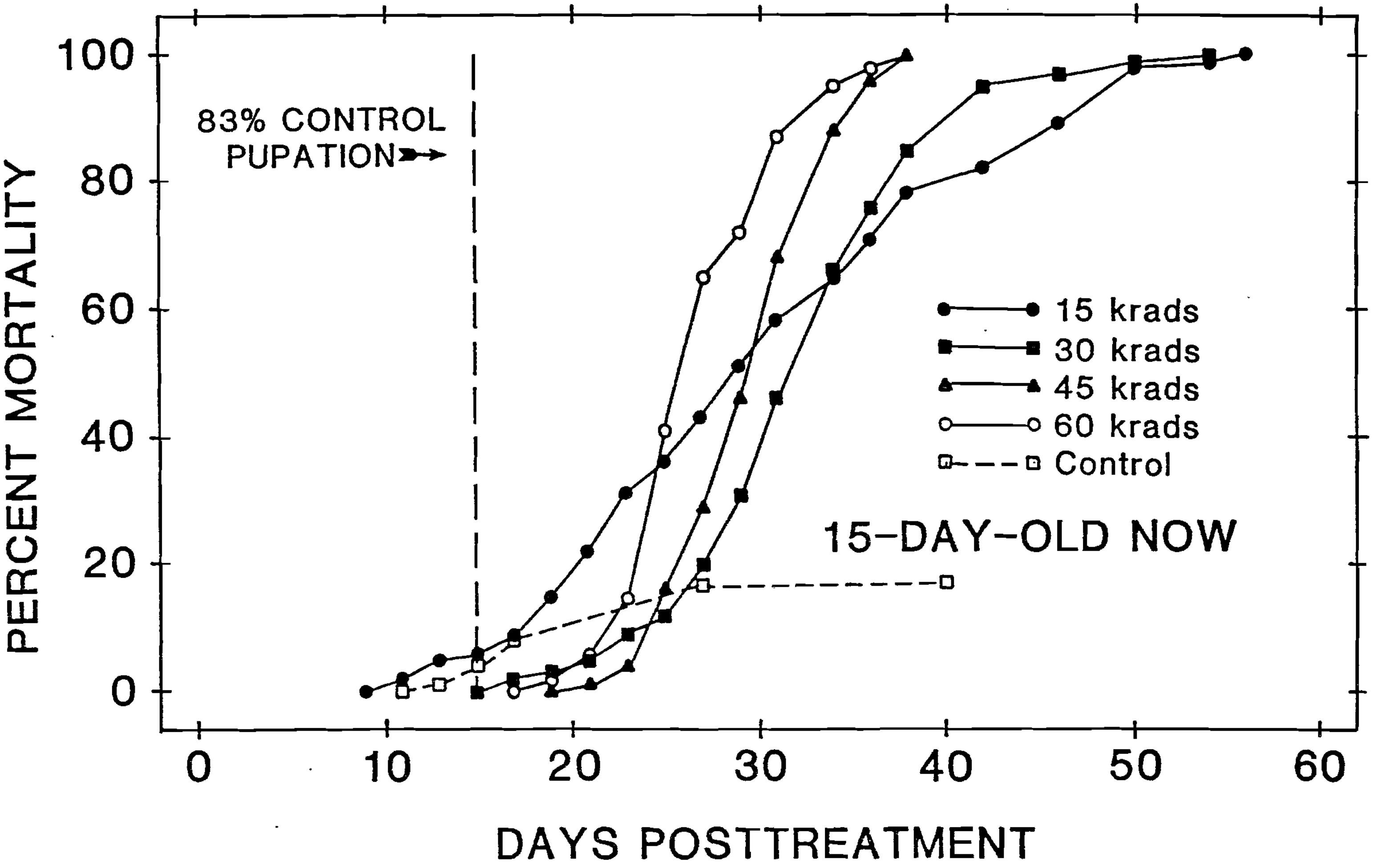

Figure 5. Posttreatment mortality of 15-day-old NOW larvae irradiated at 150, 300, 450 and 600 Gy (15, 30, 45 and 60 krad) (n = 100).

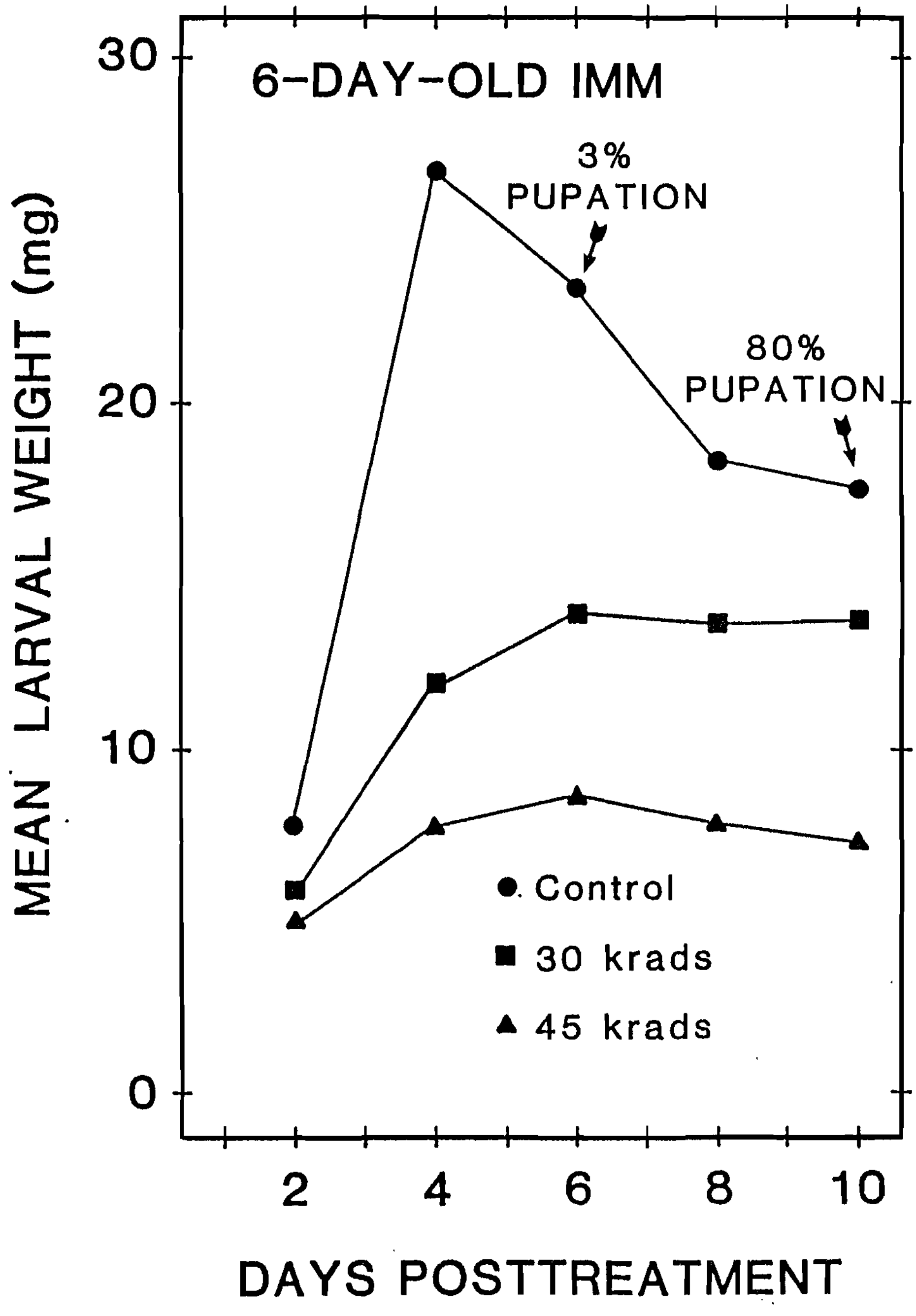

Figure 6. Posttreatment larval weights of 6-day-old IMM larvae irradiated at 300 and 450 Gy (30 and 45 krad) (n = 100).

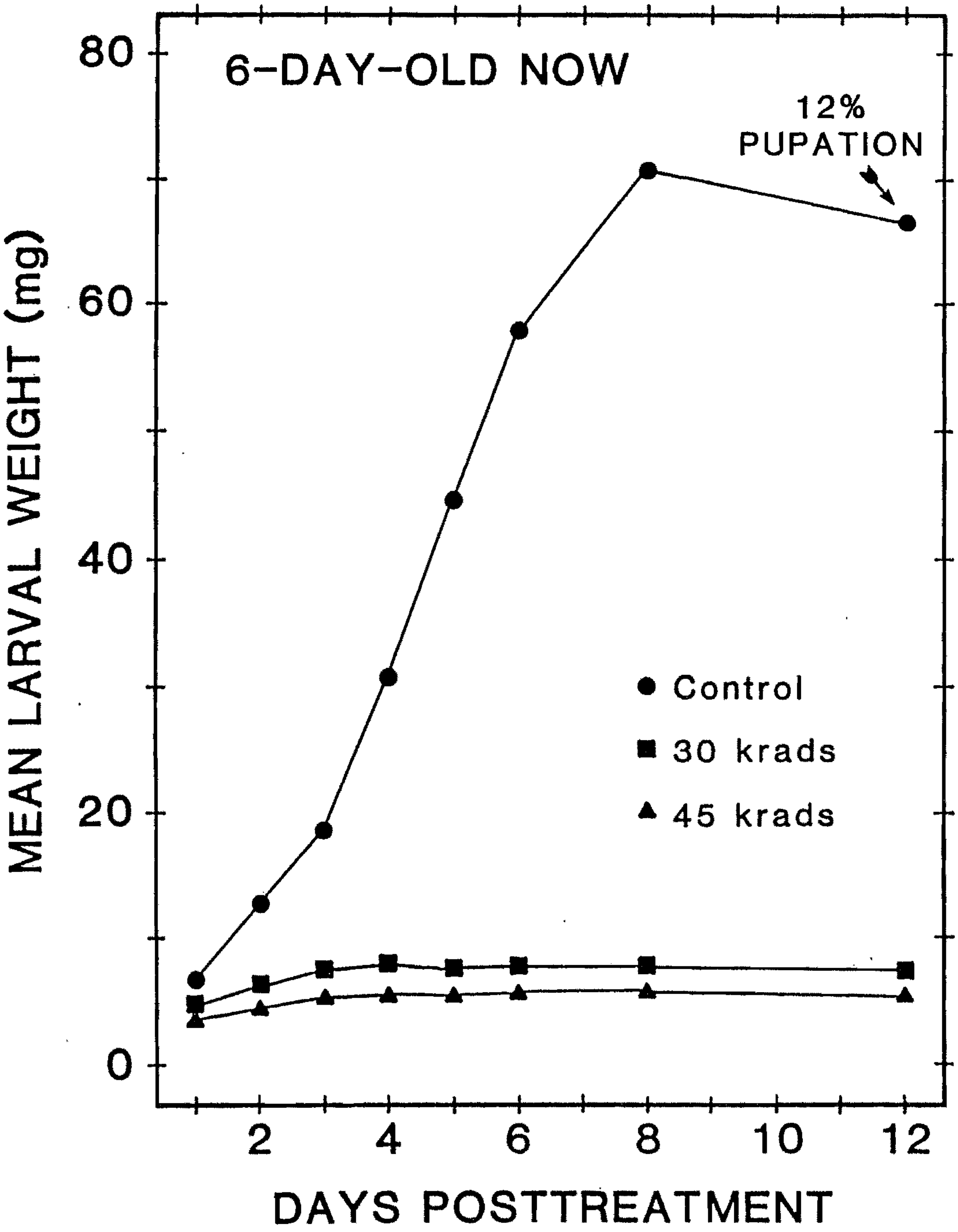

Figure 7. Posttreatment larval weights of 6-day-old NOW larvae irradiated at 300 and 450 Gy (30 and 45 krad) (n = 100).

EFFICACY OF GAMMA RADIATION TREATMENTS FOR DISINFESTATION OF WALNUTS INFESTED BY CODLING MOTH LARVAE

by

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Introduction

Larvae of the codling moth, Cydia pomonella (L.) infest walnuts as well as apples, pears, and many other deciduous fruit crops. Research at Fresno, Calif. (Hartsell unpublished) has demonstrated that methyl bromide fumigation is effective as a quarantine treatment for codling moth eggs and larvae in walnuts. Mature larvae usually leave the host fruit in search of a suitable location to spin a cocoon and, therefore, mature diapausing larvae would not be present in harvested fruit at the time of treatment. However, larvae occasionally remain in walnuts where they spin a cocoon and enter diapause to overwinter. Extended treatments using MB are required to control such diapausing larvae.

In the Northwestern USA the codling moth usually has two generations. It overwinters as diapausing larvae in cocoons, pupates in the early spring and emerges as an adult moth. Eggs are laid, hatch and produce larvae that usually pupate and produce adults in midsummer. These moths lay eggs that produce a second generation of larvae. Such larvae usually mature in late summer and leave the fruit in search of a suitable site in which they can spin a cocoon to overwinter.

Fumigation using methyl bromide has been accepted by Japan and Korea as a treatment to eliminate any codling moth infestation that may be present in cherries (Anonymous 1978, Anonymous 1984). However, thus far we have not been successful in developing such a treatment for most other hosts.

Research has demonstrated that irradiation is an effective treatment for stored grain as well as fruit pests (Tilton and Burditt 1983). Research on development of quarantine treatments at Yakima, Wash. has indicated that gamma irradiation would be effective against mature, cocooned diapausing and non-diapausing codling moth larvae in fiberboard strips and against mature or immature codling moth larvae in apples (Burditt and Moffitt 1985, Burditt et al. 1985). Research was undertaken at USDA-ARS laboratories in Fresno, Calif. and Yakima, Wash., in cooperation with the U. S. Department of Energy, to determine if radiation would be a suitable alternative to fumigation as a treatment for disinfestation of dried fruits and nuts. Studies on codling moth larvae infesting walnuts were conducted at Yakima to determine the dose of irradiation required to prevent pupation of larvae and emergence of adults (Burditt 1986).

Materials and Methods

Codling moth larvae used in this research were from a colony that has been maintained on thinning apples for over 20 years as described by Hamilton and Hathaway (1966) and Burditt and Moffitt (1985). Non-diapausing larvae were obtained by holding infested thinning apples in fiberboard trays at ca 24°C and 60-80% RH with a 16:8 hour light: dark cycle. Diapausing larvae were obtained by holding the fruit in trays at 16-18°C and 60-80% RH with an 8:16 hour light: dark cycle.

The effect of gamma radiation on development of non-diapausing codling moth larvae was determined by treatment of infested thinning apples. On

May 24, 1984 codling moth eggs were placed on thinning apples, in 36 fiberboard trays, each containing ca 380 infested thinning apples.

On May 30, 10 of the trays of infested apples were selected at random. Ten fruit from each of these trays were placed in each of 33 3.8-litre (17 cm diameter x 18 cm high) paperboard cartons. Fluted fiberboard strips were placed in each carton to provide a suitable site in which mature larvae would be able to spin cocoons and subsequently pupate. On May 31, the 100 fruit in 1 carton were cut to determine the stages of development of larvae present. The remaining cartons, each containing 100 infested fruit, were irradiated, as described below, at applied doses of 0, 9.8, 19.6, 39.2, 58.7, 78.3, 97.9 or 117.5 Gy. [Previously published data (Burditt et al. 1985) used nominal doses.]

On June 7, 10 more of these trays of infested apples were selected and the above procedure was repeated. On June 8, the cartons of infested fruit were treated at applied doses of 0, 19.6, 39.2, 58.7, 78.3, 97.9, 117.5 or 138.0 Gy.

Fiberboard strips were placed on the infested apples in the remaining 16 trays to collect mature larvae. On June 11, the strips were removed and placed in 32 paperboard cylinders 4 cm diameter x 11.4 cm long. These were treated on June 12 at applied doses of 0, 41.4, 62.0, 82.7, 103.4, 124.1, 145.7 or 166.4 Gy.

The fiberboard strips from each treatment were removed and replaced at weekly intervals for 3 weeks and held in 1-quart cartons to permit mature larvae to form pupae and adults to emerge. Adult emergence was determined daily from June 21 until July 18. The strips were held until August 8 to insure that emergence was complete. Subsequently the strips were opened to determine the number and stage of development of any insects remaining in the strips. Finally, the infested apples were cut to determine the number and stage of development of insects remaining in the fruit.

Samples were exposed to gamma radiation supplied by an AECL Gammabeam-650 irradiator at Battelle Pacific Northwest Laboratories, Richland, Wash. It had an initial (1971) loading of 50,000 Ci of cobalt-60. The unit has 12 vertical tubes into which the cobalt is raised and held in place pneumatically during the timed exposure period. The 12 source tubes are adjustable to a closed position (7 cm diameter space between the tubes) or an open position (80 cm diameter space) or any intermediate position. The tubes had an initial sequential loading of 8, 4, 0.5, 8, 4, 0.5, 8, 4, 0.5, 8, 4, 0.5, Ci; i.e., the loading was symmetric but not uniform. Since any one or group of tubes can be raised, this gives dose rate flexibility. The dose rate can also be adjusted by placing material outside the array of tubes on a platform rotating 3 times a minute. The room housing the source is 7.3 x 7.3 meters with the source in the center.

The gallon cartons containing infested apples or the paperboard cylinders containing strips, were placed on a Nordic Micro-Go-Round No. 62304 food rotator which rotated at approximately 0.5 rev/min. Two cartons were placed one on top of the other on the Go-Round which was in the center of the open tubes; i.e., 80 cm diameter spacing. Four cylinders, held together by a rubber band, were placed on the Go-Round for treatment.

A series of measurements made with direct NBS-traceability indicated the mid-point dose rate was 9.4 Gy/min. Measurements with the cartons of apples in place with both a Victoreen thimble and with TLD chips (LiF) indicated the mean dose at the center of the carton was 8.9 Gy/min. The 5% difference is accounted for by the dose absorbed by the apples. There was up to a 15% dose variation with position of the apples in the two stacked cartons; i.e., the mid-point was highest with lower doses above and below the mid-point during the May 31 and June 8 exposures. The paperboard cylinders containing cocooned larvae in fiberboard strips were exposed on June 12 so that the dose rate delivered to the larvae was 9.4 Gy/min. Exposure times were: May 31 - 1.1, 2.2, 4.4, 6.6, 8.8, 11 and 13.2 minutes; June 8 - 2.2, 4.4, 6.6, 8.8, 11, 13.2 and 15.5 minutes; June 12 - 4.4, 6.6, 8.8, 11, 13.2, 15.5 and 17.7 minutes.

The effect of gamma radiation as a treatment for disinfestation of walnuts infested by codling moth larvae was determined by treatment of nuts containing mature, cocooned larvae. In order to estimate the dosage required to prevent emergence of adults from mature larvae, a total of 26 trays, each containing ca. 380 infested apples, were held under conditions for production of non-diapausing larvae. After 16 days, when the larvae were in the 4th or 5th instar, 35 walnuts were placed on each tray of thinning apples. Holes 0.4 cm diameter had been drilled through the shell of each nut. As the larvae reached maturity, they left the apples and entered the nuts in search of a suitable site in which to spin their cocoons. After 3 days the infested nuts were removed, randomized and 5 nuts from each of 13 trays were placed in a 3.8 litre paperboard carton for irradiation.

Nuts from 1 carton from each of the replicates were examined to estimate the maturity and number of larvae in the nuts at the time of treatment. The remaining cartons of nuts were irradiated as described above. Two cartons containing infested walnuts were stacked vertically on food rotator in the center of the open irradiator tubes (Burditt et al. 1985). They were treated at the rate of 7.05±0.05 Gy/min. with doses of: 0, 42.3, 84.6, 126.9, 169.2 or 338.4 Gy. Following treatment, the nuts were placed in metal codling moth emergence boxes (Hutt et al. 1972) and adult emergence was determined daily until no moths had emerged for at least 30 days to insure that emergence was complete. Subsequently the boxes and nuts were opened and examined to determine the number of insects remaining and their stage of development.

An additional test was conducted to determine if adults could emerge following exposure of mature larvae to an irradiation dose estimated to prevent such emergence based on other research. Codling moth eggs were placed on thinning apples in 40 fiberboard trays, 20 of which were subsequently held under non-diapause-inducing conditions and 20 trays which were held under diapause-inducing conditions. Walnuts were placed on the former trays of apples after 16 and 19 days and on the latter trays after 36 and 40 days. After the larvae had entered the nuts and spun cocoons, the nuts were removed, randomized and 5 nuts from each of 10 trays were placed in 3.8 litre glass jars for irradiation. The jars of nuts were placed on the rotating platform surrounding the sources, with the jars placed 55 cm. from the cobalt sources, which were in the closed position. The nuts were exposed to 177 Gy at the rate of 3.62± 0.36 Gy/min. Halfway through the treatment the jars were rotated 180° to give a more uniform exposure. Following treatment the nuts with larvae were held under non-diapause conditions to permit further development and adult emergence.

Treated and untreated larvae were held under similar conditions but in separate rooms to reduce the possibility of accidental contamination. Adult emergence was determined daily. When apparently normal males and females were available from larvae irradiated at 42.3 Gy, they were placed in plastic bags for mating and oviposition. Subsequently, the nuts were opened to determine how many of the remaining larvae had pupated.

Results and Discussion

Examination of a sample of the infested apples that was irradiated on May 31 showed that 54.6% of the young larvae present were 1st instar, 40.5% were 2nd instar and 4.9% were 3rd instar at the time of treatment. Examination of those that were irradiated on June 8 showed that 17.6% of the older larvae were 3rd instar, 17.6% were 4th instar and 64.8% were 5th instar. Examination of a sample of strips handled in a manner similar to strips irradiated on June 12 showed that 12% of the mature cocooned larvae could have transformed to pupae.

Data on the number of insects surviving exposure to gamma radiation as larvae and their subsequent development are summarized in Table 1. Data for the control treatments (0 Gy) were analyzed to determine if there were significant differences in the number of larvae in the initial population tested. These analyses showed that there was no significant difference in the total number of insects recovered from the populations tested on May 31 and June 8. However, the population of larvae tested on June 12 was significantly lower than the others since this population contained only the larvae that had matured, left the fruit and entered the strips prior to June 11 when they were removed for treatment.

