Ionizing Energy

in Food Processing and Pest Control: II. Applications

Task Force Report
No. 115 June, 1989

Council for Agricultural Science and Technology

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Council for Agricultural Science and Technology

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Cover Photograph

A buffet setting of foods that had been
treated with ionizing energy.
Photograph courtesy of Eugen Wierbicki,
Eastern Regional Research Center,
U. S. Department of Agriculture,
Philadelphia

Dedication

The late Dr. Eugen Wierbicki, with the equipment he used to treat foods with ionizing energy at the U.S. Department of Agriculture's Eastern Regional Research Center in Philadelphia.

This publication is dedicated to the late Eugen Wierbicki, the original Task Force Chairman. Dr. Wierbicki died suddenly on June 29, 1986, after the first report prepared by the task force had gone to the printer and the writing of this second report was well underway. The first report was entitled *Ionizing Energy in Food Processing and Pest Control: I. Wholesomeness of Food Treated With Ionizing Energy.*

As task force leader, Dr. Wierbicki outlined the subject matter for the two reports and assigned to task force members their respective responsibilities for writing the first drafts of the various topics. Additionally, he wrote sections in his own area of special competence and edited the manuscripts received from task force members. Although in declining health, Dr. Wierbicki devoted all his talents and energies to the task at hand. His successor as Task Force Chairman, in completing this second report, attests to the significance of Dr. Wierbicki's contributions.

Dr. Wierbicki was born in 1922 in Krasnoe, Byelorussia, and received doctorates in Agricultural Sciences at the Munich Technical Institute in 1949 and in Biochemistry at The Ohio State University in 1953. His research on the use of ionizing energy in food processing began at the Rath Packing Company, where he worked from 1956 to 1962. It continued at the U.S. Army's Laboratories at Natick, Massachusetts, from 1962 to 1980 and at the U.S. Department of Agriculture's Eastern Regional Research Center in Philadelphia, Pennsylvania, from 1980 until his death. In 1976, he received the Distinguished Meat Research Award from the American Meat Science Association.

Dr. Wierbicki is survived by his widow, Else, and by a daughter, Elizabeth, and a son, Alexander.

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Foreword

The decision to establish a task force to prepare a report on "Ionizing Energy in Food Preservation and Pest Control" was made by the CAST Board of Directors as a consequence of a Congressional request. Behind this request were concerns about the use of ionizing energy for food preservation as a commercial process and as a substitute for chemicals employed to control pests in food products for export and domestic use.

Upon receipt of nominations from the member societies, a task force was developed by CAST Board of Directors member James D. Kemp. The task force included expertise in agricultural engineering, consumer relations, dairy science, entomology, food science, health physics, horticulture, meat science, mechanical engineering, microbiology, nematology, plant pathology, poultry science, radiation physics and chemistry, sociology, toxicology, and weed science.

The original task force chairman, the late Dr. Eugen Wierbicki, prepared an outline of subject matter in cooperation with several members of the task force, and this was used as a basis for developing topic assignments to be covered by individuals or groups of task force members. Several meetings were held among small groups of task force members to facilitate the planning and development of the subject matter.

As the manuscript developed, it became apparent to Dr. Wierbicki and cochairman Dr. Edward S. Josephson that the subject matter should be divided into two reports, one dealing with the wholesomeness of food treated with ionizing energy and a second dealing with applications. The manuscript on wholesomeness was prepared first because this subject was considered fundamental to all uses of ionizing energy on food products. Before the wholesomeness report was published as CAST Report No. 109 in 1986, the word "processing" was substituted for "preservation" in the original title because more than preservation is involved in the applications of ionizing energy to food products. The term "pest control" was retained because, although pest control in food may be considered a part of processing, some applications of ionizing energy that are covered in the second report represent pest control in food production and not in food as such.

Dr. Wierbicki unfortunately did not live to see the printed publication resulting from his efforts. He died suddenly while the manuscript was being printed. Dr. Josephson then assumed the responsibility for completing the manuscript for this second report, which emphasizes applications.

On behalf of CAST, we thank the task force members, who gave of their time and talents to prepare this report as a contribution of the scientific community to public understanding. We thank also the employers of the task force members, who made the time of the members available at no cost to CAST. We thank Dr. Charles A. Black, retired executive chairman of the CAST Board of Directors, for his many hours of dedication as the editor of this report. The members of CAST deserve special recognition because the unrestricted contributions they have made in support of the work of CAST have financed the preparation and publication of this report.

This report is being distributed to members of Congress, the Food and Drug Administration, the Environmental Protection Agency, the U.S. Department of Agriculture, and the National Cancer Institute; to media personnel; and to institutional members of CAST. Individual members may receive a copy upon request. The report may be republished or reproduced in its entirety without permission. If copied in any manner, credit to the authors and CAST would be appreciated.

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1. Summary

The facilities for treating foods with ionizing energy derived from electron beams, x-rays, and certain radionuclides are analogous to those now widely employed to sterilize medical products. The safety requirements are those of sufficient shielding to protect workers during normal operation, plus fail-safe designs employing special locks that prevent accidental human exposure even in case of electrical or mechanical failure. The safety of the radioactive sources during transport is assured by the use of tested procedures, as required by the U.S. Nuclear Regulatory Commission and other governmental agencies.

Ionizing energy has a number of applications in food processing and pest control. All applications are consequences of the temporarily increased energy states of individual atoms and molecules in the products or contaminating organisms exposed to ionizing energy from one of these sources. The increased energy states create increased molecular reactivity, as is true also when the energy state of a molecule is increased by heat. Some molecules are split, and the resulting fragments may recombine or react in various ways. These processes take place throughout the food and within the living organisms normally present in the food.

The new molecules formed as a result of exposing foods to ionizing energy are the same kinds of compounds already present in unprocessed foods and in foods processed by other accepted means. The failure to find any compounds unique to foods that have been processed with ionizing energy is the reason for the current lack of a practical method to tell by chemical analysis whether or not a food has been exposed to ionizing energy.

Although the molecular changes in living organisms that result from exposure to ionizing energy take place normally and continuously in traces as a result of the omnipresent background radiation, sufficiently extensive changes lead to death of the organisms. Relatively low doses of ionizing energy are sufficient to inactivate insects, parasites, and most disease-causing microorganisms in foods. These doses reduce the numbers of viable spoilage microorganisms and may lengthen to a useful degree the time required for microbial populations to build up to spoilage levels, thereby increasing the shelf life of the food. In some instances, exposure of foods to these low doses of ionizing energy can make the difference between products that are acceptable and those that must be either discarded or used for animal feed or other purposes. Sterilizing doses produce products that, with proper packaging, can be stored indefinitely without refrigeration.

With most fresh fruits and vegetables, the low doses of ionizing energy required to eliminate insects or delay maturation and senescence can be used without problems from unfavorable secondary effects; however, with the higher doses required to reduce the microbial populations, many of these products may become soft and develop other undesirable qualities, such as discoloration. Although some exceptions exist, the undesired effects limit the use of ionizing energy for controlling microbial spoilage in fresh fruits and vegetables. A more promising application is joint treatments with ionizing energy and heat designed to produce the desired effect with a reduced dose of both types of energy.

Poultry, red meats, and seafood are always contaminated with spoilage bacteria, and sometimes with disease-causing bacteria and parasites. Low doses of ionizing energy generally can be applied without difficulty to refrigerated products to extend the shelf life and inactivate the parasites and most disease-causing bacteria. To maintain palatability, sterilizing doses generally must be applied when the products are frozen and packaged under vacuum or an inert atmosphere. Otherwise, the quantities of certain volatile compounds that are formed upon absorption of the ionizing energy may be great enough to cause off-flavors and off-odors. A preliminary heating or blanching of products to be sterilized is required to inactivate enzymes that would produce undesirable texture and flavor changes during storage without refrigeration. Certain bacteria as well as certain viruses that are relatively resistant to ionizing energy are also inactivated by the preliminary heating. Pouches and cans suitable for packaging both sterile and nonsterile products that have been treated with ionizing energy have been approved by the Food and Drug Administration.

Although the usual objective in applying ionizing energy for insect control is to kill the insects directly, one of the first and most successful applications of ionizing energy in the food chain was the use of doses just great enough to produce sexual sterilization of insects. This capability was used in eradicating the screwworm from the United States and most of Mexico. The screwworm, an insect pest that infests livestock, wildlife, and occasionally humans, was once a very important hazard in livestock production in the southern United States and Mexico, as well as points south. Large numbers of screwworm flies that had been sterilized with ionizing energy were released to mate with the flies in the native population and prevent reproduction. The same technique has been used to eliminate other insects, such as the Mediterranean fruit fly, from smaller areas in the United States and other countries.

A number of applications of ionizing energy in food processing lead to potentially valuable uses. Examples include: (a) extending the shelf life of some products, such as mushrooms, by inhibiting the growth and maturation; (b) inhibiting undesired sprouting of bulb, tuber, and root crops during storage; (c) increasing the hydration rate of dehydrated vegetables, as in soup mixes; (d) increasing the yield of juice from grapes without affecting the winemaking quality; (e) increasing the rate of drying of fruits, such as prunes; (f) reducing the cooking time of such products as dried beans; (g) increasing the size of loaves of bread made from flour used in formulas with small amounts of added sugars; (h) reducing the amount of barley needed in beer production by increasing the yield of the malted grain; (i) reducing the flatulence-producing propensity of beans; (j) reducing the quantity of sodium nitrite needed in meat curing; and (k) tenderizing beef. Another application, the sterilization of flesh foods, involves economies in energy use and convenience in product storage and transport, plus quality improvements.

Some foods can be treated with low or high doses of ionizing energy with no acceptability problems. For a few foods, treatment with ionizing energy has undesirable side effects that have not yielded to research. Between these extremes are foods for which low doses can be useful without creating acceptability problems, and others for which high doses can be used with beneficial results under special conditions. Extensive use has been made of trained taste panels and untrained consumers to evaluate the products.

2. Overview

The principal uses of ionizing energy in food processing are to eliminate or reduce the populations of microorganisms, parasites, and insects in foods, to inhibit postharvest sprouting of tubers and bulbs, and to delay maturation and senescence of fruits. Another purpose is to enhance the properties of the foods as such. Additionally, ionizing energy is used in a special process to eradicate certain insect pests that are detrimental to food production.

Sources of Ionizing Energy

Four sources of ionizing energy are approved for use in food processing: cobalt-60, cesium-137, electron beam generators, and x-ray generators. The first two are radionuclides that emit gamma rays. The last two are machine sources. X-rays have physical characteristics like those of gamma rays, but electron beams have some different properties. These four sources, with certain limitations on the maximum energy for electron beams and x-rays, have been selected in part because they produce no measurable residual radioactivity in foods.

Facilities for Treating Foods

The design and safety aspects of facilities for treating foods with ionizing energy are analogous to those now widely employed to sterilize medical products, such as surgeons' gloves and sutures. Such facilities are different from those required in power plants or weapons production in that they contain no uranium or other fissionable material and no source of neutrons to produce fission. The energy quantities involved in processing food by ionizing energy are relatively low, and they produce little heat. There are no hot fluids or gases that could generate an explosion; no radioactive gases, liquids, or solids that could be disseminated accidentally in the surrounding environment; and no known ways in which the sources could be used to produce nuclear weapons. The safety requirements of the facilities are those of sufficient shielding to prevent undue exposure of the persons employed in the facilities, and fail-safe designs that prevent human exposure in case of electrical or mechanical failure. The safety of the radioactive sources during transport is assured by conservative regulations that have been supplemented by practical tests. The lead-lined steel shipping containers are virtually unbreakable. Thousands of shipments all over the world have been made since the 1950s without a single release of radioactive material. Transport of the machine sources poses no special hazard because they operate only when energized with electricity.

Effects of Energy on Foods

When a food is subjected to infrared radiation in broiling and baking, for example, the energy state (manifested as heat) of all the surface molecules is raised, and the surface molecules pass along some of the energy to underlying molecules, so that the interior of the food is gradually heated. The extra energy makes the molecules more reactive chemically. A small portion of them split, with formation of "free radicals" that are very reactive chemically. The free radicals formed combine with each other or with other atoms or molecules, producing some of the changes in chemical composition of foods that are associated with broiling or baking. The same kinds of processes take place when foods are cooked in a vessel, but then the energy reaches the foods by conduction through the container.

In contrast, ionizing energy penetrates foods virtually instantaneously. The individual energy units supplied make direct hits on a few atoms and add to these particular atoms a relatively large amount of energy. As a consequence, the reactivity of these atoms and the molecules containing them is increased, and free radicals may be formed. For each kilogray of ionizing energy absorbed, fewer than ten food molecules in each million are split. The free radicals formed combine with each other or with other atoms or molecules, normally almost instantaneously. If, however, the free radicals are produced in frozen foods or dry foods, where their mobility is very slight, some may persist for months. The immobilized free radicals disappear when frozen foods are thawed or when dry foods are moistened.

The physical laws that govern the nature of chemical reactions and the stability of chemical substances are the same, whether the molecular reactivity is enhanced by heat energy supplied by infrared radiation, microwaves, or other sources, or by ionizing energy supplied by radionuclides, accelerated electrons, or x-rays. The most reactive molecules take part in reactions that lead to the least reactive and most stable compounds. As a result, the molecules that form when foods are exposed to ionizing energy are not a new breed of compounds, but the same kinds of compounds that are encountered in untreated foods and in foods processed by approved methods. No chemical compounds have ever been found in foods treated with ionizing energy that have not been found in the corresponding unprocessed foods or in foods processed by other accepted methods.

The fact that no unique chemical substances have been found in foods processed with ionizing energy means that, to date, the alleged production of such compounds in foods is not a valid basis for questioning the safety of the foods. At the same time, however, the inability to find such substances has prevented the development of a method of analysis to determine whether foods have been exposed to ionizing energy.

Effects of Ionizing Energy on Organisms

Ionizing energy breaks chemical bonds within the DNA and other molecules that make up the vital portions of cells. Living organisms are able to repair the molecular damage done by small amounts of ionizing energy, as evidenced by the fact that life continues even though such energy is constantly present at low levels everywhere. Large enough amounts, however, are fatal to all living organisms, and this is the basis for the principal use of ionizing energy to rid foods of insects, parasites, and microorganisms that may produce spoilage or disease. To produce these or other desired effects without producing undesired side effects requires proper conditions of exposure and appropriate doses.

Development of Resistance

Experience has shown that populations of organisms treated repeatedly with sublethal doses of control agents gradually become more resistant to the control agent used. This problem has been important with numerous pesticides and antibiotics, to which an initially sensitive population may become relatively resistant in time. Development of resistance has not proved to be of practical significance where the control agent is ionizing energy. Although some laboratory studies have shown that successive generations of treated microorganisms may have increased resistance, the more resistant organisms that developed were found to be less vigorous; hence, they would be more readily overwhelmed by competing organisms. Additionally, the "once through" nature of the treatment of foods with ionizing energy means that successive generations of foodborne organisms normally would not be exposed.

Pesticides and antibiotics generally act on the basis of a specific molecular effect, whereas ionizing energy can affect many different molecules in different ways. The improbability of simultaneous development of genetic remedies for all the biochemical disruptions caused by ionizing energy may explain the difference between ionizing energy and specific biological control compounds in promoting the development of resistant populations. Resistance of insects to ionizing energy does not appear to be a by-product of resistance to insecticides.

Control of Parasites and Bacteria

Low doses of ionizing energy are effective in controlling parasitic protozoa that cause human diseases, particularly in the humid tropics. A number of parasitic helminths (worms) are also controlled by low doses. The most well known example is *Trichinella spiralis*, the cause of trichinosis. This disease results from eating infested pork that is raw or inadequately cooked. Nonspore-forming disease-causing bacteria, such as *Salmonella*, *Campylobacter*, *Yersinia*, and *Staphylococcus*, are killed with relatively low doses of ionizing energy, but spores of some bacteria, such as *Clostridium botulinum*, require high doses.

Insect Eradication

The first and most well known example is the eradication of the screwworm. A noxious pest that infests livestock, wildlife, and occasionally humans, the screwworm was once endemic in the warmer regions of the United States and points south. The pest was eradicated by flooding the natural population of screwworm flies with flies that had been sexually sterilized with a low dose of ionizing energy, whereupon the wild population failed to reproduce upon mating with sterile flies. Thanks to this technique, the screwworm has been eradicated from the United States and is held at bay below the Isthmus of Tehuantepec in southern Mexico, where the land mass is narrow and the barrier resulting from the continual releases of sterile flies can be maintained relatively economically. The same technique has been used on several other insect pests, such as the Mediterranean fruit fly and the tsetse fly, in smaller areas in Africa, Central America, the United States, and Canada.

Treatment of Plant Products

Dry products, such as dry seeds, dry spices, and dry vegetable seasonings, generally can be treated with relatively high doses of ionizing energy without significant side effects. Tree nuts are a special case. Low doses of ionizing energy may be useful for eliminating insects from tree nuts, but higher doses accelerate the development of rancidity in some nuts.

Commercial treatment of dry products with ionizing energy is underway in 15 countries. Spices and seasonings are being exposed to high doses of ionizing energy in the United States and elsewhere to eliminate or reduce the microbial content and simultaneously to eliminate insects, which are vulnerable to low doses. The largest single operation for insect control is in the USSR, where 400,000 metric tons of imported grain are being disinfested of insects per year at the port elevator in Odessa.

Fresh fruits, vegetables, and grain generally can be disinfested of insects with doses low enough to avoid damaging the products. Although some other applications of low doses, such as inhibiting sprouting in tubers and bulbs, delaying maturation and senescence in certain fruits, and extending the shelf life of mushrooms, may be of considerable value, little or no improvement has been found with a number of products. Unfavorable secondary effects, such as softening and discoloration, may become of importance at doses too low to obtain the net improvement that otherwise might result from controlling the fungi and bacteria that cause deterioration of the products. In these instances, a treatment with ionizing energy may be combined with a heat treatment to take advantage of the reduction in both types of energy needed to produce the desired shelf-life extension when they are used jointly.

At present, fresh fruits and vegetables may be treated with certain chemicals to control insects and spoilage microorganisms. Controlled environments involving certain temperatures and atmospheric gas compositions are of great importance for postharvest preservation. Ionizing energy could substitute for some of the chemical treatments, should the currently used chemicals be withdrawn from approved lists in the absence of available substitutes.

The softening effects of ionizing energy on certain fresh fruits and vegetables are usually undesirable, but with some foods the same kinds of molecular changes (thought to be splitting of some of the molecules of cellulose, hemicellulose, and pectins that are the principal constituents of cell walls) are looked upon with favor. These include (a) increasing the hydration rate of dehydrated vegetables in soup mixes, (b) increasing the yield of juice from grapes without affecting the wine-making quality, (c) increasing the rate of drying of fruits, such as prunes, and (d) reducing the cooking time of such products as dried beans.

Another favorable effect is that of increasing the size of loaves of bread produced using wheat flour that has been processed with ionizing energy. This effect is a consequence of action of the ionizing energy on the starch to produce a few short-chain units that are fermented by yeast more readily than the parent starch. The increase in loaf size occurs only with low-sugar formulas.

Processing bulb, tuber, and root crops with ionizing energy is useful in inhibiting undesired sprouting during storage. The first commercial use of ionizing energy for food processing was in Japan, where a plant with capacity to treat up to 10,000 tons of potatoes per month to inhibit sprouting started operation in 1973.

Exposure of dry barley to ionizing energy reduces the amount of barley needed in beer production. This effect appears to be a consequence of reducing the sprout length, which increases the yield of the malted grain from which the alcohol is produced by fermentation.

Beans can be treated with ionizing energy to reduce flatulence. This is an indirect effect that is brought about by exposing the beans to ionizing energy to stop germination after the germination process has proceeded long enough for the enzymes to split most of the sugar polymers of low molecular weight (oligosaccharides) that are responsible for the intestinal gas production, but before the germination has proceeded far enough to damage the beans for food purposes.

Treatment of Animal Products

Poultry, red meats, and seafood (collectively called flesh foods) are always contaminated with spoilage bacteria as processing begins, and sometimes they are contaminated with disease-causing bacteria and parasites as well. Hygienic conditions can limit the build-up of microbial populations during processing, but disease-causing organisms may be spread to originally uncontaminated carcasses despite good processing practices. The further build-up of microbial populations in the processed products is normally retarded by refrigeration, freezing, curing, or smoking. Proper cooking can inactivate all the bacteria and parasites, but this is not always practiced. Moreover, products that are contaminated when they arrive in the home or food-service facility may be a source of contamination for other products handled there that are not cooked or that have already been cooked.

Treating flesh foods with ionizing energy at the end of the processing line can reduce the populations of spoilage bacteria, with attendant increase in the shelf life of the products. The bacteria that cause the common intestinal infections are relatively sensitive to ionizing energy, and a petition to use ionizing energy to inactivate these bacteria in poultry has been submitted to the Food and Drug Administration by the Food Safety and Inspection Service of the U.S. Department of Agriculture. The use of ionizing energy to inactivate the *Trichinella spiralis* parasites in infested pork that cause the disease known as trichinosis has already been approved. Seafood may be processed at sea with ionizing energy for shelf-life extension if the period between the catch and the time the products are ready for marketing is long enough.

Fats, which normally develop rancidity as a result of free radical reactions with atmospheric oxygen, become rancid more rapidly under the influence of ionizing energy. The remedy for the acceleration of the process during treatment of susceptible products with ionizing energy is elimination of atmospheric oxygen, which usually is done by evacuation of air from the sealed containers holding the products.

In addition to rancidity, flesh foods treated with ionizing energy develop small amounts of certain volatile compounds that may cause off-flavors and off-odors. These compounds always form, and the amounts increase with the dose, the temperature at which the food is processed, and the presence of atmospheric oxygen. The low doses of ionizing energy needed for shelf-life extension generally can be used on refrigerated flesh foods without producing enough of the volatile compounds to compromise the palatability of the products to an important degree. The relatively large doses needed for sterilization, however, require that most flesh foods be processed with ionizing energy while frozen in evacuated containers to retain their palatability.

Achieving sterility in flesh foods requires the inactivation of spores of the *Clostridium botulinum* bacteria that produce the deadly botulinum toxin. These spores are far more resistant to ionizing energy than are the nonsporeforming bacteria responsible for the common foodborne intestinal diseases, and they require high doses. Certain foodborne viruses and bacteria of another group are even more resistant, but these more resistant organisms are not a problem in practice. The reason is that flesh foods to be sterilized with ionizing energy must be heated enough (blanched) to inactivate certain enzymes that otherwise would produce undesirable texture and flavor changes during storage. The combination of the preliminary heating and the ionizing energy inactivates the relatively resistant organisms, so that the foods treated with enough ionizing energy to kill the *Clostridium botulinum* spores are truly microbiologically sterile.

The U.S. Army spearheaded the development of foods sterilized with ionizing energy to permit long-term storage without refrigeration, justifying the program on the basis that suitable treatment with ionizing energy could (a) provide shelf-stable food with better taste and texture than food preserved by canning, (b) reduce food handling costs, and (c) decrease the need for refrigeration. Some energy saving in food processing results from the use of ionizing energy. For example, the total processing energy associated with 1 kilogram (2.2 pounds) of boneless meat is about 4,000 kilocalories (diet calories) for meat sterilized with ionizing energy, 8,300 kilocalories for heat-sterilized meat, and 12,800 kilocalories for freeze-dried meat.

Another possible application to flesh foods is the substitution of ionizing energy for the sodium nitrite used in producing "cured" products. Sodium nitrite is used in combination with salt and other substances in bacon, ham, and certain other meat products in processes that impart a characteristic color and flavor, reduce oxidative changes, and retard the growth of microorganisms, including *Clostridium botulinum.* Under refrigeration, these foods can have a shelf life as long as 50 days. The potential application of ionizing energy to these products is for maintaining the shelf life, while allowing a reduction in the quantity of sodium nitrite used. The desire to reduce sodium nitrite use has resulted from the fact that nitrosamines are formed when nitrite interacts under appropriate conditions with certain nitrogenous compounds present in flesh foods and formed in them during digestion and during frying at high temperatures. Some nitrosamines have been found to be potent animal carcinogens. Research has shown that treatment with ionizing energy allows a substantial reduction in the amount of sodium nitrite used in curing without loss of the traditional flavor and color. When ionizing energy is used to substitute for all the sodium nitrite, however, the products are palatable, but they do not have the distinctive color, flavor, or both associated with the products treated with sodium nitrite. Hence, a small amount of nitrite is needed to retain the traditional qualities.

Treatment of beef with substerilizing doses of ionizing energy to extend the shelf-life tenderizes the meat to some extent by inhibiting microbial activity and thus prolonging the action of indigenous protein-splitting enzymes. A direct tenderizing effect may result from the action of the ionizing energy in splitting a few of the molecules in the protein collagen, which is a principal constituent of connective tissue. The tenderizing effect may be of some benefit in connection with the current move toward leaner beef. From the production standpoint, lean beef tends to be relatively tough because it usually is derived from cattle that have made much of their growth on the low-energy vegetation of rangelands and little or none in feedlots, where they are fed high-energy rations and reach market weight more rapidly. Exposure to ionizing energy could tenderize range-fed beef, increasing its palatability.

Patients with AIDS, and others whose immune responses have been suppressed to prevent rejection of organ transplants or as a side effect of chemotherapy for cancer, can be highly susceptible to bacterial infections. The infection hazard for such patients has been reduced by using ionizing energy to treat their food, so that they can be presented with sterile diets. Similarly, diets of animals required to be either free of specific disease-causing organisms or "germ free" can be treated with ionizing energy.

Packaging

Food and Drug Administration approval must be obtained for packaging materials that come in contact with food when it is being exposed to ionizing energy. Obtaining approval requires data demonstrating that the packaging will maintain the hygienic, nutritional, and taste qualities of the food and will not create a hazard as a consequence of migration of substances from the packaging into the food. The petition for approval must indicate the nature, amount, and possible toxicologic significance of any migrating substance. Additionally, the packaging must resist possible injurious effects of the food. Tests of various packaging materials have been made, and the Food and Drug Administration has approved certain materials for use.

Standard tinplated steel cans used for canning have been tested with various enamel liners and end-sealing compounds. Certain components have been found satisfactory for treating foods with ionizing energy at the very low temperatures used to sterilize flesh foods. Releases of substances from the various components to food-simulating solvents upon exposure to doses of ionizing energy in excess of those that would be used in food processing have been found inconsequential when the components were treated under conditions simulating foods with exaggerated water content, acidity, and fat content. Additional shipping and storage tests have been conducted, with satisfactory results.

A number of single- and multi-layered flexible packaging materials have been evaluated also. These materials have undergone the same tests mentioned for the tinplated steel cans. Although single-layer plastic packaging is considered sufficient for most foods that are treated with low doses of ionizing energy to extend the shelf life, it is unsuitable for long-term storage of sterilized foods because of possible small imperfections, such as pinholes, and slow diffusion of oxygen through the plastic films. Several multilayer flexible packages have been developed to protect sterilized foods from microbial recontamination, insect penetration, light, oxygen, moisture, and rough handling during long-term storage without refrigeration. In addition to layers of different plastic materials, these packages included aluminum foil. In practical tests involving production of the packages of sterilized food, shipping, and storage under nonrefrigerated conditions, the rejection rate of 0.03% due to defective pouches by the end of 2 years was well within acceptable limits. The rejection rate could have been reduced further by enclosing the pouches in paperboard folders.

Empty packaging for use with dairy products and bulk bag-in-box products is now being sterilized on a commercial scale by exposure to ionizing energy. This presterilization assures a significantly increased distribution case life for the perishable refrigerated products that go into the containers.

Acceptability of Products

With some foods, no significant acceptability problems have been encountered in the use of ionizing energy to produce the desired beneficial effects. At the other extreme are a few foods in which ionizing energy creates acceptability problems that have not been solved by research. Between the extremes are some foods for which low doses can be useful for some purposes without creating acceptability problems, and others for which means have been found to produce beneficial results with high doses.

Exposure of foods to ionizing energy, like cooking, affects a number of the factors involved in food acceptability. Many experiments must be undertaken to find by trial and error the combination of products, doses of ionizing energy, and conditions of exposure that preserve or enhance the acceptability and those that do not. In an attempt to make these evaluations as objective as possible, extensive use has been made of expert food evaluation panelists. Additionally, many trials have been made in which foods that had been processed with ionizing energy were rated by military personnel and other untrained "consumers."

The results of the sensory evaluations indicate that through improvements in processing techniques that have evolved during the past 40 years, it is now possible to process many foods with ionizing energy in ways that yield products with flavor, color, odor, and textural qualities similar to and sometimes superior to those of the same foods that have been processed by the well established methods in commercial use today. The same is true for nutritional qualities, which can be assessed by objective methods.

3. Introduction

Peaceful applications of ionizing energy have been under investigation for many years, and a number of uses are now commonplace. As with the other applications, the use of ionizing energy for food processing and pest control has been researched to find the combinations of conditions required to obtain the desired effects with only minor unwanted side effects. Analogous research is generally required with new technologies of all kinds, and the emphasis on side effects diminishes as research points the way to proper use and as appropriate applications are adopted in practice.

Of all the potential applications, the uses for food processing have been perhaps the most difficult to bring to the practical commercial stage. The unique concerns for human safety where food is concerned, together with special problems in the United States associated with political decisions, changing regulatory requirements, and public controversy over use of atomic energy in general have combined to slow the research and development processes leading to commercialization.

Although the United States was looked upon originally as a leader in the development of processes for treating food with ionizing energy, it fell behind after 1968. Other countries with fewer inhibitory conditions proceeded more rapidly with research and development. Japan was the first country in the free world to start a commercial program, when it put into operation in 1973 the first plant to treat potatoes to eliminate sprouting during storage.[1]

Many applications of ionizing energy to food processing have been approved in nations throughout the world. Initially, all potential uses were approved on a product-by-product, treatment-by-treatment basis. This procedure was changed in 1980, when an international expert committee representing the World Health Organization, the Food and Agriculture Organization of the United Nations, and the International Atomic Energy Agency concluded that any food treated with an average dose of 10 kilograys[2] or less of ionizing energy is wholesome, and recommended that exposure of foods to such doses should be approved without further testing for wholesomeness.

In the early 1960s, the U.S. Food and Drug Administration (FDA) approved the use of ionizing energy to sterilize bacon, to disinfest wheat and wheat products of insects, and to inhibit the sprouting of white potatoes. As a result of adoption of increasingly stringent standards for safety testing, however, FDA rescinded the approval for bacon in 1968. The approvals for the treatment of wheat and wheat products and potatoes, although still in effect, have never been exploited by commercial application. In both instances, chemical treatments meet the needs for the time being. Whether or not the use of the currently employed chemicals or others is permitted in the future will influence the potential for use of ionizing energy for the approved purposes mentioned.

Additional approvals were granted in 1985 for controlling trichinae in pork and in 1986 for decontaminating dried spices and vegetable seasonings. Also in 1986, FDA approved a low-level treatment with ionizing energy (up to 1 kilogray) for fruits, vegetables, and foods in general to disinfest them of insects and to delay ripening and senescence.

A number of applications of ionizing energy may be made to food processing. The purpose of some is to enhance the qualities of the products as such. The purpose of others is to eliminate insects or parasites or to reduce the numbers of contaminating microorganisms. The purpose of still others is to sterilize properly protected products so they can be stored like canned foods at room temperatures without spoiling. Additionally, ionizing energy is used in a special process for eradicating certain important insect pests. All these applications are discussed in this report, which reviews the economic and consumer aspects as well as the technology involved. This document is the sequel to a previous report by Wierbicki and coworkers (1986) dealing with the wholesomeness of foods that have been treated with ionizing energy.

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[1] The most significant historical aspects of the development of ionizing energy for food processing are reviewed in Appendix II.

[2] In this report, the doses of ionizing energy absorbed by foods, pests, and other materials are expressed in units of kilograys. One kilogray is equivalent to one kilojoule or to 240 gram calories per kilogram of material. See Appendix I for a glossary of terms used in processing food by ionizing energy. Table V-1 in Appendix V lists doses of ionizing energy suitable for various applications to food.

4. Sources of Ionizing Energy

The technology of sources of ionizing energy for treating food is well established. Similar or identical sources are widely used in hospitals, universities, and industry and have been used in research on food for more than 40 years.

Industrial facilities for sterilizing medical products by exposure to ionizing energy usually use the radionuclide cobalt-60. Facilities for cross-linking and polymerizing plastics and for grafting different chemical compounds to surfaces usually use electron beam generators.

The forms of ionizing energy approved for use in food processing are derived from radionuclide and machine sources. The only radionuclide sources permitted are cobalt-60 and cesium-137, both of which emit gamma rays. The machine sources produce either x-rays or electron beams. X-rays have physical characteristics similar to those of gamma rays, but electron beams have some different properties.

Radionuclides

Cobalt-60 is produced by exposing natural cobalt-59, a steel-like metal, to neutrons in a nuclear reactor. Cesium-137, usually in the form of cesium chloride powder, is produced in the nuclear fission of uranium and is thus a by-product of nuclear power or nuclear weapon production. As used for food processing, both of these gamma-ray-emitting sources are doubly encapsulated in stainless steel. The arrangement of a typical facility using a radionuclide source is shown schematically in Figure 1. Radionuclide sources and their application to processing of food with ionizing energy have been described by Brynjolfsson (1974) and Manowitz (1965).

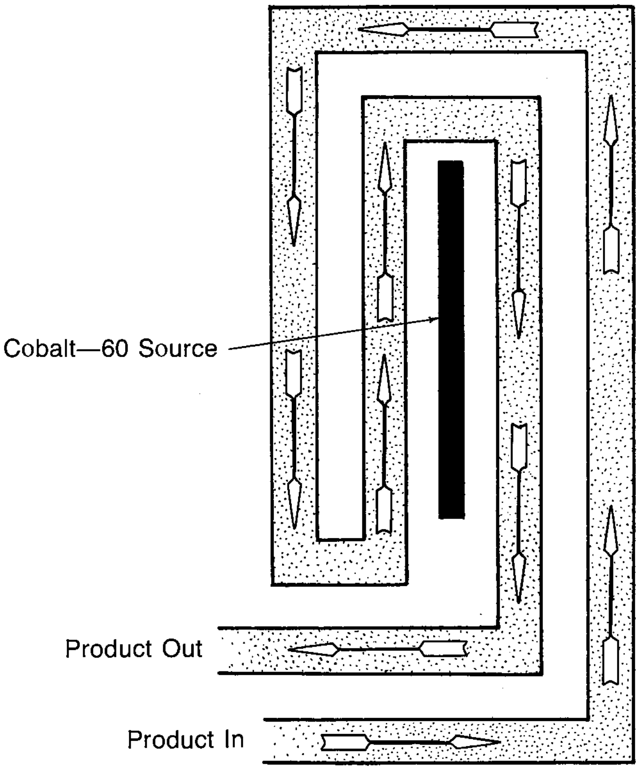

Figure 1. Schematic arrangement of a facility to expose food to ionizing energy from a radionuclide source.

Electron Beam Generators

There are many different types of electron beam generators or electron accelerators. The main differences among them are in the methods used for creating the high voltage required. But in principle, an electron accelerator is similar to a television tube or to a monitor for a computer. On one end (corresponding to the back of the television tube or computer monitor) is a hot filament that emits electrons into an evacuated chamber. These electrons are attracted by a high positive electric potential and are focused into a narrow beam. At the end of the accelerator, the electron beam usually passes between the poles of an electromagnet with a changing magnetic field that causes the beam of electrons to sweep from side to side; in the television tube, the beam also moves up and down to form the picture. In the television tube, the electrons are accelerated to a few thousand volts and are stopped in the fluorescent layer of the screen without penetrating the transparent glass. But in the accelerator, the electrons are accelerated to a few million volts and attain almost the speed of light. They have such high energy that they penetrate the window, which is made of very thin metal foil, and are first stopped in the food.

In the television tube, the electron beam is focused to form a sharp picture, but in an accelerator the window scatters the focus of the beam so that each "scanner" line has a width of a few centimeters as it hits the food. The beam is swept so frequently that there is much overlap as the food moves along on a conveyor, and this results in a uniform dose on the surface of the food.

When high-speed electrons are stopped, x-rays are always generated. In a television tube, the x-rays have such low energy that they are stopped in the thick glass screen in front of the tube. In electron accelerators for food processing, however, the x-rays have such high energy that 60 to 140 inches (150 to 360 centimeters) of concrete are required to shield the workers. Although the x-rays are very penetrating, they contribute on the average only about 0.5% of the dose absorbed by the food. About 99.5% of the dose is due to the fast electrons. Electron accelerators and their applications to processing of food with ionizing energy have been described by Koch and Eisenhower (1965), Brynjolfsson (1963), Brynjolfsson and Martin (1971), and McKeown and Sherman (1985).

X-Ray Machines

X-ray sources are closely related to electron accelerators because x-rays are produced by electrons from accelerators. When high speed electrons hit a metal target, they cause the metal to emit x-rays, which are similar to the gamma rays emitted by radionuclide sources. An electron beam generator can be modified to produce x-rays by adding an appropriate metal target. X-rays penetrate deeply, like gamma rays; however, the energy of the x-rays derived from an electron beam generator producing electrons with energy of 5 million electron volts is less than 11% of the energy of the electron beam. Therefore, by changing an electron beam source to an x-ray source, one can treat food of greater thickness, but with a much lower energy input than with the original electron beam. X-ray sources and their application to food processing have been described by Koch and Eisenhower (1965).

5. Physical Effects of Ionizing Energy

The initial effects of exposing a substance to ionizing energy are physical effects on the atoms of the substance. The number of individual physical processes increases with the amount of energy received from the source. The primary physical effects, which occur within a trillionth of a second, are followed by chemical effects. The chemical effects, discussed in a succeeding section, are responsible for the desired changes in foods and food-contaminating organisms.

Effects on Atoms

The initial effects of ionizing energy on foods are caused primarily by high-speed electrons. Fast electrons can be beamed on foods from external machine sources, or they can be produced within the foods by x-rays or gamma rays that penetrate the foods.

As fast electrons move through foods, they generally transfer their energy to atoms and molecules along their paths. The transferred energy increases the reactivity of these "excited" atoms and molecules.

Fast electrons with sufficient energy may also knock electrons out of even the innermost, most stable, electron orbits of atoms. When an electron is lost in this way from the kinds of atoms that are in the great majority in foods, an electron from an outer orbit drops in to fill the vacancy caused by the ejection of the inner electron. The energy imparted to the atom causes the other electrons in the outer orbits to move about so vigorously with the acquired energy that one or more of them may fly off, leaving the atom positively charged and very reactive chemically.

Effects on Molecules

Following the dislodging of electrons and excitation of atoms, the excess energy is lost by recombination of the affected atoms and molecules and by combination of the affected atoms and molecules with surrounding atoms and molecules. These may be called chemical changes. They will be discussed in the section on chemical effects of ionizing energy. Effects on molecules are slower than the initial effects on electrons, but most occur within a thousandth of a second.

The chemical changes that result when foods are treated with ionizing energy are relatively low-energy changes involving the outer shell of electrons, including the valence electrons, which control the way atoms combine in molecules and the way molecules react. The same is true for the chemical changes that result from other methods of processing. The physical laws that govern the nature of chemical reactions and the stability of substances are the same, whether the addition of energy that disturbs the status quo comes from ionizing radiation, heat, or the decomposition of organic substances in respiration by living organisms. Thus, the products that result when foods are exposed to ionizing energy are not a new breed of compounds, but the same types of compounds that are ordinarily encountered in fresh and processed foods.[3]

Dose Distribution in Foods

In foods receiving ionizing energy from an external source, the distribution of the absorbed energy is one of the primary concerns. All portions of the food must receive enough energy to accomplish the desired goal, and no portion may receive an excessive dose.

High-speed electrons lose their energy gradually through a number of small energy transfers as they progress through food, which means that the deeper they penetrate, the slower is their speed. When they have lost their excess energy, they are eventually captured by positive ions.

When high-speed electrons are directed at foods, some of them are reflected back, and some penetrate. Those that penetrate are deflected in all directions, some of them back in the direction from which they came. As a consequence, the dose of ionizing energy imparted to the food increases with depth for a short distance and then drops off rapidly because of the decreasing energy of the electrons. Figure 2 shows the relative dose distribution in

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[3] Neither the physical laws governing the nature of chemical reactions and the stability of chemical substances nor more than a third of a century of research experience in analyzing foods processed with ionizing energy support the frequently cited hypothesis put forward by the Food and Drug Administration (FDA, 1980, 1986a) that "unique radiolytic products" are formed when foods are treated with ionizing energy. No chemical compounds have ever been found in foods treated with ionizing energy that have not been found in the corresponding unprocessed foods or in foods processed by other accepted methods. The discovery of a unique radiolytic compound, however, could be helpful, in that it might provide the basis for a method to estimate the dose of ionizing energy a food has received because the quantities of radiolytic products are proportional to the dose within certain limits (Merritt et al., 1975). See the section on "Dose Measurements on Foods" for some potential substitutes for unique radiolytic compounds to provide estimates of absorbed doses.

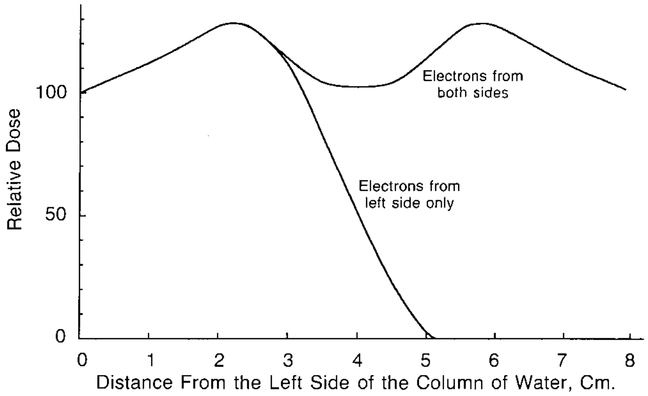


Figure 2. Relative dose distribution in an 8-centimeter thickness of water receiving high-speed electrons (10 million electron volts) from a source located to one side or both sides of the water (based on data from Brynjolfsson, 1963).

water that receives accelerated electrons from one side and two sides. Humphreys et al. (1973) published a report on dose distribution in other substances.

Useful depths of penetration (defined as the depths at which the dose is equal to the dose at the surface) are shown for water in Table V-2, Appendix V. As indicated in the table, the useful depth of penetration of electrons with energy of 10 million electron volts (the maximum legal energy for food processing) in water is only 1.3 inches (3.2 centimeters), but if the water is exposed to fast electrons from both sides, the dose uniformity is reasonably good for a thickness of 3.2 inches (8.1 centimeters). The data in Figure 2 and Table V-2, Appendix V, apply approximately to solid foods, which generally have a density similar to that of water (1 gram per cubic centimeter). For a loosely packed product (such as dry vegetables) with bulk density of 0.32 gram per cubic centimeter, however, electrons with 10 million electron volts of energy could effectively expose from one side a package almost 4 inches thick instead of the 1.26 inches given in the table for water.

In contrast to high-speed electrons, gamma rays and x-rays proceed through food with essentially undiminished energy until they interact with an atom. When a gamma ray or x-ray photon does interact with an orbital electron in an atom, a fraction of the photon energy is transferred to the electron. The remainder of the energy is carried away by the scattered photon, which will interact subsequently with other atomic electrons until finally absorbed. Most of the ionizations and excitations in the food result from the fast electrons produced by the photons in these interactions. Gamma ray or x-ray photons thus may be looked upon as generators of fast electrons, which produce most of the effects of the ionizing energy.

Gamma rays and x-rays do not have a definite range in matter. Some of them are absorbed by each succeeding layer of food, but some penetrate deeply. In practice, a solid food product 10 to 20 inches (25 to 50 centimeters) thick usually can be exposed to gamma rays or x-rays with good distribution of dosages if the energy comes from all sides. Typical dose distributions for gamma rays are shown in Figure 3.

Although the physical effects of gamma rays and x-rays on matter are a consequence of the accelerated electrons they produce, the thickness of food that can be treated effectively with these electromagnetic radiations is essentially determined by the penetration of the gamma rays and x-rays, not the electrons. The reason is that the energy of the ejected electrons is so low (usually in the range of 0.01 to 0.8 million electron volts compared with the 10 million electron volt maximum permitted for electron beams) that the maximum distances traveled by the accelerated electrons in solid foods are well under 0.04 inch or 1 millimeter.

Dose Measurements

In the irradiation chamber in a food processing facility, the food usually moves along on a conveyor and receives ionizing energy from one or more stationary sources. The total amount of energy absorbed by the food will depend upon the mass, bulk density, and thickness of the food, the kind and strength of the source, and the time of exposure. The amount of energy absorbed by a given unit of food will depend, in addition, upon its location.

If all parts of the food are to receive at least the minimum desired dose of ionizing energy, some units evidently will receive more than this amount. There are

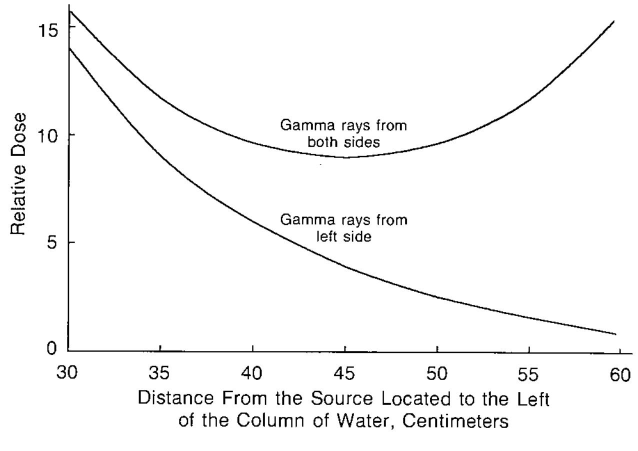


Figure 3. Relative dose distribution in a 30-centimeter thickness of water receiving gamma rays from cobalt-60 located 30 centimeters to one side or both sides of the water (based on data from Brynjolfsson, 1974).

both regulatory and practical reasons for limiting the range of doses, a fact that must be taken into account in designing the equipment and arranging the product for exposure. To assure that the minimum and maximum dosages are within the specified range, some independent means of estimating the absorbed dose is required. No method is available as yet by which a precise estimate of absorbed dose can be made on the basis of analyses made on the processed food. Measuring the doses is known as dosimetry, and the devices used to make the measurements are known as dosimeters or dose meters. A comprehensive treatise on dosimetry was published by the International Atomic Energy Agency (IAEA, 1977).

Kinds of Dosimeters

There are two general kinds of dosimeters -- primary and secondary. A primary dosimeter, sometimes called a reference dosimeter, is one that provides measurements from which the amount of absorbed ionizing energy (the absorbed dose, generally expressed in kilograys -- see the definitions in Appendix I) can be calculated directly. The most common primary dosimeter is a calorimeter, in which the amount of heat resulting from absorption of ionizing energy is measured. Except in electron accelerators, where calorimeters have been used to evaluate the energy absorption from electron beams (Brynjolfsson, 1963, 1973; Jarrett and Halliday, 1979), calorimeters have not been found practical for dosimetry in food processing facilities.

Secondary dosimeters, sometimes called routine dosimeters, yield measurements that vary with the amount of ionizing energy absorbed, but they do not provide values from which the absorbed energy can be calculated directly. Secondary dosimeters must either be selected with absorption properties that match the food, or corrections must be made to account for the difference in absorption characteristics (Brynjolfsson, 1968; Brynjolfsson et al., 1978). Table V-3 in Appendix V lists the most commonly used secondary dosimeters and their effective dose ranges.

Secondary dosimeters operate on a variety of different principles. One of the most commonly used is the Fricke dosimeter, which consists of a solution of ferrous sulfate and sulfuric acid in water. The radiolytic products formed in the solution upon absorption of ionizing energy oxidize the ferrous (Fe^{++}) ions to ferric (Fe^{+++}) ions. The quantity of ferric iron produced is related to the amount of absorbed ionizing energy. The usual useful range of the Fricke dosimeter is from about 40 to 400 grays. If extremely pure reagents and water are used, the lower limit can be reduced to about 4 grays. If an atmosphere of pure oxygen is substituted for air, the upper range can be extended to 2,000 grays (2 kilograys). The Fricke dosimeter often is considered to be a primary dosimeter. For routine use, sheets of polymethylmethacrylate plastic (often known by the trade names Plexiglas, Lucite, or Perspex), either clear or containing a dye, often are favored. The change in transmission of light that occurs upon absorption of ionizing energy can be measured instrumentally.

Dosimeter Calibration

When secondary dosimeters are used, the absorbed dose is estimated from a calibration curve in which measurements made by the secondary dosimeters are plotted against the measurements made under similar conditions by the primary dosimeter. Sometimes secondary dosimeters are calibrated against a primary dosimeter in one facility, but are used in another facility.

Irradiator Calibration

Once secondary dosimeters have been properly calibrated, they can be used to estimate the dose of ionizing energy absorbed by food. The dosimeters must be placed so as to determine the maximum and minimum doses absorbed by the food. If the difference between the maximum and minimum dosages is greater than can be allowed, modifications must be made in the configuration of the sources of the energy, the configuration of the packages of food being processed, or both. If the food is being exposed on one side only, the facility might be redesigned so the food receives ionizing energy from both sides, which would in effect about double the thickness that could be given an acceptably uniform dose. Alternatively, the food might be presented in a thinner layer for processing. When calibrating an irradiator facility in practice, a number of factors must be considered to assure that the secondary dosimeters are measuring the maximum and minimum absorbed doses in the food. Factors that may influence the maximum and minimum absorbed dose values in a given food-container-exposure configuration include variations in the bulk density, volume, and shape of the food product; changing from a product with one bulk density to the same food with another bulk density; and including containers of the same or other foods with different bulk densities.

Dose Measurements on Foods

The preceding sections have dealt with measurements of dose by instruments placed in strategic locations with respect to the food as a means of finding the maximum and minimum doses to which the various parts of the food have been exposed. The ideal dosimeter would be the food itself, in which the change in the characteristic measured is unique to absorption of ionizing energy, is proportional to the dose of ionizing energy absorbed, and does not change with time after absorption.

Finding a food characteristic that could serve as a dosimeter has been problematic because the magnitude of the chemical changes induced by ionizing energy is very small and because the chemical compounds formed merely add to the quantities of the same compounds that were present before the ionizing energy is added or are produced by other methods of processing. Recent research has opened the field with a number of possibilities, each of which, if proved satisfactory, would apply only to specific foods.

The progress made in identifying foods that have been treated with ionizing energy was reviewed in a symposium edited by Bögl et al. (1988), and the findings were presented in a summary table, which is reproduced as Table V-11 in Appendix V. The techniques investigated include viscosity, thermoluminescence or chemiluminescence, electron spin resonance (free radicals), conductivity or impedance, chemical changes (in DNA, protein, or carbohydrates), volatiles from fatty acids, enzymic activity, hydrogen evolution, microflora, and histology and morphology. The table emphasizes the inconclusive nature and limited applicability of the findings.

For example, a promising technique for foods containing bone, shell, or calcified cuticle is measurement of the electron spin resonance signal from free radicals induced in bone by absorption of ionizing energy. Desrosiers and Simic (1988) found that this signal could be distinguished from the indigenous signal measured on untreated bone. A linear relationship existed between the absorbed dose and the intensity of the induced signal over the range of 1 to 5 kilograys tested, and no decay of the signal was found during a period of 4 months.

Free radicals are formed throughout food when ionizing energy is absorbed, as indicated in the section of this report on chemical effects of ionizing energy. The free radicals disappear from moist foods almost instantaneously when ionizing energy is no longer being absorbed, but may persist in very dry foods or in deep-frozen foods because of immobility. Bone is a special case in that although it may be surrounded by moist meat, it is composed of solid mineral crystals embedded in a protein matrix, and the free radicals produced are relatively immobile and consequently may exist for long periods.

In the United Kingdom, an immediate need exists for simple and reliable methods to determine whether a food has been treated with ionizing energy. Although the U.K.'s Advisory Committee on Irradiated and Novel Foods recommended approval of foods treated with ionizing energy (Burgen et al., 1986), the health authorities decided to suspend steps to implement the recommendations until suitable detection methods are available, stating that such methods are needed to regulate the process.

6. Safety of Sources and Facilities

No new technology is without its real or perceived hazards. The use of ionizing energy to process foods and other materials is no exception. In few other industries, however, have the hazards been so clearly defined and appropriate protective measures so effectively engineered. For radionuclide sources, three aspects of safety must be considered: transport and installation of the sources, design and operation of the facilities, and removal and disposal of the spent sources.

Machine sources of ionizing energy pose no unique safety problems in transport and disposal. These sources are activated only when connected to appropriate sources of electricity. When not in use, they can be turned off.

The ionizing energy from both gamma ray and machine sources is contained within the radiation chamber and the surrounding shielding. The shielding is of sufficient thickness and density to protect the people in other parts of the facility, and is normally concrete. Entry of personnel into the chamber while the source is in the operating mode is prevented by appropriate safety measures.

Transport of Radionuclide Sources

The transport of radionuclide sources has been under constant scrutiny for more than three decades. The concern for human safety and environmental integrity has been responsible for stringent standards. Although testing specifications may vary slightly among regulatory agencies (U.S. Department of Transportation, 1983), they generally conform to the procedures described by the International Atomic Energy Agency (IAEA, 1982).

Radionuclide sources considered practical for food processing are sealed in capsules that can be opened only by destroying the capsules. The capsules must pass an impact test, a percussion test, a heat test, and a leaching test before they are considered acceptable.

For transport, the capsules are placed in lead-lined steel shipping casks to absorb the ionizing energy emitted from the capsules and to provide further physical protection. The shipping casks must pass a heat test in which they are heated red hot by exposure to a temperature of 1,408°F (800°C), mechanical tests in which they are dropped on a flat surface and a protruding metal bar, and an immersion test in which they are covered with 49 feet (15 meters) of water.

These laboratory tests of the shipping casks have been supplemented by practical tests representing real-life situations, including the following (Huerta et al., 1978): (a) A cask was dropped from a height of 2,000 feet (610 meters). The cask was dented and scratched, but there was no loss of radioactive material. (b) A truck carrying a cask was crashed into a concrete wall at more than 80 miles per hour (129 kilometers per hour). The truck was demolished, but the cask survived without loss of integrity. (c) A truck carrying a cask was intentionally struck by a 120-ton locomotive at 80 miles per hour. Again, the truck was demolished, but the cask survived without loss of integrity.

Close monitoring and required record-keeping in the United States and nearly all other countries have provided the basis for comprehensive reports on the performance of the shipping casks (IAEA, 1982; Wolff, 1984). In the thousands of shipments that have been made worldwide since the 1950s, there have been several vehicular accidents involving sources of strong radioactivity; however, the shipping containers have never failed in a manner resulting in the release of radioactivity.

Facility Design and Operation

The environmental problems associated with the construction and operation of large nuclear-fuel power-generating plants are not characteristic of large facilities for processing food with ionizing energy. There is no gaseous, liquid, or solid radioactive effluent from the cobalt-60 or cesium-137 sources approved for food processing. Properly shielded and controlled operation of these sources results in no measurable increase in the radiation levels in the plant vicinity. Small amounts of ozone and oxides of nitrogen are produced in the air in the irradiation chamber. To avoid accumulation of these substances to toxic concentrations, the air from the chamber must be exhausted to the atmosphere.

Radiation safety at a facility for treating food with ionizing energy requires a combination of careful shielding design, "fail-safe" mechanical and electronic interlocks, and comprehensive operating procedures. Those few accidents that have happened in processing facilities over the years in the United States and abroad have all been traceable to human error, equipment failure, or both. No exposure would have resulted if the facility designs had incorporated fail-safe concepts. Although electric power outages and mechanical difficulties in source movement and product movement cannot be completely eliminated by design, proper design provides for needed adjustments and repairs without exposure of personnel.

The procedures to be used to install large radioactive sources must be carefully planned during the design of the facilities. Shielded facilities are needed to permit receipt of the very large shipping casks. Remotely operated cranes are necessary to manipulate the casks and remove the heavy lids, and remote handling tools must be available to remove the sources from the casks and to assemble the sources in an operational configuration.

Prior to receipt of the actual source, trial runs using dummy nonradioactive source components are needed. The entire procedure from receipt through assembly to operation must be performed to assure that the necessary operations can be accomplished without undue exposure of personnel.

In the 18 years of operation of the Radiation Laboratory of the Army's research facility in Natick, Massachusetts, all workers' radiation exposures were monitored, and no exposures in excess of 10% of the permissible maximum ever occurred. Almost all exposures were reported as zero, indicating exposures below the sensitivity of the film badges (Martin, 1982). The record of safety to date in processing food with ionizing energy has been excellent. With sensible design and operation of facilities, this record can be extended indefinitely.

Disposal of Spent Radionuclide Sources

Planning for the safe disposal of radionuclide sources that have decayed to levels below those required for food processing is just as important as planning for the receipt and use of the sources. Unless other uses can be arranged before receipt of the sources, it is essential that final and safe disposal be incorporated into the initial facility plans.

The cobalt-60 and cesium-137 that have been approved as sources of ionizing energy for food processing have the advantage that they do not require eternal control of disposal, as do plutonium and uranium, which have very long-lived radioactivity. Cobalt-60 decays to half of its initial radioactivity in 5.24 years, and cesium-137 decays to half of its initial radioactivity in 30 years. Cobalt-60 and cesium-137 that have decayed so much that their activity is insufficient to process foods efficiently can still be useful in industrial radiography and, with restructuring, in medical therapy. These possible uses delay disposal until the radioactivity has diminished much further.

7. Chemical Effects of Ionizing Energy

The chemistry of the changes induced in foods by the absorption of ionizing energy is essentially the chemistry of excited states, charged species, free radicals, and neutral products. This section provides a brief overview of the subject, and Appendix III provides more detail. Further information may be found in the chemical literature, including papers by Hannah and Simic (1985), Neta and Simic (1985), Simic (1983), Simic et al. (1979, 1983, 1985, 1987), Taub (1981, 1983, 1984), Taub et al. (1979), and Thomas et al. (1981).

A free radical is generally defined as a highly reactive molecular entity with an unpaired electron in the outer orbit of an atom. Free radicals may be formed when molecules are split by heat, by light or ionizing energy, or by catalytic reactions involving enzymes or metal ions. Free radical reactions take place in mammalian tissues (Machlin and Bendich, 1987; Zweier et al., 1988), and they occur in foods in general. The numbers of free radicals formed, and consequently the numbers of free-radical reactions, however, are vastly increased when foods are processed with ionizing energy.

The changes that take place when foods absorb ionizing energy may be summarized by the following equation:

Molecule + Ionizing Energy → Positive Ion + Electron
→ Free Radical(s) → Products → Effects

Free radicals are generally highly reactive. The end-products of free-radical reactions, however, are stable molecules with even numbers of orbital electrons.

Free radicals may react with each other and with other adjacent atoms and molecules as they either gain or lose the electrons required to produce stability. Because of the generally great reactivity of free radicals, an individual free radical does not travel far before it encounters another free radical or other species with which it will react. Although most foods are complex, their free-radical chemistry is simplified by the fact that the structural protein, lipid, and carbohydrate components and the water containing soluble vitamins, proteins, and sugars tend to be separated into discrete phases in different locations on a micro basis, so that most of the free-radical reactions are concentrated within the phases from which the free radicals are derived. Cross reactions between the different phases are in the minority. This dependence of free-radical chemistry upon the structure and composition of foods has another advantage in that it makes possible the extrapolation of reactions from simple foods consisting of single components to the reactions that will take place in the same components in complex foods.

In general, the amounts of ionizing energy absorbed by the various chemical components of foods, and hence the quantities of free radicals and reaction products produced, are proportional to the fractional weight of the components. Some minor components, such as the vitamins thiamin (vitamin B1) and ascorbate (vitamin C), are exceptions because they are present in solution and thus are affected by the free radicals derived from the water. Thiamin and ascorbate can be either largely destroyed or largely conserved, depending upon the process used. For example, in a graphic summary of experimental results on thiamin, Kraybill (1982) showed that the loss of thiamin from pork sterilized by ionizing energy was about 96% when the dose of 48 kilograys was administered at 77°F (25°C), but about 12% when 43 kilograys were administered at -112°F (-80°C). The loss was about 82% when the pork was sterilized by heat. Moist foods to be sterilized by ionizing energy thus are processed while frozen to conserve essential dietary nutrients. Thiamin is unusually sensitive to ionizing energy and is unlike most vitamins, which are not significantly affected.

Many free radicals react preferentially with atmospheric oxygen, which has two unpaired electrons and acts as a diradical. Atmospheric oxygen oxidizes fats and causes the development of rancidity. These reactions are speeded when fat-containing foods are processed with ionizing energy in the presence of atmospheric oxygen. To reduce the undesirable oxidative changes, the processing of sensitive foods, such as meats, may be done on packaged frozen products after evacuation or flushing with nitrogen to eliminate atmospheric oxygen.

Free radicals form and disappear continuously as long as ionizing energy is supplied. When the source of ionizing energy is turned off, or when the food is removed from the path of the energy, the free radicals previously generated ordinarily disappear. The rate of disappearance, which can be monitored by various kinds of measurements, including electron spin resonance, depends upon the mobility of the radicals and the concentrations of reactive species around them.