Based on the stage of development of larvae at the time of treatment, we suggest that those larvae that were in the 2nd and 3rd instar when irradiated on May 31 apparently were able to continue their development and emerge as adults following exposure to 39.2 Gy. However, only the 3rd instar larvae were able to emerge as adults following exposure to 78.3 Gy and 89% of those were obviously abnormal in appearance, having malformed wings or abdomens. At an exposure of 97.9 Gy some of the 2nd and most of the 3rd instar larvae were able to form pupae. Larvae in the 1st instar at the time of treatment apparently were not able to mature and form cocoons following exposure to 58.7 Gy, although they were able to continue development and emerge as adults following exposure to 19.6 Gy. First instar larvae that died before reaching maturity apparently decomposed and could not be accounted for when the fruit or strips were examined (Table 1).

Based on the stage of development of larvae treated on June 8, we suggest that those larvae that were in the 3rd instar were not able to form pupae following exposure to 58.7 Gy, and most were unable to become mature larvae following exposure to 78.3 Gy. The groups of 3rd instar larvae that had been treated on May 31 developed to this stage twice as rapidly as those treated on June 8. Further research is needed to confirm our above suggestions. This would require detailed research on the effects of irradiation on further development of larvae treated in various stages of development and time required to reach a specific instar. Exposure on June 8 of older larvae to 78.3 Gy resulted in less adult emergence than expected, based on development when treated. However, the larvae were able to form pupae. Those larvae destined to become female moths were more susceptible to irradiation than the males, and terminated development as pupae.

The percentage of adult emergence from irradiated larvae was compared to adult emergence from untreated larvae to obtain the mortality due to irradiation dose. Percentage mortality was transformed to probits (Bliss 1935) in order to estimate the dose required for quarantine security based on probit 9 of 99.9968% mortality (Baker 1939). [Data reported previously (Burditt et al. 1985) were based on nominal doses. Those reported here have been corrected based on actual doses.]

Analyses of the dosage-mortality data for larvae irradiated on May 31 showed that quarantine security based on probit 9 (99.9968%) mortality could be achieved by an exposure to 130 Gy based on adult emergence. Exposure to 340 Gy would be required to prevent any 1st, 2nd or 3rd instar larvae reaching maturity and spinning cocoons. However, exposure to a dose of 116 Gy would eliminate 95% of the mature larvae.

Analyses of the dosage-mortality data for older or mature larvae (those irradiated on June 8 or 12) showed that the doses required to prevent adult emergence at the probit 9 security level were 174 and 223 Gy, respectively. Since many of the former larvae already were in the 5th instar, it was not possible to prevent such larvae from reaching maturity.

2. Efficacy of gamma radiation as a treatment for disinfestation of walnuts infested by codling moth larvae (Burditt 1986)

Data to estimate the dosage required for quarantine security using infested walnuts are summarized in Table 2. These data show that 83.2% of the untreated larvae were able to continue their development and emerge as adults, compared to 65.3, 22.3 and 0.9% for larvae in nuts exposed to doses of 42.3, 84.6 and 126.9 Gy, respectively. Many of the adults from irradiated larvae had malformed wings, abdomens, or other appendages. At these doses 40.7, 98.0 and 100%, respectively, of the insects that emerged as adults obviously were abnormal on external examination, compared to 2.0% of the adults from untreated larvae. When the larvae had been exposed to 169.2 or 338.4 Gy ca. 33% formed pupae but none emerged as adults.

Further examination of the adults developing from larvae in walnuts exposed to 42.3 Gy showed that 76% were males compared to 56% for adults developing from untreated larvae. All of the adults developing from larvae exposed to 84.6 or 126.9 Gy were males. At these doses, larvae destined to become female moths were unable to complete their pupal development. Attempts were made to mate apparently normal moths developing from larvae that had been exposed to 42.3 Gy. No eggs were laid by such moths.

The dosage-mortality curves resulting from probit analysis of these data are shown in Figure 1. The dose required for quarantine security (probit 9=99.9968% mortality) would be 127 Gy to prevent emergence of apparently normal adults and 188 Gy to prevent emergence of any adults from larvae reared under non-diapause conditions and irradiated as mature fifth instar cocooned larvae, in walnuts (Table 3).

Results from the exposure of larvae at 177 Gy are summarized in Table 4. These data show that diapausing larvae were more susceptible to irradiation than non-diapausing larvae. No adults emerged from diapausing larvae in walnuts that had been exposed to 177 Gy and only 2.9% of the larvae were able to form pupae. In contrast, 35.8% of the non-diapausing larvae formed pupae and 1.2% of the larvae continued their development and emerged as adults. However, these adults were obviously abnormal. These data also show that differences in development and emergence of adults from untreated diapausing and non-diapausing larvae were statistically significant. More adults emerged from those reared in non-diapause conditions and there were more larvae and abnormal adults from those reared in diapause conditions.

This research has demonstrated that irradiation from a cobalt 60 gamma ray source is effective as a quarantine treatment for inshell walnuts infested by mature cocooned diapausing or non-diapausing codling moth larvae (Burditt 1986). Previous research has shown that gamma radiation would prevent emergence of adults from larvae that had been irradiated as immature larvae in apples or as mature larvae in fiberboard strips (Burditt and Moffitt 1985, Burditt et al. 1985).

Conclusions

Research was conducted at the Yakima Agricultural Research Laboratory to determine the effect of gamma radiation on codling moth, *Cydia pomonella* (L.), larvae as a pest of quarantine importance infesting walnuts. Research on immature larvae could not be done using infested walnuts, since such infestations occur in immature nuts on the tree. Therefore, such studies were conducted using thinning apples. Research on mature larvae was conducted using mature, cocooned larvae either in fluted fiberboard strips or in mature, harvested walnuts.

Codling moth larvae reared on thinning apples at ca 24°C, 60-80% RH and 16:8 hours light: dark cycle were divided into 3 groups according to age. Young (1-3 instar) or older (3-5 instar) larvae in apples or mature, cocooned, non-diapausing codling moth larvae in strips were exposed to gamma radiation at doses up to 166.4 Gy (16.64 krad). Following irradiation the larvae were held to permit further development, pupation and adult emergence. The number of adults emerging as well as mature larvae and pupae present that did not produce adults was determined. Two deformed adults developed and emerged from the young larvae exposed to 97.9 Gy. Six deformed adults developed and emerged from older larvae exposed to 117.5 Gy and one from 138.0 Gy. Of the mature larvae treated at 124.1, 145.7 and 166.4 Gy, 14, 3 and 2 adults emerged, respectively. One of those from each of the 124.1 and 145.1 Gy treatments appeared to be normal in external appearance. At lower doses (39.2 to 82.7 Gy) adult emergence was reduced and many of those that did emerge were physically deformed. At 58.7 Gy, and above, adult emergence was restricted to mostly males. Examination of the dead puparia showed that many of the females were unable to complete their development and eclose as adults. Data from these studies were used to predict doses of gamma irradiation required as a quarantine treatment to prevent emergence of codling moth adults from fruit infested by larvae. These doses were 130, 174 and 223 Gy for young, older and mature larvae, respectively.

Irradiation was considered as a potential treatment for disinfestation of either diapausing or non-diapausing mature cocooned codling moth larvae in walnuts. Exposure of larvae to 42.3 or 84.6 Gy from a cobalt-60 gamma source significantly reduced emergence of normal adults. The dose required for quarantine security (99.9968% mortality) was 188 Gy based on emergence of any adults from treated larvae. Apparently normal adults did not emerge from larvae exposed to 177 Gy in walnuts.

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Table 1. Development of codling moth larvae following irradiation[a]

		Mean number of surviving insects and stage of development completed				
Date Irradiated	Dose (Gy)	Mature Larvae	Pupae	Adults		Total
				Abnormal	Normal	
May 31, 1984	0	2.7 ab	12.5 ab	5.7 bc	178.2 e	199.2 f
	9.8	6.0 abc	6.5 a	3.2 abc	158.5 d	174.2 de
	19.6	2.0 a	11.0 ab	5.0 abc	166.7 d	184.7 ef
	39.2	2.2 ab	14.7 abc	17.0 d	132.0 c	166.0 d
	58.7	6.5 abc	22.5 cd	23.7 e	42.7 b	95.5 c
	78.3	11.2 c	30.5 d	8.2 c	1.0 a	51.0 b
	97.9	7.7 bc	17.7 bc	.5 ab	.0 a	26.0 a
	117.5	5.5 ab	11.5 ab	.0 a	.0 a	17.0 a
June 8, 1984	0	1.5 a	6.0 ab	3.7 a	189.7 d	201.0 c
	19.6	2.7 a	3.0 a	4.0 a	160.5 c	170.2 abc
	39.2	4.7 a	9.2 ab	14.7 b	160.7 c	189.5 bc
	58.7	5.2 a	35.0 c	39.2 c	90.2 b	169.7 abc
	78.3	20.7 b	77.7 d	48.5 d	6.5 a	153.5 ab
	97.9	60.0 c	84.7 d	13.2 b	.5 a	158.5 ab
	117.5	108.2 d	71.5 d	1.5 a	.0 a	181.2 abc
	138.0	120.5 e	26.7 bc	.2 a	.0 a	147.5 a
June 12, 1984	0	2.2 a	11.2 a	4.7 ab	136.5 d	154.7 a
	41.4	1.7 a	10.2 a	19.5 cd	103.5 c	135.0 a
	62.0	2.7 a	41.0 a	69.7 e	40.0 b	153.5 a
	82.7	2.2 a	91.5 b	29.2 d	3.5 a	126.5 a
	103.4	2.7 a	109.2 b	14.5 bc	1.0 a	127.5 a
	124.1	20.0 b	97.2 b	3.2 ab	.2 a	120.7 a
	145.7	24.7 b	96.7 b	.5 a	.2 a	122.2 a
	165.4	26.5 b	84.5 b	.5 a	.0 a	111.5 a

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[a] Means within each date and column followed by the same letter are not significantly different at P = 0.05, using Duncan's new multiple range test.

Table 2. Development of mature, cocooned fifth instar non-diapausing codling moth larvae in walnuts following irradiation at various dosages

Dose (Gy)	Stage of development completed (%)[a] Mature larvae	Pupae	Adults Abnormal	 Normal	Larvae treated (Number)
0	6.7 a	10.1 a	1.6 a	81.6 c	181
42.3	11.7 ab	22.8 ab	27.8 b	37.6 b	248
84.6	19.0 b	58.7 c	21.9 b	.4 a	222
126.9	40.2 c	59.0 c	.9 a	.0 a	237
169.2	67.9 d	32.1 b	.0 a	.0 a	218
338.4	65.9 d	34.1 b	.0 a	.0 a	153

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[a] Mean percentages followed by the same letter within a column are not significantly different at $P = 0.05$ (Duncan 1955).

Table 3. Probit analysis statistics for irradiation of mature fifth instar cocooned codling moth larvae to prevent adult emergence

Statistic	Dose required to prevent eclosion of: "Normal" adults	Total adults
LD_{50} (Fid. limits)	41.8 (39.3 - 44.0)	73.6 (66.5 - 78.2)
LD_{95} (Fid. limits)	66.0 (59.8 - 77.9)	108.1 (101.8 - 119.6)
$LD_{99.9968}$ (Fid. limits)	126.8 (100.3 - 192.1)	187.5 (156.6 - 263.1)
Slope (SE)	8.3 (1.2)	9.8 (1.6)
Intercept (SE)	-8.4 (1.4)	-13.4 (1.3)

Table 4. Development of mature, cocooned fifth instar codling moth larvae following irradiation in walnuts

		Stage of development completed (%)[a]				Larvae	Walnuts
Dose	Type of	Mature	Pupae	Adults		treated	treated
(Gy)	larvae	larvae		Abnormal	Normal	(No.)	(No.)
0	Diapause	13.1 b	12.8 a	13.8 c	60.3 b	224	200
	Non-diapause	0.4 a	15.1 a	3.8 b	80.7 c	658	200
177	Diapause	97.2 d	2.9 a	0.0 a	0.0 a	1931	1200
	Non-diapause	64.2 c	34.7 b	1.2 a	0.0 a	4023	1200

[a] Mean percentages followed by the same letter within a column are not significantly different at P=0.05 (Duncan 1955).

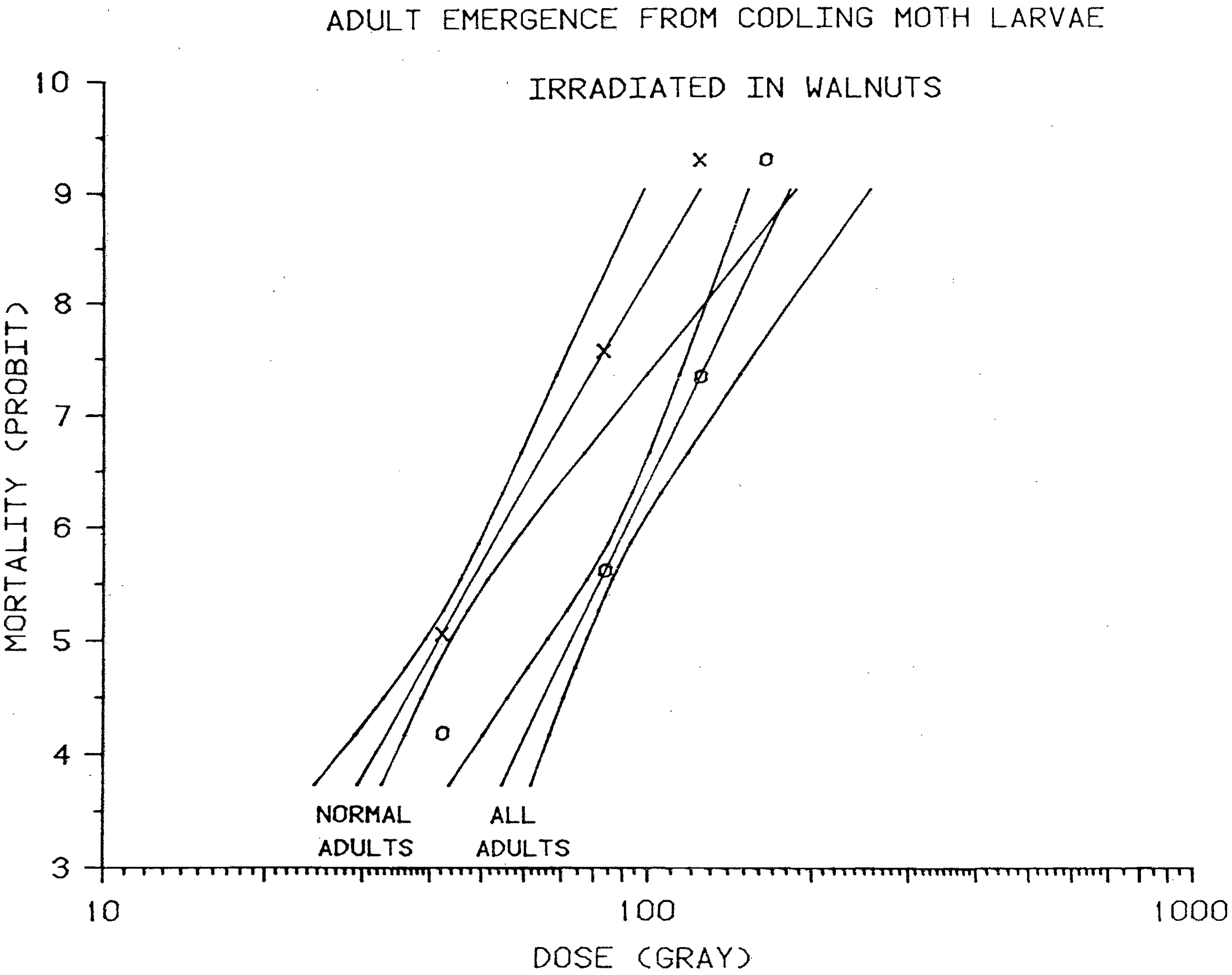

Figure 1. Dosage-mortality curve for adults developing from mature non-diapausing codling moth larvae irradiated in walnuts, X-emergence of "normal" adults, O-emergence of all adults.

QUALITY EVALUATION OF IRRADIATED DRIED FRUITS AND TREE NUTS

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Introduction

Irradiation of agricultural commodities offers an alternative to fumigation as a means of insect disinfestation (Moy, 1977). The attractiveness of irradiation depends on a number of factors: Economics, availability of chemical fumigants, and whether or not there are problems with consumer acceptance of irradiated products, among others. Part of the question of consumer acceptance is whether or not deleterious organoleptic changes occur when commodities are irradiated to kill or sterilize insect pests. It has been known that radiation-induced physiological changes may occur in fresh fruits and vegetables (Maxie et al., 1971). With dried fruit and tree nuts, physiological changes are not important, but there remains the possibility that new compounds will appear as a direct result of irradiation or as a consequence of free radical oxidation reactions initiated by irradiation.

Commodities containing high levels of unsaturated lipids are particularly likely to suffer oxidation which is evidenced by rancidity. Such oxidation processes have been reviewed by Frankel (1984). Free radicals are readily formed in polyunsaturated fatty acids. Reaction with oxygen continues chain reactions producing organic peroxides, which then suffer thermal breakdown to polymeric products and oxygenated compounds of low molecular weight. It is the latter compounds which are responsible for characteristic rancid odors and flavors of oxidized foods. Although many of the compounds characteristic of rancidity can be isolated and identified by instrumental techniques such as gas chromatography combined with mass spectroscopy (GC-MS), sensory evaluation by trained individuals is often the most sensitive method. This technique requires panels of judges and the application of statistical techniques (Kramer, 1965). The experiments described herein were designed to test whether detectable changes were brought about in dried fruit and tree nuts by gamma irradiation at doses suitable for insect disinfestation or by subsequent storage.

Materials

Almonds

For the first year's tests, shelled almonds from the 1983 crop which had been fumigated with methyl bromide (inorganic bromide residues 50 ppm or less) were obtained through the Almond Board of California. Unfumigated samples of the same varieties (Mission and Nonpareil) were obtained from the hullers and cleaned at the USDA Western Regional Research Center (WRRC), Albany. CA. Samples were stored at 34°F until they were irradiated in April 1984. During the second year's experiments, samples of shelled Mission almonds and unshelled Nonpareil (NP) and Mission (M) almonds were also obtained through the Almond Board in October 1984 and stored at 34°F until irradiation in July and August of 1985. For irradiation the nuts were packaged in 2-lb samples in plastic bags with holes for aeration.

Walnuts

In the tests run in 1984, shelled walnut halves fumigated once with methyl bromide from the 1983 crop were obtained from Diamond Walnut Growers. These were stored at 34°F and packaged in 2-lb samples in aerated plastic bags for irradiation. For the second year's testing, both shelled and unshelled walnuts were obtained from Diamond in closed cellophane or plastic bags (2 lbs unshelled and 1 lb shelled) and held at 34°F until irradiated.

Raisins

A 140-lb sample of 1983 crop raisins, cleaned and fumigated once, was obtained from Sun Maid. This was stored at 34°F, then divided into 2-lb samples and packaged in aerated plastic bags. The second year samples from the 1984 crop were already packaged in 15-oz commercial packages and stored at 34°F until they were irradiated in the package.

Pistachios

These were tested only during the second year. Unshelled pistachios from the 1984 crop were obtained from the California Pistachio Association and held in cold storage at 34°F. When ready for irradiation, they were packaged as 2-lb samples in aerated plastic bags.

Prunes

These also were examined only in the second-year tests. Unpitted prunes from the 1984 crop were obtained in commercial plastic 1-lb bag packages from Sunsweet Prune Growers. They were stored at 34°F and irradiated in the package.

Methods

In the first phase, the 2-lb samples were irradiated in the Sandia Irradiator for Dried Sewage Solids (SIDSS) Facility. A 40-lb control lot of each type of sample (shelled fumigated and unfumigated Mission and Nonpareil almonds, shelled walnuts and raisins) was held at WRRC Albany, at ambient temperature during the time the other samples were irradiated. The rest of the material was sent to Sandia National Laboratories in Albuquerque, NM during the week of April 2, 1984. They were irradiated on April 12 and 13 and returned to Albany by air freight. Portions of each commodity were given nominal doses of 150, 300, 600 and 900 Gy (15, 30, 60 and 90 krad, respectively), using cesium-137 as the source of gamma-radiation. Samples in bags were placed in the bottom of buckets (Figure 1) in a single layer. The buckets on a continuous conveyor were then passed over and under the cesium-137 source, the rate of speed of the conveyor determining the nominal radiation dose. One sample of a commodity selected at random at each level of radiation was supplied with TLD-400 dosimeters at 10 strategic locations at the bottom and top of the bag. The dose at each level was obtained from an average of the 10 dosimeter readings (Figure 2). The average rates were all quite close to the desired value (Table 1).

The SIDSS Facility was no longer in operation in 1985, so irradiation at Sandia was done in the Gamma Irradiation Facility (GIF). Here, the samples were placed near a stationary gamma-source (137Cs) and time of exposure determined the dose. Nominal doses of 300 and 600 Gy were given to samples of each commodity on July 12, 1985, and additional samples were irradiated at 300 Gy on July 12, followed by an additional 300 Gy dose on August 21. The latter samples were held at ambient temperature in Albuquerque between irradiations. There was some variability in actual dose rates (Table 2), but average rates were near those desired. After the last irradiation, the samples were returned to Albany, CA. All samples from both sets of irradiations were in Albany within 5 days of irradiation with the exception of the raisins and pistachios from the two successive 300 Gy treatments one month apart. The box containing these samples was lost by the shipper and turned up 2 weeks after irradiation after considerable travel between New Mexico, Arizona, and California. Two controls were used the second year. One (C2) was held at Albany at ambient temperature until arrival of the first samples from Albuquerque. The second set of controls (C1) was shipped to Albuquerque, but was held without irradiation and returned with the irradiated samples.

When samples were returned to Albany, they were treated essentially the same as in both 1984 and 1985. Some retainer samples of all commodities were put into storage at 34°F. One-fourth of the rest were sent immediately to the Department of Food Science and Technology, Oregon State University (OSU), for panel testing. The other samples were stored in the packages in which they were irradiated in a constant temperature room at 98°F. At this temperature, our experience is that 90-day storage is roughly equivalent to one year at ambient temperature. One-third of the storage samples were removed and sent to Oregon State after 30, 60 and 90 days. The samples left during the last storage period of the first year were at ca. 120°F for 5 days when a control failure occurred. They were tested anyway by the taste panel.

The samples were evaluated through the first year's storage by a panel of 25 experienced judges (staff and students at OSU) supervised by Dr. Mina McDaniel. During the second year phase, a similar panel of 22 judges was used (some judges were carry-overs from the first panel). The judges were asked to rate the coded samples in relation to the reference (stored control the first year, control C1 the second) for difference on an 8-point scale with "same as reference" = 1 and "extremely different" = 8. They then rated all the coded samples for desirability on a 6-point scale with "very desirable" = 6 and "not at all desirable" = 1.