At the temperature of liquid helium, free radicals in frozen food are relatively immobile and may persist for days. Free radicals are still relatively immobile at the temperature of liquid nitrogen (-320°F or -196°C). When the temperature is increased above -112°F (-80°C) (the temperature of dry ice), the rate of disappearance increases greatly. The rate of decay at 14°F (-10°C) is illustrated in Figure 4. When the temperature is raised above the

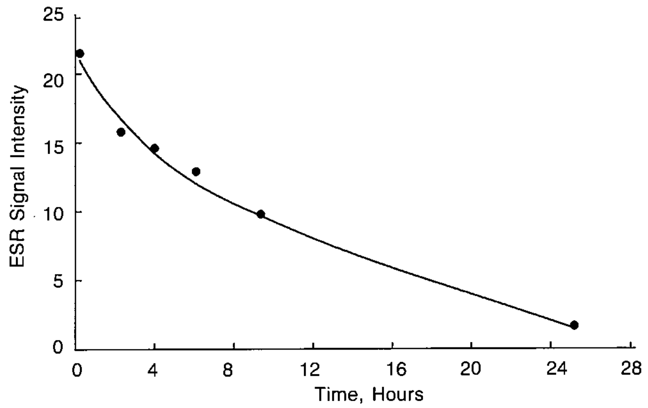


Figure 4. **Relative amounts of free radicals in myosin (a muscle protein) at different times after absorption of 50 kilograys of ionizing energy, as indicated by the intensity of the electron spin resonance signal. The myosin was exposed to ionizing energy at -40°F (-40°C), and the time at which the temperature of the sample reached 14°F (-10°C) was taken as the time of origin in the plot (Taub et al., 1978).**

freezing point (30 to 32°F or -1 to 0°C), free radicals disappear within seconds, and some disappear even faster.

Free radicals are relatively immobile also in dehydrated foods and may persist in such foods for many days. The presence of only a little water, however, greatly speeds the disappearance, as illustrated for starch in Figure 5.

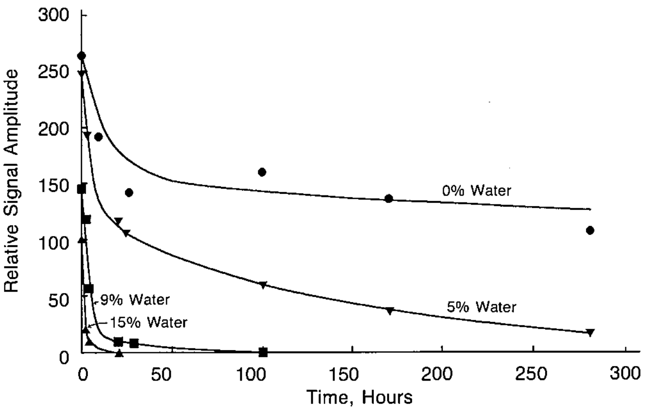


Figure 5. **Relative amounts of free radicals in samples of starch differing in water content, as indicated by the intensity of the electron spin resonance signal at different times after the starch had absorbed 10 kilograys of ionizing energy (Diehl, 1972).**

Even at 15% water content, the maximum illustrated in Figure 5, all the water would be bound to the colloidal particles of starch, and the product would have the appearance of a dry powder. Free radicals disappear immediately when a dry product containing free radicals is cooked with water.

ionizing energy, such as might be designed to delay spoilage of food and destroy microorganisms of public health significance, does indeed leave behind organisms that are more resistant to ionizing energy than the ones that were killed. These surviving microorganisms consist of spores of spore-forming bacteria and some highly resistant vegetative cells (Grecz et al., 1983). The food so treated must be preserved subsequently by one of the traditional methods, such as refrigeration or maintenance in a dry condition, to derive the maximum benefit from the reduction in numbers of bacteria.

Davies and Sinskey (1973) cultured bacteria that did not succumb to substerilizing doses of ionizing energy and found that after several repetitions of the process the resulting population of bacteria was markedly more resistant to ionizing energy than was the original population. Tiwari and Maxcy (1972) found that *Salmonella* that survived the ionizing energy treatment were less infective than the original population, as judged by the egg yolk test. In subsequent experiments, Maxcy (1977) found that each step of acquired bacterial resistance through selection was accompanied by a reduction in vigor. Thus, if a given specimen of food were given a second substerilizing dose of ionizing energy, the disease-causing organisms might not be eliminated, but the virulence of those remaining would be reduced. And if treated bacteria were recycled into the environment where they would be in competition with other bacteria that had not been treated with ionizing energy, the relatively radiation-resistant but poorly competitive cells would be either eliminated or relegated to a minor status in the population.

Insects

Cornwell and Morris (1960) found no increase in the resistance of two generations of granary weevils from a parent population that had received a sublethal dose of ionizing energy. Brower (1974a,b,c,d) found no evidence of a pronounced increase in resistance of any of four insect species to treatment with ionizing energy after repeated treatment with substerilizing doses for as many as 30 generations. On the contrary, the "fitness" of the surviving populations tended to be reduced, as evidenced by increased sterility and reduced fecundity and life span. Matin (1975) reported similar results for the rice weevil. The evidence available indicates that development of insect resistance to ionizing energy is not a potential problem.

Brower (1973) found that two strains of Indianmeal moth that were highly resistant to malathion insecticide were just as susceptible to control by ionizing energy as was the control (susceptible) population. He noted further (Brower, 1974) that a strain of red flour beetle resistant to DDT and malathion possessed no greater resistance to ionizing energy than did a susceptible strain. Cole et al. (1959) found that a highly DDT-resistant strain of the human body louse was no more resistant to ionizing energy than a DDT-susceptible strain. Erdman (1966) found that a strain of red flour beetle that was slightly more resistant to DDT than the control strain was more sensitive than the control to ionizing energy. Indications are, therefore, that insects that have developed resistance to insecticides do not simultaneously develop resistance to ionizing energy. Ionizing energy thus may be useful for disinfesting grain or other stored commodities of insects that have developed resistance to certain insecticides.

From the theoretical standpoint, the concern about development of organisms resistant to control treatments is far greater with pesticidal chemicals and antibiotics than with ionizing energy. The reason is that pesticidal chemicals and antibiotics have specific biochemical modes of action, whereas ionizing energy is less specific. For example, the action of some pesticides may depend upon blocking the action of a specific essential enzyme in the target species. A few organisms in the population may have another enzyme that can accomplish the same transformation to some degree, and these organisms will tend to proliferate when the other members of the population are eliminated. Ionizing energy, on the other hand, has a broad-spectrum effect in that all enzymes and other compounds are targeted and may be damaged. The probability that a population of organisms could simultaneously evolve significant resistance to many possible biochemical disruptions is vanishingly small.

8. Biological Effects of Ionizing Energy

Effects on Life

As a consequence of the natural background radiation from cosmic rays, radon gas in buildings, and the naturally radioactive atoms in foods and living tissues, the kinds of changes in atoms that take place when a strong dose of ionizing energy is absorbed by food also occur in much smaller numbers in the absence of artificially applied ionizing energy. The development of life forms has therefore required the presence of mechanisms by which living organisms can control their internal compositions and protect themselves from damage due to the ever-present ionizing energy from natural sources.

The significance of the protective mechanisms may be perceived from the fact that in the human body the natural background radiation ejects an inner electron from 1 to 10 million phosphorus atoms in the DNA (genetic material) per hour. Each such event results in addition of about 2,000 electron volts of energy within the phosphorus atom and its immediate neighborhood, and usually leads to a double strand break in the DNA. Each of these breaks theoretically could lead to development of a cancer if not repaired. Living organisms have the ability to repair breaks in their DNA, to metabolize unneeded chemical compounds that may be produced by the doses of ionizing energy normally received, and to survive. The DNA must be "hit" many times before the cell in which it occurs is irreparably damaged. Further protection is provided by the ability of surrounding cells to digest or kill irreparably damaged cells. Nonetheless, when the limits of possible repair and protection are exceeded, the organism succumbs. This is the basis for the effectiveness of elevated doses of ionizing energy in killing bacteria, parasites, and other organisms in foods.

Sufficient doses of ionizing energy kill all living organisms, including plants and animals, from the simplest forms to the most complex forms. Damage to the DNA is the major cause of cell death. Breakage of chemical bonds may also disrupt the cytoplasmic membrane, which maintains the integrity of living cells (Grecz et al., 1983).

The proportion of the chemical bonds affected by the doses of ionizing energy applied to control insects and other living organisms in foods is relatively small. As a point of reference, fewer than ten chemical bonds in each million chemical bonds present in moist food are broken per kilogray of ionizing energy absorbed. Breakage of enough bonds in the DNA, however, is fatal to all living cells.

A given dose of ionizing energy may be fatal to certain cells, while only injuring other similar cells. Under favorable conditions, injured cells may undergo self repair. The effects on an organism as a whole are a consequence of the effects on all its parts.

Relative Resistance

The effects of ionizing energy upon living tissues depend upon the nature and condition of the tissues and the conditions of exposure. The content of water is a very important factor (Bruns and Maxcy, 1979). The drier the cell, the less sensitive it is to ionizing energy.

Among the bacteria, those in the spore state are generally the most resistant. Those in the vegetative or growing condition are generally the least resistant, but the range is considerable. For example, 90% of the sensitive pseudomonads commonly associated with spoilage of food, particularly fresh meat, may be destroyed by a dose of 0.25 kilogray, while a dose approximately 40 times greater may be required to kill 90% of very resistant vegetative cells of some bacteria or a comparable fraction of most spores.

Development of Resistance

A gradual increase in resistance of organisms to control by a given treatment with a given agent is a universal biological response that is explained in terms of a combination of selection of relatively resistant organisms from the population originally treated, together with mutations. By selection is meant the multiplication of relatively resistant members of the population after the more sensitive members have been killed by the control agent. This problem has been of great concern with pesticides and antibiotics because with repeated treatments of a pest population by a given control agent, a pest species that is initially sensitive may become strongly resistant. That is, the control agent may lose its initial effectiveness to a greater or lesser degree. The resistance phenomenon has been investigated with ionizing energy because of the potential importance of development of organisms that resist doses found to be effective initially.

Bacteria

Maxcy (1983) pointed out that a substerilizing dose of

9. Disease Control

Ionizing energy has broad applications to disease control, encompassing not only diseases of humans, but also diseases of animals and diseases that affect plant products after harvest. Considered in this section are disease-causing organisms that are not invariably associated with food products from plants and animals.

Parasitic Protozoa

Infestations by parasitic protozoa, spread by ingesting contaminated water and food, are an important cause of human disease in the humid tropics. A general review of the use of ionizing energy to control these protozoa has been published by King and Josephson (1983).

Entamoeba histolytica

The amoeba known as *Entamoeba histolytica*, sometimes found in food and drinking water, is a cause of amoebic dysentery in humans. Severe cases are marked by dysentery, griping pain, and erosion of the intestinal wall.

During digestion of food in the small intestine, the feeding forms of the amoebae (trophozoites) are liberated and can invade the walls of the large intestine to cause the typical symptoms of amoebic dysentery. The amoebae can also invade the liver, where they form cysts and emerge later via the feces to cause new infections in susceptible exposed persons.

Most infections are associated with eating raw fruits and vegetables that have been fertilized with human feces in certain third world countries. The disease is uncommon in the United States, but there was much publicity in newspapers about an outbreak that occurred among persons drinking contaminated water in a Chicago hotel during the 1933 World's Fair in that city. Although a 1961 estimate gave 600,000,000 as the number of people infested with this amoeba worldwide, only a small fraction of those affected show clinical symptoms (Noble and Noble, 1976).

As shown in Table V-4 in Appendix V, treatment of food and water with as little as 0.25 kilogray of ionizing energy results in 100% destruction of cysts. A dose of 2 kilograys is needed to kill the feeding forms.

Toxoplasma gondii

Toxoplasma gondii is an intracellular protozoan parasite found in humans, cats, dogs, cattle, pigs, sheep, chickens, pigeons, mice, and wild mammals. This organism can be transmitted to humans in at least three ways: (1) to the fetus through the placenta, (2) by eating contaminated, inadequately cooked meat, and (3) by direct oral transmission after contact with contaminated cat feces or indirect oral transmission by insects that come in contact with food after contacting contaminated cat feces (U.S. Department of Agriculture, 1975).

Toxoplasmosis, the disease caused by *Toxoplasma gondii*, is a serious affliction in humans. It is capable of seriously damaging the central nervous system of infants, causing a usually fatal encephalitis. The parasite occurs most commonly in warm humid areas, but is distributed worldwide.

As shown in Table V-4 in Appendix V, exposure of *Toxoplasma gondii* to ionizing energy at a dose of 0.1 kilogray causes this parasite to lose its lethal infectiveness. The organism is killed by a dose of 0.3 kilogray.

Parasitic Helminths

Helminths are worms, some of which attack and parasitize vertebrate and invertebrate organisms. There are three classes of helminths: nematodes (roundworms with unsegmented bodies), cestodes (parasitic flatworms with no mouth or intestinal canal, including the tapeworm), and trematodes (parasitic flatworms, including flukes). Helminths are found in all areas of the world, including land and marine habitats. Ionizing energy can play an important role in controlling helminths in food products, especially foods from animal sources.

The use of ionizing energy to control helminths parasitic in animals and humans has been considered for *Anisakis marina*, *Anisakis simplex*, *Ascaridia galli*, *Ascaris lumbricoides*, *Trichinella spiralis*, and *Trichostrongylus axei* (King and Josephson, 1983). The effects of ionizing energy on several of these parasites are shown in Table V-5 in Appendix V.

As noted by Varga (1973), helminth species differ in sensitivity to ionizing energy; within species, the various stages in the life cycles also differ in sensitivity. Moreover, certain tissues are more sensitive than others in the same organism. For example, an organism may be sexually sterilized at a much lower dose than is required to kill it. Moreover, the sex ratio of eggs can be changed with exposure to ionizing energy, and a dose can be used that terminates male development. Certain animal parasites, including *Trichostrongylus axei* (Ciordia and Bizzell, 1960), *Trichinella spiralis* (Shichobalova, 1958), and *Ascaridia galli* (Ruff and Hansen, 1967), have been found to possess these characteristics.

Several studies have been made on animal products to determine the effects of ionizing energy on parasitic helminths that may constitute a hazard to food production or humans. The findings made in research on helminths of greatest importance to humans are summarized in the following paragraphs.

Anisakis

Round worms (nematodes) in the genus *Anisakis* are responsible for a disease called anisakiasis. The nematodes' final host is either marine life or birds; the organisms do not mature in humans, but they can survive long enough to be pathologically important. *Anisakis* larvae are found in the gut and muscle tissue of fish, and they are ingested live when fish are eaten raw or lightly salted.

The nematode can cause inflammation, ulceration, or a tumor-like reaction of the digestive tract in humans. If the organism is able to penetrate through the intestinal walls, it migrates to other body tissues, causing more severe symptoms.

Exposure to x-rays controls the parasite. Van Mameren and Houwing (1968) found that absorption of 10 kilograys of ionizing energy by infected tissue in a 6% or 9% saline solution resulted in a 100% kill. Further research is needed to see if doses lower than 3 kilograys will cause this parasite to lose its pathogenicity and to determine the appropriate conditions for exposure of the infested tissue to the ionizing energy.

Ascaris lumbricoides

Ascaris lumbricoides is a common "roundworm" found in the intestinal tract of humans. It causes abdominal pain, intestinal blockage, diarrhea, and ulcers. The nematode eggs are able to persist in soil or sewage. When ingested by humans in fecally contaminated food or water, the larvae hatch in the intestine, penetrate the intestinal wall, and are carried to the liver and lungs through the circulatory system. They migrate to the pharynx, are again swallowed, migrate to the intestine, mature, and reproduce. Eggs are passed through the feces, and the life cycle is continued. Damage to tissues during migration and maturation has been seen not only in the intestinal tract, but also in other organs, including the lungs and the liver.

A subspecies of this nematode, *Ascaris lumbricoides suum*, is found in hogs. Villella et al. (1958) reported that 100% control was obtained with absorption of 1.5 kilograys of ionizing energy by segmented eggs. Absorption of 2.5 kilograys of ionizing energy did not kill all of the unsegmented eggs tested, but it did completely inhibit reproduction. Sivinski (1975) later found that simultaneous application of heat and ionizing energy had a synergistic effect on *Ascaris lumbricoides* eggs, and control was obtained with 0.4 kilogray of ionizing energy at 117°F (47°C).

Trichinella spiralis

The human disease known as trichinosis is caused by the nematode *Trichinella spiralis*, which is derived from raw or inadequately cooked pork. Larvae encysted in the pork muscle tissue are released when the tissue is digested in the stomach. Both males and females mature in the stomach and mate in the intestinal mucosa. The females deposit larvae in the intestinal walls, and the larvae then migrate to all parts of the body and become encysted in the muscle tissue.

Although trichinosis is not as prevalent as it used to be, it occurs worldwide. Lapage (1963) estimated that 28 million people suffered from this disease in 1947. Olsen (1974) estimated the incidence of trichinosis in the United States in the early 1970s at about 4% of the population.

Wharton (1957) and Shichobalova (1958) found, respectively, that 0.047 to 0.140 and 0.047 to 0.065 kilogray of ionizing energy suppressed maturation of the nematode sufficiently to prevent invasion of the muscle tissue. Kraybill (1959) observed that exposure of whole pig carcasses to 0.11 kilogray of ionizing energy from a cobalt-60 source resulted in sexual sterilization of the female nematode. Gibbs et al. (1964) found that the maturation of *Trichinella spiralis* could be suppressed with 0.2 to 0.3 kilogray of ionizing energy without affecting the flavor of the meat. These observations and others led to a successful petition to FDA to permit exposure of pork to 0.3 to 1 kilogray doses of ionizing energy to control trichinae.

Bacteria

Most foods have an inherent population of bacteria that is considered natural. The microorganisms are associated with the growth of the product and its contact with natural environmental entities. Other bacteria, considered contaminants, are added during harvesting, processing, and distributing the products and in preparing them for consumption.

Almost any food may harbor microorganisms that are pathogenic or capable of producing toxins. *Salmonella*, *Campylobacter*, and *Yersinia* are important groups of bacteria that cause intestinal infections. Toxin producers of concern to public health include *Staphylococcus aureus* and *Clostridium botulinum*.

Drying and refrigeration retard the multiplication of existing organisms and kill some of them; pasteurization, cooking, and sterilization kill existing organisms; and packaging reduces or eliminates further contamination. These processes increase the safety of food products for consumption.

All bacteria can be killed by ionizing energy, which makes exposure of food to gamma rays and other forms of ionizing energy a potentially valuable way of reducing or eliminating the hazard of foodborne diseases due to bacteria (Anonymous, 1982). The doses of ionizing energy required to kill bacteria are much greater than those needed to kill the insects and animal parasites discussed in preceding paragraphs. Because the doses needed to kill some bacteria may be great enough to have undesirable side effects on some foods, it is necessary to find by actual testing the dose that is appropriate for different combinations of species or subtype of disease-causing bacteria and type of food product. These details will be treated at some length in the sections on processing different food types with ionizing energy. Bacteria that produce intestinal disease, including *Yersinia enterocolitica*, *Campylobacter jejuni*, and most species of *Salmonella*, are among the groups most sensitive to ionizing energy. Low doses of ionizing energy can therefore be useful in reducing the risk to public health from foods that carry these bacteria.

10. Insect Eradication

The usual procedures for controlling insect pests involve treatments with insecticides and other means to reduce the numbers or eliminate the insects completely on a local basis. These techniques provide only temporary relief because reinfestation and multiplication of residual populations continually recreate the original problems.

The Screwworm

In 1937, E. F. Knipling of the U.S. Department of Agriculture conceived the idea of releasing large numbers of sterile insects repeatedly on an area-wide basis to achieve complete eradication of the pest species of concern. His hypothesis (Knipling, 1955) was that if enough sterile insects could be released to provide a high ratio of sterile to wild fertile male insects, most of the wild females would mate with sterile males and as a consequence would not produce offspring. Only a few of the wild females would mate with wild males and produce fertile eggs to carry on the species. After a few generations with repeated releases, the species would be eradicated.

Eventually a suitable combination of knowledge, administrative approval, and financial support was brought together to test the hypothesis. The test was made on the screwworm, a serious insect pest of livestock and wildlife (and occasionally people) in the warmer regions in the United States, Mexico, and points south. Protecting livestock from screwworms was for many years labor-intensive drudgery for livestock producers in the South. They had no choice. They either provided frequent surveillance and prompt treatment of infested animals, or they lost the animals (Scruggs, 1975).

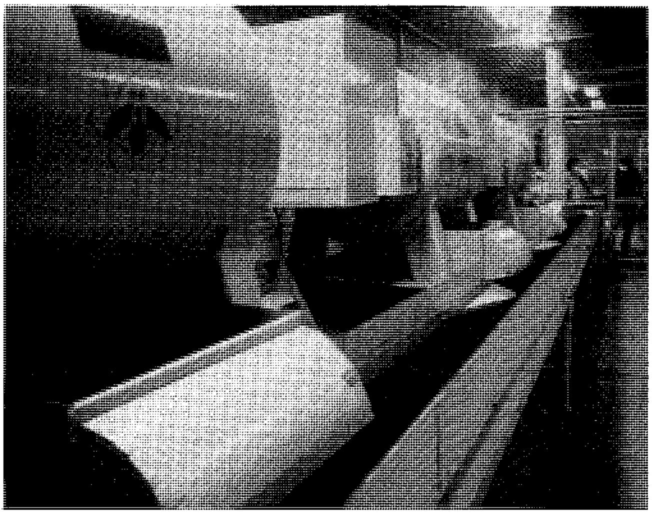
The adult screwworm flies lay their eggs at the edge of a wound or infected body opening. The larvae develop in the flesh, and the open infested area gradually enlarges as more flies lay their eggs and more larvae develop. Infested animals that are not treated become weak and eventually die from the action of the larvae or secondary infections.

In addition to the great importance of the screwworm as a pest, there were two important practical reasons for testing the hypothesis on the screwworm. First, the number of sterile flies needed would be relatively low because the population of screwworm flies was relatively low, even in heavily infested areas, and because the female flies generally mate only once, whereas the males may mate repeatedly. Second, screwworms could be cultured artificially on a mass-production basis to provide the necessary supplies of sterile flies (Bushland and Hopkins, 1953; Baumhover, 1963; Baumhover et al., 1966).

The first successful test was made in the early 1950s on the island of Curacao off the coast of South America, where reinfestation from outside sources would be unlikely. The screwworm was promptly eradicated. Then began a long and much more difficult operation in which the screwworm was eradicated first from Florida and then gradually from states to the north and west, and from Mexico. The pest now is held at bay by a barrier at the Isthmus of Tehuantepec in southern Mexico where the land mass is narrow and the required continual releases of sterile flies to prevent northern migration can be accomplished relatively economically.

The critical part in the process played by ionizing energy is the sterilization of the flies. At present, the sterilization is done in Husman rotary irradiators containing the isotope cesium-137 (Goodenough et al., 1983). The irradiators provide operator safety through nearly total shielding of the radioactive source.

A dose of 0.07 to 0.1 kilogray is applied to the pupae approximately 24 hours before the adult flies emerge. This dose is enough to produce sexual sterility without reducing appreciably the vigor of the flies. The sexually sterilized flies that are released in the field seek out mates. When sterile males mate with fertile females, sterile eggs are produced. When fertile or sterile males mate with sterile females, no eggs are produced. Failure to find new egg masses in wounds of test animals in the field after



A battery of Husman rotary irradiators in which cesium-137 is used to sexually sterilize screwworm flies before they emerge from the pupae. This picture was taken in a factory in southern Mexico that produces sterile screwworm flies for continual release to prevent the fertile flies from migrating northward from Central America and reinfesting Mexico and the southern United States. Photograph courtesy of L. N. Meyer, Animal and Plant Health Inspection Service, U.S. Department of Agriculture.

repeated releases of sterile flies thus is evidence that eradication is complete.

The dosage required to sterilize screwworms is very low compared with that used in treating foods, and is closely controlled at the screwworm production facility. The hazard of releasing fertile flies as a result of underdosing is limited by a series of quality control checks. Overdoses would not constitute a hazard to the environment, but if sufficiently great they would reduce the mating efficiency of the artificially reared flies (Crystal, 1979). Because no detectable residual radioactivity is present in the flies, they do not constitute a radioactive hazard to predators that might consume them. The irradiated flies may carry induced mutagens (Muller, 1941), but these are not transferred to the native population because sterile flies do not produce offspring.

Remote and incomprehensible to most persons, but of paramount importance to the individuals involved, is elimination of the agony experienced by livestock, wildlife, and humans infested with this vicious pest. A symposium edited by Graham (1985) and a book by Meyer (1988) provide ample documentation of the screwworm eradication program, in which a capability supplied by ionizing energy has played such a prominent role.

Other Insects

The techniques and lessons learned in the screwworm eradication program are now being applied to other insect pests. According to the International Atomic Energy Agency (IAEA, 1981, 1987), the most important insects that can be controlled by the sterile-insect technique are the cotton bollworm (corn earworm), the screwworm, various fruit flies, the tsetse fly, and mosquitoes. In the United States, the technique has been used repeatedly in programs to eliminate incursions of the Mediterranean fruit fly. In Guatemala, it has successfully eliminated the Mediterranean fruit fly from much of the country. It has also proved successful in eliminating the heel fly of cattle in a test area in northern Montana, with an extension into southern Alberta.

The International Atomic Energy Agency (IAEA, 1981) noted that "in Africa alone Nagana (animal trypanosomiasis) and related diseases profoundly affect economic development. The tsetse fly as the transmitter of Nagana is spread over an area of more than 7 million square kilometers .... If these diseases could be eliminated in Africa alone, the cattle population could be increased by at least 120 million head with a resultant yearly increase of meat production of 1.5 million tonnes having a value of 750 million US dollars."

The sterile-insect technique has been used to eradicate the tsetse fly from a 3,500-square-kilometer pastoral zone in Burkina Faso and from a 1,500-square-kilometer agricultural zone in Nigeria. The latter effort is now being extended to a wider area. In Kenya, the technique is in use in the beginning stages of a program to eradicate mosquitoes (IAEA, 1987).

11. Treatment of Foods

Guidelines for operating industrial sources of ionizing energy and for controlling the quality and processing of the products have been in use with these facilities for about 20 years. As is true for other industrial uses of ionizing energy, its use in food processing is only one step in a chain of production, handling, processing, and distribution operations, each of which requires certain quality controls.

For example, poultry that has been cut up and inspected is often packaged on trays, which are then packed into cartons and moved on a conveyor from the processing floor through a blast freezer. An appropriate place for the irradiation facility for controlling disease-causing bacteria would be in the processing plant just after the blast freezer. If the product were Hawaiian papayas to be disinfested of insects before shipment to the mainland, an appropriate place for the irradiation facility would be a harbor location, so that the processed fruits could move directly from the storage area to the hold of the ship. To prevent reinfestation of the fruit after processing, the inside of the enclosure in which the fruit is moved to the ship and the inside of the hold of the ship would need to be disinfested by fumigants.

For food, both U.S. national guidelines (e.g., Food and Drug Administration, Department of Agriculture) and international guidelines (*Codex Alimentarius General Standards for Irradiated Foods*) specify that "good manufacturing practices" be applied to all foods before, during, and after exposure to ionizing energy. The good manufacturing practices for operating sources of ionizing energy are less well known than those for conventional food handling facilities. The following paragraphs describe the fundamental aspects of the process upon which the practical procedures are based.

The Process

Foods are exposed to ionizing energy in a shielded chamber through which the foods usually pass on a conveyor belt. The stronger the source and the slower the food moves through the chamber, the greater is the dose of ionizing energy absorbed. The characteristics of the specific food being treated must be taken into account in determining the absorbed dose.

As the product leaves the irradiation facility, it usually is stamped automatically with the date, the dose, and a number identifying the facility. If the carton contains subunits, these are marked before packing and processing. If desired, these subunits could have identification markers that change color upon absorption of ionizing energy. The markings make it possible for the processor, distributor, government inspector, or consumer to identify the product and review the records at a later date if desired.

Facilities are licensed to process foods in accordance with good manufacturing practices. Federal inspections are made for interstate shipments of foods to assure that the facilities continue to meet the approved standards and that the staff is properly trained.

Plant Products

The use of ionizing energy to extend the postharvest life of plant products has been investigated for more than 30 years. Reviews of the many published scientific reports (Abdel-Kader and Maxie, 1967; Kader and Heintz, 1983) make it clear that ionizing energy has some potential applications to food commodities of plant origin, but that it also has limitations (Bramlage and Couey, 1965; Bramlage and Lipton, 1965; Lipton et al., 1967; Maxie et al., 1971; Dennison and Ahmed, 1975; Urbain, 1986; and Sommer and Mitchell, 1986). Exposing plant products to ionizing energy will not solve all the problems of postharvest deterioration of plant products. Rather, this technology should be considered as a supplement to refrigeration and other temperature-management procedures.

The effects of ionizing energy on plant commodities depend not only upon the dose, dose rate, and environmental conditions during exposure, but also upon type of commodity, variety, maturity at harvest, initial quality, degree of contamination with microorganisms, and postharvest handling procedures. Preharvest factors, including climatic conditions and cultural practices, influence product composition and quality, which in turn may affect the responses to ionizing energy. The sensitivity of plant commodities to other stresses, such as physical impacts and chilling injury (physiological damage due to exposure of sensitive commodities to temperatures above their freezing point and below 41 to 55°F or 5 to 12.5°C), is often increased by exposure to ionizing energy.

At doses of ionizing energy up to 1 kilogray, beneficial effects include inhibition or delay of sprouting in tuber, bulb, and root crops; delay of ripening in some fruits; and insect disinfestation (Clarke, 1971; Staden, 1973; Urbain, 1978, 1986; Loaharanu and Urbain, 1982; Kader, 1986). At doses between 1 and 3 kilograys, ionizing energy has fungicidal and fungistatic effects that can be useful in controlling decay in some commodities that are not injured or are only slightly injured. Fresh plant commodities apparently do not tolerate doses above 3 kilograys without detrimental effects.

Fresh Fruits and Vegetables

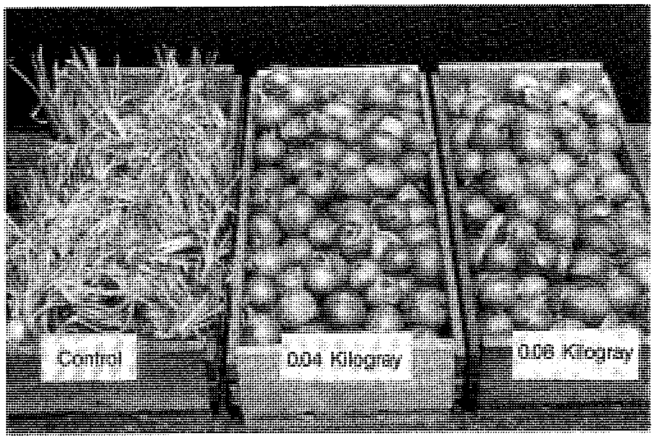
Table 1 provides a convenient summary of the effects of ionizing energy on fresh fruits and vegetables. More details are given in the following paragraphs.