The 60- and 90-day samples were also rated against controls held in cold storage. For each storage period, several packages of raisins from each treatment were combined. Then small samples were placed in coded cups for presentation to the panel. Prune "meat" was cut away from the pits, then chopped into small pieces for serving.

The unshelled almonds were shelled. A reference sample and a 200-g test sample of all almonds, shelled and unshelled, were then ground 100 g at a time, for 25-35 seconds in a Cuisinart DLC-7PRO Food Processor. Walnuts were shelled, if necessary, and then processed in the same manner as almonds, but were ground for only 8-10 seconds. It has recently been learned from industry personnel that grinding in this way may lead to bitter flavors in some samples because the pellicle may release tannins and related compounds. The pistachios were shelled and processed the same way for 12-15 seconds.

Samples were served in 3-oz paper portion cups labeled with 3-digit random numbers in random presentation. The panelists were seated in individual testing booths under red lighting. The same two samples were served together (random order of presentation) for all four test periods.

Results

The results are summarized in Tables 3a through 8. Each type of sample can be followed through the storage time in an individual table. Scores of all panelists were averaged and a statistical least significant difference (LSD) was determined at the 5% and the 1% levels. Although there are a number of isolated points at which a 95% probability of a real difference between samples and control are shown, one cannot rely too much on the statistics. For example, there are samples which show a significantly different flavor score, yet which cannot be differentiated by "difference from control". Thus, we were cautious in attributing a real trend to irradiation or irradiation plus time. When the control is compared to itself, for example, the average numbers are often between 2 and 3 where they should be 1.0. Such variations must be within the sample and could be caused by grinding and mixing one very rancid nut with a number of others which are acceptable.

Walnuts (Tables 3a-3d)

No level of irradiation used appeared to cause immediate significant differences. However, at the longer storage times, both replicates the first year and the unshelled walnuts the second year demonstrated significant differences from control after 60 and/or 90 days. Several of these points were flavor scores less than 3.0. Walnuts have a high degree of polyunsaturation and are susceptible to early rancidity, even without irradiation. Hence, it is probable that higher levels of irradiation cause additional oxidation during storage.

Almonds (Tables 4a-4c, 5a-5d)

No sample of Nonpareil almonds had a flavor score of less than 3.0 throughout irradiation and subsequent storage. Irradiated samples were virtually indistinguishable from controls. Mission almonds the first year gave problems because the control, unfumigated samples turned rancid during storage, while irradiated nuts did not. Both shelled and unshelled Missions maintained high flavor quality the second year at all radiation levels.

Raisins (Tables 6a-6c)

Isolated samples of raisins did show deterioration with time, but there was no obvious correlation with radiation levels. Such changes are consistent with past experience. One sample, irradiated at 600 Gy and stored 90 days, became quite unpalatable in both sets of replicate taste tests. However, the 900 Gy-sample was not affected.

Pistachios (Table 7)

No samples received a low score, but two samples irradiated at 600 Gy and stored 60 and 90 days were significantly lower in flavor score than the control. The sample given two nominal 300 Gy irradiations did not drop in flavor score.

Prunes (Table 8)

There were no significant differences in flavor attributable to either irradiation or irradiation plus storage.

Conclusions

Irradiation up to 900 Gy did not cause immediate deterioration in organoleptic quality of any of the commodities tested. With storage time, differences were more frequent or more noticeable at the higher irradiation levels. The highest level of irradiation, 900 Gy, caused walnuts to deteriorate significantly. It is recommended that irradiation of the commodities, especially walnuts, for insect disinfestation be done at less than 600 Gy, preferably at 300-450 Gy. Multiple doses appear to be acceptable as long as the total dose does not exceed the limit. However, current regulations allow only a single irradiation.

Suggestions for Further Work

Refrigerated storage and/or ambient temperature storage over periods of up to one year are more representative of current practice than the conditions used in the experiment. However, accelerated storage allows quicker comparison. If time and money allow, some storage tests at ambient temperature should be evaluated. These could include additional factors such as possible protection by use of antioxidants.

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Table 1

DOSIMETRY DATA FOR

Walnuts, Almonds and Raisins, First Year

April 12-13, 1984

TLD No.	DOSE (Gy)	TLD No.	DOSE (Gy)	
1	139	1	279	
2	147	2	308	
3	138	3	272	
4	148	4	312	
5	153	5	279	
6	146	6	310	
7	162	7	361	
8	163	8	336	
9	172	9	353	
10	166	10	341	
Average	153	Average	315	
1	584	1	810	
2	568	2	894	
3	584	3	777	probably bad data point
4	583	4	869	
5	598	5	909	
6	592	6	950	
7	667	7	969	
8	606	8	865	
9	673	9	1030	probably bad data point
10	672	10	984	
Average	613	Average	905	

Table 2

Dosimetry Data for Commodities, Second Year
July 12-15, August 21, 1985

Commodity	Irradiation Dose, Gy				
	I1	I2	I3		
			1. Irr.	2. Irr.	Total
Almonds, shelled	557	320	349	204	553
Almonds, in shell (2 varieties)	629	316	347	229	576
Walnuts, shelled	632	335	339	257	598
Walnuts, in shell	603	331	338	255	593
Pistachios, in shell	641	351	333	258	591
Raisins	617	331	324	239	563
Prunes	672	379	335	239	574

Explanatory Notes for Tables 3 Through 8

[a] Difference from control was rated on a scale of 1 through 8: 1 = the same as control, 8 = extremely different from control. Means within a column sharing the same superscript letter are not significantly different.

[b] Ratings of commodities were as follows: 6 = extremely desirable, 1 = extremely undesirable. Means within a column sharing the same superscript letter are not significantly different.

[c] LSD = least significant difference.

Table 3a. Walnuts (Shelled), 1st Year
Replicate 1

DIFFERENCE FROM CONTROL a)

			Time	
Treatment	T_0	30 Days	60 Days	90 Days
C_0 (0°C)	-	-	2.44^{a}	2.88^{a}
C_1	2.68^{ab}	2.48^{a}	2.84^{ab}	2.44^{a}
150 Gy	2.44^{a}	2.52^{a}	2.52ab	2.6^{a}
300 Gy	2.32^{a}	2.12^{a}	2.36^{a}	2.2^{a}
600 Gy	3.00^{ab}	2.56^{a}	2.64^{ab}	2.2^{a}
900 Gy	3.40^{b}	3.48^{b}	3.24^{b}	2.32^{a}
LSD c) (.05)	0.84	0.60	0.79	0.74
LSD (.01)	1.11	0.86	1.05	0.98

OVERALL DESIRABILITY b)

			Time	
Treatment	T_0	30 Days	60 Days	90 Days
C_0 (0°C)	-	-	3.96^{c}	4.32^{c}
C_1	3.56^{ab}	3.80^{b}	2.84^{a}	3.32^{ab}
150 Gy	4.24^{c}	3.60^{b}	3.44^{abc}	3.76^{bc}
300 Gy	4.04^{bc}	3.84^{b}	3.48^{bc}	3.68^{abc}
600 Gy	3.64^{abc}	3.68^{b}	3.64^{c}	3.44^{ab}
900 Gy	3.08^{a}	3.00^{a}	2.96^{ab}	2.96^{a}
LSD c) (.05)	0.64	0.45	0.61	0.76
LSD (.01)	0.85	0.63	0.81	1.01

Table 3b. Walnuts (Shelled), 1st Year
Replicate 2

DIFFERENCE FROM CONTROL[a)]

Treatment	T_0	30 Days	60 Days	90 Days
C_0 (0°C)	-	-	2.52^{ab}	2.96^{a}
C_1	2.23^{a}	2.32^{a}	2.64^{b}	2.92^{a}
150 Gy	2.36^{a}	2.96^{ab}	2.32ab	2.32^{a}
300 Gy	2.68^{ab}	2.52^{a}	1.92^{a}	2.4^{a}
600 Gy	2.52^{ab}	3.48^{a}	2.44^{ab}	2.8^{a}
900 Gy	3.24^{b}	3.28^{b}	2.56^{ab}	2.72^{a}
LSD[c)] (.05)	0.80	0.70	0.70	0.74
LSD (.01)	0.96	0.99	0.93	0.98

(Time spans 60 Days column header: T i m e)

OVERALL DESIRABILITY[b)]

Treatment	T_0	30 Days	60 Days	90 Days
C_0 (0°C)	-	-	4.0^{d}	3.56^{bc}
C_1	3.72^{ab}	3.80^{c}	3.24^{abc}	3.8^{cd}
150 Gy	4.40^{c}	3.84^{c}	3.44^{bcd}	4.32^{d}
300 Gy	3.80^{b}	3.44^{b}	3.56^{cd}	3.16^{ab}
600 Gy	3.76^{b}	2.92^{ab}	2.88^{ab}	3.16^{ab}
900 Gy	3.20^{a}	2.84^{a}	2.72^{a}	2.92^{a}
LSD[c)] (.05)	0.56	0.51	0.59	0.53
LSD (.01)	0.79	0.76	0.78	0.70

Table 3c. Walnuts (Shelled), 2nd Year

DIFFERENCE FROM CONTROLa)

			Time	
Treatment	T_0	30 Days	60 Days	90 Days
C_1 (Reference)	1.86^{a}	2.32^{ab}	1.68^{a}	2.00^{a}
C_2 (Sample held at Albany)	1.91a	1.59^{a}	1.91^{a}	2.00^{a}
300 Gy	1.91^{a}	2.50^{b}	2.45^{ab}	1.95^{a}
600 Gy	2.41^{a}	2.91^{b}	2.95^{b}	2.68^{b}
300 Gy plus 300 Gy	--	3.00^{a}	3.00^{b}	2.23^{ab}
LSDc) (.05)	0.69	0.84	0.79	0.65
LSD (.01)	0.92	1.11	1.04	0.87

OVERALL DESIRABILITYb)

			Time	
Treatment	T_0	30 Days	60 Days	90 Days
C_1 (Reference)	4.27^{a}	3.64^{a}	4.18^{b}	4.14^{c}
C_2 (Sample held at Albany)	4.27^{a}	4.41^{b}	3.77^{ab}	3.95^{bc}
300 Gy	4.00^{a}	3.86^{ab}	3.41^{a}	3.50^{abc}
600 Gy	4.09^{a}	3.64^{a}	3.45^{a}	3.36^{ab}
300 Gy plus 300 Gy	--	3.27^{a}	3.45^{a}	3.8^{a}
LSDc) (.05)	0.73	0.68	0.68	0.65
LSD (.01)	0.97	0.90	0.90	0.86

Table 3d. Walnuts (Not Shelled), 2nd Year

DIFFERENCE FROM CONTROL a)

			Time	
Treatment	T_0	30 Days	60 Days	90 Days
C_1 (Reference)	2.00^{a}	1.77^{a}	2.27^{a}	1.68^{a}
C_2 (Sample held at Albany)	2.14a	2.45^{a}	2.55^{ab}	2.59^{b}
300 Gy	2.59^{a}	2.27^{a}	1.91^{a}	2.95^{b}
600 Gy	2.36^{a}	2.36^{a}	3.05^{b}	3.05^{b}
300 Gy plus 300 Gy	--	2.73^{a}	2.36^{a}	2.41^{ab}
LSD c) (.05)	0.69	0.74	0.65	0.77
LSD (.01)	0.92	0.98	0.86	1.02

OVERALL DESIRABILITY b)

			Time	
Treatment	T_0	30 Days	60 Days	90 Days
C_1 (Reference)	4.27^{ab}	3.55^{ab}	3.55^{b}	3.73^{c}
C_2 (Sample held at Albany)	4.45^{b}	4.00^{b}	4.14^{c}	3.59^{c}
300 Gy	3.68^{a}	3.09^{a}	3.09^{ab}	2.77^{ab}
600 Gy	3.77^{a}	3.59^{ab}	2.91^{a}	2.50^{a}
300 Gy plus 300 Gy	--	3.14^{a}	2.73^{a}	3.36^{bc}
LSD c) (.05)	0.66	0.67	0.58	0.75
LSD (.01)	0.87	0.89	0.76	0.99

Table 4a. Almonds-NP, Shelled, 1st Year
Unfumigated

DIFFERENCE FROM CONTROL[a)]

Treatment	T_0	30 Days	60 Days	90 Days
			Time	
C_0 (0°C)	-	-	2.36^a	2.2^a
C_1	2.48^a	2.00^a	2.28^a	1.92^a
150 Gy	2.08^a	1.88^a	2.00^a	2.36^{ab}
300 Gy	2.32^a	2.08^a	2.16^a	2.08^a
600 Gy	2.04^a	2.04^a	2.56^a	2.2^a
900 Gy	3.28^b	2.72^b	2.6^a	2.8^b
LSD[c)] (.05)	0.74	0.51	0.70	0.55
LSD (.01)	0.98	0.71	0.93	0.72

OVERALL DESIRABILITY[b)]

Treatment	T_0	30 Days	60 Days	90 Days
			Time	
C_0 (0°C)	-	-	4.08^{ab}	4.4^{ab}
C_1	4.56^{ab}	4.64^{bc}	4.08^{ab}	4.68^b
150 Gy	4.84^b	4.56^{bc}	4.52^b	4.32^{ab}
300 Gy	4.40^{ab}	4.76^c	4.32^b	4.32^{ab}
600 Gy	4.36^{ab}	4.32^{ab}	3.76^a	4.6^b
900 Gy	4.00^a	4.00^a	3.68^a	4.12^a
LSD[c)] (.05)	0.63	0.38	0.51	0.41
LSD (.01)	0.84	0.52	0.68	0.55

Table 4b. Almonds-NP (Shelled), 1st Year
Fumigated

DIFFERENCE FROM CONTROLa)

			Time	
Treatment	T_0	30 Days	60 Days	90 Days
C_0 (0°C)	-	-	1.88^{a}	2.08^{a}
C_1	1.88^{a}	2.28^{a}	2.44^{ab}	1.68^{a}
150 Gy	2.20^{ab}	2.12^{a}	2.12^{ab}	2.2^{ab}
300 Gy	2.72^{b}	2.28^{a}	2.24^{ab}	2.12^{ab}
600 Gy	2.16^{ab}	2.12^{a}	2.56^{b}	2.04^{a}
900 Gy	2.64^{b}	3.08^{b}	2.36^{ab}	2.76^{b}
LSDc) (.05)	0.58	0.65	0.61	0.65
LSD (.01)	0.82	0.92	0.81	0.84

OVERALL DESIRABILITYb)

			Time	
Treatment	T_0	30 Days	60 Days	90 Days
C_0 (0°C)	-	-	4.88^{c}	4.24^{c}
C_1	4.72^{b}	4.32^{b}	3.40^{a}	3.72^{ab}
150 Gy	4.12^{a}	4.80^{c}	3.92^{b}	3.56^{ab}
300 Gy	4.20^{a}	4.16^{ab}	4.24^{b}	3.96^{bc}
600 Gy	4.24^{ab}	4.32^{b}	4.12^{b}	3.6^{ab}
900 Gy	4.12^{a}	3.84^{a}	4.28^{b}	3.44^{a}
LSDc) (.05)	0.50	0.44	0.51	0.48
LSD (.01)	0.71	0.62	0.67	0.64

Table 4c. Almonds-NP (Not Shelled), 2nd Year

DIFFERENCE FROM CONTROL[a)]

			Time	
Treatment	T_0	30 Days	60 Days	90 Days
C_1 (Reference)	1.82^{a}	1.86^{a}	1.86^{ab}	1.86^{a}
C_2 (Sample held at Albany)	1.73^{a}	1.95^{ab}	1.59^{a}	1.82^{a}
300 Gy	2.05^{a}	2.41^{ab}	2.23^{abc}	1.77^{a}
600 Gy	2.05^{a}	2.05^{ab}	2.86^{c}	2.45^{b}
300 Gy plus 300 Gy	--	2.55^{b}	2.45^{bc}	2.14^{ab}
LSD[c)] (.05)	0.61	0.65	0.71	0.58
LSD (.01)	0.82	0.86	0.94	0.77

OVERALL DESIRABILITY[b)]

			Time	
Treatment	T_0	30 Days	60 Days	90 Days
C_1 (Reference)	4.60^{a}	3.91^{a}	4.36^{bc}	4.45^{a}
C_2 (Sample held at Albany)	4.73^{a}	3.82^{a}	4.27^{abc}	4.18^{a}
300 Gy	4.60^{a}	4.23^{ab}	4.41^{c}	4.23^{a}
600 Gy	4.36^{a}	4.55^{b}	3.77^{ab}	4.00^{a}
300 Gy plus 300 Gy	--	3.86^{a}	3.68^{a}	4.00^{a}
LSD[c)] (.05)	0.42	0.63	0.61	0.53
LSD (.01)	0.55	0.84	0.81	0.70

Table 5a. Almonds-Mission (Shelled), 1st Year
Unfumigated

DIFFERENCE FROM CONTROL a)

			Time	
Treatment	T_0	30 Days	60 Days	90 Days
C_0 (0°C)	-	-	3.64^{c}	3.72^{c}
C_1	1.88^{a}	1.96^{a}	1.84^{a}	1.84^{a}
150 Gy	1.68^{a}	3.12^{bc}	3.36^{bc}	3.44^{c}
300 Gy	2.00^{ab}	3.32^{c}	2.96^{bc}	2.68^{b}
600 Gy	2.08^{ab}	2.72^{b}	2.80^{b}	2.68^{b}
900 Gy	2.36^{b}	2.80^{bc}	3.16^{bc}	3.08^{bc}
LSD c) (.05)	0.47	0.56	0.71	0.71
LSD (.01)	0.66	0.79	0.95	0.94

OVERALL DESIRABILITY b)

			Time	
Treatment	T_0	30 Days	60 Days	90 Days
C_0 (0°C)	-	-	4.2^{b}	3.92^{bc}
C_1	4.52^{ab}	3.48^{a}	2.4^{a}	2.08^{a}
150 Gy	4.76^{b}	4.40^{b}	3.92^{b}	4.28^{c}
300 Gy	4.56^{ab}	4.68^{b}	3.92^{b}	3.84^{bc}
600 Gy	4.36^{ab}	4.32^{b}	3.84^{b}	3.64b
900 Gy	4.32^{a}	4.28^{b}	3.88^{b}	3.64^{b}
LSD c) (.05)	0.42	0.48	0.53	0.61
LSD (.01)	0.59	0.68	0.70	0.80

Table 5c. Almonds-Mission (Shelled), 2nd Year

DIFFERENCE FROM CONTROL[a)]

			Time	
Treatment	T_0	30 Days	60 Days	90 Days
C_1 (Reference)	1.82^{ab}	1.59^{a}	2.18^{a}	1.54^{a}
C_2 (Sample held at Albany)	2.00^{ab}	1.95^{a}	2.32^{ab}	2.04^{ab}
300 Gy	1.64^{a}	1.95^{a}	2.09^{a}	2.14^{b}
600 Gy	2.41^{b}	2.77^{b}	2.95^{bc}	1.82^{ab}
300 Gy plus 300 Gy	--	2.18^{ab}	3.00^{c}	2.05^{ab}
LSD[c)] (.05)	0.71	0.61	0.68	0.55
LSD (.01)	0.94	0.81	0.90	0.74

OVERALL DESIRABILITY[b)]

			Time	
Treatment	T_0	30 Days	60 Days	90 Days
C_1 (Reference)	4.82^{b}	4.68^{b}	4.09^{a}	4.36^{a}
C_2 (Sample held at Albany)	4.68^{b}	4.50^{b}	4.09^{a}	4.00^{a}
300 Gy	4.64^{ab}	4.77^{b}	4.18^{a}	4.27^{a}
600 Gy	4.14^{a}	3.64^{a}	3.86^{a}	3.86^{a}
300 Gy plus 300 Gy	--	4.32^{b}	4.00^{a}	3.91^{a}
LSD[c)] (.05)	0.52	0.52	0.64	0.51
LSD (.01)	0.70	0.68	0.85	0.67

Table 5b. Almonds-Mission (Shelled), 1st Year Fumigated

DIFFERENCE FROM CONTROL$^{a)}$

Treatment	Time			
	T_0	30 Days	60 Days	90 Days
C_0 (0°C)	-	-	2.64^{a}	2.64^{b}
C_1	2.00^{ab}	1.72^{a}	2.12^{a}	2.2^{ab}
150 Gy	1.88^{a}	2.24^{b}	2.28^{a}	1.92^{a}
300 Gy	2.20^{ab}	1.88^{a}	2.48^{a}	2.12^{ab}
600 Gy	2.48^{b}	1.92^{ab}	2.28^{a}	1.96^{a}
900 Gy	2.00^{ab}	2.24^{b}	2.56^{a}	2.56^{b}
LSD$^{c)}$ (.05)	0.58	0.42	0.69	0.60
LSD (.01)	0.82	0.60	0.92	0.79

OVERALL DESIRABILITY$^{b)}$

Treatment	Time			
	T_0	30 Days	60 Days	90 Days
C_0 (0°C)	-	-	4.44^{b}	5.4^{b}
C_1	4.48^{ab}	4.44^{a}	3.96^{ab}	4.04^{ab}
150 Gy	4.52^{b}	4.16^{a}	4.24^{b}	4.08^{ab}
300 Gy	4.24^{ab}	4.24^{a}	4.16^{ab}	3.52^{a}
600 Gy	4.08^{a}	4.40^{a}	3.68^{a}	3.68^{a}
900 Gy	4.52^{b}	4.16^{a}	3.68^{a}	3.6^{a}
LSD$^{c)}$ (.05)	0.42	0.36	0.48	1.43
LSD (.01)	0.60	0.51	0.63	1.89

Table 5d. Almonds-Mission (Not Shelled), 2nd Year

DIFFERENCE FROM CONTROL[a)]

			Time	
Treatment	T_0	30 Days	60 Days	90 Days
C_1 (Reference)	1.95^a	2.27^a	1.77^a	2.14^{ab}
C_2 (Sample held at Albany)	1.68^a	1.95^a	1.41^a	2.23^{ab}
300 Gy	2.18^a	2.18^a	2.27^{ab}	1.95^a
600 Gy	1.82^a	2.41^a	2.41^b	2.50^b
300 Gy plus 300 Gy	--	2.41^a	2.41^b	2.00^{ab}
LSD[c)] (.05)	0.52	0.67	0.62	0.61
LSD (.01)	0.68	0.88	0.82	0.81

OVERALL DESIRABILITY[b)]

			Time	
Treatment	T_0	30 Days	60 Days	90 Days
C_1 (Reference)	4.60^a	3.95^a	4.50^a	3.77^a
C_2 (Sample held at Albany)	4.32^a	4.27^{ab}	4.41^a	4.00^a
300 Gy	4.30^a	4.27^{ab}	4.27^a	4.04^a
600 Gy	4.50^a	4.05^a	4.09^a	3.82^a
300 Gy plus 300 Gy	--	4.55^b	4.14^a	3.68^a
LSD[c)] (.05)	0.43	0.47	0.55	0.49
LSD (.01)	0.57	0.63	0.73	0.65

Table 6a. Raisins, 1st Year
Replicate 1

DIFFERENCE FROM CONTROL$^{a)}$

Treatment	T_0	30 Days	Time 60 Days	90 Days
C_0 (0°C)	-	-	4.36^c	3.24^b
C_1	2.16^a	1.72^a	1.36^a	2.0^a
150 Gy	2.32^a	2.36^b	3.72b	3.56^b
300 Gy	2.32^a	1.72^a	3.76^{bc}	2.16^a
600 Gy	2.12^a	2.12^{ab}	3.92^{bc}	5.6^c
900 Gy	1.84^a	3.04^c	3.72^b	2.36^a
LSD$^{c)}$ (.05)	0.50	0.50	0.62	0.80
LSD (.01)	0.71	0.71	0.82	1.06

OVERALL DESIRABILITY$^{b)}$

Treatment	T_0	30 Days	Time 60 Days	90 Days
C_0 (0°C)	-	-	4.36^b	4.16^c
C_1	4.56^a	4.84^c	2.32^a	4.24^c
150 Gy	4.28^a	4.32^b	3.96^b	3.32^b
300 Gy	4.32^a	4.76^c	4.4^b	4.32^c
600 Gy	4.28^a	4.64^{bc}	4.36^b	1.52^a
900 Gy	4.52^a	3.68^a	4.0^b	4.0^c
LSD$^{c)}$ (.05)	0.44	0.43	0.64	0.67
LSD (.01)	0.63	0.60	0.85	0.89

Table 6b. Raisins, 1st Year
Replicate 2

DIFFERENCE FROM CONTROL[a)]

Treatment	T_0	30 Days	60 Days	90 Days
C_0 (0°C)	-	-	3.28^b	2.80^b
C_1	2.08^a	2.28^a	2.28^a	1.88^a
150 Gy	2.04^a	2.36^{ab}	2.24^a	3.92^c
300 Gy	2.16^a	2.36^{ab}	2.16^a	1.96^a
600 Gy	1.96^a	2.72^{ab}	2.4^a	5.52^d
900 Gy	2.12^a	2.96^b	2.24^a	2.08^a
LSD[c)] (.05)	0.47	0.64	0.73	0.71
LSD (.01)	0.66	0.90	0.96	0.94

OVERALL DESIRABILITY

Treatment	T_0	30 Days	60 Days	90 Days
C_0 (0°C)	-	-	4.16^a	4.0^c
C_1	4.76^a	4.56^b	4.12^a	4.32^c
150 Gy	4.92^a	4.60^b	3.92^a	3.12^b
300 Gy	4.76^a	4.80^b	4.04^a	4.44^c
600 Gy	4.80^a	3.96^a	4.16^a	1.92^a
900 Gy	4.72^a	3.96^a	4.08^a	4.16^c
LSD[c)] (.05)	0.32	0.44	0.53	0.67
LSD (.01)	0.45	0.62	0.70	0.88

Table 6c. Raisins, 2nd Year

DIFFERENCE FROM CONTROL a)

			Time	
Treatment	T_0	30 Days	60 Days	90 Days
C_1 (Reference)	1.95^{a}	2.09^{a}	1.86^{a}	2.32^{a}
C_2 (Sample held at Albany)	1.77^{a}	2.32^{a}	2.14^{abc}	2.05^{a}
300 Gy	2.00^{a}	1.95^{a}	2.82^{c}	2.64^{a}
600 Gy	2.27^{a}	2.09^{a}	2.09^{a}	2.41^{a}
300 Gy plus 300 Gy	--	--	2.64^{bc}	2.36^{a}
LSD c) (.05)	0.69	0.64	0.69	0.71
LSD (.01)	0.91	0.85	0.91	0.94

OVERALL DESIRABILITY b)

			Time	
Treatment	T_0	30 Days	60 Days	90 Days
C_1 (Reference)	4.86^{a}	4.18^{a}	4.23^{b}	4.23^{a}
C_2 (Sample held at Albany)	4.73^{a}	4.36^{a}	4.09^{b}	3.77^{a}
300 Gy	4.95^{a}	4.55^{a}	3.36^{a}	3.82^{a}
600 Gy	4.77^{a}	4.55^{a}	4.00^{b}	3.82^{a}
300 Gy plus 300 Gy	--	--	4.27^{b}	4.32^{a}
LSD c) (.05)	0.47	0.63	0.50	0.62
LSD (.01)	0.63	0.84	0.67	0.83

Table 7. Pistachios (Not Shelled), 2nd Year

DIFFERENCE FROM CONTROL$^{a)}$

	Time			
Treatment	T_0	30 Days	60 Days	90 Days
C_1 (Reference)	1.55^{a}	2.05^{a}	2.09^{ab}	1.64^{a}
C_2 (Sample held at Albany)	2.18^{b}	1.73^{a}	1.77^{a}	2.18^{ab}
300 Gy	2.23^{b}	2.14^{a}	1.91^{ab}	1.91^{ab}
600 Gy	2.64^{b}	2.05^{a}	2.55^{b}	2.55^{b}
300 Gy plus 300 Gy	--	--	2.32^{ab}	2.18^{ab}
LSD$^{c)}$ (.05)	0.63	0.64	0.68	0.71
LSD (.01)	0.84	0.85	0.91	0.95

OVERALL DESIRABILITY$^{b)}$

	Time			
Treatment	T_0	30 Days	60 Days	90 Days
C_1 (Reference)	4.27^{a}	4.73^{b}	4.41^{ab}	4.45^{a}
C_2 (Sample held at Albany)	4.77^{b}	4.73^{b}	4.59^{b}	4.32^{a}
300 Gy	4.09^{a}	4.14^{a}	4.36^{ab}	4.36^{a}
600 Gy	3.82^{a}	4.32^{ab}	3.82^{a}	4.09^{a}
300 Gy plus 300 Gy	--	--	4.32^{ab}	4.14^{a}
LSD$^{c)}$ (.05)	0.50	0.51	0.59	0.58
LSD (.01)	0.67	0.67	0.78	0.77

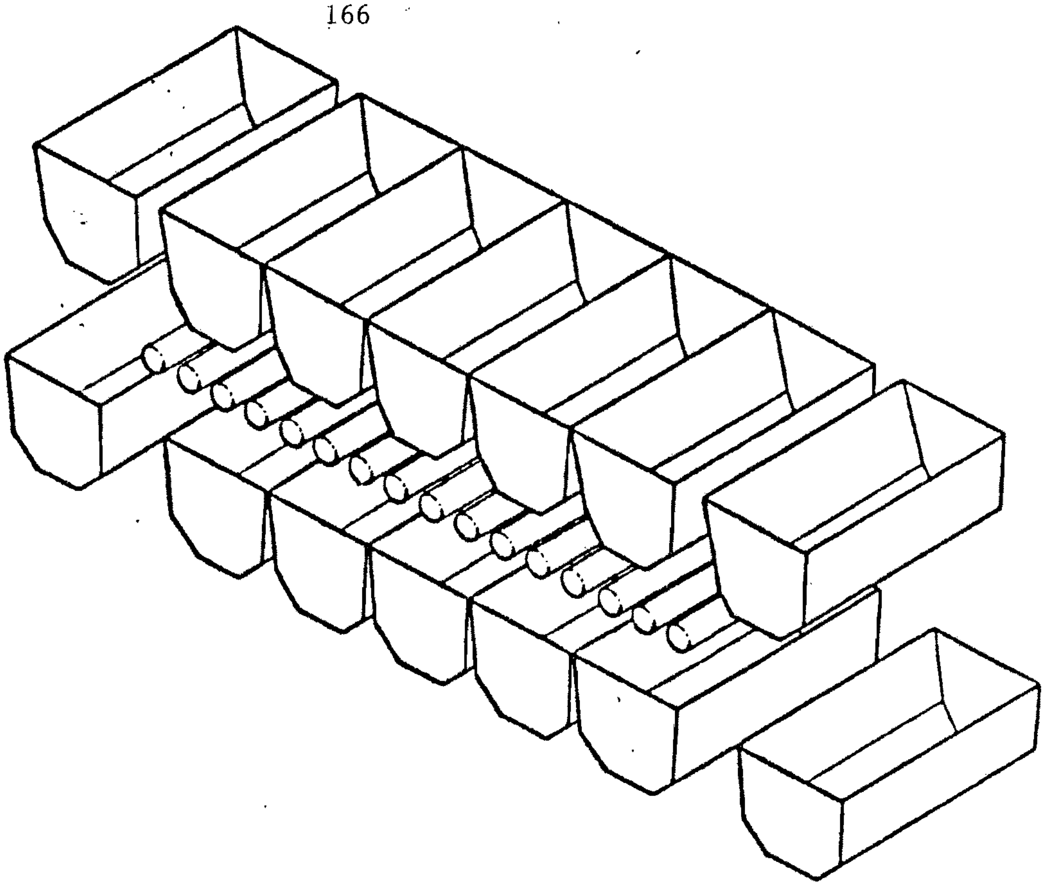
Table 8. Prunes, 2nd Year

DIFFERENCE FROM CONTROL a)

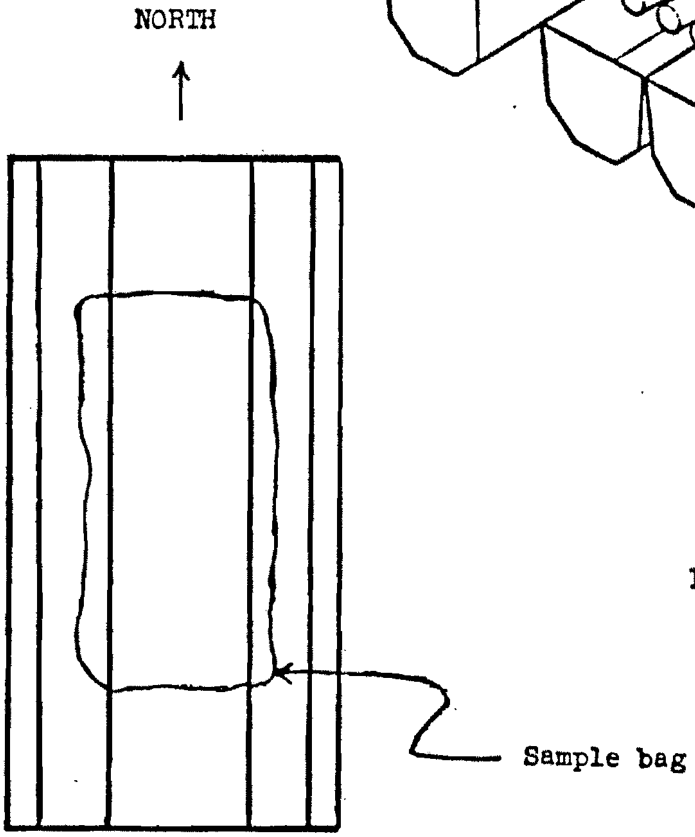
			Time	
Treatment	T_0	30 Days	60 Days	90 Days
C_1 (Reference)	2.82^{ab}	2.45^{ab}	2.05^{a}	2.50^{ab}
C_2 (Sample held at Albany)	3.20^{b}	2.50^{ab}	3.45^{b}	2.86^{b}
300 Gy	2.23^{a}	2.14^{ab}	2.14^{a}	2.09^{a}
600 Gy	2.60^{ab}	2.05^{a}	2.05^{a}	2.36^{ab}
300 Gy plus 300 Gy	--	2.82^{b}	2.41^{a}	2.23^{ab}
LSD c) (.05)	0.75	0.77	0.83	0.76
LSD (.01)	0.99	1.02	1.11	1.01

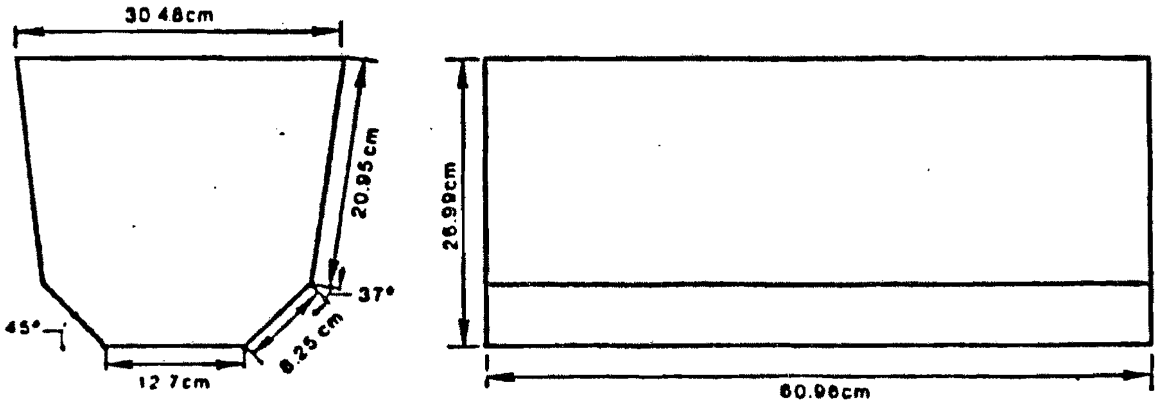
OVERALL DESIRABILITY b)

			Time	
Treatment	T_0	30 Days	60 Days	90 Days
C_1 (Reference)	3.77^{ab}	3.86^{ab}	4.14^{b}	3.95^{a}
C_2 (Sample held at Albany)	3.41^{a}	4.36^{b}	3.09^{a}	3.50^{a}
300 Gy	4.05^{b}	4.18^{b}	4.09^{b}	3.77^{a}
600 Gy	3.73^{ab}	3.86^{ab}	3.86^{b}	4.05^{a}
300 Gy plus 300 Gy	--	3.41^{a}	3.86^{b}	3.55^{a}
LSD c) (.05)	0.61	0.69	0.69	0.63
LSD (.01)	0.81	0.91	0.92	0.84



Isometric View of Buckets and Capsules





Bucket Dimensions

Figure 1

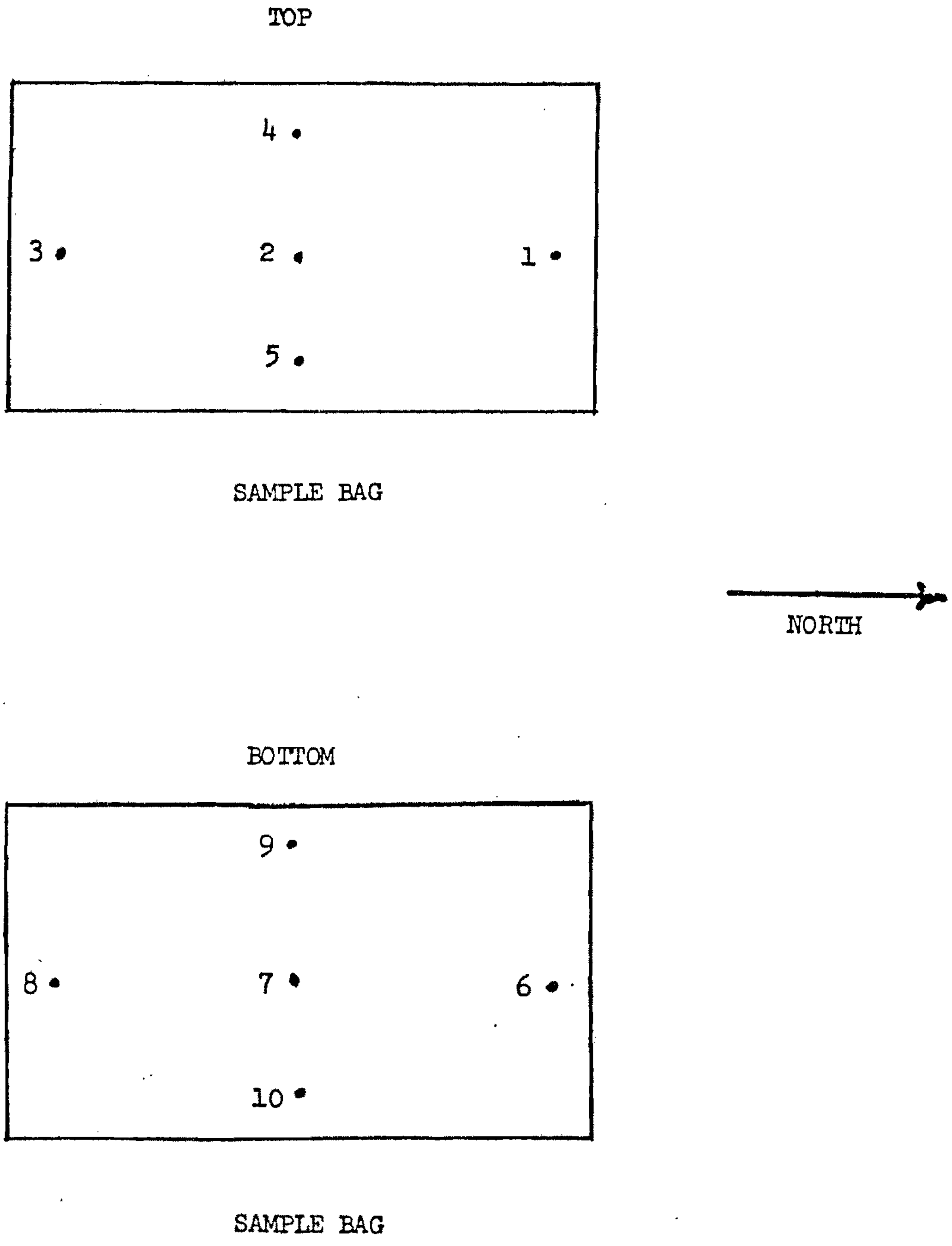


Figure 2

ECONOMIC ENGINEERING FEASIBILITY OF IRRADIATION AS A POSTHARVEST DISINFESTATION TREATMENT FOR CALIFORNIA DRIED FRUITS AND NUTS

by

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ECONOMIC ENGINEERING FEASIBILITY OF IRRADIATION AS A POSTHARVEST DISINFESTATION TREATMENT FOR CALIFORNIA DRIED FRUITS AND NUTS

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Introduction

The purpose of this study is to evaluate the economic engineering feasibility of irradiation as a disinfestation treatment for California dried fruits and nuts. The study focuses on the four largest dried fruit and nut crops: almonds, walnuts, raisins and prunes, for which irradiation is most likely to be economical. The study compares irradiation with current practice, i.e. fumigation and other chemical controls, as well as with other alternatives to current practice: modified atmospheres and refrigeration. Possible insect control programs to replace all chemical treatments using either modified atmospheres and refrigeration alone, or some combination of modified atmospheres, refrigeration and irradiation are described, and the costs of these insect control programs are estimated.

In the event that replacements for chemical controls must be found, new insect control concepts may be developed which may be superior to all those considered here. Nevertheless, the results of this study identify which, if any, dried fruit and nut disinfestation needs might possibly best be served by irradiation, at least in the event that chemical controls are not available. At the same time, estimated costs of alternative insect control programs are provided, which place an upper bound on the cost of replacing some of all chemical controls by alternative treatments.

In conducting a comparative, economic engineering study of this kind a number of difficulties must be faced. The most important problems are:

(1) Irradiation, modified atmospheres and refrigeration can each be applied in a number of ways in each treatment situation. Recognition of the best ways of applying the technologies is essential in evaluating the potential cost-effectiveness of the technologies.

(2) Irradiation and modified atmospheres are new technologies for the commercial applications considered here. Only rough, conceptual level cost estimates can be given for their potential applications.

(3) The cost of each potential insect control program will be processor specific, depending on such variables as throughput, seasonal handling schedules, processor insect control policy and existing physical plant. In particular, the per-ton cost of irradiation is highly dependent on the irradiator capacity required to handle peak loads, and on the percent utilization of irradiator capacity throughout the year.

The approach of the present study is to consider practical methods of applying the competing treatment technologies and their associated estimated costs for hypothetical processing plants which are constructed to represent actual processor situations. Calculations are given showing the effect of processor-specific variables on estimated costs. Hence, processors can infer cost estimates relevant to their individual operations.

This report is organized into five main sections. In the first section, current industry insect control practices are reviewed, and control costs for typical processor situations are estimated. In the second section, application methods and cost elements for irradiation, modified atmosphere and refrigeration treatments are described. Estimated costs of alternative insect control programs for the constructed, hypothetical plants are developed in section 3. Section 4 discusses possible, supplementary demand for in-house dried fruit and nut irradiators. Finally, the conclusions of this study are stated in section 5.

Insect Control in California Almonds, Walnuts, Prunes and Raisins

Almonds, walnuts, prunes and raisins are stored and processed at a number of plants in California,[1] although in each case a quarter or more of the commodity is processed by a single firm or grower cooperative at a single location.[2] Annual production and prices vary, but average about 2,000 million

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[1] Sixty-three processors were counted in 1983.

[2] Data provided by industry representatives.

pounds with a farm value of \$1,000 million,[3] or about \$2,000 million after processing and packaging.[4] Half or more of California's almonds and prunes and about one-fourth of its walnut and raisin production is exported in a typical year.[5] Over 75% of these exports are shipped from California ports.[5]

Insect control during storage and processing of the commodities is essential to prevent insect contamination and damage of the products which could lead to lost sales and even to regulatory action (Baur, 1984). Moreover, USFDA regulations require that the processing plant itself be kept free of infestation. In addition to monitoring and preventive measures, one or more routine commodity disinfestation treatments are an annual part of most processors' insect control programs. The reasons for the commodity treatments are 1) to protect the commodity from infestation during long-term storage, and 2) to eliminate insects infesting the commodity at a single point in time when the commodity is in transit. "In-transit" commodity disinfestation treatments may be made to a) remove damaging field pests from newly harvested crop, b) ensure that the commodity is insect-free when it is brought in from long-term storage so that the processing plant does not become infested, and c) ensure that no live insects remain in the finished product. Typical processor insect control programs for the commodities considered here are described below.

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[3] Farm value and production in recent years reported by California Crop and Livestock Reporting Service.

[4] Processing and packaging value added taken from <u>Sun-Diamond Grower</u>, Feb-March, 1985.

[5] Recent years' data from California Crop and Livestock Reporting Service.