Inhibition of Growth

Doses of 0.05 to 0.15 kilogray have been found to inhibit sprouting of potato, yam, Jerusalem artichoke, sweet potato, ginger, sugar beet, table beet, turnip, carrot, onion, and garlic. Treatment during dormancy is most effective for sprout control. The minimum dose required varies among commodities and among varieties within a given commodity. Doses below 0.15 kilogray have little or no effect on quality attributes of tuber, bulb, and root crops. Doses above 0.15 kilogray may induce undesirable side effects, such as tissue browning or darkening, decreased wound healing ability, increased storage rot, sweetening, and decreased vitamin content (Matsuyama and Umeda, 1983; Thomas, 1984a, 1984b).

Commercial processing of onions and potatoes is underway in several countries (Table V-10 in Appendix V). The most extensive operation appears to be in Japan, where a commercial plant with a monthly capacity to process 10,000 tons of potatoes was established in 1973 at Shihoro, Japan (Matsuyama and Umeda, 1983).

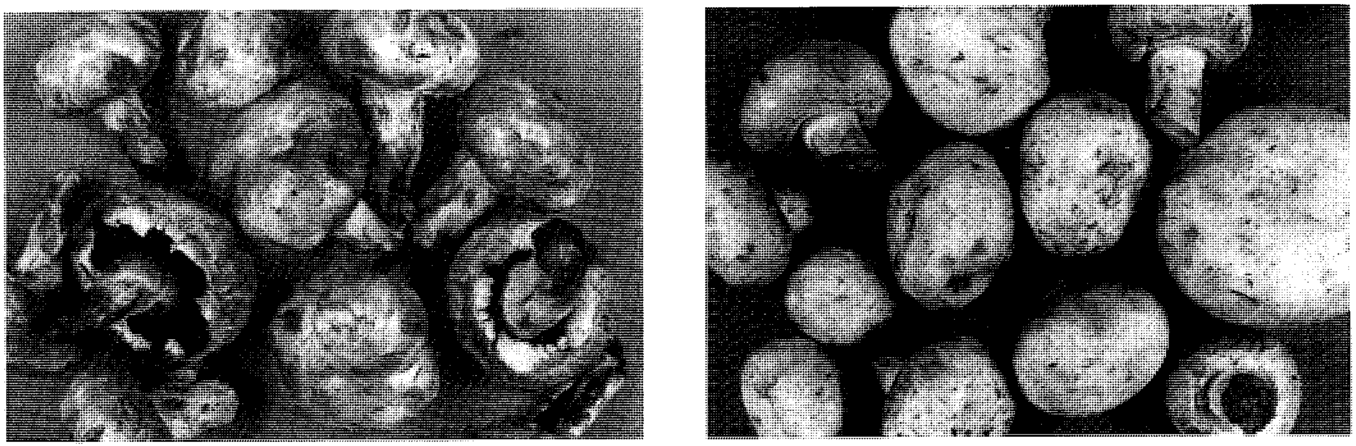
In the United States, maleic hydrazide is used as a preharvest treatment to inhibit sprouting of onions and potatoes, and chloroisopropyl carbamate is used as a postharvest treatment of potatoes. Whether or not the use of these chemicals or others is permitted in the future will influence the potential for the use of ionizing energy to control sprouting.



Exposing onions to 0.04 or 0.08 kilogray of ionizing energy inhibits sprouting during storage. Photograph courtesy of Eugen Wierbicki, Eastern Regional Research Center, USDA, Philadelphia.

Doses of 0.05 to 0.15 kilogray inhibit the elongation and curvature of asparagus spears; higher doses are detrimental to quality and storage life. Postharvest growth of asparagus spears is currently and effectively controlled by temperature management. The curvature of the cut spears that takes place in response to gravity when the spears are maintained in a horizontal position during transport and storage is avoided by keeping them vertical.

Mushrooms can be kept in prime condition for only 1 or 2 days at 50°F (10°C). Treating them with 0.06 to 1 kilogray of ionizing energy inhibits cap opening and stalk



Appearance of mushrooms after storage at 55°F (13°C) for 7 days. Those on the left were untreated, and those on the right were treated with 1 kilogray of ionizing energy. Photographs courtesy of Ron A. Matason, Krista Weidner, and James J. McClure, *Penn State Agriculture*, The Pennsylvania State University.

Table 1. Some potential applications and limitations of the use of ionizing energy in the processing of fresh fruits and vegetables

Commodites	Treatment objective	Estimated minimum dose required, kilograys	Estimated maximum dose tolerated, kilograys	Detrimental effects above maximum dose tolerated	Alternative treatments available
Potato, onion, garlic, carrot, table beet, radish, turnip, Jerusalem artichoke, sweet potato, yam, cassava, taro, ginger	Inhibition of growth (sprouting and rooting)	0.05-0.10	0.15	Decreased wound healing ability[a] Tissue discoloration Increased susceptibility to decay	Use of sprout inhibitors (e.g., maleic hydrazide and chloroisopropyl carbamate) Maintenance of optimum temperature and relative humidity
Asparagus	Inhibition of growth (elongation and curvature)	0.05-0.10	0.25	Tissue breakdown Increased susceptibility to decay	Vertical packing and maintenance of optimum temperature (36°F, 2°C) and relative humidity (95-98%) Use of elevated carbon dioxide atmospheres
Mushrooms	Inhibition of growth (cap opening and elongation) Reduced discoloration	0.06-0.50	1.0	Development of off-flavors	Prompt cooling and maintenance of optimum temperature (32°F, 0°C) and relative humidity (95-98%)
Artichoke, asparagus, broccoli, brussels sprouts, cabbage, cauliflower, lettuce, spinach, other leafy vegetables	Insect disinfestation (prevention of adult emergence)	0.15-0.30	0.25	Loss of green color Stem pitting of artichoke Tissue discoloration	Fumigation with hydrogen cyanide (can be detrimental to quality of most commodities in this group)
Snap beans, sweet corn, cucumber, eggplant, okra, green peas, bell peppers, summer squash	Insect disinfestation	0.15-0.30	0.50	Loss of green color Increased denting of sweet corn Tissue discoloration	Fumigation with methyl bromide (can be detrimental to quality)
Cantaloupe, honeydew melons, Persian melons, casaba melons, tomatoes	Insect disinfestation	0.15-0.30	1.00	Accelerated softening Abnormal ripening	Fumigation with methyl bromide (can be detrimental) Short vapor heat treatment
Apple, apricot, blueberry, cherry, fig, loquat, nectarine, peach, pear, persimmon, plum, pomegranate, raspberry, strawberry, tamarillo	Insect disinfestation	0.15-0.30 depending on the commodity	0.50-1.75	Accelerated softening Abnormal ripening	Fumigation with methyl bromide (can be detrimental) Cold treatments
	Control of postharvest molding	1.50-2.00	3.0		Use of postharvest fungicides
Avocado, grapefruit, grape, kiwifruit, kumquat, lemon, lime, olive, orange, tangelo, tangerine	Insect disinfestation	0.15-0.30	0.25-0.75 depending on the commodity	Accelerated softening Tissue discoloration Surface pitting	Cold treatments (can be detrimental)
Banana, mango, papaya, pineapple, plantain, guava, lychee, longan, rambutan, cherimoya, carambola, passion fruit, sapodilla	Insect disinfestation	0.15-0.30	0.50-1.50, depending on the commodity	Accelerated softening Uneven ripening Tissue discoloration	Hot water or vapor heat treatments Fumigation with methyl bromide (can be detrimental)
	Retardation of ripening	0.25-1.0			Temperature management Ethylene removal Controlled atmospheres

[a] This is a problem only for wounds that are made after processing. Prior wounds can be allowed to heal before processing.

elongation (Staden, 1973). Within this dose range, the quality is not affected adversely, and the shelf life may be extended to as long as 1 week (Thomas, 1988).

Insect Disinfestation

The most commonly used method for controlling insects in harvested fresh fruits and vegetables has been treatment with fumigants, such as ethylene dibromide, methyl bromide, phosphine, and hydrogen cyanide. The U.S. Environmental Protection Agency withdrew ethylene dibromide from the list of approved chemicals in 1984.

Cold treatments (10 days at 32°F (0° C) to 16 days at 36°F (2.2°C) or below) are approved quarantine treatments for controlling certain fruit flies. Such treatments can be used on some commodities (for example, apple, pear, grape, orange, kiwifruit, persimmon, and pomegranate), but they are not suitable for highly perishable commodities (for example, berries and stone fruits) or for commodities sensitive to chilling (for example, grapefruit, lemon, avocado, papaya, mango, tomato, and pepper). Hatton and Cubbedge (1982) found that conditioning grapefruit for 7 days at 61°F (16°C) before applying the cold treatment significantly reduced chilling injury. This method has been used successfully to treat some grapefruit for shipment to Japan.

Heat treatments are currently used as a substitute for ethylene dibromide treatment of papayas harvested at the mature-green stage, but some undesirable effects on ripening rate and uniformity have been noted. Other treatments, such as modified atmospheres, fumigation with certain naturally occurring volatile substances, ultrasound, microwave radiation, and treatment combinations are under investigation for their potential use in insect control (Couey, 1983).

Doses of ionizing energy below 1 kilogray are effective in controlling fruit flies, the mango weevil, the navel orangeworm, the potato tuber worm, the codling moth, spider mites, scale insects, and other insects that are important in postharvest handling and marketing of fresh horticultural crops (Anonymous, 1973; Burditt, 1982; Tilton and Burditt, 1983; Moy, 1985). Most insects are sexually sterilized at doses of 0.05 to 0.75 kilogray. Some adult moths survive 1 kilogray, but their progeny are sterile. A minimum absorbed dose of 0.15 kilogray has been suggested as an effective quarantine treatment for fresh fruits and vegetables against fruit flies because it stops their reproduction. Adoption of this procedure, however, would require a change in current quarantine regulations, which state that all living stages of pest species in commodities must be killed for a quarantine treatment to be acceptable.

Most fresh fruits and vegetables tolerate doses of at least 0.25 kilogray with no detectable detrimental effects on quality. At doses between 0.25 and 1 kilogray, some commodities (for example, table grapes) can be damaged under some conditions. Such doses may be reached in commercial gamma irradiators in which, because of the thickness of the product exposed, a dose as great as 0.5 kilogray may be needed on the outside to achieve a dose of 0.25 kilogray in the center. Lettuce, artichokes, and other nonfruit vegetables are generally much more sensitive to ionizing energy than are apples, peaches, and other fruits and fruit-vegetables (such as tomatoes and melons) that are consumed ripe. Fresh fruits and fruit-vegetables can be arranged into the following four groups on the basis of their tolerance to ionizing energy at doses below 1 kilogray (Kader, 1986): (1) Only slight detrimental effects reported, ready for pilot-scale testing: apple, cherry, date, guava, longan, mango, muskmelon, nectarine, papaya, peach, rambutan, raspberry, strawberrry, tamarillo, tomato. (2) Inconsistent results among reports, further evaluation needed: apricot, banana, cherimoya, fig, grapefruit, kumquat, litchi, loquat, orange, passion fruit, pear, pineapple, plum, tangelo, tangerine. (3) Most published data indicate significant detrimental effects, further investigation likely to be nonproductive: avocado[4], cucumber, grape, green bean, lemon, lime, olive, pepper, sapodilla, soursop, summer squash. (4) No published data, evaluation needed: kiwifruit, pomegranate.

Effects on Ripening and Senescence

Ripening of bananas is inhibited at doses of 0.25 to 0.35 kilogray, and the treated fruits can be ripened later to good quality by use of an ethylene treatment, as is commonly done with bananas that have not been treated with ionizing energy. Similar results have been reported for mango, papaya, guava, and several other subtropical and tropical fruits (Anonymous, 1968; Akamine and Moy, 1983; Moy, 1983; Thomas, 1986a). Because all these fruits are susceptible to chilling injury and cannot be held below about 50 to 59°F (10 to 15°C), depending upon commodity, variety, and maturity stage, supplemental treatments to retard their ripening might be very useful. The potential usefulness of ionizing energy for retarding ripening will depend upon its cost relative to other treatments, such as modified atmospheres and ethylene removal methods, that elicit a similar response.

Most temperate-zone fruits, for example, apples, pears, and stone fruits, require doses exceeding 1 kilogray for

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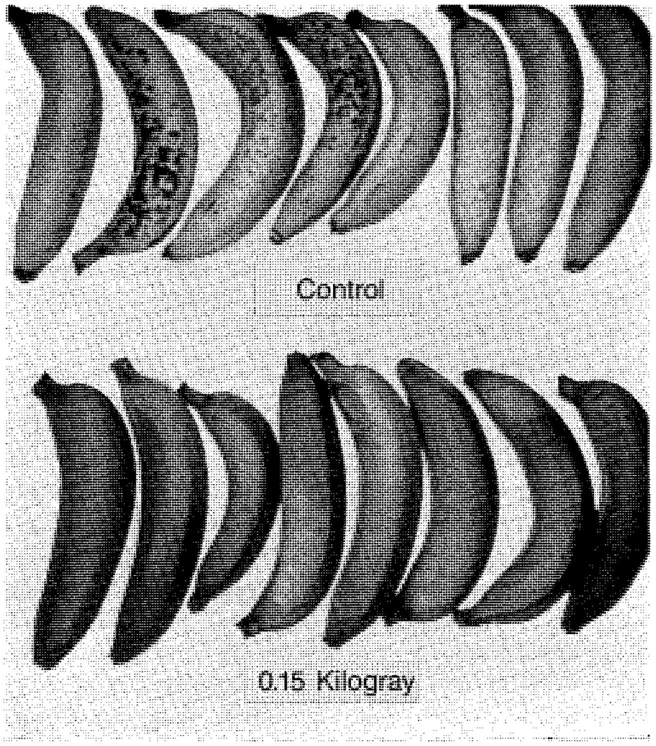
[4] The effects of ionizing energy vary with the variety and stage of fruit development (Urbain, 1986). In 1983, avocados grown in Chile were treated there with a low dose of ionizing energy for insect disinfestation and delay of ripening, and were shipped by sea to Wageningen, the Netherlands, for evaluation. The quality of the treated fruit was reported to be excellent.



Exposing green bananas to 0.15 kilogray of ionizing energy delays ripening. Photograph courtesy of Eugen Wierbicki, Eastern Regional Research Center, USDA, Philadelphia.

effective inhibition of ripening. Serious detrimental effects of such treatments have been observed, including uneven ripening and excessive softening, which increases their susceptibility to physical damage and may result in mushy fruit reaching the consumer. Ionizing energy also increases the respiration rates of all types of fruits. At doses less than 4 kilograys, it stimulates ethylene production by the fruits, and at greater doses it inhibits ethylene production (Maxie and Abdel-Kader, 1966). The higher doses reduce the sensitivity of most fruits to the ripening action of ethylene.

Doses exceeding 0.5 kilogray accelerate degreening of citrus fruits, especially lemons. The use of ionizing energy for fruit degreening is impractical, however, because of its possible detrimental effects and the availability of a relatively simple degreening method using ethylene.

Treatment with ionizing energy, especially doses in excess of 1 kilogray, may result in various physiological disorders (Bramlage and Couey, 1965; Bramlage and Lipton, 1965; Maxie and Abdel-Kader, 1966; Lipton et al., 1967; Maxie et al., 1971; Staden, 1973; Thomas 1986a, 1986b, 1986c). These include swelling of oil glands followed by peel pitting in oranges and grapefruits; internal cavities in lemons and limes; skin damage to bananas; internal browning in avocados; softening, skin discoloration, and stem darkening of grapes; external and internal discoloration of olives; surface browning of Kadota figs; accelerated yellowing of cucumbers, summer squash, and peppers; stem pitting of artichokes; reddish-brown sunken spotting on leaf midribs of lettuce and endive; and increased denting of sweet corn kernels (denting normally is associated with aging). In addition to these specific effects on certain commodities, sensitivity to chilling injury and other stresses may be increased, as mentioned previously.

Doses of 1 to 2 kilograys reduce the incidence and severity of scald on apples (a physiological disorder manifested as an unsightly brown discoloration of the skin, suggesting injury by heat) (Clarke, 1971; Moy, 1983). Diphenylamine and Ethoxyquin, the chemicals used commercially as scald inhibitors, are currently under study by health authorities. Should approval for use of these chemicals be withdrawn, exposure to ionizing energy could become an alternative for commercial application.

Effects on Composition and Quality

Treating fresh fruits and vegetables with ionizing energy at doses they can tolerate does not reduce their caloric value. In general, changes in nutritional quality and flavor are not limiting at tolerated doses.

Only negligible losses of niacin, thiamine, riboflavin, and beta-carotene (provitamin A) have been observed. Ascorbic acid (vitamin C) is more sensitive; observed losses have ranged from 0 to about 25%[5], depending upon dose, commodity, variety, and duration and temperature of storage (Maxie and Abdel-Kader, 1966). Changes in pigments in fresh fruits and vegetables subjected to doses of ionizing energy below 3 kilograys have been significant, but reported changes in sugars, fats, proteins, and enzymes have been within the experimental errors of measurement (Romani, 1966; Urbain, 1986). Other observed compositional changes, which may be desirable, include a decrease in acidity of some commodities, loss of astringency in persimmons, increased juice yield in grapes, and inhibition of chlorophyll and solanine formation in potatoes exposed to light (Anonymous, 1973, 1978a; Loaharanu and Urbain, 1982; Moy, 1983).

The solubilization of pectins, cellulose, hemicellulose, and starch in response to doses exceeding 0.6 kilogray is important because it results in softening of fresh fruits and

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[5] When higher losses have been reported, the measurements have been based upon only the reduced form of ascorbic acid. Much of the reduced form of ascorbic acid that disappears during the processing of fruits and vegetables with ionizing energy is oxidized to dehydroascorbic acid, which retains vitamin C activity. The real losses of vitamin C at these low doses are small.

Table 2. Maximum doses of ionizing energy that do not cause changes in the flavor of fresh fruits and vegetables and their products (Metlitskii et al., 1967)

Product[a]	Maximum dose in kilograys
Fresh fruits and vegetables	
Leaf lettuce	0.36
Lima beans	0.36
Bananas	1.44
Plums	3.60
Grapefruit	4.32
Oranges	4.32
Strawberries	4.32
Green peas	7.20
Sweet cherries	9.00
Pod beans	11.40
Asparagus	18.00
Spinach	18.00
Carrots	21.60
Fruit and vegetable products	
Lemon juice	0.72
Tomato juice	2.16
Orange juice	4.32
Currants	6.12
Apple juice	9.00
Apple sauce	18.00
Whole canned tomatoes	18.00
Dried plums	25.20

[a] All products treated when unfrozen.

vegetables, which is undesirable for postharvest handling. The undesirable effects of ionizing energy on firmness can be reduced by processing the commodities at low temperatures, under an atmosphere of nitrogen, or both (Maxie and Abdel-Kader, 1966). These conditions also reduce the effectiveness of ionizing energy in controlling insects and microorganisms.

Table 2 contains information summarized by Metlitskii et al. (1967) on the maximum doses of ionizing energy that could be employed on fruits and vegetables and their products without causing detectable changes in flavor. Although the sources of the individual entries in the table were not referenced by the authors, the data were derived mainly from research in West Germany. For the fresh fruits and vegetables, the critical doses generally exceed those that can be tolerated from the standpoint of physical quality (see Table 1), so that effects on flavor are not of concern.

Exposing the strawberries on the right to 2 kilograys of ionizing energy inhibited molding during storage for 2 weeks at 37°F (3°C). Photograph courtesy of Eugen Wierbicki, Eastern Regional Research Center, USDA, Philadelphia.

Decay Control

The potential use of ionizing energy to control postharvest diseases depends upon the sensitivity of the particular molds (fungi) or bacteria relative to the ability of the commodity to withstand the required dose. The effectiveness of ionizing energy in controlling fungi depends upon the specific organism, its stage of growth, and the number of viable fungal cells on or within the tissue. Generally, the minimum dose required for effective inhibition of postharvest fungi is 1.75 kilograys (Sommer and Fortlage, 1966), which is not far below the approximate maximum dose of 2.25 kilograys that most fresh commodities can tolerate without serious loss of firmness, increased susceptibility to mechanical injury, ripening abnormalities, and altered flavor (Maxie et al., 1971).

Combination treatments, such as heat plus ionizing energy, may be beneficial in terms of product quality by making it possible to obtain a given fungistatic effect with the use of smaller doses of ionizing energy. Such combinations are effective in controlling brown rot on stone fruits and anthracnose on papaya and mango fruits (Sommer and Fortlage, 1966).

Methods now used to control postharvest decay include fungicides, atmospheres containing reduced oxygen concentrations, either 10 to 15% carbon dioxide or 5 to 10% carbon monoxide, and hot water treatment. For ionizing energy to become a viable alternative for some commodities, it must provide equal or better control than other methods at a competitive cost. The competitive position of ionizing energy would be enhanced, should some postharvest fungicides be withdrawn from approved lists of chemicals in the absence of available substitutes.

Akamine and Moy's (1983) findings in a review of the effects of ionizing energy on the delay in postharvest ripening and senescence of 27 fruits are shown in Figure 6. In addition to the eight fruits shown in the figure as benefiting from treatment with ionizing energy, Table V-9 in Appendix V lists approvals for the use of ionizing energy on avocados (South Africa), grapes (Bulgaria, Hungary), peaches, cherries, and raspberries (Bulgaria), red currants and pears (Hungary), apples (China), and dates (Chile and Thailand).

Moy (1983) summarized the benefits and limitations of exposing fresh fruits and vegetables to low doses of ionizing energy (usually 2 to 3 kilograys, but sometimes as high as 5 to 6 kilograys). The limitations in many

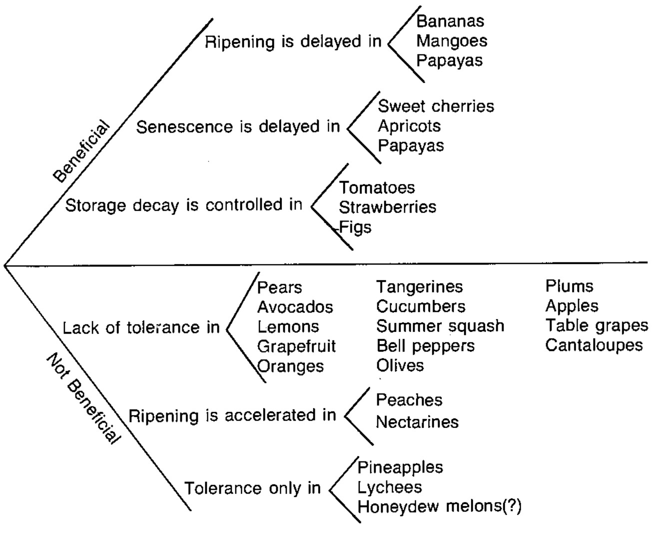

Figure 6. The response of 27 fruits to ionizing energy (Akamine and Moy, 1983).

instances result from the food being more sensitive to quality change, such as softening, than the bacteria, yeasts, and fungi for which the treatment is intended. He concluded that "the more promising application is to combine ionizing radiation with heat treatment so as to take advantage of the synergistic effect between the two in order to use a lower dose and lesser amount of heat to achieve the purpose of pasteurization."

Logistics

The logistics of treating fresh fruits and vegetables with ionizing energy need to be considered carefully, especially if the technology is to be used for quarantine purposes. For example, in Fresno County, California, alone, about 680,000 tons of tree fruits, grapes, tomatoes, and melons are shipped fresh to markets during an approximately 5-month season. Average daily production is about 4,500 tons, but daily harvests can reach 20,000 tons. If half of the average daily harvests were processed with ionizing energy at an average dose of 0.4 kilogray, the plant would need a capacity about twice that of the one used for wheat in Odessa, U.S.S.R. Transportation, handling, scheduling, public policy, and other questions would have to be considered in a realistic assessment of the feasibility of widespread use of ionizing energy for processing fresh products, because most must be marketed without extensive delay.

Nuts and Dried Fruits and Vegetables

Disinfesting products of insects is the most important benefit of processing nuts and dried fruits and vegetables with ionizing energy. Other potentially beneficial effects of treating nuts with ionizing energy include inactivating disease-causing bacteria and inhibiting sprouting, which otherwise may be a problem in chestnuts. A 0.4 kilogray dose is sufficient to control the saw-toothed grain beetle and the Indianmeal moth in dried fruits and vegetables. If packages of nuts and dried fruits and vegetables contain only eggs or young larvae, a dose of 0.2 kilogray is adequate for controlling the insects noted. The use of ionizing energy for insect control is advantageous because it can be applied after the commodity is in its final package; thus, reinfestation is avoided if the package is made of insect-proof materials.

Exposure of dried fruits and vegetables to ionizing energy, especially at doses exceeding 4 kilograys, can reduce the toughness, rehydration time, and cooking time (Thomas, 1988). The same doses may accelerate the development of rancidity in most tree nuts during subsequent storage. For example, the flavor of walnuts that received a dose of 0.9 kilogray of ionizing energy was unaffected immediately after treatment, but had deteriorated appreciably after 60 to 90 days of storage. Almonds withstood such treatment without damage to flavor, and pistachios treated with 0.6 kilogray were moderately less desirable than the controls. The flavor of raisins and prunes was unaltered by any of the treatments (Fuller, 1986).

Spices and Related Materials

Whole and ground natural spices and related materials, such as dehydrated vegetable seasonings, harbor large numbers of molds, bacteria, and their heat-resistant spores. The numbers of viable molds may range from 100 to 100,000 per gram, and the total count of viable microorganisms may be as great as 100 million per gram. Although only small amounts of spices and vegetable seasonings are used, the large numbers of microorganisms they may contain can cause serious microbial contamination of the meats, fish, cheese, baked goods, and other foods to which they are added.

Spices commonly have been treated with ethylene oxide to reduce the microbial count to a satisfactory level. Ethylene oxide, however, can cause undesirable changes in the color and flavor of some spices. There are additional health-related concerns about the use of ethylene oxide. Processing products with ethylene oxide constitutes a potential occupational hazard for workers, and tests indicate that the residues of ethylene oxide and derived substances remaining in the spices may have mutagenic and carcinogenic properties.

Ionizing energy is more effective than ethylene oxide in reducing the numbers of microorganisms in spices and related materials. In most instances, a dose of 5 to 8 kilograys reduces the microbial count to 1,000 to 10,000 organisms per gram. Doses of 8 to 20 kilograys achieve near sterility (Farkas, 1983, 1988; Urbain, 1986). Industry concern for survival of spores has led to a proposal for doses in the 40- to 50-kilogray range.

Bachman and Gieszczynska (1973) reported that the threshold doses required to produce detectable flavor changes in several spices were in the range of 7.5 to more than 15 kilograys. Urbain (1986) reported that doses of ionizing energy exceeding 10 kilograys caused detectable flavor changes in certain spices, although the changes were not sufficient to affect the normal sensory characteristics and uses of the spices. Farkas (1988) detected no flavor changes in meat products prepared with spices processed with a dose of 20 kilograys, and no alteration in flavor profile of spices processed with 26 kilograys.

Commercial treatment of spices with ionizing energy has been practiced in Europe for several years. In the United States, the Food and Drug Administration issued regulations permitting the treatment of spices, natural flavorings, and dehydrated vegetable seasonings with doses of ionizing energy up to 10 kilograys in 1983 and up to 30 kilograys in 1986. The U.S. spice industry now is beginning to process its products in accordance with the regulations. Ionizing energy probably will replace the chemical treatment with ethylene oxide.

Some spices are infested with insects as a result of contamination at the source, and others are infested during storage. Because the doses suitable for reducing the microbial contamination are far greater than those needed for insect disinfestation, any insects that may be present are controlled incidentally.

Grain and Grain Products

The principal use of ionizing energy on grain and grain products is for insect control. Research prior to World War II was not very productive because the sources of ionizing energy then available were too weak (Hilchey, 1957). Interest was revived with the availability of manmade radionuclides in the early 1950s. Nelson (1962, 1967) discussed the principles and research findings with the newer techniques.

The doses of ionizing energy required to control insects that infest grain and grain products during storage are relatively low, generally less than 1 kilogray. One of the first clearances granted by the Food and Drug Administration (in 1963) for use of ionizing energy on foods was for disinfesting wheat and wheat products of insects.

The fumigants and other insecticides now used to control insects in stored grain are effective when properly used, but residues and the development of resistance by certain insects have been of some concern (Champ and Dyte, 1976). Ionizing energy offers an alternative to these treatments and could become the method of choice, should approval for use of the chemical treatments be withdrawn. Ionizing energy leaves no residue, and development of resistance by insects is not a problem. In 1980, the USSR began using accelerated electrons for large-scale processing of grain imported through Odessa (Farkas, 1988).

Doses of ionizing energy exceeding 2 kilograys can also reduce the number of microorganisms in grain and grain products and extend their storage life. Higher doses have been shown to reduce the cooking time of legumes and to affect the baking quality of wheat flour.

Treating wheat flour with ionizing energy has been found to increase the loaf size of bread baked from formulas containing only small amounts of added sugars. The ionizing energy breaks down some of the long-chain starch molecules to short-chain molecules that are more readily metabolized by yeasts to produce carbon dioxide and water than are starch molecules. The result is greater porosity of the bread because of the greater amount of carbon dioxide produced. On the other hand, with bread formulas containing more sugar, the loaves baked from flour treated with ionizing energy are smaller than those from untreated flour. In this situation, carbon dioxide production is not limited by the supply of readily metabolized carbohydrates. The decrease in volume appears to be a consequence of the effect of the ionizing energy in splitting some of the molecules of the gluten proteins that give dough its tough, elastic quality. The gluten molecules of course have been affected, whether the dough is low or high in added sugars, but the influence of this molecular change on loaf volume is merely masked by the influence of the extra carbon dioxide produced in doughs low in sugars (Lee, 1959; Lorenz, 1975).

Sources of Ionizing Energy

Grain and grain products usually are stored in large quantities. As a consequence, special handling methods are required to assure that all parts of these commodities receive doses of ionizing energy within the desired range.

The technique usually suggested for use with accelerated electrons, which have little penetrating power, is moving the grain past the accelerator at high speed in an air stream. A disadvantage of this technique is that some kernels are cracked or broken.

X-rays and gamma rays have greater penetrating power than accelerated electrons, and the thin layers or air-stream transport required for electron beams are not needed. The large lots of grain involved in world trade, however, are almost invariably moved from shore to ship and vice versa by blowing the grain through tunnels. All three sources of ionizing energy thus could be applied with such transport, although accelerated electrons are the most economical.

The air stream and the impact of the grain at the end of its movement enhance the kill of adult moths, which are the most radioresistant insects that infest stored products. All adult and immature insects, including the many species of beetles that live external to the grain kernels, probably would also suffer a high degree of mortality.

Cogburn et al. (1972) attributed a major portion of the control of insects during exposure to gamma rays to movement of the grain in the air stream. Adem et al. (1978) found that gamma rays from cobalt-60 were more effective than accelerated electrons against pupae and adults of two species of stored grain insects. At doses of 0.15 or 0.25 kilogray, the two types of ionizing energy were equally effective in preventing the development and emergence of the two insect species.

Dosimetry

Measurement of the dose of ionizing energy received by grain that flows past a source of accelerated electrons in either a concentrated stream under gravity or an air stream presents special problems because the dosimeter must withstand being mixed with the grain, must have the same flow characteristics as the grain, must remain undamaged, and must be easily recoverable after treatment. Tilton et al. (1971) found that dosimeters consisting of 50-milligram quantities of lithium fluoride powder in small capsules were satisfactory. The capsules were a little larger than the grain and were separated from the treated grain by sieving for subsequent measurement of the thermoluminescence produced by exposure to the ionizing energy.

Radiosensitivity of Stored-Product Insects

A major problem in disinfesting commodities of insects is the fact that many species may be present, and the dose of ionizing energy employed must consequently be great enough to sterilize or kill the most resistant species. Tilton and Brower (1973, 1987) tested more than 30 species of insect pests of stored products for radiosensitivity using techniques yielding results that are comparable among species. They found that the most resistant beetles are six to seven times more resistant than the most sensitive species. The depressed flour beetle was the most resistant of the beetles tested. Both males and females reproduced after exposure to 0.3 kilogray of ionizing energy.

In general, the females of a species are more sensitive than the males. Thus, in some situations, a dose great enough to sterilize the females might be selected even if viable males persist.

The *Lepidoptera* (moths) as a group are more resistant to ionizing energy than are the *Coleoptera* (beetles), especially if the comparison is made on the basis of the dose required for sterilization. One kilogray may not sterilize all adults of some moth species, but fertility and fecundity are very low after this dose.

The dose of ionizing energy selected to control stored-product insects can be reduced if only the more sensitive beetles are present. If commodities are infested with many species, a dose of 0.5 kilogray will control even the most resistant beetle species and the immature stages of moths (Tilton and Brower, 1973). Some of the adult moths might remain fertile, but the few progeny they produce would be sterile because of inherited genetic damage (Tilton and Brower, 1987; Ashrafi et al., 1972).

Combinations of Treatments

The temperature modifies the effects of ionizing energy on insects, apparently by affecting the metabolic state of the insects (Tilton and Brower, 1983). Cornwell (1966) found that the mortality rate of adult granary weevils was increased by high temperatures (86°F or 30° C) before or after treatment with ionizing energy, but not during treatment. Lai and Ducoff (1977) found that the sensitivity of confused flour beetles to ionizing energy was increased by high temperatures immediately before or after the treatment with ionizing energy was applied; however, if an hour elapsed before exposure to a high temperature, the sensitivity was not increased. This observation suggests that the high temperature interfered with the beetles' ability to repair the damage caused by the ionizing energy.

Tilton and Brower (1985) found that when certain insects in stored wheat were treated with relatively low doses of ionizing energy, infrared energy, or microwave energy, combinations of the latter two sources of energy with ionizing energy produced somewhat greater mortality than the sum of the treatments applied individually. The beneficial effect of the combined treatments on insect kill was great enough to reduce the total cost of the disinfestation below the cost required for control by the use of ionizing energy alone.

Tilton and Burditt (1983) found that red flour beetles were slightly more susceptible to malathion insecticide when the beetles had previously absorbed 0.1 kilogray of ionizing energy. Erdman (1966) found that DDT in combination with ionizing energy was more effective than either DDT alone or ionizing energy alone, but there was no indication that the effect of the combined treatment exceeded the sum of the effects of the two treatments applied individually. Similarly, Tilton and Brower (1973) reported that small doses of ionizing energy and low-dosage fumigation with methyl bromide produced some mortality of insects in grain if used singly. When both controls were used, the joint effect was increased when 1 week or more had elapsed between treatments, but there was no clear indication that the joint effect was greater than the sum of the effects obtained when the treatments were applied singly.

Several additional studies have been made to determine how the nature of the gases in the atmosphere and the atmospheric pressure affect the sensitivity of insects to ionizing energy (Clark and Herr, 1955; Baumhover, 1963; Smittle, 1967; Langley and Maly, 1971; O'Brien and Wolfe, 1964; Ohinata et al., 1977; Tilton and Vardell, 1982). In general, these studies have shown that the sensitivity is decreased when the supply of atmospheric oxygen is decreased by evacuation or substitution of other gases. Thus, it appears unlikely that any technique involving an oxygen deficiency will result in improved control of insects by ionizing energy.

Control Modes

Complete control of insects in bulk grain may be defined in several ways that result in different effects and involve different costs. Immediate mortality of all stages of all insect populations can be obtained by relatively high doses of ionizing energy. Control can be obtained with lower, more economical doses if the insects die short of their normal life span and do not reproduce. Control can be obtained with still lower doses if the resident pupal or adult populations are merely sterilized and if eggs and larvae are killed.

As noted by Cornwell (1966), the presence of sterile but sexually competitive insects offers some protection against reinfestation of stored grain because the sterile insects are incapable of reproducing. On the other hand, most insects that have been sterilized by sublethal doses of ionizing energy continue to feed and to damage the commodity. Brower and Tilton (1973) reported that wheat consumption during a 5-week period was 90 and 97% lower when rice weevils and lesser grain borers had been exposed to ionizing energy than when they were untreated. Rogers and Hilchey (1960) reported that although red flour beetles continued to feed after treatment with ionizing energy, it was at a reduced rate. Cornwell (1964) found that the consumption of food by granary weevils was reduced by half after they had absorbed a dose of 0.16 kilogray of ionizing energy. Watters and MacQueen (1967) found that four stored-product insect species could still damage wheat 14 weeks after a dose of 0.0625 kilogray, but that the damage was greatly reduced. The reduced feeding that occurs with the smaller doses appears to result primarily from damage to the midgut of the insects (Tilton and Brower, 1973).

Mature insects rarely are found in products from clean modern mills or cereal processing plants. When infestation occurs, the only stages likely to be present in freshly milled or processed products are eggs and very young larvae. Insects in these stages succumb promptly to doses of ionizing energy below 0.5 kilogray, and appropriate dosages for immediate kill of the species present can be used (Tilton et al., 1974a, 1974b, 1978). Insects in older stages of development may live up to 3 months after treatment. The use of ionizing energy to disinfest products in which the infestation has progressed to stages beyond the presence of eggs and very young larvae is generally impractical, however, because such an infestation would have created an unacceptable condition regardless of the method used for disinfestation.

The Sterile-Insect Technique for Insect Control

Exposing insects to ionizing energy to produce sterility and then releasing the sterilized insects to compete with the wild population in mating has been used successfully to inhibit reproduction in field populations of insects. Eradication of the screwworm from the Island of Curacao was the first successful project, as mentioned previously in this report.

According to Brower and Tilton (1975), four aspects of the biology of moths that infest stored products in warehouses make the moths possible subjects for the sterile-insect technique: (1) the adult moths are nonfeeding, (2) infestations of single species of moths occur frequently, (3) most species are primarily surface feeders, and (4) the adults of most species emerge from the product before mating, so that the resident population could mate easily with the sterile moths that are introduced in the space above the grain or other product. If the numbers of introduced sterile moths are much greater than the numbers of resident moths, practically all mating members of the resident population will mate with members of the introduced population. Only the matings between fertile males and fertile females of the resident population will result in viable eggs. Repeated introductions of sterile moths thus could eliminate the resident population completely. A disadvantage of this technique could be the fact that the dead moths would remain as contaminants in the product.

Adult beetles, on the other hand, do not emerge from the grain mass for mating. Many of the resident beetles are buried deeply in the grain, and the probability of getting introduced sterile beetles to mate with them is low. Also important is the fact that the treated beetles tend to be lethargic and poor sexual competitors because they are starving as a result of the damage done to their midgut by the ionizing energy. Moreover, because adult beetles do some feeding, the introduced sterile beetles would contribute to damage of the stored product. Indications are, therefore, that introducing large numbers of sterile adult insects has some possibility of being a useful technique if the grain is infested with a single species of moth, but not if the insects are beetles.

Animal Products

Poultry Meat[6]

Production, Marketing, and Distribution

Today, chicken broilers are marketed predominantly by integrated firms that own the hatcheries, the feed mills, and the processing plants. The firms supply the chicks and the feed to producers, with whom they contract to grow the birds, and the producers provide the houses and the labor.

Virtually all poultry offered to consumers are eviscerated, and more than 50% of the chicken meat eaten is cut up or further processed. More than 50% of the turkey meat is consumed as processed items, such as turkey rolls, turkey steak, turkey salami, and turkey ham.

Bacterial Contamination and Shelf Life

Live poultry are contaminated both externally and internally with many bacteria, some of spoilage types and others disease-causing. Evisceration removes the major part of the internal microbial population, but the carcasses are still contaminated externally and may retain internal and external contamination from the intestinal contents. The numbers of contaminating microorganisms tend to increase throughout the successive processing operations.

The shelf life of chilled fresh poultry is generally considered to be 8 to 10 days, but it may be 3 to 7 days longer if well controlled sanitary conditions have been used during processing, and it may be shorter if the conditions are less sanitary. The numbers of spoilage bacteria may reach approximately 100 million per square centimeter of skin surface before the off-odor and appearance of slime that are the common subjective indications of deterioration become evident.

Disease-Causing Bacteria

The *Salmonella* bacteria that are an important cause of human intestinal disease can exist in the digestive tracts of poultry and other birds, rodents, insects, wild animals, and livestock. All these animals and their products are potential sources of human infections.

Contaminated poultry meat appeared to be the source of 12% of the reported foodborne disease outbreaks in the United States from 1966 to 1974 (Horwitz and Gangarosa, 1976). The proportion of chicken carcasses positive for *Salmonella* as the carcasses left the chillers in the processing lines averaged 21% in 1959 and 12% in 1979 according to one study of a number of processing plants (Campbell et al., 1983). Many opportunities exist for cross contamination of carcasses during processing.

Complete eradication of *Salmonella* from the production and processing aspects of the poultry industry would be difficult. Proper treatment with ionizing energy as the packaged products leave the processing plant for marketing, however, would eliminate most of the problem for consumers.

Although *Salmonella* receive major emphasis, other bacteria may also be important. *Staphylococcus aureus*, *Clostridium perfringens*, *Campylobacter jejuni*, *Yersinia enterocolitica*, and *Listeria monocytogenes* deserve special mention. No outbreaks of human listeriosis originating from poultry meat have been reported, but the potential exists if poultry meat is improperly handled, as indicated by Bailey and Fletcher's (1987) finding that 43.5% of the broiler chickens they tested were contaminated with *Listeria monocytogenes*.

Decontamination and Shelf-Life Extension

Most chicken broilers are marketed unfrozen because of potential bone darkening when they are frozen. Most turkeys, however, are marketed frozen, which greatly extends the shelf life.

Freezing turkeys in a blast freezer or by immersing them (while encased in a protective film) in a salt solution cooled below the freezing point of water reduces the numbers of total surface microflora by 96 to 98% (Kraft et al., 1963). Staphylococci and enterococci are generally more resistant than coliforms to destruction by freezing. A five-cycle freeze-thaw treatment was found to reduce the numbers of inoculated *Salmonella typhimurium* by 95% (Olson et al., 1981), but some contaminants remained. The effect of such a treatment on the palatability of the poultry meat has not been investigated.

Prachasitthisakdi et al. (1984) found that a dose of 4 kilograys or less of ionizing energy was adequate for inactivating disease-causing organisms in poultry meat, as

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[6] For more detailed coverage of the first three topics in this section, see Appendix IV.

indicated by risk analysis. A dose of 3 kilograys of ionizing energy is considered adequate to control the parasites and nonspore-forming disease-causing organisms that contaminate a significant percentage of the poultry meat produced in the United States. The Food and Drug Administration has approved the use of 0.3 to 1 kilogray of ionizing energy to control *Trichinella spiralis* in pork, and is considering a U.S. Department of Agriculture petition to allow doses up to 3 kilograys to control disease-causing organisms in poultry.

Exposing chilled poultry to a maximum dose of 3 kilograys of ionizing energy also reduces the populations of the nonspore-forming spoilage bacteria enough to extend the shelf life of refrigerated poultry by 1 to 2 weeks. This dosage conserves the nutritional quality and does not produce a detectable off-flavor. Enough spoilage organisms survive a dosage of 3 kilograys to assure that the poultry will spoil before it could become unsafe as a result of production of the botulinum toxin by any clostridia that might be present. *Clostridium botulinum* bacteria, however, have not been found in poultry meat. If they did occur, except for type E, the refrigeration temperatures commonly used would prevent formation of the botulinum toxin. Type E requires holding the product at temperatures below 38°F (3.3°C) for safety. Type E has limited distribution and normally is found only in certain fin fish and shellfish, principally fin fish caught off the coast of northeastern United States and eastern Canada.

The resistance of disease-causing bacteria to ionizing energy varies with the organism, the substrate, and the conditions. Resistance values must be determined experimentally. Ingram and Farkas (1977) and Farkas (1987) tabulated many values that had been published in the scientific literature. The ranges given in Table 3 are derived mostly from the individual values summarized by Farkas (1987).

Doses of perhaps 5 to 7 kilograys would be required to decontaminate frozen poultry because freezing increases the resistance of some microorganisms to ionizing energy. The nutritional quality and palatability are conserved more effectively if the meat is frozen during exposure to ionizing energy, but the cost of energy treatment is then increased. Where feasible, therefore, it may be economically advantageous to process the prepackaged meat with ionizing energy when chilled and then freeze it for storage and marketing.

Table 3. Resistance of some disease-causing bacteria in red meat and poultry to exposure to ionizing energy (Farkas, 1987)

Genus	Kilograys of ionizing energy required to reduce the number of viable bacteria to one-tenth of the original value
Campylobacter	0.08 - 0.16
Escherichia	0.30 - 0.55
Listeria[a]	0.20 - 1.10
Salmonella	0.31 - 1.30
Staphylococcus	0.34
Streptococcus	0.69 - 1.20
Yersinia	0.04 - 0.21

[a] Stegeman (1988)

Evaluation of Treated Products

In a summary of data derived mostly from research in West Germany and the United Kingdom, Metlitskii et al. (1967) reported that the maximum dose of ionizing energy that could be given to unfrozen chicken meat without perceptible flavor alteration was 18 kilograys. A threshold dose of 7.5 kilograys was obtained in British work (Metlitskii et al., 1967). Sudarmadji and Urbain (1972) reported a threshold dose of 2.5 kilograys for chicken meat and 1.5 kilograys for turkey meat. As would be expected, the strength of the flavor resulting from the method of preparation affects the threshold dose. The relatively low thresholds obtained by Sudarmadji and Urbain were for boiled meat. All these doses were at substerilizing levels.

Table 4 shows the beneficial effects of low temperatures on the color, flavor, and odor of chicken meat sterilized by exposure to 45 kilograys of ionizing energy. Having the meat frozen during exposure was evidently important in preventing the development of an off-odor of the product.

Table 4. Expert panelist ratings of color, flavor, and odor of chicken meat after sterilization with ionizing energy at different temperatures[a] (Wierbicki, 1975)

Temperature during exposure to ionizing energy	Color	Flavor and odor
14.0 to 22.1°F (-10 to - 5.5°C)	↑ Increasingly pinkish	↑ Increasing off-flavor and off-odor
3.2 to 10.4°F (-16 to -12.0°C)		
-7.6 to -4.0°F (-22 to -20.0°C)		↕ Good quality; some off-flavor and off-odor
-23.8 to -22.0°F (-31 to -30.0°C)		
-41.8 to -40.0°F (-41 to -40.0°C)		
-59.8 to -58.0°F (-51 to -50.0°C)	↕ Normal	↕ No off-flavor or off-odor
-77.8 to -76.0°F (-61 to -60.0°C)		

[a] Chicken meat was vacuum packed and sterilized with 45 kilograys of ionizing energy from cobalt-60 at the various temperatures before evaluation by the panelists.

Eggs

A significant percentage of the eggs from *Salmonella*-infected poultry is also infected with this disease-causing bacterium, as has been known for at least 40 years. Morgan and Siu (1957) reported that *Salmonella* could be inactivated in whole eggs and egg magma when exposed unfrozen to 3 to 6 kilograys of ionizing energy. Processing with ionizing energy under these conditions, however, resulted in some deterioration in quality.

In the early 1960s, the U.S. Army's laboratories at Natick, Massachusetts, found that shelled frozen eggs and powdered eggs (used by the baking industry) could be freed of *Salmonella* without significant impairment in quality by treatment with 5 kilograys of ionizing energy. This discovery was not followed by a petition to the Food and Drug Administration to approve the process because of the low interest by the egg and baking industries.

According to a review by Farkas (1987), a dose of 2 kilograys in air would reduce the numbers of *Salmonella* in whole egg powder or egg yolk solids by 100- to 1000-fold without impairing the flavor or functional properties. Treating the products in oxygen-free containers could improve flavor retention and improve the feasibility of the treatment with ionizing energy.

Salmonella-infected eggs have been receiving increasing attention. St. Louis et al. (1988) reviewed outbreaks of salmonellosis traced to infected eggs in northeastern United States. According to the *Boston Globe* for December 8, 1988, the British Junior Health Minister, Edwina Currie, stated that "most British eggs are infected with salmonella bacteria, which can cause food poisoning," and warned the public to "shun raw eggs." This widely publicized statement led to a precipitous drop in egg purchases, economic loss to egg producers, and the resignation of the minister. In the Netherlands, action on a commercial scale to control *Salmonella* is being taken by treating powdered eggs with ionizing energy (see Appendix V, Table V-10).

Red Meats

Marketing and Distribution

Most red meats (beef, pork, lamb) produced in the United States reach the domestic market as fresh products without processing other than chilling and cutting. The time between slaughter and sale at the retail level is generally less than 2 weeks. During this time, the meat is preserved by refrigeration at 30 to 40°F (-1 to 4.5°C). Very little fresh red meat is marketed frozen. Some meat to be used in subsequent processing may be held frozen for long-distance shipment or to meet seasonal demands. Certain meat items may be preserved by canning.

Much of the pork is used to make cured products, such as ham, bacon, and sausage. A small portion of the beef is used to make pastrami and other cured products. Cured meats generally are refrigerated, and vacuum packaging is used to help preserve sausage (e.g., frankfurters), cold cuts, and sliced bacon.

Although it would be more efficient to produce and package retail cuts of meat in packing plants than in retail stores, this shift has not been made with fresh meats because their perishability increases when they are cut into small pieces. The salable life of retail cuts of fresh beef under good refrigeration is no more than 72 hours. The shift of fresh-meat manufacturing operations from the retail store to the packing plant has been taken about as far as current technical and economic conditions permit by the shipment of "boxed" beef instead of "sides" of beef from packing plants to retail stores and by the use of vacuum packing for retail cuts of the more lightly pigmented meats.

Bacterial Contamination and Shelf Life

Meat is preserved by delaying or avoiding spoilage, which is caused largely by the growth of microorganisms and by chemical processes. Chemical spoilage results mostly from the action of atmospheric oxygen on the pigments, causing a change in color, and on the fats, producing rancidity. Another type of change that can be considered spoilage is the exudation of a watery liquid, usually called "drip," which can make a cut of meat unsightly.

Not all aspects of the processes just described constitute health hazards, but the changes are termed spoilage because the affected products fail to meet market requirements. For example, meat showing a color deterioration might be just as palatable and safe as meat with the normal color, but it could be considered "spoiled" in that purchasers would discriminate against it and retailers would lose sales on account of it.

Substerilizing doses of ionizing energy are used to kill most of the contaminating organisms. The use of substerilizing doses to extend the shelf life is analogous to the pasteurization commonly accomplished by heat, and is termed "radurization." The use of substerilizing doses of ionizing energy to inactivate nonspore-forming disease-causing organisms is termed "radicidation." Sterilization of foods with ionizing energy is termed "radappertization."

For veal, pork, and lamb, the first evidence of spoilage is usually the development of odors associated with bacterial activity. The shelf life of these meats may be extended by use of substerilizing doses of ionizing energy to reduce the initial microbial populations. With beef, which is much more strongly pigmented, the first evidence of spoilage is usually a brownish discoloration due to conversion of the surface oxyferromyoglobin (red) to ferrimyoglobin (brown) by atmospheric oxygen (Giddings, 1974). This color change precedes the development of odors resulting from bacterial buildup.

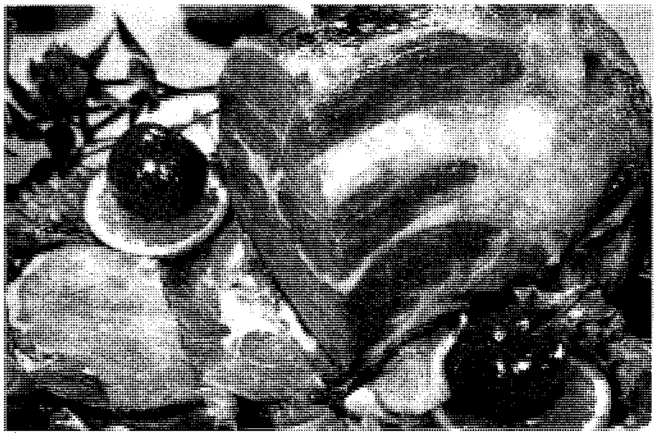
Although substerilizing doses of ionizing energy will control the development of bacteria in beef, as in veal, pork, and lamb, a special technique is needed to deal with the more critical color change. Urbain (1973) described a process in which ionizing energy is used to control both the bacterial buildup and the loss of the red color of freshly cut beef. The retail cuts of beef are treated with condensed phosphates to prevent the loss of fluid and then are wrapped individually in plastic film permeable to oxygen and impermeable to moisture. For processing with ionizing energy, transport, and temporary holding, the individual wrapped cuts are overwrapped with an oxygen-impermeable film or bulk container that is evacuated. With this packaging, lack of oxygen causes the meat to darken temporarily as a result of loss of oxygen from oxymyoglobin to form deoxymyoglobin. The deoxymyoglobin remains in that form until the plastic overwrap is removed about half an hour before the meat is put on display for retail sale. Within the half-hour period, atmospheric oxygen enters the inner wrap and reacts with the deoxymyoglobin to reform the oxymyoglobin that gives beef its pristine red color. After reformation, this color persists for about the same 3-day period as it would if the meat were sold immediately without the market-life extension permitted by the ionizing energy treatment.

Processed chilled meats usually are cooked, cured, or sometimes both cooked and cured before they are offered for sale. Unlike the pigment in fresh meat, which requires oxygen to maintain the normal red or pink color, the pigment in cured meats processed with nitrite (which produces the nitric oxide that binds to myoglobin to form the pigment) is affected by oxygen. For this reason, many cured meats are vacuum packed to exclude atmospheric oxygen. Vacuum packaging also helps control microbial spoilage because most spoilage organisms require oxygen for growth.

Refrigerated vacuum-packed cured meats, such as sliced bacon, frankfurters, and sliced cold cuts, can have a shelf-life as long as 50 days. This time is adequate for distribution with little or no spoilage. As a consequence, little is to be gained by processing these products with ionizing energy. On the other hand, ionizing energy can be advantageous as a substitute for nitrite if attempts are made to reduce the addition of sodium nitrite in the curing process. This subject is addressed later under "Other Applications."

Disease-Causing Bacteria

Human disease caused by *Salmonella* bacteria continues to be an important concern for the red meat industry. Livestock are often infected on the farm by feed containing *Salmonella* or by animal-to-animal contact. Further cross contamination can occur during slaughter and food handling (Silliker and Gabis, 1986). Most of the salmonellosis outbreaks attributed to meats in the United States from 1973 to 1976 occurred primarily as a result of mishandling the meats in homes and food service establishments (Bryan, 1981). Many of the outbreaks resulted from improper cooling, inadequate cooking, or cross contamination from a raw food product, such as meat or poultry.



Ham that had been sterilized with 45 to 56 kilograys of ionizing energy and stored 1 year without refrigeration before baking. Hams that have been rendered shelf-stable by sterilization with ionizing energy have eating quality equivalent to that of hams preserved by refrigeration. Photograph courtesy of Eugen Wierbicki, Eastern Regional Research Center, USDA, Philadelphia.

Other disease-causing bacteria have become important in red meats in recent years (Doyle, 1985, 1986). *Campylobacter jejuni* is found in 3.5 to 8% of the red meat. *Yersinia enterocolitica* has been isolated from swine, but it has not been a major cause of human illness. *Listeria monocytogenes* recently has become a disease-causing organism of major concern. This bacterium has been found in the intestinal tract of cattle, swine, poultry, and sheep. It was found in more than 10% of the healthy cattle tested. A disease-causing strain of *Escherichia coli* has been implicated in two outbreaks involving ground beef. This bacterium has also been isolated from pork chops.

Evaluation of Treated Products

In a summary of research data from various sources, Metlitskii et al. (1967) reported that the maximum doses of ionizing energy that could be absorbed by unfrozen beef and pork without a detectable change in flavor were 9 and 18, respectively. Sudarmadji and Urbain (1972) reported corresponding threshold values of 2.5 and 1.75.

Table 5. Preference ratings made by panelists on ham stored different lengths of time, with and without prior sterilization by exposure to 35 to 44 kilograys of ionizing energy at different temperatures (Josephson, 1967)

Storage before consumption, months	Mean of preference ratings by panelists[a]				
	Products sterilized at indicated temperatures				Unsterilized control
	41°F 5°C	-0.4°F -18°C	-40°F -40°C	-112°F -80°C	
1	—	5.9	5.9	6.8	7.5
1	5.6	6.1	6.4	7.1	6.9
4	5.5	5.8	5.6	6.6	6.1
12	5.4	—	—	6.2	6.9
12	6.1	—	—	6.8	6.4

[a] The number of panelists was 30 for the 1- and 4-month samples and 32 for the 12-month samples. Preference ratings were on a 9-point scale in which 1 = dislike extremely, 5 = neither like nor dislike, and 9 = like extremely.

British work (Metlitskii et al., 1967) yielded a value of 4 kilograys for beef. As mentioned previously, the strength of the flavor associated with the method of preparation of the product for eating affects the threshold value for detecting a difference in flavor due to treatment with ionizing energy. The least flavor is imparted by boiling; this was the method of meat preparation used by Sudarmadji and Urbain, who reported the lowest threshold values.

Considerable research has been done on sterilized products because of the importance of these to the U.S. Army's food research program. In some of the work, a comparison was made with unsterilized products. Results with ham are shown in Table 5. In this experimental work, the preference ratings increased as the temperature during the treatment with ionizing energy decreased. When the treatment was applied at -112°F (-80°C), the preference ratings were about the same for the sterilized products and the unsterilized control. All the products rated above 5 on the 9-point hedonic scale of Peryam and Pilgrim (1957), which is considered the acceptable range.

Table 6 shows preference ratings of round steak that had been sterilized at different temperatures. In this investigation, the ratings of the sterilized products were below that of the unsterilized control, but were still well above 5 at the two lowest temperatures. Additional preference ratings of various meats that had been sterilized with ionizing energy are found in Appendix V, Tables V-12 and V-13. All these evaluations were made by expert taste panels.

Seafood

Consumption of seafood in the United States in 1987 reached 3.7 billion pounds (1.7 billion kilograms), of which about 65% was marketed as fresh and frozen products, 33% was canned, and the remaining 2% was cured (U.S. Department of Commerce, 1988). Seafood is difficult to preserve in the preferred fresh, unfrozen condition long enough to market it in the interior of the country. Consequently, means of limiting the growth of bacteria and extending the shelf life would be of value to both distributors and consumers.

Disease-Causing Organisms

Salmonella, *Staphylococcus*, *Clostridium perfringens*, and *Escherichia coli* often pose a problem, but these bacteria are found mainly in fish caught in contaminated inland

Table 6. Sensory evaluations made by expert panelists on choice top round steak after sterilization at different temperatures by ionizing energy[a] (Wierbicki, 1975)

Temperature during exposure to ionizing energy		Off-color[b]	Off-flavor[b]	Off-texture[b]		Overall preference rating[c]
°F	°C			Mushiness	Friability	
+50	+10	3.9	4.1	2.9	2.9	3.9
-112	-80	2.3	2.1	3.0	2.5	5.8
-292	-180	2.3	1.5	1.6	1.8	6.5
Nonsterilized control		1.2	1.0	1.4	1.4	7.6

[a] Exposed to 45 to 56 kilograys of ionizing energy from cobalt-60.

[b] Evaluations on an intensity scale from 1 = none to 9 = extreme.

[c] Evaluations on a 9-point scale on which 1 = dislike extremely, 5 = neither like or dislike, and 9 = like extremely.

waters or in fish that have been improperly handled and stored. *Vibrio parahaemolyticus* is mainly a problem for those who consume raw fish. *Yersinia enterocolitica* has been isolated from raw seafood. This organism can grow under commonly used refrigeration temperatures and is therefore of concern.

Clostridium botulinum type E requires special attention. It can produce the botulinum toxin at temperatures as low as 38°F (3.3°C). This organism is more resistant to ionizing energy than most of the other spoilage microorganisms in fish (Eklund, 1982). If type E is a potential problem, the usual recommendation is that the dose of ionizing energy be limited to 2.2 kilograys (and sometimes to 1 or 1.5 kilograys, depending upon the type of fish) to assure that other spoilage microorganisms will dominate and will cause the fish to spoil before type E can develop the toxin. As a further precaution, the usual recommendation is that the temperature be kept below 38°F (3.3°C). The same doses of ionizing energy are also adequate to extend significantly the market life of good quality fish.

Vibrio cholera appears to be a part of the normal microflora, but outbreaks usually are due to mishandling the fish. *Shigella* also can be a problem. In a recent outbreak in the Netherlands (Kayser and Mossel, 1984), 14 persons died out of a total of 59 persons affected by bacterial dysentery due to *Shigella flexneri*. Contaminated shrimp apparently were the source of the infections.

Public health problems may also result from disease-causing helminths, such as the fish tapeworm and *Anisakis* in raw herring. The hepatitis virus and other viruses may occur in shellfish from polluted waters.

Paralytic shellfish poison (PSP) sporadically becomes a serious problem in shellfish taken from waters off the coasts of the United States. Ionizing energy at 70 kilograys was found ineffective in activating a purified concentrate of this toxin (Dymsza et al., 1989).

Potential Applications

The principal potential market for seafood processed with ionizing energy is for the products that are sold fresh and frozen. In the United States, restaurants and fast food chains use the major part of the fresh and frozen products.

Shrimp is a very important target seafood for the use of ionizing energy. In 1987, the total U.S. supply was 807 million pounds (366 million kilograms), of which most was marketed frozen (U.S. Department of Commerce, 1988). About three-fourths of the U.S. supply is imported, and many of the imports come from areas where contamination with *Salmonella* is common. The use of ionizing energy to complement good handling practices would help to assure the marketing of shrimp products free of *Salmonella* and other disease-causing organisms. The numbers of the *Salmonella* species studied have been found to be reduced to one ten-millionth of the original count by a dose of 5 kilograys.

Fish fillets and steaks are another prime target market. These products are in high demand. The U.S. supply in 1987 amounted to 898 million pounds (407 million kilograms), of which 69% was imported.