Stopping Infestation in Prunes and Raisins During Long-term Storage

Dried prunes and raisins are attractive to a variety of insects including infesting species such as the Indianmeal moth, Plodia interpunctella (Hüebner), which can reproduce rapidly in the stored commodity. Even though prune and raisin bins are stored inside warehouses or, if stored in stacks outdoors, are covered with plastic and paper laminate sealed at the ground with oiled sand, total exclusion of infesting insects is virtually impossible. Frequent insect control treatments are necessary to prevent infestations which could seriously damage and contaminate the commodities.

Prunes are completely disinfested after harvest by the heat of the mechanical drying process, but may become reinfested during temporary storage at remote drying facilities or during transport to the central processing plant. To eliminate possible infestation, the processor may routinely fumigate the entire raw storage warehouse in mid to late fall when most of the crop has been received. Either methyl bromide or hydrogen phosphide may be used, but methyl bromide is preferred because it penetrates the commodity pack and kills insects more rapidly. Using methyl bromide, the entire fumigation operation may be accomplished over a weekend so no working days are lost.

In addition to complete disinfestation during drying and initial fumigation, measures are required to prevent reproduction of insects which gain entry from outside. Repeated fumigations may be needed to interrupt the life cycles of any reinvading insects. As an alternative, some prune processors apply aerosol forms of insecticide in storage warehouses as needed at night during the warm months when infesting insects fly. Usually a solution of pyrethrin and its synergist, piperonyl butoxide is used. The aerosol does not penetrate the commodity packs, but reinfestation is prevented before it can start by elimination of egg laying adults. Because pyrethrin and piperonyl butoxide break down rapidly in heat and light, the area is safe for entry during normal working hours.

The bulk of the California raisin crop is sun-dried in the field, and may already be infested when it is placed in storage. Infesting insects reproduce well in raisins, so an initial slight infestation could become serious. To break the life cycles of infesting insects, processors fumigate raisins as required, usually several times during the storage period. As with prunes, methyl bromide is the preferred fumigant for raisins stored in permanent warehouses. Hydrogen phosphide is used for most fumigations of raisins in yard stacks. Although it is slower, it eventually penetrates better than methyl bromide. The superior penetration of hydrogen phosphide is important in temporary storages such as yard stacks where there are no recirculating fans. Moreover, since yard stacks are designed for long-term storage and are never entered by people, the extra time required for hydrogen phosphide fumigation is not a consideration.

Disinfestation of In-transit Commodities

Disinfestation at harvest.

In comparison to the dried fruits, almonds and walnuts are less frequently reinfested during storage. However, newly harvested almonds and walnuts may be infested by damaging field pests such as the navel orangeworm, Amyelois transitella (Walker), which attacks the maturing nuts as soon as the hulls begin to split. Timely insect control is needed to prevent a large portion of the kernels from being damaged, and this need is a major consideration in scheduling harvest, hulling and drying, and transport of the crop to the processing facility for fumigation (Kader, 1985; Ramos, 1985; Nelson et al., 1980). Processors rush to move all commodity into some kind of bulk storage facility (steel bin, concrete warehouse, or horizontal shed) where it can be fumigated. Walnuts are usually fumigated with relatively fast acting methyl bromide since the early part of the walnut crop is shipped at once to competitive foreign and domestic early season markets. In the case of almonds, the need for rapid disinfestation (within two days to a week of receipt) is the processors' overriding concern. Hydrogen phosphide is used for many almond treatments because it does not leave detectable residues.

Pre-processing disinfestation. Every effort is made to exclude insects from processing areas where an infestation may be difficult and expensive to locate and destroy. While dried fruits are kept under constant insect control programs up to the time of processing, in-shell almonds and walnuts may be stored several months without repeat treatment after their initial fumigation. Some processors may refumigate nuts just before processing, to ensure that live insects are not brought into the plant. Practice varies, but, typically, almonds may be refumigated if the almonds have been in storage longer than six months, i.e. if they are processed after April 1. Walnuts may be refumigated before cracking even if they have been in storage for only a short time. Either methyl bromide or hydrogen phosphide may be used for pre-processing fumigation.

Pre-shipment disinfestation. The possibility of infestation is of great concern to processors since even a single live insect found in the commodity would seriously disturb a consumer and could cause a commercial buyer to reject an entire lot as infested (Baur, 1984). To satisfy quarantine regulations in some Asian markets, in-shell walnuts must be inspected and certified to be free of codling moth larvae, *Cydia pomonella* (L), which may remain in walnut shells after harvest following infestation in the field.

Although the processor cannot ensure that commodities do not become infested after they have left the plant, every effort is made to ship an insect-free product. This effort may include a routine pre-shipment fumigation of some or all outgoing commodity either before or after the packaging step. Some processors fumigate only product destined for foreign shipment. In some plants, the entire shipping warehouse may be regularly fumigated, but some product may be shipped untreated. Methyl bromide is used for most pre-shipment treatments because of its relatively short turn-around time.

Costs of Fumigation and Other Chemical Control

Costs of the insecticide materials used for postharvest insect control in California dried fruits and nuts can be readily computed, given assumptions concerning their unit prices, the required dose rate, and the product's specific volume in the situation where it is fumigated. Typical values for these variables and the resulting cost estimates are shown in Table 1.

Additional cost components of fumigation or fogging include labor, which is often the biggest component, wear and tear on recirculation fans and other, minor equipment, and miscellaneous materials (e.g. tape) used to seal doorways and other openings. These costs are more difficult to estimate and will vary depending on the size of the lot to be fumigated. Detailed studies for the California industries (Gardner et al., 1982; Soderstrom et al., 1984) have shown that fumigation costs in 800-ton (1600-bin) raisin yard stacks and in 500-ton bulk almond silos are in the range of 20¢ to 60¢ per ton, in addition to the cost of the fumigant. Informal interviews with industry representatives made by the authors indicated that this cost range is also about right for fumigation of bulk commodities in other storage situations (concrete warehouse, metal silo, horizontal shed), as well as for fumigation of packaged product in fumigation chambers or in the shipping warehouse.

Costs to fumigate bulk prunes may be somewhat less, since most of a year's receipt may be fumigated at once in one warehouse. Based on information provided by industry representatives, bulk prune fumigation is estimated to cost 5¢ to 10¢ per ton, in addition to fumigant costs.

Pyrethrin fogging is estimated to cost 45¢ per ton handled annually to fog six nights per week during eight months of the year. This cost estimate was provided by a professional pest control operator, and is based on the assumption that an automatic dispensing system is used.

Cost Elements of Physical Alternatives to Chemical Control

As an alternative to fumigation, commodity disinfestation may be accomplished by physical methods which include irradiation, modified atmospheres, and temperature manipulation (e.g. freezing, superheating), as well as highly experimental techniques using ultrasound and microwaves (Mitchell and Kader, 1985). In addition, sublethal temperatures can be used to inhibit reproduction and feeding of insects within the stored commodity, and to discourage insects from flying into the storage area from outside.

Possible methods of applying irradiation, modified atmospheres and sublethal-temperature (ca. 50°F) refrigeration, and their associated estimated costs for insect control in the California dried fruit and nut processing industries are as follows.

Irradiation

Irradiation may be usefully applied at any point where a commodity disinfestation treatment is required. Possible application points for the irradiation of bulk in-shell almonds are the initial receipt and pre-processing steps. In-shell walnuts may also be irradiated on receipt and before processing, while processed walnut meats, raisins and prunes may be irradiated either before or after packaging. To spread out peak loads, some in-shell almonds and walnuts may be refrigerated to sublethal temperatures for a short time between receipt and irradiation. Refrigeration could also be used to stop insect activity in prunes and raisins during long-term storage before and/or after a single irradiation disinfestation treatment.

Radiation sources which may be used for food irradiation are two gamma-ray emitting isotopes, cobalt-60 and cesium-137, as well as energized electrons (E-beams) up to 10 MeV and X-rays up to 5 MeV. On the molecular level, similar results can be achieved with either energized electrons or photons (gammas and X-rays) since photons transfer their energies to secondary electrons within the absorbing materials (Cleland and Pageau, 1985). At the 5 MeV level, the X-ray spectrum has similar penetration to cobalt-60 (ibid.). However, even at the 10 MeV level, E-beams are still far less penetrating than cobalt-60 or cesium-137. In practice, E-beam processing of dried fruits and nuts would probably be limited to bulk product applications. Estimated costs of possible irradiation treatments using cesium-137, cobalt-60 and machine sources are described below.

Cost of Cobalt-60 or Cesium-137 Irradiation

The cost of dried fruit and nut cesium-137 irradiation was estimated by a U.S. Department of Energy (USDOE) contractor, CH2M HILL, by considering existing isotope irradiation systems which could be adapted to handle dried fruits and nuts both in packages and in bulk form. Two sample irradiator designs which might be used have been discussed in the literature. The first system is used in the pilot-scale Sandia Irradiator for Dried Sewage Solids, which has been described by Sivinski and Ahlstrom (1984). The pilot-scale irradiator contains a source rack lying in a horizontal plane, while the conveyor system consists of buckets supported by a heavy link chain. The second system was designed by Atomic Energy of Canada Ltd. (Varaklis, 1983) and is currently used for sterilizing packaged medical products. In this system, the source rack is placed in a single vertical plane, and product is passed by the source in long vertical carriers. Bulk product could be dropped into the carrier from an overhead conveyor belt. In the event that the drop (of 6 to 10 feet) is too damaging for the product, the carrier could be positioned horizontally for loading, as is currently done when carriers of this type are loaded with packaged medical products. The carriers are then stood upright before they are moved into the radiation zone.

Actual costs of integrating irradiation into an existing dried fruit or nut processing stream will be plant-specific, depending on such considerations as the necessary plant modifications which may be required to bring the product from more or less widely spaced packing lines or receiving stations through a single irradiation facility. The USDOE contractor's "conceptual level" estimated costs (+30% to -40% accuracy range) of owning and operating five sizes of cobalt-60 or cesium-137 irradiators are shown on an annualized basis (see assumption 1 below) in Table 2. Important assumptions and considerations underlying the annualized cost estimates reported in Table 2 are listed and discussed below.

(1) Capital costs for the initial source loading and physical plant are amortized at 12% interest over 20 years. Hence the annualized costs approximately equal 0.1338 times the capital outlays. Periodic source replenishment expenses are annualized by assuming a sinking fund at 12% interest.

Twelve percent interest may be considered a low estimate of the cost of using or acquiring capital for investment in a new technology such as food irradiation. On the other hand, the amortization period of 20 years may be less than the useful life of the physical plant, estimated to be about 30 years by the USDOE contractor. Because risks of obsolescence, change in demand etc. are involved in any physical plant investment, many firms undertake such investments only if they appear economically justified when amortized over much shorter periods than the projected life of the new facility or equipment. For example, amortization periods of 3 to 5 years may be applied in deciding whether it will pay to invest in equipment which may have a projected useful life of over 20 years.

(2) Although cesium-137 radiation has a lower energy spectrum than cobalt-60's, and is therefore slightly less penetrating, it is assumed that the design and cost of the irradiation facility will be similar for both isotopes.

(3) Cesium-137 is assumed to cost 24¢ per curie, equivalent to cobalt-60 at $1 per curie given the present amortization schedule of 12% interest over 20 years, the relative curie requirements (assuming 1 curie cobalt-60 = 7 curies cesium-137 in processing), and the relative half-lives of the two isotopes.

These are low estimates of the isotope costs. A price of $1.15 per curie is currently being quoted for cobalt-60 by its main supplier, Atomic Energy of Canada Ltd. (AECL), while currently existing supplies of reprocessed cesium-137 are in short supply and are not expected to be available to dried fruit and nut processors under terms recently quoted by the USDOE. It is not possible to predict the future prices of cobalt-60 and cesium-137 since these will be determined by possible new sources of demand (such as food irradiation) as well as by supplier decisions. It is generally believed that the price of cobalt-60 will remain above $1 per curie, however.

(4) In the present analysis, it is assumed that the maximum radiation dose which would be used is 750 Gy (= 75 krad), while a dose of about 350 Gy (35 krad) would be adequate for many applications where insect feeding and reproduction must be stopped, but a quick kill is not essential.

(5) Although the cost estimates reported in Table 2 were constructed on the basis of a 750 Gy dose, it is assumed that throughput capacities corresponding to the 750 Gy dose can be doubled with no increase in total cost, if the required dose is 350 Gy, or slightly less than half of the original dose.

On the conceptual level, the processing capacity of a fixed size irradiator is inversely proportional to the required dose. Only the product handling and receiving space categories must be increased to increase product throughput at a lower dose, and these can be doubled at an annualized cost of 5% to 10% of the total estimated annualized cost of owning and operating the irradiator.

(6) A net source utilization efficiency of 30% is assumed.

This is a fairly high net source utilization efficiency for an isotope irradiator designed to handle dried fruits and nuts in packages (bags or boxes) or in some mixture of packaged and bulk-form loads. An irradiator designed to handle only bulk-form products such as in-shell almonds might be able to achieve a higher net source utilization efficiency, and so would require less source. Conceptual designs and pilot plants for cobalt-60 bulk grain irradiators with estimated or projected source utilization efficiencies greater than 50% have been reported (Cornwell, 1965; Tilton and Brower, 1971).

(7) For the dried fruit and nut applications considered here, additional automatic equipment (conveyors, depalletizers etc.) required to move both bulk and packaged product through a single irradiator is estimated to cost $300,000. Amortizing this cost at 12% interest over 20 years, and assuming annual maintenance costs 5% of capital, the annualized cost of the added equipment is about $55,000, which is in addition to the annualized cost of the single-purpose irradiator reported in Table 2.

If both bulk and packaged product forms are disinfested in a single irradiator, extra costs are incurred. For example, the irradiator may be located near the front end of the process, if most of the throughput is for pre-processing disinfestation of bulk commodity. At the other end of the process, the product is packaged and built into pallet loads. For irradiation, the pallet loads must then be conveyed back up to the front end of the process. An additional, relatively simple conveyor system may be used to irradiate the pallet loads, or the pallets may be broken up for irradiation and then rebuilt. In either case, automatic equipment (conveyors, depalletizers etc.) for the extra product handling is required.

(8) Minimum unit costs of irradiation reported in Table 2 are based on the assumption that the irradiator is operated at its maximum capacity 24

hours per day 350 days per year, with only two weeks per year downtime for maintenance.

For actual disinfestation applications, required irradiator capacity will usually exceed throughputs which can be maintained throughout the year, due to the seasonality of processing steps such as product receipt and and some shipments, and the natural yearly fluctuation in agricultural production. In the most extreme case, if the irradiator is used only for the initial disinfestation of newly harvested almonds or walnuts, it would then sit idle for all but a few months of the year.

(9) For the purpose of the present study, it is assumed that the cost of owning and operating a given irradiator is fixed, independent of seasonal changes in utilization.

Unfortunately, potential cost savings when the irradiator is not in use are minimal. For the sample irradiators constructed for this analysis, conveyor system maintenance and utilities which could be saved during months when the irradiator is completely shut down amount to only 3% of total annualized costs. Wage labor which could be employed on a seasonal basis, as opposed to specialized irradiation personnel, accounts for about 13% of total annualized costs, as the cost estimates were constructed for this analysis. Product handling for bulk product irradiation, which is likely to be the most seasonal, will be more highly automated, however, and thus will require less wage labor.

The relationships among required dose, annual throughput capacity, estimated minimum (full-utilization) unit costs, and typical dried fruit and nut industry production levels are illustrated in Figure 1, where the minimum unit cost curves were derived by plotting annual throughput capacities against minimum unit costs reported in Table 2, and interpolating on the resulting curve. From Figure 1 it can be seen that over 50% of California's dried fruit and nut production would have to be irradiated in a continuous, uniform stream to achieve the lowest possible unit costs of $2 to $3 per ton, depending on dose. The biggest product volume handled by any single processing plant is about 200,000 tons per year. Hence, even assuming the largest processor's entire product volume is irradiated in a continuous, even stream over the entire year, in-house cobalt-60 or cesium-137 irradiation disinfestation would cost $4 to $5 per ton, according to the cost estimates reported in Table 2.

Relative Cost of E-beam Processing

Unlike isotope sources, E-beam generating units do not increase in cost in proportion to their power ratings which determine their processing capacity. Hence E-beam processing becomes increasingly cost-competitive as throughput volume and dose requirements increase. In addition, unlike isotopes which continuously disintegrate, E-beam units can be switched off when not in use, providing savings for seasonal irradiation applications.

Table 3 shows average manufacturers' cost estimates for 10 MeV E-beam units with 20 kW and 40 kW power ratings. Following Cleland and Pageau (1985), it is assumed that the E-beam units can replace 1 MCi of cobalt-60 for each 10 kW of their power rating, based on an assumed difference in net utilization efficiency of 50% for the E-beam versus 30% for the isotope source. The cost of the 20 kW E-beam unit is also compared with the cost of a 1 MCi cobalt-60 source in Table 3, under the assumption that the E-beam unit would operate only 12 hours per day. The biggest processing rate considered in Table 3 is 2,000 tons per day. This processing rate appears to be achievable for products such as bulk almonds and walnuts at the net source utilization efficiency of 50% assumed here (Daniel Sloan, personal communication).

Operating costs for the E-beam unit during use hours include the electricity input requirement, as well as an average cost for parts and maintenance. Following Cleland and Pagaeu (1985), parts and maintenance costs are indicated in Table 3 as $25 per hour of E-beam unit operation.

Comparison of the amortized capital and operating costs of the E-beam units with annualized initial loading and replenishment costs for equivalent isotope sources (Table 3) indicates that E-beam units may cost about the same as isotope sources for throughput requirements as small as 1,000 tons per day at a 350 Gy dose, if the irradiator is employed only three months out of the year. If the irradiator is operated year-round, E-beam units may be competitive with isotope sources for throughputs greater than 2,000 tons per day at a 350 Gy dose.

As was previously mentioned in the discussion of estimated isotope irradiation costs (assumption 6), better source efficiency and hence lower cobalt-60 or cesium-137 source costs may be achieved in an irradiator which is designed to handle bulk products only. Single-purpose bulk product irradiators may also require a smaller radiation chamber so that less total concrete for shielding is required. A simpler and less expensive conveyor system may be used for products such as bulk in-shell nuts, e.g. a gravity-impelled system which channels the product over and around encapsulated source rods such as the conceptual design described by Cornwell (1965), or the functioning pilot plant described by Tilton and Brower (1971).

For large-volume bulk product irradiation, E-beam processing may be expected to be less expensive in terms of physical plant requirements as well as the cost of the source itself. This is because E-beams can be focused, whereas isotope sources emit radiation in all directions. Efficient E-beam processing of bulk products may be accomplished using relatively simple conveyor systems, e.g. flat belt conveyance, or gravity impelled flow through a pipe (Zakladnoi et al., 1982) or aperture (Cornwell, 1965), or down a vibrating ramp (Rutt, 1984).

Bulk in-shell almonds appear to be the most promising candidate for E-beam processing, because they have relatively good flow properties (as compared to other dried fruits and nuts) and are resilient enough to be handled like grain. Processing rates as high as 4,000 tons per day or higher may be achievable, since the almonds can tolerate impacts which they may encounter in fast, gravity-impelled or belt conveyor systems. As was discussed above, the cost of integrating irradiation into an existing process stream will be a function of many plant-specific variables. A lower bound to the cost of E-beam processing may be obtained by considering the costs of the

E-beam unit, concrete shielding and conveyor system which will certainly be required. For example, E-beam unit manufacturers estimate that the shielding and conveyor system for a 10 MeV E-beam facility capable of processing 4,000 tons per day would each cost about $500,000 for a combined cost of about $1 million. Amortizing this cost at 12% interest over 20 years and adding 5% of the capital cost annually for maintenance, the estimated annual E-beam facility plant cost would be about $184,000. Labor and overheads for the E-beam facility are estimated by E-beam unit manufacturers to cost about $400,000 if the facility is run 8,000 hours per year. If the E-beam facility were run 12 hours per day during three months of the year, its total annualized cost would be $762,300, or about $7.60 per ton for a processor who handles 100,000 tons per year, assuming the E-beam unit capital, power and maintenance costs are as shown in Table 3, and labor and overheads cost $200,000 per year for the 12 hour per day, three month per year operation. If 200,000 tons per year are handled by the same E-beam facility in the same number of hours, the unit cost of irradiation would fall to $3.80 per ton. At full utilization, the 4,000 ton per day capacity facility could treat 1.4 million tons in a 350 day year, or about 1.4 times California's entire annual production of almonds, walnuts, raisins and prunes combined.

Lower energy E-beam units are also currently available which have much higher power ratings than those considered thus far. For example, one major manufacturer produces a 150 kW, 3 MeV E-beam unit which has a quoted installed price of about $2 million. The manufacturer estimates that the plant cost for a bulk almond irradiation facility using this machine is about $1 million. If the almonds can be moved past the beam fast enough to take advantage of the high power output, and in a thin enough stream (e.g. single layer) to be penetrated by the lower energy beam, this machine would have the advantage of being able to handle even the biggest daily receipts in the normal working day.

Relative Cost of X-ray Processing

E-beam units can be modified to produce X-rays by placing a heavy metal target (e.g. tungsten) between the E-beam source and the product. Although the conversion process is simple, less than 10% of the E-beam energy is converted to X-rays at the maximum allowable energy level of 5 MeV, the remaining 90+% being lost in the form of heat. At lower energy levels the conversion efficiency is considerably reduced. Although future technological advances may change this, generated X-rays are not now competitive with isotope sources, given the high accelerator power rating and electricity input required.

The use of X-rays as an adjunct to E-beams may still be of interest to processors who can justify a powerful E-beam unit for large volume but seasonal bulk product irradiation, while also needing to disinfest smaller daily volumes of packaged product throughout the remainder of the year. In this case there would still be additional costs to make the irradiation system suitable for the dual use, however. Additionally, the E-beam unit might need to be adjustable within the 5 MeV to 10 MeV range, and so would cost more, since the higher energy level might be needed to achieve the high throughputs of bulk products required. Labor, electricity, and parts and maintenance costs would be incurred for the hours the E-beam unit is employed for X-ray processing.

A hypothetical example will serve to illustrate the per ton cost of machine source maintenance during use in the X-ray mode. Suppose a 40 kW, 5 MeV E-beam unit produces 4 kW of X-ray power, equivalent in processing to 0.4 MCi of cobalt-60 or capable of processing 400 tons per day at a 350 Gy dose. If the machine's hourly electricity and parts and maintenance cost is $40 (see Table 3), this cost alone amounts to $2.4 per ton of supplementary X-ray processing at the 350 Gy dose.