Additional potential applications of ionizing energy to seafood include: (1) reducing bacterial numbers in minced or specialty products, such as surimi, codfish cakes, and frozen frog legs; (2) decontaminating molluscan shellfish as a supplement to cleansing techniques to permit harvesting potentially contaminated shellfish from certain polluted producing areas (approved by Bangladesh, India, the Netherlands, and Thailand); and (3) treating fish products used in animal feed to eliminate *Salmonella* and other undesirable organisms. A specific application of the third use is discussed in the section on "Other Applications."

Research

Research on processing seafood with ionizing energy in the United States began in the early 1960s with support by the Atomic Energy Commission. Most of the work involved substerilizing doses (less than 10 kilograys); however, the Army Research Laboratories at Natick, Massachusetts, conducted research on shrimp and codfish cakes that had received sterilizing doses. The use of substerilizing doses of ionizing energy to eliminate disease-causing organisms from shrimp and to extend the shelf life has been investigated at length in the Netherlands (Mossel and Stegeman, 1985).

The shelf life of fish and shellfish can be extended substantially with substerilizing doses of ionizing energy. For example, Ronsivalli et al. (1969) reported that cod fillets that had absorbed 1.5 kilograys of ionizing energy kept for 36 days at 33°F (0.6°C), whereas the shelf life of comparable untreated fillets at the same temperature was only 15 days. The extension varies with the species used, the dose level, and the quality of the product when treated, as well as the subsequent storage conditions.

Ampola and Ronsivalli (1969) found that the shelf life extension of iced eviscerated haddock processed with ionizing energy decreased with increasing storage time on the fishing vessel before processing. These data suggest that the fish should be treated as soon as feasible after they are caught. Studies of surf clams, haddock, herring, and cod fish showed that the shelf life of these products was doubled or tripled with shipboard processing with ionizing energy

(Carver et al., 1969)[7]. Ehlermann (1981) found that the shelf life of whole eviscerated haddock was extended over that of iced fish when the fish were processed with ionizing energy at sea, but that there was no comparable extension of shelf life of whole red fish.

Work by Liston et al. (1969) showed that a dose of 0.5 kilogray followed 7 days later by 1 kilogray extended the shelf life of eviscerated fresh fish as much as a single-dose treatment of up to 3 kilograys. Splitting the dose of ionizing energy and applying only part on board ship at the time the seafood is caught and the rest after landing thus shows promise as a practical technique for extending the shelf life.

Studies on the commercial feasibility of treating fish fillets with ionizing energy for shelf-life extension and shipping the fillets to distant markets in the United States were carried out by the Gloucester Laboratory of the National Marine Fisheries Service in 1965. These studies were done to investigate the feasibility of preserving seafood with ionizing energy for conditions of commercial shipment. Tests were made on fillets of cod purchased on the open market, treated with low doses of ionizing energy, placed aboard commercial interstate carriers, and sent for evaluation by truck from Gloucester, Massachusetts, to Jacksonville, Florida, and by rail to Seattle, Washington, and the Department of Food Science at Michigan State University. The averages of the marketable shelf life of commercially handled and processed fillets for the shipments of cod as determined by a taste panel were 7 days for the controls and 15 and 18 days for samples processed with ionizing energy at 1 and 2 kilograys, respectively (Ronsivalli et al., 1970).

Evaluation of Treated Products

Table 7 shows the maximum doses of ionizing energy that could be absorbed by various seafoods in contact with atmospheric oxygen while frozen without any detectable deterioration in acceptability of the products. The doses are mostly in the range of 1.5 to 2.5 kilograys, and the associated shelf lives are mostly in the range of 3 to 4 weeks.

Three kilograys was obtained as the threshold value for detection of a change in flavor in British work on "fish" (Metlitskii et al., 1967), and Sudarmadji and Urbain (1972) reported threshold values of 2.5 kilograys for lobster and shrimp, and 4.5 and 5 kilograys for trout and halibut. Relatively high values of 14.4 kilograys for mackerel and 18 kilograys for halibut and pike perch were given by Metlitskii et al. (1967) in a summary of West German data.

Preference ratings obtained for fish fillets in U.S. Army dining hall tests with many evaluators are shown later in Table 10 in the section on acceptability. The results in that table indicate that the treatment with ionizing energy did not seem to have affected the palatability of the products; the differences in ratings between the treated fillets and the frozen controls were small and inconsistent.

Approvals

According to a summary by the International Atomic Energy Agency (IAEA, 1988a) (see Appendix V, Table V-9), the processing of seafood with ionizing energy has been approved by Bangladesh, Brazil, Canada, Chile, India, Netherlands, and Thailand. The approval issued in Canada is for test marketing, and the various approvals issued in the Netherlands since 1970 are provisional or for test marketing.

In the United States, the Food and Drug Administration has approved various uses of ionizing energy in food processing (see Appendix V, Table V-9), including doses suitable for controlling trichinae in pork. A petition has been submitted for the use of ionizing energy to control disease-causing organisms in poultry meat. No regulatory provision has yet been made, however, for processing seafood with ionizing energy in the United States.

Table 7. Optimal dose of ionizing energy for extending the shelf life of fish and shellfish (Slavin et al., 1966)

Product	Optimal dose of ionizing energy, kilograys[a]	Shelf life at 33°F (0.6°C), weeks
Shucked oysters	2.0	3 - 4
Shrimp	1.5	4
Smoked chub	1.0	6
Yellow perch fillets	3.0	4
Petrale sole fillets	2.0	2 - 3
Pacific halibut steaks	2.0	2
Cooked king crab meat	2.0	4 - 6
Cooked dungeness crabmeat	2.0	3 - 6
English sole fillets	2.0 - 3.0	4 - 5
Soft-shell clam meats	4.5	4
Haddock fillets	1.5 - 2.5	3 - 4
Pollock fillets	1.5	4
Cod fillets	1.5	4 - 5
Ocean perch fillets	1.5 - 2.5	4
Mackerel fillets	2.5	4 - 5
Cooked lobster meat	1.5	4

[a] Defined as the maximum dose (with resulting maximum shelf life) that could be absorbed by products packed in air in hermetically sealed cans and treated with ionizing energy while frozen without any deterioration in acceptability of the products that could be detected by taste panels.

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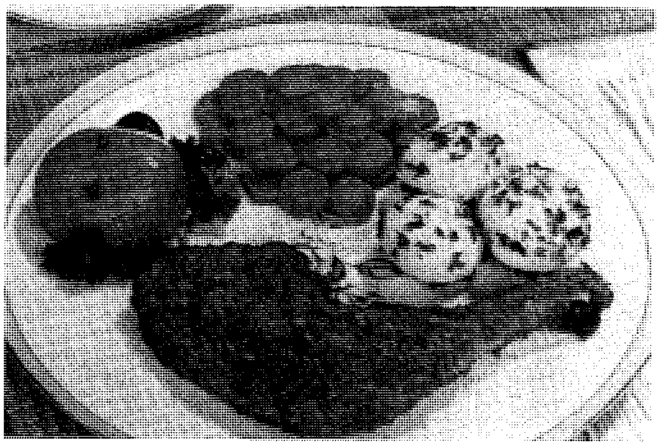
[7] The extension of shelf life by treatment with ionizing energy is the difference in the number of days until spoilage occurs in the processed and comparable unprocessed products when both are kept under refrigeration. The time is counted from the day of processing.

Sterilization

The principal objective of sterilization with ionizing energy is to obtain foods that will keep without refrigeration. The foods are heated to 158 to 176°F (70 to 80°C) to inactivate autolytic enzymes, vacuum packed in sealed metal cans or sealed flexible packages, and exposed to a controlled amount of ionizing energy at a temperature between -58 and +14°F (-50 and -10°C). The dose of ionizing energy must be great enough to assure that regardless of the length or conditions of storage after treatment, no spoilage of biological origin will be detectable as long as the food is not recontaminated by failure of the sealed container.

The technology of sterilizing certain foods by ionizing energy was developed by the U.S. Army at the Quartermaster Food and Container Institute in Chicago from 1953 to 1962 and by the U.S. Army Natick (Massachusetts) Research, Development, and Engineering Center from 1962 to 1980. Comprehensive reviews on the process have been published by Josephson (1983), Josephson et al. (1975), Urbain (1978), and Wierbicki (1981a, 1981b, 1984). Additionally, toxicologic and nutritional studies on chicken meat products sterilized with ionizing energy were conducted by the U.S. Army until October 1980 and were completed by the U.S. Department of Agriculture in 1984. Final reports on these studies were made by Wierbicki (1984), ERRC-ARS (1984), and Thayer and Wierbicki (1985).

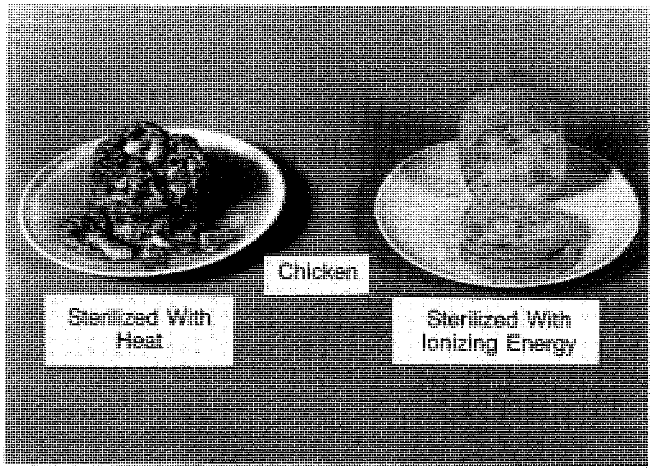
The late Dr. Eugen Wierbicki demonstrating the use of a cookhouse to inactivate autolytic enzymes in beef before sterilization with ionizing energy. Photograph courtesy of Edward S. Josephson, Department of Chemical Engineering, Massachusetts Institute of Technology.



The chicken drumstick shown here had been stored without refrigeration for a year after sterilization with 45 to 56 kilograys of ionizing energy. The potatoes and carrots had received 0.05 to 0.1 kilogray of ionizing energy to inhibit sprouting, and also had been stored for a year after treatment. Photograph courtesy of Eugen Wierbicki, Eastern Regional Research Center, USDA, Philadelphia.

Effects on Foods

The heat applied to sterilize foods during canning changes the character of most foods. For products normally canned, this is not a serious matter in terms of either the sensory or nutritive qualities. With large containers of some products, however, the containers must be heated so long at sterilizing temperatures to achieve sterility of the food in the centers of the containers that the major portion of the product between the center and the walls of the con-



Texture deterioration in chicken roll is more pronounced when sterilization is done by exposure to heat than to ionizing energy. Photograph courtesy of Eugen Wierbicki, Eastern Regional Research Center, USDA, Philadelphia.

Ionizing energy can be used to sterilize whole roasts. The roast pork and the sweet and sour pork illustrated here had been stored for a year without refrigeration after sterilization with 45 to 56 kilograys of ionizing energy. The potato had been stored for a year after treatment with 0.05 to 0.1 kilogray of ionizing energy to inhibit sprouting. Photograph courtesy of Eugen Wierbicki, Eastern Regional Research Center, USDA, Philadelphia.

tainers is overcooked. This problem is of particular concern with solid low-salt low-acid foods, such as meats. The practical consequences are altered flavor, excessive softening and tenderization, and often an undesirable reduction in the nutritional value.

In contrast, sterilization of foods by exposure to ionizing energy is a "cold" process. Even with the large doses of ionizing energy needed for achieving sterility, the product remains frozen, the temperature increases only slightly, and overcooking is consequently not a problem. Moreover, ionizing energy penetrates foods virtually instantaneously and deposits the sterilizing energy more evenly within a short time than does heating. Prepackaged whole roasts, turkeys, and other large cuts of meat that have been precooked (blanched) to inactivate enzymes that otherwise would catalyze self-digestion or softening can be sterilized with ionizing energy for subsequent nonrefrigerated storage (Wierbicki, 1981a, 1981b; Coon et al., 1985). The sensory properties are improved by keeping the products frozen and by excluding atmospheric oxygen during exposure to ionizing energy. This combination of conditions results in better retention of some vitamins, such as thiamin, than does sterilization by heat alone (Josephson, 1983).

Sterilizing meats with heat usually causes the release of a watery fluid, which is undesirable in excess. Sometimes water is added to canned products to assist in heat transfer. No comparable release of liquid occurs when foods are sterilized with ionizing energy, and there is no need for water to transfer the energy to the innermost parts of the food in the containers.

Requirements

Of principal concern in food sterilization is inactivating the spores of the *Clostridium botulinum* bacteria that thrive in nonacid foods in the absence of air and that produce the deadly botulinum toxin. These spores are more resistant to ionizing energy than are most other organisms found in foods (Anellis and Koch, 1962), and doses of ionizing energy ranging from 19 to 61 kilograys (Table 8) are required to inactivate them. Table 8 gives the minimum amounts of ionizing energy needed to reduce the numbers of viable spores of *Clostridium botulinum* types A and B from 10^{12} per container to less than 10^{0} to meet the internationally accepted margin of safety (WHO, 1965). The values differ among foods, and must be determined experimentally for each food.

The doses of ionizing energy that inactivate *Clostridium botulinum* spores also inactivate almost all other organisms associated with meats, poultry, fin fish, and shell fish, including spore-forming and nonspore-forming bacteria, yeasts, molds, and parasites, such as *Trichinella spiralis*, the cause of trichinosis. Only two types of organisms are known to be capable of surviving this dose: certain foodborne viruses (Grecz et al., 1983) and bacteria of the *Moraxella-Acinetobacter* group (Welch and Maxcy, 1975). In practice, these relatively radiation-resistant organisms are not a problem with flesh foods because of the necessity for inactivating the autolytic enzymes that otherwise would catalyze self-digestion of the foods and produce undesirable flavor and texture changes during storage. Heating flesh foods to 158 to 176°F (70 to 80°C) to inactivate autolytic enzymes is an initial step in preparing these foods for sterilization by exposure to ionizing energy. The combination of the preliminary heating and the ionizing

Table 8. Minimum doses of ionizing energy for sterilization of different foods (Wierbicki, 1984)[a]

	Temperature during sterilization		Minimum dose of ionizing energy, kilograys	
Food	°C	°F	Range	Mean
Bacon	5 to 25	41 to 77	26.5 - 28.7	27.6
Beef	-30 ± 10	-22 ± 18	36.4 - 41.2	38.9
Beef	-80 ± 10	-112 ± 18	52.0 - 61.3	57.0
Ham	5 to 25	41 to 77	30.0 - 35.0	32.5
Ham	-30 ± 10	-22 ± 18	32.0 - 38.0	35.0
Codfish cake	-30 ± 10	-22 ± 18	30.4 - 32.4	31.7
Corned beef	-30 ± 10	-22 ± 18	24.4 - 25.7	25.1
Pork sausage	-30 ± 10	-22 ± 18	23.9 - 26.5	25.2
Shrimp	-30 ± 10	-22 ± 18	19.9 - 51.2	37.2
Pork	5 to 25	41 to 77	41.9 - 49.9	45.6
Pork	-30 ± 10	-22 ± 18	43.7 - 44.8	44.3
Chicken	-30 ± 10	-22 ± 18	43.4 - 46.2	44.8
Chicken[b]	-30 ± 10	-22 ± 18	42.7 - 47.8	43.9

[a] Summarized from published sources.

[b] Chicken meat with 0.75% sodium chloride and 0.3% sodium tripolyphosphate as additives.

energy inactivates the relatively resistant organisms, so that the treated foods are truly sterile.

The minimum dose values in Table 8 are at least 10 to 15 kilograys higher than the actual dose needed to inactivate the most resistant strains of *Clostridium botulinum* bacteria (Anellis et al., 1977, 1979). Thus, they provide an ample margin of microbiological safety. The incidence of spores of *Clostridium botulinum* in poultry and meat is normally very low (Greenberg et al., 1966). A dose of 10 kilograys of ionizing energy has been found to result in sterile ham (Anellis et al., 1967), bacon (Rowley et al., 1983), and chicken (Wierbicki, 1984).

Energy Costs

Some energy saving in food processing can be realized with foods that are sterilized by ionizing energy and stored without refrigeration. Flesh foods and other foods that must receive preliminary heating to inactivate autolytic enzymes for extended storage stability at room temperature are "ready to eat." The total processing energy used per kilogram of boneless meat is about 4,000 kilocalories for meat sterilized with ionizing energy, 8,300 kilocalories for heat-sterilized meat, and 12,800 kilocalories for freeze-dried meat (Brynjolfsson, 1978) (energy usage of 4,000 kilocalories per kilogram is equivalent to 16.7 megajoules per kilogram or 7,200 British thermal units per pound).

Other Applications

Hospital Patients

Foods sterilized with ionizing energy are of value in the diets of certain hospital patients. Patients whose immune responses have been suppressed by AIDS or other diseases or by special treatment, as for organ transplants or cancer chemotherapy, are very susceptible to bacterial infections. Foods sterilized by ionizing energy reduce the exposure to bacteria, while making possible a greater variety of foods and better patient acceptance than is true for heat-sterilized foods (Josephson, 1983).

Substitution for Nitrite in Meat Curing

Nitrite is used in combination with salt and other substances in bacon, ham, and certain other meat products in a curing process that imparts a characteristic color and flavor, reduces oxidative changes, and retards the growth of microorganisms, including *Clostridium botulinum*. The discovery that the addition of nitrite may lead to the formation of nitrosamines, a number of which have been found to be animal carcinogens, brought into question the safety of this traditional method of meat curing.

Exposure of meat to ionizing energy at proper dose levels provides protection against the outgrowth of *Clostridium botulinum* bacteria from spores that may be present and against the production of the toxin that causes botulism. Treating meat products with ionizing energy without cooking the meat, therefore, has been viewed as a possible substitute for part or all of the nitrite normally used.

In the United States, research on ionizing energy as a substitute for nitrite was conducted in the U.S. Army's laboratories at Natick, Massachusetts, from 1973 to 1980. The products investigated were ham (Wierbicki and Heiligman, 1973), corned beef (Shults et al., 1977), frankfurters (Terrell et al., 1981), and bacon (Wierbicki, 1979; Wierbicki and Heiligman, 1981). The results obtained are summarized in Table 9.

The U.S. Army studies at Natick, continued at the Eastern Regional Research Center of the U.S. Department of Agriculture in Philadelphia since 1980, showed that when vacuum packed bacon without added nitrite is treated with ionizing energy, a pink color similar to that of commercial bacon results; however, the color changes to brown upon frying. But when only 20 to 40 parts of sodium nitrite per million are added instead of the 120 parts added during commercial processing, the fried product has the same stable characteristic color as commercial bacon. Addition of nitrite is not required to provide the odor and the dominant salty, smoky flavor of fried bacon (but it is required for ham and frankfurters). Absorption of 7.5 to 10 kilograys of ionizing energy at 41°F (5°C) destroys the indigenous bacteria in bacon, and absorption of 12 to 15 kilograys provides protection against *Clostridium botulinum* that is equivalent to or better than that provided by the sodium nitrite concentration of 120 parts per million in commercially produced bacon (Wierbicki, 1979; Wierbicki and Heiligman, 1981; Rowley and Brynjolfsson, 1980; Rowley et al., 1983).

Research has been conducted at the Eastern Regional Research Center to determine whether treating vacuum packed bacon with doses of ionizing energy lower than 7.5 kilograys compromises the microbiological safety of the product. Such doses are too low to reduce a theoretical population of 1 trillion *Clostridium botulinum* spores per container to one viable spore or less, but they are high enough to kill the lactic acid producing bacteria that might provide a warning against any *Clostridium botulinum* growth and toxin production (Rowley et al., 1983). Substerilizing doses of the order of 6 to 8 kilograys led to increased spoilage of ham (Anellis et al., 1967) and corned beef (Anellis et al., 1972) inoculated with *Clostridium botu-*

Table 9. Quality of meats with different additions of sodium nitrite and sterilizing doses of ionizing energy

Product	Maximum addition of sodium nitrite used commercially, PPM	Products treated experimentally with ionizing energy[a]	
		Sodum nitrite used experimentally, PPM	Product quality
Bacon[b]	120	None	Slightly different color
		20-40	Color, flavor, and taste like commercial bacon
Ham[c]	156	None	Texture excellent, different color and flavor
		25	Color stabilized with uniform distribution of sodium nitrite but faded with nonuniform distribution
Corned beef[d]	156	None	Color different, otherwise acceptable
		50	Same as commercial product if sodium nitrite is uniformly distributed
Frankfurters[e]	100	None	Acceptable, different flavor and color
		50	Same as commercial product

[a] All products were vacuum packed and treated with ionizing energy at -22 ± 18°F (-20 ± 10°C). Doses of ionizing energy supplied as accelerated electrons or gamma rays from cobalt-60 were 26 kilograys for corned beef, 30 kilograys for bacon, and 32 kilograys for ham and frankfurters.

[b] Wierbicki, 1979; Wierbicki and Heiligman, 1981.

[c] Wierbicki and Heiligman, 1973.

[d] Shults et al., 1977.

[e] Terrell et al., 1981.

linum.

In other work done by the U.S. Army at the Natick Laboratories, no confirmable concentrations of volatile nitrosamines were detected in ham and corned beef that had been treated with ionizing energy. In bacon that had been preserved by absorption of 30 kilograys of gamma rays from cobalt-60 at -22 ± 18°F (-30 ± 10°C), neither N-nitrosodimethylamine nor N-nitrosopyrrolidine could be detected, and the added nitrite (from sodium nitrite at 20 and 120 parts per million) was destroyed. Moreover, when these nitrosamines were added to meats, significant amounts were destroyed during treatment with ionizing energy (Fiddler et al., 1981).

On the basis of the foregoing findings, the National Research Council recommended the use of ionizing energy as either a complete or partial substitute for the antibacterial activity of nitrite in processed foods (McCarty et al., 1982). The use of 7.5 to 30 kilograys of ionizing energy at 41°F (5°C) as a possible means of reducing the addition of sodium nitrite below 40 parts per million in vacuum packed bacon has been investigated at the Eastern Regional Research Center.

Except for bacon, little research has been done on processing of cured meats for refrigerated storage with doses of ionizing energy below 10 kilograys as a possible substitute for part or all of the nitrite. Further research is needed to establish the optimal doses of ionizing energy to assure adequate protection against harmful and spoilage microorganisms, extend the shelf-life, and produce products of acceptable quality.

Quality Improvement

The principal direct applications of ionizing energy to foods are in preserving foods and increasing food safety by either eliminating spoilage and disease-causing organisms or decreasing their numbers. Ionizing energy has other effects on foods, however. One of these is to break some of the large molecules, such as those of cellulose, starch, pectins, and proteins, into smaller units. The general result is to make foods less firm. For example, the softening of fresh fruits and vegetables at high doses is considered undesirable. Other effects may be perceived as quality improvements.

Dried soup mixes often have dehydrated vegetables as components, and the rehydration time may be longer than desired and may be greater with some vegetables than others. Processing dehydrated vegetables with ionizing energy can reduce the molecular size of the carbohydrate components and shorten the hydration time. If desired, the dose could be adjusted for the individual components so all would have the same rehydration time. Similarly, the cooking time of such products as dried beans can be reduced by exposure to ionizing energy.

Processing wheat flour with ionizing energy tends to increase the size of loaves of bread produced using the flour if the dough contains little or no added sugar, and it decreases the size if the dough is relatively rich in sugar. These effects result from alterations of both the starch and protein fractions of the flour.

Ionizing energy significantly increases the yield of juice from grapes without affecting the wine-making quality, and it increases the rate of drying of fruits, such as prunes. These effects may be a consequence of the action of ionizing energy in splitting some of the molecules of cellulose, hemicellulose, and pectins in the cell walls.

Meat is tenderized to some extent by exposure to sub-sterilizing doses of ionizing energy for shelf-life extension, mainly because microorganisms are inhibited, while the action of protein-splitting enzymes continues. Ionizing energy thus is of potential value in tenderizing range-fed beef, which has the advantage of low fat content, but tends to be tougher than beef from feedlot cattle. Where meat is sterilized for extended storage without refrigeration, the preliminary heat treatment necessary to inactivate autolytic enzymes stops the enzyme action, but the relatively high doses of ionizing energy then exert a direct tenderizing effect by splitting some of the molecules of the proteins, including collagen. Collagen is a principal constituent of connective tissue, which contributes to the toughness of meat.

Several applications involving the control of biological processes have been devised to secure a benefit. Treating bulb, tuber, and root crops with ionizing energy to inhibit sprouting has already been mentioned. Treating dry barley with ionizing energy reduces the amount of barley needed in beer production by reducing the sprout length and thus increasing the yield of the malted grain. A second application is treatment of beans to reduce flatulence. Beans contain oligosaccharides (carbohydrates with small numbers of sugar units) that are not digested in the human stomach or small intestine, but pass through to the large intestine. In the large intestine, they are decomposed by bacteria, with production of gas. When beans germinate, the oligosaccharides are consumed. Uncontrolled germination, however, makes the beans unacceptable for food uses. If the beans are exposed to ionizing energy after a long enough period of germination to reduce the oligosaccharide content, but less than that required to damage the beans, the germination process is arrested, and beans of improved quality for food are obtained. Heat has a similar effect, but causes excessive damage to the beans. Other potential applications no doubt remain to be discovered.

Animal Food or Feed

Processing of animal food or feed with ionizing energy is an application of potential importance. Disease-causing organisms carried by animals used as pets and by animals used as sources of human food are responsible for some human infections, and contaminated feed is a source from which the animals are infected with some of the organisms. Appropriate treatment of the feed with ionizing energy could reduce human infections by reducing the feedborne infections of the animals, with additional benefits to the animals themselves. There are other benefits for laboratory animals used in research. Twelve papers were published by the International Atomic Energy Agency (IAEA, 1968) on eliminating harmful organisms from food and feed by use of ionizing energy.

Pet Food

Little work on pet food as such has been reported, but ionizing energy may be useful for sterilizing these products. Pets do not object to the off-flavors that result from the use of high doses of ionizing energy on moist unfrozen flesh foods, which makes possible an economy in processing.

For periods up to 3 years, thousands of beagle dogs were fed diets containing a broad spectrum of foods that had been treated with ionizing energy. The treated foods supplied 35% of the daily caloric intake. This testing, done between 1950 and 1983 in connection with toxicologic experiments to assess the safety for human consumption of food treated with ionizing energy, disclosed no ill effects that could be attributed to the treatment with ionizing energy.

Ley (1972) noted that in the United Kingdom there have been problems with contaminated raw meat, such as horse meat, kangaroo meat, and offal from various sources, in pet food. Treating these products with ionizing energy reduces the possible cross contamination of human food and reduces the possibility that human infections will be acquired from the pets. Ionizing energy has a competitive edge over heat treatment for this purpose in that the demand is for raw meat, not cooked meat, and the raw meat, which is imported frozen, can be treated with ionizing energy while frozen. According to Ley, cooking results in financial loss to the trade because of the associated water loss.

Ley (1972) reported that doses of ionizing energy of 5 to 7.5 kilograys reduce the population of the most radiation-resistant *Salmonella* types in meats by a factor of 100,000 to 10 million. He noted that if the treatments were applied before freezing at the point of export, the same effects could be achieved with only half the doses mentioned. He reported no increase in radiation resistance or change in ecological properties of the *Salmonella* after three cycles of irradiation and culturing the organisms, although some biochemical changes in the organisms were detected. He considered the process economically feasible. At that time, the processing cost in British currency was estimated at 0.5 to 1.5 pence per pound for a processing plant with 600,000 curies of cobalt-60 and a 13,000 ton annual throughput.

In the United States, considerable interest was expressed in the 1960s in pet food sterilized with ionizing energy. At that time, Allen Products Company (Alpo), a major pet food producer, was a member of IRRADCO, Inc. IRRADCO was a consortium of companies that had a contract with the U.S. Atomic Energy Commission to build and operate a pilot plant in Allentown, Pennsylvania, to produce a line of shelf-stable meat products using ionizing energy. Alpo's interest was in the nutritional quality and better acceptance by pets of the products sterilized with ionizing energy over the company's commercially available heat-sterilized products, and the additional advantage of shipping the dry-packed, 100% edible meat in cans or flexible pouches.

The projected hygienic and processing standards were to be the same as those for meats sterilized with ionizing energy for human consumption (which would be processed in the same facility) to provide for the possibility that some humans might choose to eat the pet foods. Because approvals by FDA and USDA for the sterilized foods did not appear imminent, the pilot plant meat irradiator was not built. More information on the interest by IRRADCO was published by the U.S. Congressional Joint Committee on Atomic Energy (JCAE, 1968).

Tsuji (1983) called attention to the need to eliminate microbial contamination in raw materials used to prepare animal health products for pets. In making his case, he noted that 6.6% of the fish powder imported from Iraq for use as a flavoring agent in vitamin-rich nutritional supplements for dogs and cats was contaminated with *Salmonella.* He pointed out that eliminating the *Salmonella* contamination by heat would be damaging in some instances if the heat were applied to the formulated products, which would be the most desirable stage for the treatment because then the treatment would control possible contamination from all sources through the completion of processing. Ethylene oxide, propylene oxide, and formaldehyde are unacceptable because of problems of penetration and toxic residues. Filtration is limited to some liquid preparations. And aseptic crystallization is too costly and less reliable than terminal sterilization of the product. Ionizing energy, however, may be used effectively and economically.

Tsuji noted that a minimum dose of 5 kilograys reduces the total microbial count (including the count of spore forming organisms) to less than one thousandth of the initial value. This dose reduces the count of vegetative organisms, including those designated by the *U.S. Pharmacopoeia* as pathogens, to less than one ten-billionth of the initial count.

Farm Animal Feed

Dougherty (1976) found in a study of a flock of 4,000 chickens that the two *Salmonella* species isolated from the chickens corresponded to those isolated from the feed, litter, and water. In a similar study on a second flock of the same size, there was little correlation between the *Salmonella* species isolated from the chickens and those found in the feed, litter, and water.

Ellis (1969) noted that "animal by-products seem to be the most often incriminated vehicle" for contaminating animal feeds with *Salmonella.* His analysis was supported by panels of experts assembled at the request of the U.S. Interdepartmental Committee on Radiation Preservation of Food. They paid special attention to the need to control *Salmonella* derived from animal protein sources (fish, swine, cattle, and poultry). They stated in their report (ICRPF, 1978) that "Of all the factors involved in the perpetuation of salmonellae in domestic animals, contaminated animal feed probably has the greatest impact. This is particularly true in the U.S. where purchased rations and high-density rearing methods characterize the majority of our production systems for meat and poultry. The potential for wide geographical dissemination of salmonellae via animal feed is enormous. In numerous instances this dissemination has been documented to be international in scope. To date no economical, highly effective measure is available to control this problem."

The panels then recommended 5 to 10 kilograys of ionizing energy to eliminate *Salmonella* from feeds. They stated that, when commercial application begins, "regulatory agencies could easily mandate *Salmonella*-free animal feeds" (ICRPF, 1978). In the same report, reference was made to animal feeding studies conducted on several generations of hogs in the Netherlands, which "demonstrated that even completely irradiation sterilized (4.5 megarads [45 kilograys]) hog breeding and fattening rations performed as efficiently as nonirradiated control rations and were superior to thermally sterilized rations. Based on this information, supplemented with excellent performance of small laboratory animals on irradiation-sterilized feeds, additional wholesomeness (animal feeding) studies would not be needed for approval" to use doses within the range of 5 to 10 kilograys to treat animal feeds.

Ley (1972) described the successful use of ionizing energy to control pathogens, such as *Salmonella*, in feedstuffs, including meat, bone, fish meals, and pelleted feeds. Although the temperature of 176 to 183°F (80 to 84°C) that develops at the cores of pellets during pelleting would be enough to pasteurize the products, recontamination may occur. Ley suggested using heat in pelleting for primary decontamination, followed by treating the bagged products with 2 kilograys of ionizing energy as a secondary measure.

In the same report, Ley noted that the Danish requirement to heat feed for 45 minutes at 257°F (125°C) to control anthrax compromises the nutritional quality. He mentioned that exposure of feed to 13 kilograys of ionizing energy decreases the population of *Bacillus anthracis* bacteria by a factor of 10 million and pointed out that Australia uses a dose of 20 kilograys to eliminate viable anthrax spores from goat hair used in carpet manufacture. In the absence of any demonstrated toxic effects due to the ionizing energy used to process animal feeds, Ley (1972) concluded that (1) 8 kilograys effectively control the Enterobacteriaceae, including *Salmonella*, in meals, (2) 20 kilograys effectively control anthrax spores, (3) using ionizing energy is better than using heat from the standpoint of the nutritional value of the protein, and (4) for products pelleted with heat, processing the final bagged product with ionizing energy is an appropriate adjunct.

Saint-Lèbe (1972) pointed to the need for decontaminating mixtures of constituents extracted from traditional agricultural products that are used for animal feed on the basis that the multiplicity of sources and the several steps in processing would increase the risk that the final products will be contaminated. Exposing food to ionizing energy is a simple, inexpensive process that can be applied to the products after packaging to eliminate the contaminating organisms.

Josephson et al. (1975) proposed the use of 5 to 10 kilograys of ionizing energy on animal feeds to eliminate the *Salmonella* contained in these products and to prevent them from serving as possible sources of contamination for the milk, eggs, poultry meat, and red meats consumed by humans. Frozen blocks of animal feed can be readily treated with ionizing energy without the need for thawing required by other methods for disinfecting the products.

As a specific example, a major commodity exported from Chile to Western Europe, Mainland China, Japan, and North America is fish meal for use in animal feeds. Some batches of the meal are contaminated with *Salmonella* and *Shigella* bacteria and *Dermestes* insects. To prevent spontaneous combustion during transport by ship, the meal is treated with an antioxidant and spread out to equilibrate in the open in the desert environment of northern Chile for 20 to 30 days before it is ready for loading. During the equilibration period, the meal is vulnerable to contamination from seagull droppings, rodent feces and urine, humans walking on the meal to stir it with shovels for ventilation, and *Dermestes*. The economics of producing a low cost product preclude constructing storage facilities to exclude the sources of contamination.

At the request of the Chilean Government, the International Atomic Energy Agency provided technical assistance in 1982, 1983, and 1984. In the final report to the government of Chile via the International Atomic Energy Agency, Josephson (1984) recommended bagging the fish meal with antioxidant in air-permeable bags for the 20 to 30-day equilibration period, then overwrapping these bags with air- and moisture-impermeable bags impregnated with insect repellent to prevent subsequent contamination by *Dermestes*. The doubly bagged fish meal would be processed with a dose of ionizing energy sufficient to eliminate the *Dermestes* and *Salmonella*, and the product could be stored safely until time for loading. The meal then could be emptied from the bags to provide for rapid loading in the holds of ships, and the bags could be saved for reuse.

In making the foregoing recommendation, Josephson drew on earlier work by Dammers et al. (1966), in which it was reported that neither processing with 10 kilograys of ionizing energy nor decontamination by heating the products to 176 to 185°F (80 to 85°C) for 30 minutes had any significant adverse effect on the nutritional value of the meals tested. Feces of pigs that had been fed the meal after processing with ionizing energy or heat were free of *Salmonella* throughout a test period of 100 days in one experiment and 155 days in another.

Laboratory Animal Diets

Many laboratory animals, particularly rats and mice, are housed and maintained under controlled environmental conditions to keep them free of disease agents. Animals protected from specific pathogens are said to be "specific pathogen free." In some countries, a relatively small number of laboratory animals are maintained in "germ free" condition and require sterile diets (Ley, 1979). The absence of all microorganisms permits long-term studies on nutrition uncomplicated by microorganisms, as well as studies of the contributions of microbial flora to nutrition. With specific-pathogen-free animals, the effects of administration of experimental materials can be investigated without complications from diseases caused by infections (Ley, 1972).

Ionizing energy is becoming increasingly the preferred method for processing laboratory animal diets over heat and ethylene oxide because the products can be treated in the final sealed plastic, cardboard, or metal packages. Nutritional quality is maintained, the products are acceptable to the animals, there are no toxic residues, and there is no problem of penetration. Ley's (1979) recommended dose of ionizing energy for diets for germ-free animals is 50 kilograys. For specific-pathogen-free animals, a dose of 25 kilograys has been found satisfactory.

Ley (1972, 1975, 1979) reported on the successful use of ionizing energy to provide diets for both specific-pathogen-free and germ-free laboratory animals in the United Kingdom. He said (Ley, 1979) that use of diets processed with ionizing energy in the United Kingdom had grown to 1200 metric tons per year by 1979, whereas in the Netherlands, West Germany, France, and Denmark about 100 metric tons were fed per year. He noted that no problem with toxicity or nutritional quality had been encountered at the 25 kilogray dose, but that there may be some loss of vitamins A, E, B_1, and B_6 at 50 kilograys. The amino acids, however, are stable to even 70 kilograys. No fortification of the diets is needed because they can be formulated before processing to contain the desired concentrations of nutrients. The animals prefer diets sterilized by ionizing energy over those sterilized by autoclaving. He reported that poultry feed treated with 10 kilograys of ionizing energy could be used to provide eggs suitable for producing vaccines free of *Salmonella* and other foodborne pathogens. He stated that a 10-kilogray dose controls infectious agents and insects in laboratory animal feed.

For processing with ionizing energy, Ley (1972, 1979) recommended bagging the feed in heavy (1000-gauge) polyethylene bags in 14- or 28-pound quantities and sealing the bags under vacuum. Each of the filled bags is then overwrapped in another evacuated heat-sealed polyethylene bag and placed in a cardboard carton, which is subjected to ionizing energy after sealing with tape. At the barrier to the animal colony, the carton and outer bag are removed, and the inner bag and contents are dipped in a tank of disinfectant. The vacuum pack helps reveal whether any leaks have occurred in the inner bag.

Ley (1972) reported that the rat colony at the Wantage Research Laboratory of the United Kingdom's Atomic Energy Agency had been successfully maintained for 5 years upon diets treated with ionizing energy. During that time, more than 600 litters were raised, and 4,000 animals remained in the colony. Similar results were obtained with the mouse colony. In the same report, it was stated that the vaccinia virus was inactivated with a dose of 25 kilograys. Spores of fowl coccidia were mixed with feces, given 25 kilograys of ionizing energy, and fed to chickens, but no viable spores remained after treatment.

In 1986, the U.S. Food and Drug Administration (FDA, 1986) approved a Ralston Purina petition calling for "microbial disinfection" of complete laboratory animal (mice, rats, and hamsters) diets at doses up to 25 kilograys employing cobalt-60, cesium-137, or accelerated electrons at energies up to 10 million electron volts. Ralston Purina subsequently began marketing a line of these sterilized diets.

Combinations of Processes

Treating some foods with ionizing energy alone may not produce the desired result. Examples of such situations are: (1) The dose of ionizing energy required to produce a specific desired effect may produce other unacceptable changes in the food. (2) Ionizing energy alone does not produce the desired effect. (3) Applying the dose required to produce the desired effect is too expensive. In such situations, a combination of processes in which ionizing energy is used along with some other treatment may produce the desired results. A number of potentially useful combinations of processes have been developed. These combinations are discussed individually at other places in this report, but they are summarized here for emphasis.

Treatments with ionizing energy in combination with refrigeration are especially valuable. Ionizing energy at substerilizing doses adds to the preservative effect of refrigeration on flesh foods, and the combination of processes is better than either process used alone. Ionizing energy would not be effective alone because more than microbiological spoilage (for example, autolysis and oxidation) is involved in the deterioration of these foods.

Heat in combination with ionizing energy reduces the required dose of ionizing energy in some instances. For example, the autolytic enzymes in meats are not inactivated completely even with doses of ionizing energy as great as 200 kilograys -- a dose approximately five times greater than that needed to produce sterile products.) But heating meats to 158 to 176°F (70 to 80°C) inactivates the enzymes and avoids the need for the very high doses of ionizing energy.

For fruits such as papayas, the control of spoilage fungi requires doses of ionizing energy great enough to damage the fruit, but dipping the fruit in water at 127°F (53°C) for 1 minute can inactivate the fungi. Ionizing energy may be needed, however, to disinfest fruits of insects. Doses of ionizing energy effective for this purpose are only about one-tenth of those needed to inactivate fungi, and these doses do not damage most kinds of fruits. The combination of heat and ionizing energy may rid fruits of both classes of pests.

All foods can be sterilized by subjecting them to sufficiently great doses of either heat or ionizing energy. With some foods, however, an acceptable product can be produced and the requirement for both heat and ionizing energy can be reduced by applying the ionizing energy treatment at temperatures above 194°F (90°C).

Another treatment that can be used to advantage in combination with ionizing energy for some foods is heating to 158 to 176°F (70 to 80°C) to inactivate autolytic enzymes, viruses, and the *Moraxella-Acinetobacter* group of bacteria, followed by freezing and treatment with ionizing energy. This combination is particularly useful for flesh foods that develop off-flavors and off-odors when given high doses of ionizing energy at temperatures above freezing.

Vacuum packaging is advantageous in preserving some foods because atmospheric oxygen is required for the growth of some spoilage organisms. Moreover, oxygen interacts chemically with some constituents in foods, notably fats, causing oxidation and off-flavors. Treatment of certain foods with ionizing energy is of value in reducing the numbers of spoilage organisms, but when done in the presence of atmospheric oxygen, it increases the reactivity of the oxygen and hastens the development of off-flavors in foods that are prone to this problem. Vacuum packaging avoids the oxygen problem and reduces the dose of ionizing energy required.

Reducing the water content of foods or the "activity" of the water is another way of inhibiting the multiplication of microorganisms. High concentrations of sugar or salt, as in fruit jellies or salted fish, reduce the activity of water and its availability to microorganisms, and have a preservative effect similar to drying. In some instances, ionizing energy can be used in combination with decreased water content or reduced water activity to preserve food with benefits in terms of both quality and economics. The preservation of partially dried shrimp with ionizing energy is an example.

Certain chemicals can also be used to advantage in combination with ionizing energy. Salt has been mentioned for its effect in reducing the activity of water. Nitrite has been mentioned for its effect in preventing spores of *Clostridium botulinum* bacteria from developing into actively multiplying vegetative cells that produce the botulinum toxin. Carbon dioxide, which increases the acidity of foods, produces a similar result because *Clostridium botulinum* bacteria cannot produce the toxin when food is sufficiently acid (pH below 4.5).

12. Packaging

Foods processed with ionizing energy, as with those processed by well established methods, may require suitable packaging. Because packaging materials could be a source of undesirable food contaminants, Food and Drug Administration approval must be obtained for packaging materials that come in contact with food when it is being exposed to ionizing energy. To obtain approval, the petitioner must provide data demonstrating that the packaging will maintain satisfactory hygienic and nutritional qualities of the food and will not create new hazards as a consequence of migration of substances from the packaging into the food. The petition must indicate the nature, amounts, and possible toxicologic significance of any migrating substances.

Additionally, the packaging must resist possible injurious effects of the food. For example, salty and acid foods might corrode metallic packaging materials. Fatty foods conceivably could penetrate the inner plastic layer of aluminum foil laminates, resulting in separation of the plastic layer from the aluminum.

During the 1950s and 1960s, the U.S. Army and the U.S. Atomic Energy Commission systematically studied a number of plastic materials for their suitability as packaging. Materials already approved and widely used for commercial food packaging were tested first. New experimental materials were evaluated only if the commercially available materials did not perform satisfactorily.

Tinplated Cans

Tinplated cans have been used successfully for more than a century for sterilizing foods at high temperatures and pressures. To investigate the suitability of cans for sterilizing foods with ionizing energy at low temperatures and high vacuums, Killoran and coworkers (1974) exposed eight different enamels coated on tinplated panels, two tinplates, three end-sealing compounds, and the side-seam solder to 30 to 75 kilograys of ionizing energy from cobalt-60 gamma rays at 41, -22, and -130°F (5, -30, and -90°C). The components used successfully are listed in Appendix V, Table V-6.

Pure tin is converted from the silver beta form to the powdery alpha form below a temperature of 64°F (18°C). The possibility existed, therefore, that exposure to ionizing energy at low temperatures would favor this conversion, with the result that the tin coating would not protect the underlying steel. Fortunately, traces of impurities in the tin retard the conversion. The combination of ionizing energy and low temperature had no demonstrable adverse effect on the properties of the tinplate and side-seam solder (Killoran, 1983).

Of the eight enamels assessed for suitability as liners of tinplated containers, the two best ones were the epoxy-phenolic enamel and the epoxy-wax enamel, both with aluminum pigment (Killoran, 1983). These enamels had the best flexibility at -130°F (-90°C). Adhesion to the tinplate was satisfactory for all the enamels studied. Of the three end-sealing compounds tested by Killoran (1974), the one preferred for use with sterilizing doses of ionizing energy at very low temperatures was the blend of cured and uncured isobutylene-isoprene copolymer.

Tests of the possible release of substances from the cans into foods were made under exaggerated conditions using water, acetic acid at pH 3.5, and n-heptane as solvents to simulate high water content, acidity, and fat content, respectively. Gamma rays were used at doses up to 71 kilograys. The results showed that the epoxy-phenolic enamel and the blend of cured and uncured butyl rubber used as an end-sealing compound released only insignificant amounts of substances to the solvents contained in the cans. This work was done at the U.S. Army's laboratories at Natick, Massachusetts.

The reliability of the tinplated cans, coated inside and striped at the inside seam with epoxy-phenolic enamel and end-sealed with a blend of cured and uncured isobutylene-isoprene copolymer, was assessed between 1971 and 1979, also at the U.S. Army's laboratories at Natick, Massachusetts. After preliminary heat treatment to inactivate autolytic enzymes, quantities of beef, chicken, pork, and ham were sealed in separate cans under high vacuum. The sealed cans with contents were cooled to -40°F (-40°C) and treated at that temperature with doses of ionizing energy between 47 and 71 kilograys. The cans then were thawed, shipped more than 1,000 miles (1,700 kilometers) by truck, and stored 2 years at room temperature, with inspections at intervals. Of the 127,000 cans included in the test, only 0.02% were defective. Details of the tests for reliability were published by Killoran et al. (1979b). Killoran (1983) concluded that according to the standards and testing procedures established by the National Canners Association and the Food Processors Institute, the commercial tinplated can is acceptable for the foods and conditions tested.

Flexible Packaging Materials

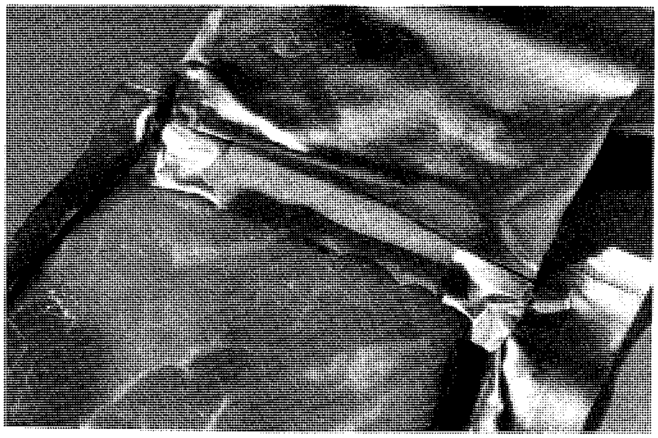
A number of single and multilayered flexible packaging materials were evaluated during the 1960s and 1970s by the U.S. Army and the U.S. Atomic Energy Commission. Tests for extractable substances were made with the same water, acetic acid, and n-heptane solvents employed in the studies with metal cans, and additional tests were made with various foods, all sealed in flexible pouches. Doses of ionizing energy ranged from 0 to 80 kilograys. As a result of the data submitted to the Food and Drug Administration on the performance of the various packaging materials, the agency approved the use of the materials listed in Appendix V, Table V-7 (Anonymous, 1988).

Because sterility is not the objective of processing foods with doses of ionizing energy below 10 kilograys, single-layer plastic packaging generally suffices for such uses. Urbain (1973), however, described a double-layer plastic packaging arrangement for extending the shelf life of beef, as described previously in the section on "Bacterial Contamination and Shelf Life" under "Red Meat." Another application of double wrapping by Josephson (1984) was described previously in the section on "Farm Animal Feed."

Since the Atomic Energy Commission began to phase out its research and development work on processing foods with ionizing energy in 1969, very little has been published on the use of plastic films for packaging foods at doses up to 10 kilograys. Because of the increased use of plastic films for food packaging since that time and the increasing numbers of approvals in the United States and abroad for foods processed with ionizing energy, research to investigate the suitability of the new films for packaging is in order.

Single-layer plastic packaging does not provide adequate protection to sterilized foods from microbial recontamination, insect penetration, and deleterious effects of light, oxygen, moisture, and rough handling during long-term storage without refrigeration. The FDA-approved plastic films provided a starting point for research to develop flexible multilayered plastic-foil laminates suitable for packaging sterilized foods.

Light-weight, inexpensive, flexible packaging for foods that would have long shelf-life without refrigeration was considered by the U.S. Army to be important for feeding military personnel anywhere in the world, and between 1953 and 1980, the Army researched the development of such foods and the packaging to contain them. The general procedure developed was (a) to trim away inedible portions of the foods, (b) to heat the foods to 158 to 176°F (70 to 80°C) to inactivate autolytic enzymes that otherwise would cause undesirable texture changes in the foods during extended storage without refrigeration, (c) to vacuum-seal the foods in flexible multilayered plastic-foil pouches, (d) to freeze the pouches at -40°F (-40°C), (e) to expose the pouches to a sterilizing dose of ionizing energy, and (f) to thaw the pouches and store and transport them without refrigeration.



A slice of ham sterilized with ionizing energy (37-43 kilograys) and protected in a laminated foil-plastic pouch. The slice was from the same lot as that eaten on the moon by the Apollo 17 astronauts. Photograph courtesy of Eugen Wierbicki, Eastern Regional Research Center, USDA, Philadelphia.

Studies using the water, acetic acid, and n-heptane solvents described previously showed that the release of chemical substances into the solvents from the pouch systems listed in Appendix V, Table V-8, during absorption of 71 kilograys of ionizing energy was insignificant. Killoran (1983) also reported insignificant release of chemicals from the adhesive used to bond the layers of the pouches. The treatment with ionizing energy improved the bonding of the layers and the seal strength of the pouches.

The reliability of the flexible multilayer pouches for sterilizing, shipping, and storing beef, chicken, ham, and pork was tested in the same experiment with the tinplate metal cans described previously. In all, 725,000 pouches were tested. The rejection rate due to defective pouches by the end of 2 years was 0.03% -- higher than that for the metal cans, but still acceptable. The rejection rate could have been reduced by enclosing the pouches in paperboard folders (Killoran et al., 1979a).

Empty Packaging

Packaging for use with dairy products and bulk bag-in-box products is now being sterilized on a commercial scale by exposure to ionizing energy (Rice, 1986). This presterilization assures a significantly increased distribution case life for the perishable refrigerated products that go into the containers. It is considered cost-effective.

13. ACCEPTABILITY

Foods are considered acceptable if they are safe for consumption, have nutritive, sensory, and keeping qualities appropriate for the products, and can be purchased at competitive prices. Sensory qualities involved in acceptability include appearance, flavor, odor, and texture.

In the United States, safety assurance is provided by the Food and Drug Administration, which must authorize the ionizing energy treatments employed in food processing. Analogous approvals are required in most countries.

Approvals by national regulatory authorities for human consumption of foods that have been processed with ionizing energy do not automatically result in the use of the approved processes on a commercial scale and the appearance of the foods in homes and restaurants. Commercial food processors must be concerned with the production problems involved in supplying high quality products while assuring worker safety, a "nuclear clean" environment in and around their plants, and a reasonable and timely return on their financial investment.

Deficiency in only one criterion for acceptability may be enough to prevent the use of the process on a commercial scale. For example, the 1964 Food and Drug Administration approval of the use of ionizing energy on white potatoes to inhibit sprouting and thus extend the shelf life has never been followed by commercial use of the process in the United States because chemicals can accomplish the effect more economically.

Although all the criteria for acceptability may be met for some products, actual acceptance is still not guaranteed. Active, vocal minority groups that oppose the use of ionizing energy may engage in various activities designed to prevent or hinder the adoption of the process. The generous media coverage these groups enjoy extends their influence.

Sensory Qualities

Many properties of foods can be measured objectively by scientific methods. The acceptability of foods for consumption, however, is a subjective matter. From almost the beginning of research on exposure of foods to ionizing energy, panels of experts have been employed to evaluate in as nearly an objective manner as possible the sensory qualities of treated foods. These evaluations have been important because, especially in the early days, numerous unfavorable results were obtained. The doses and treatment conditions that yield products acceptable for consumption and those that do not must be found by trial and error.

Following the evaluations made by panels of experts may be evaluations by untrained consumers in relatively simple tests. Beyond evaluations by consumers, additional information on acceptability may be derived from surveys, market tests, and commercial experience.

Improvements in Processing

With some food products, such as cereal grains and flours, no significant acceptability problems have been encountered in the use of ionizing energy. At the other extreme are dairy products and lettuce, which have acceptability problems that have not yielded to research. Other products — flesh foods for example — have benefited from improvements in processing techniques. Many foods can now be processed with ionizing energy in ways that yield products with certain superior qualities and with flavor, color, odor, and texture similar to, and in some cases superior to, those of the same foods that have been processed by the well established methods in commercial use today. The same is true for nutritional qualities, which were reviewed by Wierbicki et al. (1986).

The improvements in quality of foods processed with ionizing energy that have been made possible by research are the result of one or more of the following: (1) controlling the absorbed dose of ionizing energy more precisely, (2) increasing the rate at which the dose is applied, (3) excluding air from the food by vacuum packaging or flushing with nitrogen gas, (4) keeping the food frozen while it is being exposed to ionizing energy, and (5) using better packaging.

A side effect of ionizing energy on foods that has stimulated much research has been the development of off-flavors and off-odors. This problem has been greatest with the relatively high doses required for sterilization of flesh foods. Unacceptable products are generally obtained if the foods are processed with high doses of ionizing energy in air at room temperature, but palatable products are obtained if the foods are processed while frozen and packaged in containers that have been evacuated or flushed with nitrogen to remove the gaseous oxygen. The critical temperature is about -4°F (-20°C). Best results are obtained with treatments at or below the critical temperature because, except for high doses, this temperature assures that the products will remain frozen as the temperature rises during processing (about 7 to 11°F or 4 to 6°C for each 10 kilograys of ionizing energy absorbed).

With foods that tolerate vacuum packaging and freezing, the effects of even high doses of ionizing energy (up to 71 kilograys) are in most instances below the threshold of detection by most persons, although they may be discerned by expert panelists. Under industrial conditions for producing sterilized foods, in which the ratio of the maximum dose to the minimum dose received by the food may be as great as 1.5, some foods may need to be frozen to -58 to -76°F (-50 to -60°C) to assure that the final temperature of some portion of the food does not rise above the critical value. Smoked fish, bacon, and ham are exceptions. These foods retain high acceptability ratings even if sterilized while unfrozen.

The off-odors and off-flavors in many flesh foods that have been sterilized while unfrozen are associated with certain volatile compounds that can be identified and determined quantitatively. These compounds still form when the foods are processed while frozen and evacuated, but the amounts under such conditions are very small. For example, the data evaluated for toxicologic significance by the Federation of American Societies for Experimental Biology (FASEB, 1977) showed a total of 10 parts of identified compounds formed per million of beef as a result of treatment with 56 kilograys of ionizing energy at -22 ± 18°F (-30 ± 10°C).

Product Evaluations

With low-dose applications, many foods are acceptable without improvements in processing. But particularly with high-dose applications, improvements in processing developed through research have been needed to bring some products up to a satisfactory level of acceptability. With products for which this is true, the data from large-scale evaluations presented in this section were derived from products processed under improved conditions.

As with other methods of food processing, trial and error are involved in discovering the most appropriate procedures for use with ionizing energy. The fact that some research on ionizing energy has shown unfavorable results with certain procedures is thus no different in principle from the burned toast, the fallen cake, or the hard cookies that result from the use of inappropriate procedures with familiar methods of processing, although these unacceptable results may not be thought of in the same context.

In food evaluation panels, each panelist rates each sample of food subjectively according to a rationale agreed upon beforehand. The usual method used by the U.S. armed services for evaluating foods that have been exposed to ionizing energy is to rate them on the 9-point scale of Peryam and Pilgrim (1957), on which 9 denotes "like extremely," 1 denotes "dislike extremely," and 5 denotes "neither like nor dislike." The preference ratings by the individual panelists are averaged, and samples with an average value above 5.0 are considered acceptable. The same general procedure was followed in the large-scale evaluations by military consumers reported in this section.

Table 10. Preference ratings obtained in dining hall tests by the U.S. Army on fish fillets with and without ionizing energy for shelf- life extension (Slavin et al., 1966)

		Average preference ratings[a]	
Product	Number of persons supplying ratings	Frozen controls	Processed with ionizing energy[b]
Haddock fillets	314	6.2	5.8
Haddock fillets	693	6.0	6.1
Petrale sole fillets	333	6.5	6.2
Cod fillets	588	6.4	6.5

[a]Evaluations on a 9-point scale on which 1 = dislike extremely, 5 = neither like nor dislike, and 9 = like extremely.

[b]Doses of ionizing energy in kilograys were 2.5 for the first haddock entry, 1.5 for the second, 2.0 for the petrale sole, and 1.5 for the cod.

During the period from 1953 to 1980, the U.S. Army spearheaded research on the use of ionizing energy to produce certain sterile foods for combat rations as replacements for thermally canned items of limited acceptability. Sterile shelf-stable chicken, codfish cakes, beef, pork, pork sausage, ham, shrimp, bacon, and corned beef with eating quality superior to that of comparable thermally processed products were produced in the research program (Josephson, 1983; Wierbicki, 1981b). Although these prototype products involved sterilization with ionizing energy, they also incorporated other important scientific and technological advances. Sterile foods well accepted by consumers have been produced by doses of ionizing energy ranging from a minimum of 12 D to a maximum of 18 D (Wierbicki, 1981a, 1981b, 1984)[8]. Some of the expert panel evaluations of these products are presented in the sections on the respective products.

Between 1958 and 1967, the U.S. Army conducted 15 consumer-type tests to determine the acceptability of a number of foods that had been processed with ionizing energy for use as components of meals in its dining halls at Fort Lee, Virginia. The total number of meals served was 42,314, of which 19,419 included the corresponding unprocessed food as a control. The preference scores indicated that the foods processed with ionizing energy were acceptable as components of standard meals (Josephson, 1967). The results of one set of the U.S. Army's dining hall tests on fish products are shown in Table 10. The products that had been exposed to ionizing energy were

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[8] The symbol D means "decimal reduction dose." When used in connection with sterilization of foods with ionizing energy, it denotes the dose needed to reduce the number of *Clostridium botulinum* (types A and B) spores to one-tenth of the initial number. A dose of 2 D would reduce the population to one-hundredth of the original number, and so on. A dose of 12 D would reduce the population to 0.000000000001 of the original; that is, an initial population of 1 trillion organisms or spores would be reduced to 1 organism or spore, or an initial population less than 1 trillion would be reduced to less than 1 organism or spore.

considered acceptable. The preference ratings indicated little or no difference between the processed and corresponding control products.

In December 1966, the Army served bacon that had been sterilized with ionizing energy as a breakfast component in 4,792 meals in dining halls at Fort Benning and 2,000 meals at Fort Gordon. During the same month, the U.S. Air Force served bacon that had been sterilized with ionizing energy in 25,656 breakfasts in its dining halls at 12 air bases. The bacon was judged an excellent product (Josephson, 1967).

Preference ratings of potatoes that had been exposed to ionizing energy to inhibit sprouting were compared with those of potatoes that had been treated with 3-chloroisopropylphenylcarbamate for the same purpose in trials on 31 metric tons of the 1966 crop of potatoes at Fort Lewis, Washington (Army); Anderson Air Force Base, Guam; Eilson Air Force Base, Alaska; and Camp Pendleton, California (Marine Corps). A test with 60 metric tons of the 1968 crop was made at Fort Lewis, Washington, and Anderson Air Force Base, Guam. The preference ratings of the two classes of sprout-inhibited potatoes were similar to each other and to those of potatoes obtained through normal supply channels (Josephson et al., 1977).

During 1967 and 1969, approximately 120 metric tons of bleached, enriched hard-wheat flour were exposed to ionizing energy to disinfest the flour of insects, and quantities were shipped to ten military installations in the United States, Panama, Azores, Spain, and the U.S.S. Guadalcanal at sea for evaluation of the quality of baked products prepared with the flour. The acceptance ratings were approximately the same as those for analogous baked items made from good quality flour not treated with ionizing energy, but obtained through regular supply channels. Testing of samples of the flour after 4 and 12 months of storage indicated that insects were controlled effectively (Josephson et al., 1977).

Surveys

"Testing the waters" with foods processed with ionizing energy has differed somewhat from analogous tests with conventional foods because of the legal requirement in the United States and many, but not all, other countries for prior approvals by health authorities at national levels. Producers must also be concerned about the possibility that legally mandated labeling would be more stigmatic than informative.

Consumers

Surveys of consumer attitudes have been made in several countries, including the United States (Anonymous, 1984a), the Netherlands (Van Kooij, 1975; Defesche, 1982); Israel (Be'ery and Lapidot, 1971), Canada (Anonymous, 1984b), and the Republic of South Africa (Van der Linde, 1983). Additional information on surveys has been reported elsewhere (IAEA, 1983; Urbain, 1986).

A small percentage of South Africans (projected to 5 to 10% of consumers) was sufficiently venturesome to be willing to accept foods processed with ionizing energy for trial. A similar percentage would not be receptive under any circumstances, and the remaining 80 to 90% took a neutral position (Webb, 1983).