Modified Atmospheres

Modified atmosphere (MA) disinfestation is a competitor for all of the insect control needs which might be served by irradiation, while long-term modified atmosphere storage is also a good replacement for multiple fumigations and foggings of bin-stored prunes and raisins. Practical aspects of using modified atmospheres for insect control have been studied in Australia and in this country since the 1950's (Jay, 1984). Recently, the efficacy, engineering considerations and costs of disinfesting California dried fruits and nuts by exothermically generated low oxygen atmosphere (GLOA), carbon dioxide and high nitrogen atmospheres have been studied (Gardner et al., 1982; Soderstrom et al., 1984; Soderstrom and Baritelle, 1984; Soderstrom and Brandl, 1984). Reported costs of the various modified atmospheres are similar, although the generated low oxygen atmosphere tends to be cheaper for large volume applications or for use on a repeat basis. Possible application methods and costs of GLOA for dried fruit and nut disinfestation are considered here, as an illustration of one modified atmosphere alternative to fumigation.

Cost of GLOA for Disinfestation Treatments and Long-term Storage

An exothermic low oxygen atmosphere generator works by burning propane or natural gas in air to produce an atmosphere which contains only about 0.5% oxygen. The low oxygen atmosphere is cooled and filtered to remove impurities, and is then piped into the storage structure where it displaces the original atmosphere. When the storage atmosphere has been purged to an oxygen content of 0.5%, a lethal atmosphere has been established which will kill all storage pests. The time required to kill infesting insects is temperature dependent, taking about three days to a week after purging at typical receiving, processing and shipment temperatures (65-80°F), according to research (ibid). Once the oxygen has been removed, the storage structure must be completely ventilated before reentry is safe.

Costs to adopt the GLOA technology include the costs of the low oxygen atmosphere generators, plumbing, gas analyzers and auxiliary equipment, as well as the cost of the utilities (propane or natural gas, electricity and water) to run the generators. Labor is required to seal up and ventilate the storage, operate the generator, and monitor the storage atmosphere's oxygen content.

In addition, some processors may encounter large costs to modify or replace existing storages so that they are sufficiently airtight for effective low oxygen or other modified atmosphere treatments. The longer treatment time which may be required for modified atmosphere disinfestation relative to fumigation may result in further large costs for some treatment applications. Special problems which may be encountered in adopting modified atmosphere technology for 1) disinfestation of newly harvested almonds and walnuts, 2) protection of raisins and prunes in long-term storage, and 3) disinfestation of finished goods are described below, along with suggested possible solutions.

(1) MA disinfestation of newly harvested almonds and walnuts. In order to achieve timely disinfestation of newly harvested almonds and walnuts, the processor must have facilities which allow consignments of nuts to be sealed off and purged within one or two days of receipt. In addition, the total capacity of the storage facilities must be sufficient so that each consignment of nuts can occupy the necessary chamber or bin space for 10 days, the estimated filling, purging, maintenance and aeration time.

Existing processor facilities may fall short of the requirements for MA disinfestation in several ways. One potential problem which may be relatively easy to correct is that existing storage bins or chambers of suitable size may be insufficiently airtight for effective MA disinfestation treatments. More serious potential problems are 1) existing storage facilities may be too large for the MA to be established in the short time required for disinfestation of newly harvested almonds and walnuts, and 2) the total capacity of existing, suitable storage facilities may be too small, given that the available space may now be occupied longer by each lot of nuts requiring disinfestation.

Further research is needed to determine how air-tight a structure needs to be to insure that no air pockets can be left and MA disinfestation will be 100% effective. It may be, however, that many concrete tilt-up buildings, concrete silos and metal bins currently used for bulk nut storage are too leaky for effective MA control. Numerous studies of sealing methods made in this country and in Australia (see e.g. Banks and Annis, 1980; Lehane, 1982; Soderstrom and Baritelle, 1984; Banks, 1984; D'Orazio, 1985) indicate that existing storage bins and chambers can be sealed to leak less than 5% of their volume per day. This standard of sealing is recommended in Australia for applications where the modified atmosphere is maintained in the storage facility during many months of storage; hence the investment in sealing is repaid in lower modified atmosphere maintenance costs. The 5% of volume per day standard of sealing is probably more than adequate to ensure efficacious low oxygen atmosphere treatments.

The most general sealing required is that of joints of concrete tilt-up buildings or bolted metal bins, bolts and seams of metal bins, openings for product in- and outloading etc. In addition, floor and wall cracks of older concrete buildings may have to be patched, or if the walls are badly cracked, as sometimes happens in older vertical concrete silos, the entire wall surface may need to be coated. Many of the sealing jobs can be accomplished using sprayable plastics, which were first developed by the U.S. Department of the Navy for strippable rust protection of topside ordnance units and other vessel machinery on the Reserve Fleet during World War II (Roop, 1949). Neoprene strips can also be used to seal floor-to-wall joins in concrete tilt-up buildings (Soderstrom and Baritelle, 1984). Sprayable polyurethane foam may be used to seal large gaps, e.g. under the eaves (Lehane, 1982).

Costs to seal concrete tilt-up chambers and bolted metal bins average about $5 per 100 cubic feet (Lehane, 1982; Soderstrom et al., 1982; D'Orazio, 1985). Good sealing jobs have been found to be reasonably durable (Thompson, 1985). An average maintenance cost of 3.5% of initial cost per year has been reported for sealing of one large horizontal shed by Lehane (1982).

Where the existing capacity of suitably sized bins and/or chambers is inadequate for timely disinfestation of all incoming nuts, several solutions are possible. One possible, at least partial solution for almonds might be to shell the nuts, thus reducing their volume by approximately half, before placing them in storage. Another solution is to build enough new storage capacity to make up the entire short-fall. For example, if the processor's existing storage capacity is in the form of large horizontal sheds, which are not suitable for rapid MA disinfestation treatments, enough new, smaller chambers or bins might be built to equal existing storage in total capacity. New usable storage capacity might also be gained by subdividing large horizontal sheds into chambers. However, construction contractors estimate that such a subdivision would amount to putting a new building within the existing one, and would cost as much as constructing new bins or chambers from scratch.

Where the shortfall in suitable storage capacity for MA treatments is large, a good solution may be to construct special chambers for the purpose of disinfestation treatments, and move all incoming nuts through these bins or chambers before they are processed or go into long-term storage. At most, the disinfestation facilities would need to be able to hold as much product as may be received in 10 days during the peak receiving season, if all incoming product is disinfested in these facilities.

Average cost estimates of construction contractors and consultants to build bulk nut bins or chambers with loading/unloading equipment are $1 per cubic foot. Less expensive bulk storage concepts such as inflatable buildings (see e.g. Soderstrom et al., 1984), and even lined trenches also exist, although the maintenance and quality problems which might arise with their use are not known. Industry sources estimate that the extra product handling, which would be required to move all product through special disinfestation facilities, could be accomplished for about $1 per ton handled.

(2) MA protection of raisins and prunes in long-term storage. A large portion of the raisin crop is stored outdoors in large stacks of bins covered with paper held in place with wooden frameworks nailed to the stacked bins. Research indicates that a low oxygen atmosphere can be effectively established and maintained in commercial-size (e.g. 1600- to 2800-bin) raisin stacks (Soderstrom and Brandl, 1984).

Part of the raisin crop and most of the prune crop are stored in bins stacked inside metal, concrete or wooden warehouses. As one approach, these warehouses might be sealed for MA storage using methods similar to those described above for sealing bulk nut storages. This approach might work well where existing warehouse space is already divided into relatively small chambers which can be filled, sealed and left until the fruit is needed for processing. In some cases, prune or raisin bins may be stored in large, open warehouse spaces which cannot be conveniently sealed off for prolonged periods. In this case, one solution would be to build covered stacks within the warehouse. Gardner et al. (1982) estimated the cost of building outdoor raisin stacks at about $5 per ton covered. However, this cost includes the cost of stacking the bins, which will not represent an extra cost in warehouse storage. The materials to cover indoor stacks will also cost less and will last longer, because they will not be exposed to the elements.

(3) MA disinfestation of finished goods. The best methods of applying modified atmospheres for disinfestation of finished goods have yet to be determined. It is known, however, that carbon dioxide is sorbed by commodities, and high carbon dioxide atmospheres can quickly penetrate a dense commodity pack (Ed Jay, personal communication). The GLOA is also about 15% carbon dioxide, and may be able to penetrate commodity packs quickly.

Some goods may receive a pre-shipment fumigation after they have been sealed in gas-tight plastic packs. In this case MA, like chemical fumigants, would be limited to killing insects around, on or in the cardboard cartons containing the sealed packages.

The exposure time required for MA disinfestation is highly temperature dependent. For example, Jay (personal communication) found that disinfestation times for a high carbon dioxide atmosphere fell rapidly as the temperature was raised above 80°F; at 110°F the carbon dioxide acted as rapidly as a conventional methyl bromide treatment, yielding a 2-day turn-around. For commodities such as raisins and prunes which may be able to tolerate elevated temperatures during short (2 to 3 day) exposure periods, rapid MA disinfestation may be achievable. Since heat is a by-product of low oxygen generators, the necessary heating would be a free good if GLOA is used to disinfest finished products.

If MA disinfestation is significantly slower than current fumigation practice, adopting the MA technology will require changes in management practice for those processors who now process and pack largely to order, and who may routinely hold only as much finished product as will be shipped in one or two days. Extra warehouse space may be required to accommodate the longer treatment. If processing and packing must be done further ahead of shipping than is now customary, some time value on the money that goes into processing and packing will be lost. Some processors might have difficulty anticipating sales, or might lose sales because of the longer time it would take them to respond. A special hardship would exist for early-season in-shell walnuts, which need to be shipped as soon as possible in order to compete in pre-Christmas European markets.

Assumptions for GLOA Cost Analysis

As is the case for irradiation, equipment and construction requirements for GLOA treatments represent fixed costs which must be sized to meet peak needs. Estimated costs of using low oxygen atmospheres as well as irradiation are reported in the next section for hypothetical processors whose product handling schedules and existing physical plant are specified. Considerations and assumptions on which the cost estimates for low oxygen atmosphere disinfestation treatments are based are listed and discussed below.

(1) Following Gardner et al. (1982) and Soderstrom et al. (1984), it is assumed that a single generator can simultaneously purge a new chamber, while maintaining several chambers which have previously been purged. Moreover it is assumed that several generators may be used to purge a single large air space. Hence there is a simple relationship between the total volume of storage space which must be purged and maintained per unit time and the generator capacity required, irrespective of the number and size of storage chambers involved.

(2) Although low oxygen atmosphere generators come in a range of types and sizes, for convenience it is assumed that only one type and size of generator is used, which is capable of producing 10,000 standard cubic feet per hour (scfh) of the GLOA. This generator has been used in field trials in California and has been found to be reasonably portable.

(3) Based on information provided by the manufacturer, the cost of each 10,000 scfh unit including gas analyzer, safety equipment and plumbing is estimated at $55,000. It is assumed that the generator and auxiliary equipment has a 20-year life if properly maintained. Hence the annualized cost of each unit is estimated at $10,110, the capital cost amortized at 12% interest over 20 years plus 5% of capital per year for maintenance.

(4) Based on the results of field trials (Soderstrom and Brandl, 1984; Soderstrom and Baritelle, 1984), it is assumed that the generated atmosphere requirements to purge are four times the total volume for raisin yard stacks and 1.5 times the total volume for full bulk nut storages. Once purged, maintenance requirements are 12% of volume per day for raisin yard stacks and 5% of volume per day for bulk nuts.

(5) Although this has not been determined experimentally, it is assumed that purging and maintenance requirements would be the same for finished goods in fumigation chambers as for raisin bin stacks. This assumption is based on the premise that the proportion of air space to total volume would be similar in fumigation chambers and in bin stacks. The desired smaller air space in fumigation situations for finished goods is achievable if fumigation chambers are loaded fully before purging, in contrast to the load factor of 50% which may now be typical in these situations (see Table 1).

(6) It is assumed that for each treatment application, the low oxygen atmosphere will be maintained for one week after purging. This should be adequate time for complete insect control at normal receiving, shipping and handling temperatures, according to research.

(7) Total utility costs are estimated at $1.42 per 1,000 scfh, based on assumed costs of propane @ $1 per gallon, electricity @ 9¢ per kWh, and water @ 23¢ per 1,000 gallons. The assumed utility requirements are based on manufacturer's data which indicate that 1.26 gallons propane, 0.5 kWh electricity and 8 gallons per minute water are used to generate each 1,000 scfh of GLOA. These utility requirements are independent of the generator capacity.

(8) Labor costs for low oxygen atmosphere disinfestation of bulk stored nuts and of finished goods are estimated to be in the same range as current fumigation costs. Labor costs for long-term low oxygen atmosphere storage of yard-stacked raisins and of tarp-covered prune bin stacks in warehouses are estimated to be in the same range as labor costs for monthly fumigations of yard-stacked raisins. This a high estimate of labor costs for low oxygen treatments. Detailed studies (Gardner et al., 1982; Soderstrom et al., 1984) have indicated that labor costs for low oxygen treatments may be less than labor costs for current fumigation practice. In particular, labor costs to maintain a low oxygen atmosphere during long term storage may be expected to be significantly less than labor costs for fumigation treatments made on a monthly or more frequent basis.

(9) As the best case scenario for adoption of low oxygen treatments for disinfestation of bulk in-shell almonds and walnuts, it is assumed that the processor's existing storage facilities can be modified and used for timely disinfestion treatments. The necessary storage modification is assumed to cost $5 per 100 cubic feet of existing capacity. The annualized cost of sealing is estimated as the capital cost amortized over 20 years at 12% interest plus 5% of capital per year for maintenance. It is assumed that the processors total existing bulk nut storage capacity is 125% of the excess of receipts over shipments during the peak receiving season.

(10) As the worst case scenario for low oxygen disinfestation of bulk in-shell almonds and walnuts it is assumed that none of the processor's existing bulk nut storage can be modified for timely low oxygen disinfestation

treatments. In this case, special low oxygen disinfestation chambers or bins must be built which are capable of holding as much product as is received in 10 days during the peak receiving season. All product must be moved through the disinfestation chambers for the initial disinfestation treatment on receipt. Construction costs for new bulk nut storages with loading/unloading equipment are estimated at $1 per cubic foot. The annualized cost of the new construction is estimated as the capital cost amortized over 20 years at 12% interest plus 5% of capital annually for maintenance. The cost of the extra product handling required to move the bulk nuts through the special disinfestation chambers is estimated at $1 per ton.

(11) It is assumed that the hypothetical processor stores raisins in paper-covered outdoor stacks, which are sufficiently airtight and strong for an effective low oxygen atmosphere to be created and maintained.

(12) It is assumed that prune bin stacks in warehouses could be sealed for long-term GLOA storage by covering each stack with a heavy, vinyl-coated nylon tarp, secured at the ground by sandsnakes. Standard 1-ton prune bins are 4' x 4' x 30" with 4" x 4" x 4' runners underneath. Hence, an 800-ton stack built 4 bins high by 10 bins wide by 20 bins deep could be covered by a 5,420-square foot tarp secured by thirty 6-foot sandsnakes. Prices quoted by a supplier for the tarp and snakes are 35¢ per square foot and 35¢ per linear foot, respectively. Assuming a five-year indoor life for the tarp and snakes, the capital cost can be amortized at 12% interest over five years, so that the materials cost to cover the bin stacks is 68¢ per ton covered each year. Assuming one man-day is required to cover and uncover each stack at a wage

rate of $11 per hour, labor costs are an additional 11¢ per ton covered annually.

(13) It is assumed that new in-plant fumigation space required for low oxygen disinfestation of finished goods is equal to 6 times existing capacity or sufficient space to hold as much product as is shipped in 12 days during the peak shipping season. This addition in fumigation space will be sufficient for a processor who currently packs only to order, and who requires a pre-shipment disinfestation treatment of 100% of outgoing goods. These are the conditions under which low oxygen disinfestation of finished goods will be most expensive.

(14) Based on average estimates of construction consultants and industry representatives, the cost of building new in-plant fumigation space is estimated at $1 per cubic foot. The annualized cost of the new construction is estimated as the capital cost amortized over 20 years at 12% interest plus 5% of capital annually for maintenance.

(15) Holding finished goods an extra week to replace methyl bromide fumigation with low oxygen disinfestation is estimated to cost the processor one week's interest at 12% on $1000 per ton value-added, equaling $3.2 per ton. The one week extra holding time for low oxygen disinfestation of finished goods corresponds to the situation where the processor's current practice is to pack only to order, and the disinfestation treatment is made after the packaging step. One thousand dollars per ton is a high estimate of the money tied up during the low oxygen treatment. The value added in processing

and packaging of California dried fruits and nuts has been estimated at 50¢ per pound (Sun-Diamond Grower, Feb-March, 1985). In fact some of the "value added" is in fixed cost overheads, and is only apportioned to goods as they are processed as an accounting practice.

Utility costs for many low oxygen atmosphere treatments (Table 4) are similar to costs for fumigant materials (Table 1). Equipment needs for the low oxygen atmosphere technology are also modest, costing, for example, 20¢ per ton for applications where a single 10,000 standard cubic feet per hour unit is used to disinfest 50,000 tons of incoming product over the receiving season. For some applications, plant-specific costs to modify existing bulk storage facilities, construct new facilities, and delay shipment of finished product may make low oxygen or other modified atmosphere disinfestation much more expensive than current fumigation practice, however.

Cost of Refrigeration in Processor Insect Control Programs

Refrigeration to a sublethal temperature (ca. 50°F) could be used to protect raisins and prunes from reinfestation during the time when the bins must be accessible for the purposes of sorting, grading and blending of the contents of a number of bins to make up orders to specifications. Neither modified atmospheres nor irradiation could fill this insect control need, which is currently taken care of with frequent (e.g. weekly) methyl bromide fumigations. Refrigeration during blending would therefore be a necessary component of any physical insect control program for prunes or raisins.

Costs to refrigerate the "blending chamber" space include the cost of retrofitting the chambers for refrigerated storage in addition to the refrigeration equipment and utility costs. Insulation of the blending chambers may be accomplished by coating the wall and ceiling surfaces with a thick layer of polyurethane foam, which in turn is covered with a protective, fire-retardant cement coating. Contractors in Washington State who are experienced with construction and retrofitting of buildings for refrigerated and controlled atmosphere storage estimate the cost of insulating the walls and ceiling at $1.50 per square foot. Thus, for example, a 20' high x 45' wide x 45' long chamber could be insulated for about $8,500 or 21¢ per cubic foot. An average manufacturers' estimate for refrigeration equipment and installation is $6 per square foot of floor space or 30¢ per cubic foot in a 20' high chamber. If the insulation and refrigeration equipment costs can be amortized at 12% interest over 20 years with 5% of the initial cost per year for maintenance, their annualized combined cost is about 10¢ per cubic foot. Utility costs to refrigerate warehouse space year-round have been estimated at 11¢ per cubic foot (Morrison, 1985). Assuming, for example, that the fruit is stacked in the warehouse space at a specific volume of 80 cubic feet per ton, and blending space is required to hold 5% of the total product volume handled annually (about as much as may be processed in a two-week period) the cost of refrigerating the blending space can be estimated at 85¢ per ton handled annually.

It would also be technically possible to refrigerate all prunes and raisins throughout long-term storage, both before and after a single irradiation disinfestation treatment. However, this would require the construction of new, insulated warehouse space for a large portion of the raisin crop which is currently stored in outdoor stacks. Even where prunes or raisins are already stored inside warehouses, the cost to refrigerate half of the annual product volume throughout the year, with sufficient capacity to refrigerate most of the product volume during the receiving season, would be in the range of \$9 to \$17 per ton handled annually, based on calculations similar to those shown above and assuming the product's specific volume is in the lowest achievable range of 40 (for prunes) to 80 (for raisins) cubic feet per ton. Hence it is evident that refrigeration alone is more expensive than GLOA for protection of prunes and raisins in long-term storage, while the GLOA also disinfests the commodity.

Refrigeration could also be used to stop insect feeding and reproduction in newly harvested almonds and walnuts, thus helping the processor spread out peak loads and improve the utilization efficiency of an irradiator. However, storage modification costs are greater for refrigeration than for modified atmosphere treatments, since insulation as well as sealing is required. The equipment capacity required to cool large quantities of nuts (1,000 tons per day or more for large processors) from field temperatures around 90°F to 50° within two days would be prodigious, and would cost far more than low oxygen generating equipment for timely purging of similar quantities of nuts. Utility costs to cool the nuts would also exceed the utility costs for GLOA disinfestation. Hence it is evident that the refrigeration adjunct to irradiation would alone exceed the cost of GLOA disinfestation of newly harvested nuts.

Cost Effectiveness of Irradiation in Insect Control Programs

From a review of treatment cost estimates reported above, irradiation appears to be a relatively expensive disinfestation method, which may cost 10 to 20 times as much as fumigation, even for large volume applications. While chemical controls are relatively inexpensive and effective, it seems unlikely that processors will move to replace them with irradiation.

It is still of interest to ask whether irradiation may be competitive with other physical disinfestation methods in programs to replace fumigants and other chemical controls, in the event that these must be eliminated entirely. Possible program combinations of irradiation, low oxygen treatments and refrigeration have been described in previous sections of this report. Estimated treatment costs for each possible program which was not clearly dominated by another physical control program are compared with estimated costs for current chemical control practice in Table 5. It should be noted that some of the treatment programs shown in Table 5 indicate multiple irradiations of some commodity, although this is not permitted by current regulations. Because regulations may change, multiple-irradiation treatment programs were included in the cost comparisons. Critical considerations and assumptions on which the cost analyses were based are discussed below.

(1) The irradiation and low oxygen treatments both require significant investment in fixed-cost items (e.g. equipment, structural modification or new construction, and professional operating staff) which the processor may use for more than one treatment application within an overall insect control

program. Hence, average per ton costs of the treatment technologies must be compared with reference to their use(s) in complete insect control programs.

(2) For a given insect control program, per ton costs of the treatment technologies depend on the processor's seasonal product handling schedules which determine the extent to which fixed cost investment items may be fully utilized throughout the year. In addition, economies of scale in both fixed and variable costs are pronounced for the irradiation technology and also exist to a much smaller extent for low oxygen treatments.

Program cost estimates are reported in Table 5 for each of two hypothetical processors whose handling volumes are typical for each of the four commodities: almonds, walnuts, raisins and prunes. Seasonal handling schedules of the hypothetical processors, which are shown in Appendix A, were constructed to reflect typical industry practice and hence give an accurate picture of processors' relative costs of adopting the alternative treatment technologies. As an illustration, monthly irradiator throughputs corresponding to each insect control program and hypothetical processor handling schedule are also shown in Appendix A.

(3) As has been discussed in a previous section, processor costs of adopting low oxygen disinfestation treatments are critically dependent on the suitability of existing facilities, as well as on the compatibility of current handling practices. For the cost analyses reported in Table 5, anticipated worst cost cases for the adoption of low oxygen treatments were among the scenarios considered in order to identify any and all situations where

irradiation may be competitive. Specific assumptions concerning the costs of adopting low oxygen treatments for 1) in-shell almonds and walnuts, 2) raisins and prunes in long-term storage, and 3) finished goods have been described in a previous section.

(4) Capacity requirements for structural modification, new construction, and equipment required for GLOA treatments were in each case derived from the hypothetical processor's handling schedule reported in Appendix A, and the assumptions concerning the costs of GLOA treatments outlined in a previous section of this report. Similarly, the required daily irradiator throughput capacity was determined for each processor, insect control program combination as the biggest monthly throughput divided by 30.

(5) The cost of irradiation is in each case considered to be in the range of 60% to 130% of the estimated cost reported for five sizes of irradiator in Table 2 and inferred for intermediate size irradiators in Figure 1.

The per ton cost to adopt each treatment shown in Table 5 is the annual cost of adopting the treatment divided by the total number of tons the processor handles annually. The total costs of the complete treatment programs can be found by summing across columns in Table 5.

Care must be exercised in comparing worst case and best case cost estimates among treatments. For example, it would not be correct to compare the high cost estimate for almond alternative program 1 with the low cost estimate for almond alternative program 3, since the actual cost will in each case largely depend on the actual cost of the irradiator. Reference can be made to the detailed worksheets reported in Appendix B, to determine the relative importance of the assumptions underlying each treatment or program cost estimate.

The cost analyses reported in Table 5 indicate that the most promising applications for irradiation are the initial disinfestation treatments of in-shell almonds and walnuts at plants handling large product volumes (ca. 100,000 tons/year). At a sufficiently high throughput, irradiation may also be cost-effective for disinfestation of finished goods.

However, even where irradiation appears to hold promise, its lowest anticipated cost (60% of the "conceptual level" estimated cost derived from Table 2) is nearly equal to the worst case cost estimate for the competing GLOA treatment. Moreover, it is estimated that low oxygen and refrigeration alone can take care of all of the industries' insect control needs at an annual cost of under $20 per ton or a penny per pound.

Feasibility of a Centralized, Shared Irradiator

As the preceding analysis has shown, the unit cost of irradiation is highly dependent on the volume and uniformity of product throughput. Possibilities for minimizing unit costs of irradiation include centralized location of a contract irradiator, and time-sharing of an in-house irradiator.

Centralized or shared dried fruit and nut irradiators are unlikely to be feasible, since the extra product handling and transport required to use these irradiators may alone cost as much as $20 per ton, the estimated worst case cost for an in-house insect control program using GLOA disinfestation. Loss of processor control during the irradiation step is a further disadvantage of multi-firm irradiators, as is the increased potential for product reinfestation during transport.

Time-sharing of an in-house irradiator for treatment of non-dried fruit and nut commodities may appear as another possibility, since many of the processing plants are located in rich agricultural areas or near population centers. A review of the candidates by the authors, revealed little potential, regular demand for irradiation of local commodities, however. Quarantine insect pest problems on fresh fruits and vegetables rarely occur in California, and would not justify cost-sharing of an irradiation facility as a standby option (Mitchell and Kader, 1985). Higher radiation doses which are required to inhibit mold on fresh horticultural commodities have demonstrated phytotoxic effects (ibid.). Potatoes grown in the Central Valley region are non-storable varieties which do not require a sprout disinfestation treatment. For sanitary as well as logistic reasons, it is unlikely that a medical products sterilizer would use a dried fruit and nut irradiator on a seasonal basis.

Conclusions

There are a number of points in the postharvest handling of dried fruits and nuts where an irradiation disinfestation treatment could usefully be made. However, for every possible irradiation application, at least one other physical control alternative to chemical controls also exists. Modified atmospheres have a clear advantage over irradiation for every treatment of commodity during long-term storage. Complete disinfestation by modified atmospheres is also in every case less expensive than the refrigeration step alone, if refrigeration were to be used to stop insect activity in commodities until an irradiation treatment can be made.

"Generic" irradiation cost estimates developed for this study are only rough indicators (+30% to -40% accuracy range) of the cost of integrating irradiation into existing process streams. However, even at half of the reported, estimated cost, irradiation disinfestation of newly harvested almonds and walnuts still costs five to 10 times as much as current fumigation practice for even the largest processors. Even at 60% of estimated cost, the bottom of the estimated cost range, irradiation is also almost as costly as modified atmosphere disinfestation even under the least favorable assumptions about the suitability of the processor's existing storage facilities for modified atmosphere treatments.

Besides disinfestation of newly harvested bulk in-shell walnuts and almonds, the most promising irradiation application is the pre-shipment disinfestation of packaged product. However, even assuming substantial added costs due to expanded warehouse space requirements and product holdup, modified atmospheres are still hardly more expensive than the minimum (bottom of cost range) cost estimate for irradiation (60% of the "conceptual level" estimated cost), even assuming the largest processor in the industry makes a pre-shipment disinfestation treatment on 100% of outgoing product.

Prospects for improving irradiator utilization, and hence lowering per ton costs of irradiation are not bright. Transportation of commodity to a centralized irradiation facility may cost as much as in-house insect control programs based on GLOA disinfestation treatments. Supplementary demand for dried fruit and nut irradiators also appears to be minimal.

In the continuous insect control efforts of dried fruit and nut processors there are few special niches where a single, expensive irradiation treatment might be justified. One possible niche is the disinfestation of early season walnuts, where the need for a quick treatment may give irradiation a decisive advantage over modified atmospheres. The ability of irradiation to kill insects within a sealed package may be another advantage.

Costs of integrating irradiation into existing process streams are ill-defined, as the experience with food irradiation is still slight. In addition, while the costs of adopting modified atmospheres are well known for come applications, large unknowns cloud these costs for others. Methods and costs for new control concepts such as modified atmosphere packaging, and modified atmosphere disinfestation during transit should also be examined. However, based on the available information which was reviewed in this report it can be concluded that irradiation is unlikely to be a cost-effective component of programs to replace some or all chemical treatments for insect control in California dried fruits and nuts.

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Table 1. Costs of fumigants for commodity disinfestation treatments.

Commodity treatment	Specific volume cf/ton	Fumigant	Quanitity 1000 cf	Unit price	Fumigant cost/ton
In-shell walnuts	100	Methyl bromide	3 lb	$.65/lb	20¢
In-shell almonds	80	Hydrogen phosphide*	125 pellets	$1.86/100 ct	19¢
Yard-stored raisins	83	Hydrogen phosphide*	30 tablets	$2.75/30 ct	23¢
Raisin bins in warehouse	128**	Methyl bromide	1.5 lb	$.65/lb	12¢
Prune bins in warehouse	80**	Methyl bromide	1.5 lb	$.65/lb	8¢
Finished goods	134**	Methyl bromide	3 lb	$.65/lb	26¢

*Evolved from aluminum phosphide.
**Based on a typical load factor of 50%.

Table 2. Estimated costs of cobalt-60 or cesium-137 irradiation.

Throughput (T/day)					
750 Gy dose	50	100	500	1000	2000
350 Gy dose	100	200	1000	2000	----
Source size (MCi)					
Cobalt-60	.1	.2	1	2	4
Cesium-137	.7	1.4	7	14	28
Item	Annual cost at full utilization 350 days per year				
	- - - - - - - - - - $1,000 - - - - - - - - - -				
1. Amortized capital* (@12% over 20 years)					
-Source	22.5	45	225	450	900
-Other	120	155	252	347	487
2. Source replenishment*	11	14	40	72	136
3. Labor	225	225	276	326	402
4. Maintenance	19	29	46	66	94
5. Overheads	28	35	52	70	97
Total	427.5	503	891	1,331	2,116
Unit cost ($/T)					
750 Gy dose	24.4	14.4	5.0	3.8	3.0
350 Gy dose	12.2	7.2	2.5	1.9	-

*Source cost analysis for cesium-137.

Table 3. Relative costs of isotope sources and E-beam units.

Throughput (T/day)			
750 Gy dose	500	1000	2000
350 Gy dose	1000	2000	----
Equivalent isotope Source size (MCi)			
Cobalt-60	1	2	4
Cesium-137	7	14	28
E-beam unit			
Power rating	20 kW	20 kW	40 kW
Installed cost	$2,000,000	$2,000,000	$2.500,000
Electricity cost (@9¢/kWh)	$6.3/hour/2*	$12.6/hour	$15/hour
Parts and maintenance	$12.5/hour/2*	$25/hour	$25/hour
Annualized initial source cost Amortized @ 12% over 20 years			
Cesium-137 (@24¢/Ci)**	$225,000	$450,000	$900,000
E-beam unit	$267,600	$267,600	$334,500
Annual source replenishment/ maintenance cost			
Cesium-137 (@24¢/Ci)**	$40,000	$72,000	$136,000
E-beam unit operated			
3 months/year	$41,172	$82,344	$87,600
6 months/year	$82,344	$164,688	$175,200
9 months/year	$123,516	$247,032	$262,800
12 months/year	$164,688	$329,367	$350,400

*E-beam unit run 12 hours per day.

**From Table 2.

Table 4. Utility costs for GLOA disinfestation @ $1.42/1000 cf of GLOA.

Commodity treatment	Specific volume cf/ton	GLOA cf/ton to		Cost/ton
		Purge	Maintain	
In-shell walnuts	100	150	35/week	27¢
In-shell almonds	80	120	28/week	21¢
Yard-stored raisins	83	332	70/week	55¢ (= $2.86 for 6 months)
Prunes in tarped 800-bin stacks	42.5	170	36/week	29¢ (= $1.26 for 5 months)
Finished goods	67*	268	23/week	41¢

*Based on a load factor of 100%.

Table 5. Costs of alternative insect control programs for dried fruits and nuts using methyl bromide (MB) and hydrogen phosphide (HP) fumigation, pyrethrin fog, generated low oxygen atmosphere (GLOA), and cesium-137 or cobalt-60 irradiation to 350 Gy.

			Treatment cost per ton handled annually			
			Treatment during storage	In transit treatment		
Commodity	Processor size	Program		On-receipt	Pre-processing	Pre-shipment
Almonds	100,000 tons/yr	Current program		Fumigation (HP) = 39-79¢	Fumigation (HP) after April 1 = 11-22¢	
		Alternative 1		Irradiation = $7.14-15.47	Irradiation after April 1 = (0)*	
		Alternative 2		GLOA = $2.16-4.51	GLOA after April 1 = (11-23¢)*	
		Alternative 3		50% each: Irradiation, GLOA = $5.53-12.98	GLOA after April 1 = (11-23¢)*	

*Marginal cost for treatment assuming equipment and physical plant are already in place to carry out another treatment belonging to the program.

Table 5. Continued.

			Treatment cost per ton handled annually			
			Treatment during storage	In transit treatment		
Commodity	Processor size	Program		On-receipt	Pre-processing	Pre-shipment
Almonds	50,000 tons/yr	Current program		Fumigation (HP) = 39-79¢	Fumigation (HP) after April 1 = 11-22¢	
		Alternative 1		Irradiation = $9.11-19.75	Irradiation after April 1 = (0)*	
		Alternative 2		GLOA = $2.21-4.07	GLOA after April 1 = (11-23¢)*	
		Alternative 3		50% each: Irradiation, GLOA = $8.05-18.06	GLOA after April 1 = (11-23¢)*	

*Marginal cost for treatment assuming equipment and physical plant are already in place to carry out another treatment belonging to the program.

Table 5. Continued.

			Treatment cost per ton handled annually			
			Treatment during storage	In transit treatment		
Commodity	Processor size	Program		On-receipt	Pre-processing	Pre-shipment
Walnuts	100,000 tons/yr	Current program		Fumigation (MB) = 40-80¢	Fumigation (MB) before cracking = 24-48¢	Fumigation (MB) = 14-26¢
		Alternative 1		Irradiation = $8.32-18.02	Irradiation before cracking = (0)*	Irradiation = (0)*
		Alternative 2		GLOA = $1.12-5.50	GLOA before cracking = (28-52¢)*	GLOA = $2.88-3.00
		Alternative 3		50% each: Irradiation, GLOA = $6.24-15.05	GLOA before cracking = (28-52¢)*	Irradiation = (0)*

*Marginal cost for treatment assuming equipment and physical plant are already in place to carry out another treatment belonging to the program.

Table 5. Continued.

			Treatment cost per ton handled annually			
			Treatment during storage	In transit treatment		
Commodity	Processor size	Program		On-receipt	Pre-processing	Pre-shipment
Walnuts	10,000 tons/yr	Current program		Fumigation (MB) = 40-80¢	Fumigation (MB) before cracking = 24-48¢	Fumigation (MB) = 14-26¢
		Alternative 1		Irradiation = $33.18-71.89	Irradiation before cracking = (0)*	Irradiation = (0)*
		Alternative 2		GLOA = $1.93-6.42	GLOA before cracking = (28-52¢)*	GLOA = $3.89-4.01
		Alternative 3		50% each: Irradiation, GLOA = $30.42-66.44	GLOA before cracking = (28-52¢)*	Irradiation = (0)*

*Marginal cost for treatment assuming equipment and physical plant are already in place to carry out another treatment belonging to the program.

Table 5. Continued.

Commodity	Processor size	Program	Treatment cost per ton handled annually: Treatment during storage	In transit treatment: On-receipt	In transit treatment: Pre-processing	In transit treatment: Pre-shipment
Raisins	120,000 tons/yr	Current program	Fumigation (HP) monthly in yard-stacks = $2.58-4.98		Fumigation (MB) weekly in warehouse = 32-72¢	Fumigation (MB) = 46-86¢
		Alternative 1	GLOA in yard-stacks = $4.40-6.80		Refrigeration during grading = $1.00	Irradiation = $3.15-6.82
		Alternative 2	GLOA in yard-stacks = $4.40-6.80		Refrigeration during grading = $1.00	GLOA = $4.23-4.63
Raisins	30,000 tons/yr	Current program	Fumigation (HP) monthly in yard-stacks = $2.58-4.98		Fumigation (MB) weekly in warehouse = 32-72¢	Fumigation (MB) = 46-86¢
		Alternative 1	GLOA in yard-stacks = $4.40-6.80		Refrigeration during grading = $1.00	Irradiation = $9.20-19.93
		Alternative 2	GLOA in yard-stacks = $4.40-6.80		Refrigeration during grading = $1.00	GLOA = $4.48-4.88

Table 5. Continued.

Commodity	Processor size	Program	Treatment cost per ton handled annually			
			Treatment during storage	In transit treatment		
				On-receipt	Pre-processing	Pre-shipment
Prunes	60,000 tons/yr	Current program	Fumigation (MB) plus nightly pyrethrin fogs = 65-70¢			Fumigation (MB) = 46-86¢
		Alternative 1	GLOA in tarped stacks = $2.85-5.25		Refrigeration during grading = $1.00	Irradiation = $4.80-10.40
		Alternative 2	GLOA in tarped stacks = $2.85-5.25		Refrigeration during grading = $1.00	GLOA = $3.90-4.30
Prunes	15,000 tons/yr	Current program	Fumigation (MB) plus nightly pyrethrin fogs = 65-70¢			Fumigation (MB) = 46-86¢
		Alternative 1	GLOA in tarped stacks = $3.35-5.75		Refrigeration during grading = $1.00	Irradiation = $16.02-34.67
		Alternative 2	GLOA in tarped stacks = $3.35-5.75		Refrigeration during grading = $1.00	GLOA =$4.40-4.80

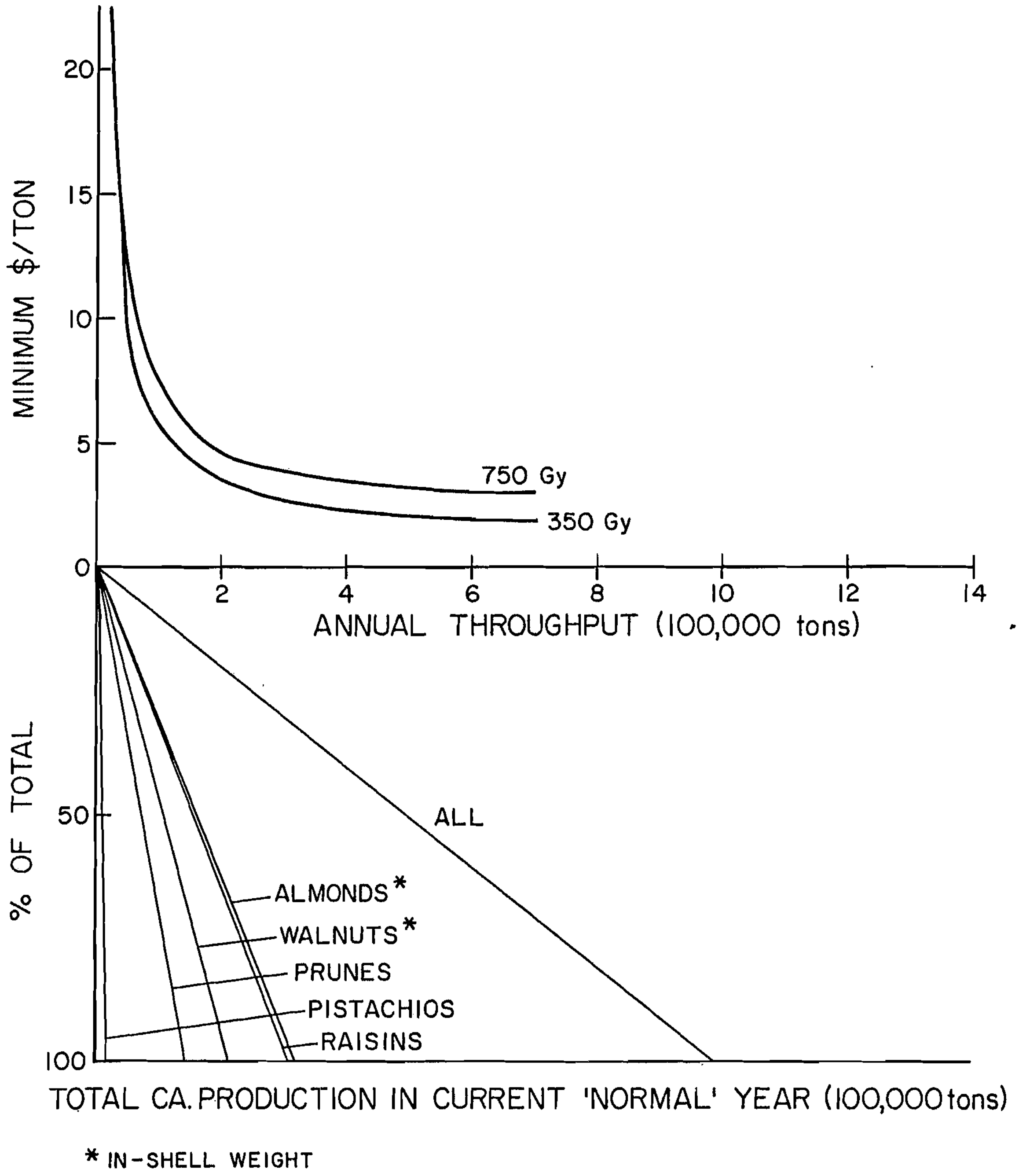

Figure 1. Minimum (full utilization) per ton cost of irradiation by annual irradiator throughput capacity, and the relationship of irradiator capacity to annual industry production.

Appendix A

Assumed Product Handling Schedules of Generic Plants

Generic Plant Description - Product Handling

Commodity - Almonds

Plant size - 100,000 tons/yr = Industry/4.

Product handling	Monthly volumes (tons)											
	8	9	10	11	12	1	2	3	4	5	6	7
1. Receipts	15,000	50,000	30,000	5,000								
2. Shipments												
Shelled nuts*	4,000	5,000	6,000	6,000	6,000	3,000	3,000	3,000	3,500	3,500	3,500	3,500
3. Irradiator Throughput												
Alternative Program 1												
Bulk in-shell product	15,000	50,000	30,000	5,000					7,000	7,000	7,000	7,000
Alternative Program 3												
Bulk in-shell product	7,500	25,000	15,000	2,500								

*In-shell weight/2.

Generic Plant Description - Product Handling

Commodity - Almonds

Plant size - 50,000 tons/yr = Industry/8.

Product handling	Monthly volumes (tons)											
	8	9	10	11	12	1	2	3	4	5	6	7
1. Receipts	5,000	20,000	20,000	5,000								
2. Shipments												
Shelled nuts*	2,000	2,500	3,000	3,000	3,000	1,500	1,500	1,500	1,750	1,750	1,750	1,750
3. Irradiator Throughput												
Alternative Program 1												
Bulk in-shell product	5,000	20,000	20,000	5,000					3,500	3,500	3,500	3,500
Alternative Program 3												
Bulk in-shell product	2,500	10,000	10,000	2,500								

*In-shell weight/2.

Generic Plant Description - Product Handling

Commodity - Walnuts

Plant size - 100,000 tons/yr = Industry/2.

Product handling	Monthly volumes (tons)											
	8	9	10	11	12	1	2	3	4	5	6	7
1. Receipts	5,000	20,000	45,000	30,000								
2. Shipments												
In-shell exports	5,000	10,000	10,000									
In-shell domestic			7,500	7,500								
Shelled nuts*	2,500	3,000	3,000	3,000	2,000	2,000	2,000	2,500	2,500	2,500	2,500	2,500
3. Irradiator Throughput												
Alternative Program 1												
Bulk in-shell product	10,000	36,000	51,000	36,000	4,000	4,000	4,000	5,000	5,000	5,000	5,000	5,000
Packaged meats	2,500	3,000	3,000	3,000	2,000	2,000	2,000	2,500	2,500	2,500	2,500	2,500
Alternative Program 3												
Bulk in-shell product	5,000	10,000	17,500	7,500								
Packaged meats	2,500	3,000	3,000	3,000	2,000	2,000	2,000	2,500	2,500	2,500	2,500	2,500

*In-shell weight/2.

Generic Plant Description - Product Handling

Commodity - Walnuts

Plant size - 10,000 tons/yr = Industry/20.

Product handling	Monthly volumes (tons)											
	8	9	10	11	12	1	2	3	4	5	6	7
1. Receipts		2,000	5,000	3,000								
2. Shipments												
In-shell exports												
In-shell domestic		1,000	1,500	1,500								
Shelled nuts*	200	400	400	400	200	200	200	200	200	200	200	200
3. Irradiator Throughput												
Alternative Program 1												
Bulk in-shell product	400	2,800	10,800	3,800	400	400	400	400	400	400	400	400
Packaged meats	200	400	400	400	200	200	200	200	200	200	200	200
Alternative Program 3												
Bulk in-shell product	1,000	1,500	1,500									
Packaged meats	200	400	400	400	200	200	200	200	200	200	200	200

*In-shell weight/2.

Generic Plant Description - Product Handling

Commodity - Raisins

Plant size - 120,000 tons/yr ≃ Industry/3.

Product handling	Monthly volumes (tons)											
	8	9	10	11	12	1	2	3	4	5	6	7
1. Receipts	30,000	70,000	20,000									
2. Shipments	10,000	10,000	12,000	12,000	9,000	7,000	10,000	10,000	10,000	10,000	10,000	10,000
3. Irradiator Throughput												
Alternative Program 1												
Packaged raisins	10,000	10,000	12,000	12,000	9,000	7,000	10,000	10,000	10,000	10,000	10,000	10,000

Generic Plant Description - Product Handling

Commodity - Raisins

Plant size - 30,000 tons/yr = Industry/10.

Product handling	Monthly volumes (tons)											
	8	9	10	11	12	1	2	3	4	5	6	7
1. Receipts	7,500	17,500	5,000									
2. Shipments	2,000	3,000	4,000	4,000	3,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000
3. Irradiator Throughput												
Alternative Program 1												
Packaged raisins	2,000	3,000	4,000	4,000	3,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000

Generic Plant Description - Product Handling

Commodity - Prunes

Plant size - 60,000 tons/yr > Industry/3.

Product handling	Monthly volumes (tons)											
	8	9	10	11	12	1	2	3	4	5	6	7
1. Receipts	10,000	20,000	20,000	10,000								
2. Shipments	4,000	4,000	5,000	5,000	4,000	4,000	4,000	4,000	4,000	4,000	4,000	4,000
3. Irradiator Throughput												
Alternative Program 1												
Packaged prunes	4,000	4,000	5,000	5,000	4,000	4,000	4,000	4,000	4,000	4,000	4,000	4,000

Generic Plant Description - Product Handling

Commodity - Prunes

Plant size - 15,000 tons/yr = Industry/10.

Product handling	Monthly volumes (tons)											
	8	9	10	11	12	1	2	3	4	5	6	7
1. Receipts	2,500	5,000	5,000	2,500								
2. Shipments	1,000	1,000	1,250	1,250	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
3. Irradiator Throughput												
Alternative Program 1												
Packaged prunes	1,000	1,000	1,250	1,250	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000

Appendix B

Partial Budget Analysis of Costs of Adopting Alternative Insect Control Programs

1. Almonds

1.1 Assumed current practice: Almonds are fumigated with hydrogen phosphide immediately on receipt. Almonds are refumigated before processing if they have been in storage 6 months or longer (i.e. if processed after April 1).

All almonds are passed through bulk storage facilities for fumigation. Current bulk storage capacity = 125% x the excess of receipts over shipments during the peak receiving season.

Table 1.1.1 — Assumed capacities of generic almond plants.

Category	Large plant (100,000 tons/yr)	Small plant (50,000 tons/yr)
1. Bulk storage @ 80 cf/ton	75,000 ton capacity = 6,000,000 cf	40,000 ton capacity = 3,200,000 cf

Table 1.1.2 — Fumigation costs for generic almond plants.

Category	Large plant (100,000 tons/yr)	Small plant (50,000 tons/yr)
1. Hydrogen phosphide fumigation	128 tons fumigated @ $.39 - .79/ton = $49,920 - 101,120/yr = $.50 - 1.01 per ton handled (pth)	64,000 tons fumigated @ $.39 - .79/ton = $24,960 - 50,560/yr = $.50 - 1.01 pth

1.2 Alternative control program 1: Almonds are irradiated immediately on receipt. Almonds are re-irradiated if they have been in storage more than 6 months (i.e. if processed after April 1). Required irradiation dose is 350 Gy.

Table 1.2 — Costs for almond alternative program 1.

Category	Large plant (100,000 tons/yr)	Small plant (50,000 tons/yr)
1. Cobalt-60 or cesium-137 irradiation	1,700 ton/day irradiator (350 Gy dose) = $714,000 - 1,547,000/yr = $7.14 - 15.47 pth	700 ton/day irradiator (350 Gy dose) = $455,500 - 987,500/yr = $9.11 - 19.75 pth

1.3 Alternative control program 2: Almonds are disinfested by generated low oxygen atmosphere (GLOA) immediately on receipt. Almonds are disinfested by GLOA a second time before processing if they have been in storage more than 6 months (i.e. if processed after April 1).

Table 1.3 — Costs for almond alternative program 2.

Category	Large plant (100,000 tons/yr)	Small plant (50,000 tons/yr)
1. GLOA		
a. Equipment	Purge 1,700 tons, maintain 11,900 tons per day requires two 10,000 scfh units = $20,220/yr	Purge 700 tons, maintain 4,900 tons per day requires one 10,000 scfh unit = $10,110/yr
b. Utilities and labor	128,000 tons treated @ $.41 - .81/ton = $52,480 - 103,680/yr	64,000 tons treated @ $.41 - .81/ton = $26,240 - 51,840/yr
2. Best case scenario*		
a. Bulk storage modification	6,000,000 cf @ $.05/cf = $55,140/yr	3,200,000 cf @ $.05/cf = $29,408/yr
Worst case scenario*		
a. New bulk storage	17,000 tons capacity = 1,360,000 cf = $249,968/yr	7,000 tons capacity = 560,000 cf = $102,928/yr
b. Extra product handling	100,000 tons @ $1/ton = $100,000/yr	50,000 tons @ $1/ton = $50,000/yr
Total	$127,840 - 1,281,840/yr = $1.28 - 12.82 pth	$65,758 - 679,518/yr = $1.32 - 13.59 pth

*Costs of _either_ best case scenario _or_ worst case scenario apply in individual cases.

1.4 Alternative control program 3: 50% of almonds are disinfested by GLOA immediately on receipt. Remaining 50% are irradiated. Almonds remaining in storage after April 1 are disinfested a second time by GLOA.

Table 1.4 — Costs for almond alternative program 3.

Category	Large plant (100,000 tons/yr)	Small plant (50,000 tons/yr)
1. Irradiation	850 ton/day irradiator (350 Gy dose) = $495,000 - 1,072,500/yr	350 ton/day irradiator (350 Gy dose) = $367,500 - 796,250/yr
2. GLOA		
a. Equipment	Purge 850 tons, maintain 5,950 tons per day requires one 10,000 scfh unit = $10,110/yr	Purge 350 tons, maintain 2,450 tons per day requires one 10,000 scfh unit = $10,110/yr
b. Utilities and labor	78,000 tons treated @ $.41 - .81/ton = $31,980 - 63,180 yr	39,000 tons treated @ $.41 - .81/ton = $15,990 - 31,590/yr
3. Best case scenario*		
a. Bulk storage modification	$27,570/yr	$14,704/yr
Worst case scenario*		
a. New bulk storage	8,500 tons capacity = 680,000 cf = $124,984/yr	3,500 tons capacity = 280,000 cf = $51,464/yr
b. Extra product handling	50,000 tons @ $1/ton = $50,000/yr	25,000 tons @ $1/ton = $25,000/yr
Total	$564,000 - 1,321,000/yr = $5.64 - 13.21 pth	$408,000 - 914,500/yr = $8.16 - 18.29 pth

*Costs of either best case scenario or worst case scenario apply in individual cases.

2. Walnuts

2.1 Assumed current practice: Walnuts are fumigated with methyl bromide on receipt. Walnuts marketed as "inshells" are disinfested only once and shipped ASAP. Other walnuts are fumigated with methyl bromide two more times; once before they are moved out of bulk storage for cracking, and a second time just before shipment.

All walnuts are moved through bulk storage facilities for fumigation. Current bulk storage capacity equals 125% x the excess of receipts over shipments during the peak receiving season.

In-plant fumigation space holds 2 days' peak shipment of packaged meats.

Table 2.1.1 — Assumed capacities of generic walnut plants.

Category	Large plant (100,000 tons/yr)	Small plant (10,000 tons/yr)
1. Bulk storage @ 100 cf/ton	50,000 ton capacity = 5,000,000 cf	5,000 ton capacity = 500,000 cf
2. In-plant fumigation space for finished goods @ 134 cf/ton	200 ton capacity = 26,800 cf	27 ton capacity = 3,610 cf

Table 2.1.2 — Fumigation costs for generic walnut plants.

Category	Large plant (100,000 tons/yr)	Small plant (10,000 tons/yr)
1. Methyl bromide fumigation		
a. In bulk storage	160,000 tons fumigated @ $.40 - .80/ton = $64,000 - 128,000/yr	16,000 tons fumigated @ $.40 - .80/ton = $6,400 - 12,800/yr
b. Packaged meats	30,000 tons fumigated @ $.46 - .86/ton = $13,800 - 25,800/yr	3,000 tons fumigated @ $.46 - .86/ton = $1,380 - 2,580/yr
Total	$77,800 - 153,800/yr = $.78 - 1.54 pth	$7,780 - 15,380/yr = $.78 - 1.54 pth

2.2 Alternative control program 1: Walnuts are irradiated on receipt. Walnuts marketed in-shell are then shipped ASAP. Other walnuts are irradiated two more times; once before cracking, and again before shipment.

Table 2.2 — Costs for walnut alternative program 1.

Category	Large plant (100,000 tons/yr)	Small plant (10,000 tons/yr)
1. Cobalt-60 or cesium-137 dual bulk/package irradiation	2,000 ton/day dual purpose irradiator (350 Gy dose) = $832,000 - 1,802,000/yr = $8.32 - 18.02 pth	200 ton/day dual purpose irradiator (350 Gy dose) = $331,800 - 718,900/yr = $33.18 - 71.89 pth

2.3 Alternative control program 2: Walnuts are disinfested by GLOA on receipt. Walnuts marketed in-shell are then shipped ASAP. Remaining walnuts are disinfested by GLOA two more times; once before cracking, and again before shipping.

Table 2.3 — Costs for walnut alternative program 2.

Category	Large plant (100,000 tons/yr)	Small plant (10,000 tons/yr)
1. GLOA		
a. In bulk storage		
(1) Equipment	Purge 1,870 tons, maintain 13,100 tons per day requires two 10,000 scfh units = $20,220/yr	Purge 193 tons, maintain 1,353 tons per day requires one 10,000 scfh unit = $10,110/yr
(2) Utilities and labor	160,000 tons treated @ $.46 - .86/ton = $73,600 - 137,600/yr	16,000 tons treated @ $.46 - .86/ton = $7,360 - 13,760/yr
b. Packaged meats		
(1) Equipment	One 10,000 scfh unit = $10,110/yr	One 10,000 scfh unit = $10,110/yr
(2) Utilities and labor	30,000 tons treated @ $.61 - 1.01/ton = $18,300 - 30,300/yr	3,000 tons treated @ $.61 - 1.01/ton = $1,830 - 3,030/yr
2. Best case scenario*		
a. Bulk storage modification	5 million cf @ $.05/cf = $45,950/yr	0.5 million cf @ $.05/cf = $4,595/yr
Worst case scenario*		
a. New bulk storage	18,700 tons capacity = 1,870,000 cf = $343,706/yr	19,300 tons capacity = 193,000 cf = $35,473/yr
b. Extra product handling	100,000 tons handled @ $1/ton = $100,000/yr	10,000 tons handled @ $1/ton = $10,000/yr
3. New in-plant fumigation space for finished goods	160,800 cf @ $1/cf = $29,555/yr	21,660 cf @ $1/cf = $3,981/yr
4. Delay (week's interest lost)	100,000 tons @ $2.3/ton = $230,000/yr	10,000 tons @ $2.3/ton = $23,000/yr
Total	$427,735 - 901,491/yr = $4.28 - 9.01 pth	$60,986 - 109,734/yr = $6.10 - 10.97 pth

*Costs of either best case scenario or worst case scenario apply in individual cases.

2.4 Alternative control program 3: 50% of walnuts are irradiated on receipt and shipped ASAP. Remaining walnuts are disinfested by GLOA on receipt and again before cracking. Packaged meats are irradiated before shipment.

Table 2.4 — Costs for walnut alternative program 3.

Category	Large plant (100,000 tons/yr)	Small plant (10,000 tons/yr)
1. Cobalt-60 or cesium-137 irradiation	1,000 ton/day dual purpose irradiator (350 Gy dose) = $567,600 - 1,229,800/yr	100 ton/day dual purpose irradiator (350 Gy dose) = $286,732 - 622,093/yr
2. Low oxygen in bulk storage		
a. Equipment	One 10,000 scfh unit = $10,110/yr	One 10,000 scfh unit = $10,110/yr
b. Utilities and labor	110,000 tons treated @ $.46 - .86/ton = $50,600 - 94,600/yr	11,000 tons treated @ $.46 - .86/ton = $5,060 - 9,460/yr
3. Best case scenario*		
a. Bulk storage modification	2.5 million cf @ $.05/cf = $22,975/yr	0.25 million cf @ $.05/cf = $2,298/yr
Worst case scenario*		
a. New bulk storage	935,000 cf @ $1/cf = $171,853/yr	96,500 cf @ $1/cf = $17,737/yr
b. Extra product handling	50,000 tons handled @ $1/ton = $50,000/yr	5,000 tons handled @ $1/ton = $5,000/yr
Total	$652,000 - 1,557,000/yr = $6.52 - 15.57 pth	$307,000 - 669,600/yr = $30.70 - 66.96 pth

*Costs of either best case scenario or worst case scenario apply in individual cases.

3. Raisins

3.1 Assumed current practice: Raisins are yard-stored in covered stacks where they are fumigated every month with hydrogen phosphide; on average raisins are fumigated 6 times during 6 months' storage in yard stacks. Raisins are stored in concrete "blending" chambers during sorting prior to processing. Blending chambers are fumigated weekly with methyl bromide; on average, all raisins are fumigated once in blending chambers. Packaged raisins are fumigated with methyl bromide before shipment.

Blending chambers hold one week's peak shipments. The density of raisin bins in the blending space is assumed to be 50% their density in yard stacks, due to head and aisle space.

In-plant fumigation space holds 2 days' peak shipments.

Table 3.1.1 — Assumed capacities of generic raisin plants.

Category	Large plant (120,000 tons/yr)	Small plant (30,000 tons/yr)
1. Blending space @ 128 cf/ton	3,000 ton capacity = 384,000 cf	500 ton capacity = 64,000 cf
2. In-plant fumigation space @ 134 cf/ton	1,000 ton capacity = 134,000 cf	250 ton capacity = 33,500 cf

Table 3.1.2 — Fumigation costs for generic raisin plants.

Category	Large plant (120,000 tons/yr)	Small plant (30,000 tons/yr)
1. Hydrogen phosphide fumigation in stacks	720,000 tons fumigated @ $.43 - .83/ton = $309,600 - 597,600/yr	180,000 tons fumigated @ $.43 - .83/ton = $77,400 - 149,400/yr
2. Methyl bromide fumigation		
a. In blending space	120,000 tons fumigated @ $.32 - .72 ton = $38,400 - 86,400/yr	30,000 tons fumigated @ $.32 - .72/ton = $9,600 - 21,600/yr
b. Packaged raisins	120,000 tons fumigated @ $.46 - .86/ton = $55,200 - 103,200/yr	30,000 tons fumigated @ $.46 - .86/ton = $13,800 - 25,800/yr
Total	$403,200 - 787,200/yr = $3.36 - 6.56 pth	$100,800 - 196,800/yr = $3.36 - 6.56 pth

3.2 Alternative control program 1: Raisins are yard-stored in stacks in a generated low oxygen atmosphere. Blending space is refrigerated. Packaged raisins are irradiated before shipment.

Structural modifications, equipment and utilities for refrigeration during blending are estimated to cost $1 per ton for raisins.

Table 3.2 — Costs for raisin alternative program 1.

Category	Large plant (120,000 tons/yr)	Small plant (30,000 tons/yr)
1. Cobalt-60 or cesium-137 irradiation	400 ton/day irradiator (350 Gy dose) = $378,000 - 819,000/yr	140 ton/day irradiator (350 Gy dose) = $276,000 - 598,000/yr
2. GLOA in yard stacks		
a. Equipment	Purge 2,333 tons, maintain 16,333 tons per day requires four 10,000 scfh units = $40,440/yr	Purge 583 tons, maintain 4,081 tons per day requires one 10,000 scfh unit = $10,110/yr
b. Utilities	120,000 tons treated @ $2.86/ton = $343,200/yr	30,000 tons treated @ $2.86/ton = $85,800/yr
c. Labor	120,000 tons treated @ $1.20 - 3.60/ton = $144,000 - 432,000/yr	30,000 tons treated @ $1.20 - 3.60/ton = $36,000 - 108,000/yr
3. Refrigeration in blending space	120,000 tons @ $1/ton = $120,000/yr	30,000 tons @ $1/ton = $30,000/yr
Total	$1,026,400 - 1,754,640/yr = $8.55 - 14.62 pth	$437,910 - 831,910/yr = $14.60 - 27.73 pth

3.3 Alternative control program 2: Raisins are yard-stored in stacks in a GLOA. Blending space is refrigerated. Packaged raisins are disinfested by GLOA treatment before shipment.

Table 3.3 — Costs for raisin alternative program 2.

Category	Large plant (120,000 tons/yr)	Small plant (30,000 tons/yr)
1. GLOA in yard stacks	$527,640 - 815,640/yr	$131,910 - 203,910/yr
2. Refrigerated blending	$120,000/yr	$30,000/yr
3. GLOA disinfestation of packaged raisins		
a. Equipment	One 10,000 scfh unit = $10,110/yr	One 10,000 scfh unit = $10,110/yr
b. Utilities and labor	120,000 tons treated @ $.61 - 1.01/ton = $73,200 - 121,200/yr	30,000 tons treated @ $.61 - 1.01/ton = $18,300 - 30,300/yr
4. New in-plant fumigation space for finished goods	804,000 cf @ $1/cf = $147,775/yr	201,000 cf @ $1/cf = $36,944/yr
5. Delay (week's interest lost on $1,000/ton)	120,000 tons @ $2.3/ton = $276,000/yr	30,000 tons @ $2.3/ton = $69,000/yr
Total	$1,154,725 - 1,490,725/yr = $9.62 - 12.42 pth	$296,264 - 380,264/yr = $9.88 - 12.68 pth

4. Prunes

4.1 Assumed current practice: Prunes are stored in bin-stacks in warehouses where they are fumigated once with methyl bromide. In addition, pyrethrin/piperonyl butoxide fogs are automatically dispensed nightly during 8 months of the year in the bulk storage warehouse. Packaged product is fumigated with methyl bromide before shipment.

In-plant fumigation space holds 2 days' peak shipments of prunes.

Table 4.1.1 — Assumed capacities of generic prune plants.

Category	Large plant (60,000 tons/yr)	Small plant (15,000 tons/yr)
1. In-plant fumigation space for finished goods	333 ton capacity @ 134 cf/ton = 44,662 cf	83 ton capacity @ 134 cf/ton = 11,122 cf

Table 4.1.2 — Fumigation and fogging costs for generic prune plants.

Category	Large plant (60,000 tons/yr)	Small plant (15,000 tons/yr)
1. Methyl bromide fumigation		
a. Bin stacks	60,000 tons fumigated @ $.20 - .25/ton = $12,000 - 15,000/yr	15,000 tons fumigated @ $.20 - .25/ton = $3,000 - 3,750/yr
b. Packaged prunes	60,000 tons fumigated @ $.46 - .86/ton = $27,600 - 51,600/yr	15,000 tons fumigated @ $.46 - .86/ton $6,900 - 12,900/yr
2. Pyrethrin fogs	60,000 tons @ $.45/ton = $27,000/yr	15,000 tons @ $.45/ton = $6,750/yr
Total	$66,600 - 93,600/yr = $1.11 - 1.56 pth	$16,650 - 23,400/yr = $1.11 - 1.56 pth

4.2 Alternative control program 1: Prune bin stacks are tarped and stored under GLOA in the warehouse for an average of 5 months. For storage of bins during "blending" to fill special size/grade orders, an area holding 1 week's peak shipment of prunes is refrigerated. Packaged prunes are irradiated before shipment.

Table 4.2 — Costs for prune alternative program 1.

Category	Large plant (60,000 tons/yr)	Small plant (15,000 tons/yr)
1. Irradiation of packaged prunes	170 ton/day irradiator (350 Gy dose) = $288,000 - 624,000/yr	50 ton/day irradiator (350 Gy dose) = $240,000 - 520,000/yr
2. GLOA storage in bins		
a. Equipment	$10,110/yr	$10,110/yr
b. Utilities	60,000 tons stored @ $.69/ton = $41,400/yr	15,000 tons stored @ $.69/ton = $10,350/yr
c. Labor	60,000 tons stored @ $1.20 - 3.60/ton = $72,000 - 216,000/yr	15,000 tons stored @ $1.20 - 3.60/ton = $18,000 - 54,000/yr
d. Materials and labor to tarp bins	60,000 tons tarped @ $.79/ton = $47,400/yr	15,000 tons tarped @ $.79/ton = $11,850/yr
3. Refrigerated blending	60,000 tons @ $1/ton = $60,000/yr	15,000 tons @ $1/ton = $15,000/yr
Total	$518,910 - 998,910/yr = $8.65 - 16.65 pth	$305,310 - 621,310/yr = $20.35 - 41.42 pth

4.3 Alternative control program 2: Prune bin stacks are tarped and stored in the warehouse under GLOA for an average of 5 months. Blending space holding 1 week's peak shipment is refrigerated. Prunes are disinfested by GLOA before shipment.

Table 4.3 — Costs for prune alternative program 2.

Category	Large plant (60,000 tons/yr)	Small plant (15,000 tons/yr)
1. GLOA storage in bins	$170,800 - 314,800/yr	$50,200 - 86,200/yr
2. Refrigerated blending	$60,000/yr	$15,000/yr
3. GLOA disinfestation of packaged prunes		
a. Equipment	$10,110/yr	$10,110/yr
b. Utilities and labor	60,000 tons treated @ $.61 - 1.01/ton = $36,600 - 60,600/yr	15,000 tons treated @ $.61 - 1.01/ton = $9,150 - 15,150/yr
4. New in-plant fumigation space for finished goods	267,732 cf @ $1/cf = $49,209/yr	66,732 cf @ $1/cf = $12,265/yr
5. Delay (week's interest lost on $100/ton)	60,000 tons @ $2.3/ton = $138,000/yr	15,000 tons @ $2.3/ton = $34,500/yr
Total	$464,719 - 632,719/yr = $7.75 - 10.55 pth	$131,225 - 173,225/yr = $8.75 - 11.55 pth