In the Netherlands, consumers apparently were more concerned abut the possible hazards of chemical preservatives in foods than they were about processing foods with ionizing energy (IAEA, 1983). Similar concerns were found in a survey reported 6 years later by Cramwinckel and Van Mazijk-Bokslag (1989). These authors found that 26% of the respondents were very concerned about the use of ionizing energy to extend the shelf life of food, and 24% were somewhat concerned. In this survey, all respondents were supplied with mushrooms and were told that they had been processed with ionizing energy, but in fact only half of the respondents received processed mushrooms. The authors found that the mushrooms treated with ionizing energy were judged significantly better than those that were not treated.

The major limitations of surveys of consumers are that many of the respondents have no prior knowledge of the process and its consequences, and some hold opinions based upon misinformation. Only 20 to 30% of consumers contacted in U.S. surveys in 1984 and 1985 had heard of foods that had been "irradiated" or treated with ionizing energy (Sharlin, 1986). The Brand Group (1986) found that two-thirds of the consumers it surveyed had never heard of "irradiation," and only 3% stated that they were familiar with the process. These limitations have taxed the ingenuity of those devising surveys to develop questionnaires that would elicit a meaningful reponse from a population in which most are unaware of the process and almost none have either seen or tasted the resulting foods.

In a survey conducted in four U.S. cities in 1988, Zellner and Degner (1989) used a different approach, querying consumers about their attitudes toward methods of increasing the microbiological safety of chicken for consumption. They did not ask the respondents about their knowledge of ionizing energy or chemical treatments, but they assured the respondents that their chances of becoming ill from treated chicken were virtually zero and that the taste, texture, and odor of the treated chicken would be unaffected by the process. They found that between 75 and 87% of respondents would purchase chicken that had been treated with ionizing energy or chemicals and that on the average they would pay more for the treated product.

The remaining 13 to 25% of the respondents would not purchase such a product even if the price were zero.

Food Industry

Most food processors, on the other hand, are knowledgeable about the process. Surveys conducted in the United States (Josephson and Wierbicki, 1973), the Netherlands, the Republic of South Africa, and elsewhere have shown that if the consumer market would establish a demand for a sufficient volume of foods to be processed with ionizing energy, production costs would be low enough to be competitive with those of other established processes. Consumers, therefore, would have to be receptive to purchasing these new products repetitively to encourage the outlay of funds needed to construct the needed facilities and to permit prompt recovery of costs.

Josephson and Wierbicki (1973) surveyed a cross section of commercial producers, processors, wholesalers, and supermarket executives in major sections of the United States to determine their interest in producing meats, seafood, and poultry that had been sterilized with ionizing energy. They found almost unanimous interest in going to production, provided that (1) the necessary government permissions would be granted, (2) the quality of the products would be high enough to please consumers' palates, (3) the cost per pound would be within consumers' food budgets, and (4) there would be no mandatory stigmatizing label that would discourage purchases.

From the standpoint of the food industry, the principal problem seems to be the large initial financial outlay needed to construct the facilities and the availability of established alternatives, such as chemical inhibitors of the sprouting of potatoes, that accomplish some purposes. An incentive is needed to convince industry sources that the potential payoff of a processing plant would justify the attacks such a plant might encourage among antinuclear activists. Possible incentives might include the banning of some chemical alternatives or heightened demand for meats that have been decontaminated of *Salmonella*, other disease-causing bacteria, and parasites, so that a market would exist for decontaminated products.

Market Tests

In the United States, market tests on fresh fruit disinfested of insects by use of ionizing energy have been conducted on mangoes in North Miami Beach, Florida (Giddings, 1986), and on papayas in Irvine and Anaheim, California (Bruhn and Noell, 1987). Abroad, market tests have been conducted in Israel, the Netherlands, Japan, South Africa, Uruguay, Italy, Hungary, Chile, the Federal Republic of Germany, Thailand, the U.S.S.R., and other countries. These studies indicate that the foods processed with ionizing energy were readily accepted by an overwhelming proportion of the consumers, who either purchased the foods for consumption at home or ate them gratis at the supermarket or other store where they were offered. According to Appendix V, Table V-10, foods are now being treated with ionizing energy on a commercial basis in 20 countries.

In the conduct of market tests, care is needed to avoid biasing the outcome (Josephson, 1985). For example, in a series of market tests in Israel, consumers consistently preferred onions and potatoes that had been treated with ionizing energy over those that had not when the products were offered in supermarkets in which there was little interaction between the supermarket personnel and consumers. In contrast, in green groceries in which contact between market personnel and consumers was all-pervasive, the attitude of the market personnel determined whether consumers would accept or reject the products treated with ionizing energy.

Market testing has been impeded by activists opposed to the use of ionizing energy in food processing. For example, a particular supermarket in Canada recently planned a test of acceptability of potatoes that had been treated with ionizing energy to inhibit sprouting. When an activist group learned of the plan, the group threatened to call for a boycott of all members of the supermarket chain in both Canada and the United States. Because such a threat would be widely publicized by newspapers and would be certain to have some effect, the store management called off the proposed test.

Costs

In anticipation of full commercial production at some future time of a broad spectrum of foods processed with ionizing energy in the United States, several "pencil and paper" studies have been published on the projected costs. These include publications by Pomerantz and Siu (1957), Barnes et al. (1961), Yankelovich (1966), Urbain (1966), Josephson et al. (1968), Deitch et al. (1972), Brynjolfsson (1973a), Deitch (1982), Nickerson et al. (1983), Giddings (1984), Morrison (1985), and Morrison and Roberts (1985).

Especially important as determinants of cost are the dose to which the food is exposed, the plant capacity, and the amount of idle time, but Deitch (1982) listed many additional cost factors that could vary from one circumstance to another. The range of cost estimates has been from less than a cent per pound to several cents per pound. The Japanese cite cost figures of less than 0.5 cent per pound for their Shihoro, Hokkaido, plant that treats potatoes to inhibit sprouting. Some of the estimates in the literature would need to be increased for present conditions because of the inflation that has occurred. Comparisons of ionizing energy with other forms of processing, however, should be more constant. Barnes et al. (1961) estimated that costs for sterilizing foods with ionizing energy would be in the same general range as those for sterilizing the foods by heat and processing the foods by freezing or freeze drying.

Almost 25 years ago, Siu (1965) testified before the Congressional Subcommittee on Research, Development, and Radiation of the Joint Committee on Atomic Energy that "The economics have always been in the ball park where it is attractive. Even though we will never get solid data without pilot plant experience, there have been repeated economic calculations from all angles. Every year someone makes a calculation and their results always remain in the ball park." The economic calculations continued, and Urbain (1986) summarized the available information with the statement that "Operating costs for irradiation generally fall in a range to be commercially feasible. Fixed costs are moderately high and require fairly large product volumes for their support. A substantial capital investment for an irradiation facility is needed."

An important aspect of cost per unit of product is the capability to operate a facility continuously. As noted previously, the approval granted by the Food and Drug Administration for processing potatoes with ionizing energy to inhibit sprouting has never been followed by commercial adoption. To keep a potato-processing plant busy during the major part of the year in which there are no potatoes to process, economics dictates that other products be available for processing. To date, the number of approvals issued by the Food and Drug Administration has not been great enough to keep food processing plants operating continuously, thus increasing the cost per unit of product. In Japan, where the use of antisprouting chemicals is not permitted, the treatment of potatoes with ionizing energy is a government operation designed to keep speculators from running up the price when the supply is short. The plant stands unused most of the time.

Giddings (1984) estimated that the total start-up capital investment for a complete automated facility with 200,000 curies of cobalt-60 would be about $1.7 million. With throughput of 21 million pounds (almost 10 million kilograms) of edible product per year at doses not exceeding 2.2 kilograys, the processing cost would be 5 cents per pound (11 cents per kilogram) of product. Giddings' estimates were for a commercial operation that would produce a profitable return on the investment.

In some instances, the treatment with ionizing energy provides a price advantage that increases the competitive position of ionizing energy. For example, by extending the shelf life of seafood, ionizing energy can permit the marketing of more of the product in the preferred fresh condition, and less of it frozen. The U.S. Department of Commerce (1985) reported that in 1984 the retail price of fresh cod fillets was $2.88 per pound compared with $2.22 per pound for frozen cod fillets. This difference in price would pay for the ionizing energy treatment many times over.

Labeling

Labeling of foods treated with ionizing energy has been one of the most controversial issues related to commercial production. The Joint FAO/IAEA/WHO Expert Committee concluded that with foods that had been approved as safe to eat there was no valid scientific reason for identifying the products with a label at the retail level when similar labeling is not required for the other commonly used processing methods (WHO, 1981).

An expert consumer panel convened by FAO/IAEA in Vienna in 1982 took the same position on the grounds that singling out processing with ionizing energy could be construed to imply that there may be doubt about the safety of the food for consumption (IAEA, 1983). The issue of a retail label is the right of the consumer to know versus unnecessarily stigmatizing a safe product. There was no controversy regarding the need for labeling at the production and wholesale stages because of the need to comply with regulations forbidding the treatment of a food with ionizing energy more than once.

The Codex Alimentarius Commission, after receiving the recommendations of the Joint FAO/IAEA/WHO Expert Committee, referred the labeling aspects to its Committee on Labeling. This committee, which meets every 2 years in Ottawa, Canada, is concerned with uniformity in labeling among the approximately 130 Codex member countries, including the United States, to facilitate international trade. At its meeting April 3 to 7, 1989, the committee agreed to recommend that the use of a logo or symbol be optional, but that "the label of a food which has been treated with ionizing radiation energy shall carry a written statement indicating that treatment in close proximity to the name of the food."

In response to demands by activists, the U.S. Food and Drug Administration (FDA, 1986) imposed a rule in April 1986 requiring that retail labels on foods that had been treated with ionizing energy must display the international symbol for food treated with ionizing energy, along with the statement, "treated by irradiation." After 2 years, only the logo was to be required, without the accompanying statement in words. The requirement for the logo and the accompanying statement, however, was extended for a second 2-year period in 1988 (FDA, 1988). This extension without final action should facilitate bringing the ultimate U.S. requirement for labeling into conformity with the procedure to be adopted at some future time by the Codex Alimentarius Commission. Minor ingredients in a food, such as spices, that have been treated with ionizing energy are exempt from the Food and Drug Administration's labeling requirement.

Some countries, such as Chile, require no label for foods that have been treated with ionizing energy; others advocate complete labeling of all treated foods and all treated components of these foods. Time and patience are required to achieve uniformity in a labeling requirement.

In the United States, the reduction with time in the labeling requirement for foods that have been treated with ionizing energy is perhaps a consequence of the original position of the U.S. Department of Health and Human Services that labeling is not needed for such foods, once they have been accepted by the Food and Drug Administration as safe for human consumption. Requiring labeling of foods processed with ionizing energy without requiring parallel labeling of foods processed in other ways is a non sequitur in that the amount of scientific evidence available on the safety for human consumption is far greater for foods processed with ionizing energy than for foods processed in any other way. Nonetheless, except for pasteurized milk, there is no requirement for labeling foods processed in other ways.

The Outlook

The many years of detailed research verifying the safety of foods for consumption after processing with ionizing energy, plus the demonstrated value of the technology for food preservation and other purposes, have satisfied the regulatory agencies in numerous countries (see the list of approvals in Table V-9, Appendix V). Commercial use of ionizing energy for food processing is now underway in the 20 countries listed in Table V-10, Appendix V. As a step to promote the use of the technology in the United States, the Department of Energy is negotiating contracts to build pilot plants in Alaska, Florida, Hawaii, Iowa, Oklahoma, and Washington. In the Department of Energy's project cooperators' meeting on March 15 and 16, 1989, the electron accelerators for the Florida and Iowa plants were reported to be undergoing fabrication. The Hawaiian project was on the governor's desk for decision. The Oklahoma and Washington projects were in earlier stages of development, and the Alaska project was on hold.

The outlook is for eventual commercial adoption of ionizing energy for food processing in the United States on the basis of its commercial merits. The beginning will be slow, as a result of efforts of antinuclear activists. The optimism is rooted in the belief that where the technology is advantageous, the slow beginning will be followed by adoption at an increasing rate as scientific knowledge gradually prevails.

At a December 1988 conference of delegates from 54 countries held in Geneva under the sponsorship of the Food and Agriculture Organization, the World Health Organization, the International Atomic Energy Agency, and the International Trade Center, agreement was reached on a set of principles for international trade in foods treated with ionizing energy under strict controls by competent national authorities. Labeling of treated food was recommended, but no specific form was specified, pending action by the Codex Alimentarius Commission's Committee on Labeling at a meeting to be held in April 1989.

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Edward S. Josephson
Cambridge, Massachusetts

February 1989

Appendix I: Glossary

Accelerator. In food processing with ionizing energy, a device for producing beams of electrons with high speed and energy.

Alpha particle. A positively charged particle emitted from a nucleus and composed of two protons and two neutrons. It is identical in all measured properties with the nucleus of a helium atom.

Aqueous electron. The hydrated electron, a radiolytic product of water.

Becquerel. A unit of radioactivity. It is equal to one disintegration per second.

Beta particle. A charged particle emitted from the nucleus during radioactive decay and having a mass and charge equal in magnitude to those of the electron. A negatively charged beta particle is physically identical to the electron.

British thermal unit. The amount of heat required to raise the temperature of 1 lb of water 1°F at or near 39.2°F.

Carcinogen. A substance or agent that may induce cancer.

Cathode ray. A stream of electrons emitted by the cathode of a gas discharge tube or by a hot filament in a vacuum tube. The electron beams generated by accelerators are cathode rays.

Chemiclearance. Regulatory clearance of a particular use of ionizing energy on a particular food on the basis of knowledge of the radiolytic products produced and an evaluation of the effect of these products on the safety of the food for human consumption.

Curie. A basic unit used to describe the intensity of radioactivity of a radionuclide. One curie equals that quantity of radioactive material having 3.7×10^{10} disintegrations per second. This approximates the activity of 1 gram of radium. One curie is equivalent to 3.7×10^{10} bequerels.

Decimal reduction dose. The dose (D) of ionizing energy needed to reduce a population (e.g., of bacteria) by a factor of 10, or one log cycle, leaving as survivors 10% of the original population. See "12D dose."

Disinfestation. In food processing with ionizing energy, the inactivation of foodborne insects or parasites.

Dose. The amount of ionizing energy absorbed per unit mass of a material. In food processing and preservation, low doses are below 1 kilogray, intermediate doses are between 1 and 10 kilograys, and high doses are above 10 kilograys.

12D dose. The dose sufficient to reduce the number of viable *Clostridium botulinum* spores by a factor of 10^{12} required for sterilization of foods by ionizing energy (radappertization).

Dose-equivalent index. The index of biological effectiveness of different kinds of ionizing energy relative to the effectiveness of x-rays with an energy of 200,000 electron volts. It replaces the previously used relative biological effectiveness.

Dosimeter. A device for measuring dose.

Dosimetry. The process of measuring dose.

Electron. A negatively charged particle that is a constituent of all atoms.

Electron volt. The amount of kinetic energy gained by an electron accelerated through an electric potential difference of 1 volt. One electron volt equals 1.6×10^{-19} joule. One electron volt absorbed per gram is equivalent to a dose of 1.6×10^{-16} gray.

Free radical. A molecular entity with an unpaired electron in the outer orbit of an atom. A free radical is formed by the cleavage of a molecule upon reaction with another reactive chemical entity or upon absorption of sufficient energy from either an energetic photon or a fast moving particle.

G value. The number of molecules changed per 100 electron volts of energy transferred to the system.

Gamma ray. A quantum or unit of short-wavelength electromagnetic radiation produced when an unstable atomic nucleus gains stability by release of energy.

Gray. A unit of absorbed dose of ionizing energy. It is equivalent to 1 joule, 10^7 ergs, 6.25×10^{18} electron volts, or 0.24 gram-calorie, all per kilogram. It replaces an older unit, the radiation absorbed dose (rad). One gray is equivalent to 100 radiation absorbed dose units.

Half life. The time required for a radioactive source to decay to one-half of its original radioactivity. The half life of cobalt-60 is 5.27 years, and the half life of cesium-137 is 30.3 years.

Hertz. The frequency or number of cycles of electromagnetic radiation per second.

High dose. In food processing, doses of 10 kilograys or more.

Induced radioactivity. Radioactivity resulting from exposure to ionizing energy.

Ion. An isolated electron or positron or an atom or group of atoms bearing an electrical charge, either positive or negative, caused by an excess or deficiency of electrons.

Ionization. Creation of ions by forming units of one or more atoms bearing positive or negative charges as a result of a deficiency or excess of electrons.

Ionizing energy. In food processing, high-speed electrons from machine sources or radiant energy from x-rays or gamma rays. The standard gamma ray sources are cobalt-60 and cesium-137.

Irradiation. The process of applying any kind of radiant energy. In the context of food processing, it means to expose food to ionizing energy supplied by gamma rays from cobalt-60 or cesium-137, by accelerated electrons with energy less than 10 million electron volts, or by x-rays with energy less than 5 million electron volts.

Irradiator efficiency. The percentage of the total ionizing energy emitted by the irradiator source that is absorbed by the product being processed.

Isotopes. Atoms of a given chemical element having in the nucleus the same number of protons but different numbers of neutrons. Isotopes that are radioactive are termed radionuclides.

Joule. A unit of work or energy equivalent to 10^7 ergs or approximately 0.7375 foot-pound.

Low dose. In food processing with ionizing energy, doses less than 1 kilogray. See also the definition for medium dose.

Medium dose. In food processing with ionizing energy, doses from 1 to 10 kilograys. In earlier literature, this dose range (substerilizing) was included in the low dose range. The recent division of the substerilizing dose range into low and medium is a result of FDA's notice in the Federal Register on March 27, 1981, of its proposed intent to approve without further wholesomeness testing all fruits, cereals, and vegetables exposed to doses up to 1 kilogray.

Mutagenicity. The capacity to induce mutations or heritable genetic changes.

Nitrosamines. Any of various neutral compounds characterized by the grouping $=\mathrm{N{-}N{=}O}$, some of which are powerful carcinogens.

Organoleptic. Affecting or employing one or more of the organs of special sense, e.g., taste and smell.

Photon. One unit or quantum of radiant energy.

Phytotoxicity. Poisonous to plants.

Positron. A positively charged particle having the same mass and magnitude of charge as the electron and constituting the antiparticle of the electron.

Protein efficiency ratio. The gain in weight per unit weight of protein consumed. The measurement usually is made with male rats under standard conditions of a 4-week assay period with diets containing 10% protein and adequate amounts of other nutrients. Casein (the milk protein), used as the reference, has an efficiency ratio of about 2.5.

Radappertization. Treatment of food with a dose of ionizing energy sufficient to prevent microbial spoilage or toxicity of microbial origin, no matter how long or under what conditions the food is stored after treatment, provided that the food is not recontaminated.

Radiation. Radiant energy. Any form of energy radiating from a source, such as sound waves, electromagnetic waves (including radio waves, microwaves, radar waves, infrared rays, visible light, ultraviolet rays, x-rays, and gamma rays), and subatomic particles (including alpha particles and beta particles). In food processing, the term is limited to gamma rays, x-rays, and electron beams. See "irradiation."

Radiation absorbed dose (rad). An outdated term for absorbed dose. One radiation absorbed dose is equivalent to 100 ergs of absorbed energy per gram. One gray is equivalent to 100 rads.

Radicidation. Treatment of food with a dose of ionizing energy sufficient to reduce the number of viable specific nonspore-forming pathogenic bacteria to such a level that none is detectable in the treated food when it is examined by any recognized bacteriological testing method. Such treatment also inactivates food-borne parasites.

Radioactivity. The property possessed by some elements of spontaneously emitting radiation, such as alpha particles, beta particles, or gamma rays, from the nuclei of the atoms.

Radiolytic. Related to chemical decomposition as a result of exposure to radiation.

Radionuclide. An unstable form of an element that decays or disintegrates spontaneously, emitting radiation. Replaces the older term, radioisotope.

Radurization. Treatment of food with a dose of ionizing energy sufficient to enhance its keeping quality by causing a substantial reduction in the numbers of viable specific spoilage microorganisms.

Relative biological effectiveness. An obsolete term now replaced by the dose biological effectiveness equivalent index.

Ripening. To approach or come to full development.

Roentgen. The dose of gamma or x-radiation producing ion pairs carrying one electrostatic unit of charge per cubic centimeter of standard air surrounded by air. In air, it is equivalent to 0.0088 gray.

Roentgen equivalent man (rem). An obsolete unit of dose equivalence, now replaced by the sievert. One sievert is equivalent to 100 rems.

Senescence. The phase of plant growth from full maturity to death, characterized by an accumulation of metabolic products, increase in respiratory rate, and a loss in dry weight, especially in fruit and leaves.

Sievert. The dose of ionizing energy that produces the same biological effect on humans as a dose of one gray from gamma rays or fast electrons. It replaces the older term, roentgen equivalent man (rem). One sievert is equivalent to 100 rem. For other forms of ionizing energy, the relationship between the sievert and the gray is not 1 to 1.

Teratogenicity. The ability to cause developmental malformations and monstrosities in the progeny of the exposed individual.

Unit prefixes. Pico (10^{-12}), nano (10^{-9}), micro (10^{-6}), milli (10^{-3}), kilo (10^{3}) and mega (10^{6}).

X-ray. A short-wavelength electromagnetic radiation produced when high-energy charged particles (usually electrons) strike a metal target.

Wholesomeness. Foods processed with ionizing energy are generally considered wholesome when harmful microorganisms and microbial toxins are absent, when the ionizing energy has produced no measurable toxic effects or radioactivity, and when the food presents no significant nutritional deficiency relative to the same food that has not been processed with ionizing energy or has been processed by conventional methods.

Appendix II: Historical Development of Ionizing Energy for Food Processing

X-radiation and radioactivity were discovered in the last years of the 19th Century. Shortly thereafter, scientists observed that these sources of energy were effective in killing bacteria. Because bacteria are a major cause of food spoilage, Professor Samuel C. Prescott of the Massachusetts Institute of Technology suggested in 1904 that foods could be preserved by killing spoilage bacteria by exposing foods to x-radiation or radioactivity. After World War II, machine sources of ionizing energy (electrons and x-rays) and artificially produced radioactive isotopes (cobalt-60 and cesium-137) became available in sufficient amounts and at low enough prices to stimulate research in their use for food processing.

The United States

After World War II, research on the use of ionizing energy for food processing began at the Massachusetts Institute of Technology and at three industry locations. It soon became apparent that the resources required to verify the wholesomeness of the products and to develop the technology would be too great for universities and industry to supply. Accordingly, the Atomic Energy Commission in 1950 and the Army Quartermaster Corps in 1953 assumed the role of program sponsors. The program gained great impetus when, on December 8, 1953, President Eisenhower proposed the "Atoms-for-Peace" policy to the United Nations. This proposal led to the formation of a National Food Irradiation Program by the U.S. Government and the creation, in 1956, of the Interdepartmental Committee on Radiation Preservation of Food, with members representing ten departments and agencies of the executive branch.

Because preservation of food by ionizing energy is an important peaceful application of atomic energy, the U.S. Government's program was reviewed periodically by the Joint Committee on Atomic Energy of the U.S. Congress. The interest, encouragement, and support of this committee were vital to the program. Much information about the program is contained in the committee's published Hearings on Food Irradiation dated March 31-April 1, 1954; May 9, 1955; June 4-8, 1956; January 14-15, 1960; March 31, 1960; March 6-7, 1962; May 13, 1963; June 9-10, 1965; September 12, 1966; and July 18 and 30, 1968.

Between 1953 and 1961, most of the work on the National Food Irradiation Program took place under the Army's sponsorship. In 1961, the Army was joined by the Atomic Energy Commission. Between 1961 and 1980, the Army gave primary emphasis to sterilizing doses of ionizing energy (doses exceeding 10 kilograys). This emphasis was justified on the basis that suitable treatment with ionizing energy could (a) provide foods that could be stored several years without refrigeration and that would have better taste and texture than foods preserved by canning, (b) reduce food handling costs, and (c) decrease the need for refrigeration.

The Atomic Energy Commission, until it began phasing out its program in 1969, concerned itself with doses below 10 kilograys. The justification for this emphasis, which was complementary to that described for the Army, was that doses below 10 kilograys had good potential for civilian uses, such as destroying *Salmonella* and other food-borne disease-causing organisms in meat and poultry; extending the refrigerated shelf life of fruits, vegetables, fin fish, and shellfish; and disinfesting grains, grain products, and fruits of insects.

On two occasions, the Army and the Atomic Energy Commission had plans to construct pilot plants to introduce and test foods treated with ionizing energy for military and civilian applications. In the first instance, the Army planned in 1957 to have a pilot plant built at Stockton, California, in partnership with a consortium of food companies to develop production techniques for treating foods with ionizing energy and to produce sufficient quantities of treated foods to test their acceptability.

Plans for the Stockton plant were abandoned as a consequence of the enactment in 1958 of an amendment to the Food, Drug, and Cosmetic Act legally defining ionizing energy as a food additive. The amended law, administered by the Food and Drug Administration (FDA), bans all new food additives from commercial use, but provides for exemptions when petitions are approved by FDA. The law also requires FDA approval for packaging materials in contact with the food during processing. The act of Congress banning all new food additives unless exempted by a successful petition to FDA had a profound negative worldwide impact on programs involving the use of ionizing energy in food processing.

In response to a request from the Army, the Atomic Energy Commission had developed a new set of plans in 1966 to develop a pilot production facility at Allentown, Pennsylvania, to sterilize ham (and subsequently other foods) with ionizing energy. This project, like its predecessor in Stockton, California, was to be undertaken jointly with an industry consortium. Plans for the Allentown facility were canceled when the Army's petition to FDA and the U.S. Department of Agriculture (USDA) to approve ham sterilized with ionizing energy was judged to contain insufficient supporting evidence for wholesomeness, an action that will be explained further in a subsequent paragraph.

The plant at Allentown was to be used for sterilizing 300,000 pounds of meats each year for the military and for investigating, testing, and developing the civilian market with 700,000 pounds of meat each year for the first 3 years of operation. Building the facility was contingent upon FDA approval of ham sterilized with ionizing energy. When the approval did not occur during the 1960s, plans for construction were canceled.

In 1955, the Army Medical Department began a 10-year contract program to assess the safety for consumption of 21 foods representing the major foods and food classes in U.S. diets. The assessment of sterilized bacon was completed first, and the Army's petition to FDA and USDA was approved in 1963. Later in the same year, FDA approved the use of ionizing energy to disinfest wheat and wheat products of insects. Treatment of white potatoes for sprout inhibition was approved in 1964. Upon completion of wholesomeness testing of the 21 foods, the Surgeon General, Department of the Army (1965), concluded that foods treated with up to 56 kilograys of ionizing energy from cobalt-60 or with accelerated electrons with energies up to 10 million electron volts were wholesome.

At the conclusion of the wholesomeness study with the 21 foods, the Army submitted to FDA in 1966 the wholesomeness data on bacon (previously approved in 1963) and pork as the basis for a petition to approve the treatment of ham with ionizing energy. The rationale for this petition was that ham is a pork product intermediate between uncured pork and bacon, a highly cured product, so that interpolation should be feasible. In the meantime, FDA had raised its standards for data requirements and, in 1968, offered the Army the option of withdrawing its petition without prejudice because the criteria for assessing the wholesomeness of foods in 1968 were considerably more stringent than those in 1955, when the wholesomeness studies began. Although the Army accepted FDA's offer to withdraw the petition without prejudice and to submit at a later date a new petition with additional data to meet the new requirements, FDA's failure to approve the petition almost resulted in the termination of all U.S. work on treatment of food with ionizing energy. The Atomic Energy Commission did drop its program.

In response to urging by the U.S. Congress, the Secretary of the Army agreed to continue the Army program to prove or disprove unequivocally whether foods sterilized by ionizing energy are wholesome. At first, the Army planned to conduct studies on ham that would meet the test criteria of the 1970s to answer the questions raised by FDA. Eventually, however, the decision was made to do the testing on beef because of the possibility that work on ham might prove useless if FDA should rule against the use of nitrite as a curing agent for ham on the basis of a cancer hazard.

In an attempt to assure that the previous experience would not be repeated, the Army again enlisted the advice of experts through the National Academy of Sciences-National Research Council and coordinated the new program on beef with FDA. In what turned out to be an ill-fated move, however, the Army contracted with Industrial Biotest Laboratories, a commercial toxicology testing company, to make the study according to the approved criteria. After some problems with the test diets for rodents during the first 2 years, the program seemed to be going well, and in 1976 the Army awarded the company additional contracts to test the wholesomeness of sterilized ham and pork. In the same year, the company began to encounter management and business problems with some of its other clients and with regulatory agencies of the U.S. and Canadian governments on matters unrelated to its contracts with the Army. These problems led to lawsuits and bankruptcy of the company, with attendant loss of all the data on the wholesomeness studies in progress for the Army.

In the meantime, during the late 1960s and early 1970s, dramatic improvements had been made in the quality of foods sterilized by ionizing energy by keeping the foods frozen in sealed, evacuated containers during the sterilization treatment. In the early 1970s, the rations supplied to astronauts included various meats that had been sterilized with ionizing energy.

In November 1976, the Interdepartmental Committee on Radiation Preservation of Foods requested the Army to conduct a study to determine if the U.S. Government should resume sponsoring research and development on the use of low levels of ionizing energy in food processing and pest control. The phase-out of the Atomic Energy Commission's program in this area had begun in 1969, and no work had been done for some time. Four panels of experts from government, academia, and industry made the requested study for meat, poultry, seafood, and fruits and vegetables. These panels reported in December 1978 that the need for low-dose treatment of foods with ionizing energy warranted resumption of government support. Among the key issues prompting this decision were the need for food and energy conservation, elimination of foodborne disease-causing organisms, and overcoming quarantine barriers (Panels of Experts, 1978).

In 1974, the Atomic Energy Commission and USDA were copetitioners to FDA to issue a regulation approving the use of ionizing energy to disinfest papayas of the Mediterranean fruit fly. A quarantine barrier prevents the importation of papayas grown in Hawaii to the mainland of

North America because of the presence of the Mediterranean fruit fly in Hawaii. Should the Mediterranean fruit fly become established on the mainland, it could cause great damage to the many U.S. fruits and vegetables it would attack. FDA made no direct response to this petition, but eventually published in the *Federal Register* in 1986 a regulation permitting the use of ionizing energy for fruits and vegetables at doses not to exceed 1 kilogray. This dosage is sufficient to kill Mediterranean fruit flies, their larvae, and eggs.

The U.S. General Accounting Office made a thorough critical assessment in 1977 and 1978 of treatment of food with ionizing energy, with special emphasis on the Army's efforts to use this form of energy to produce sterilized foods. The conclusion was that the program had sufficient merit to continue it to the point at which a petition for a sterilized food could be brought to FDA for evaluation (U.S. General Accounting Office, 1978). The intent was to have FDA decide unequivocally whether sterilization of food with ionizing energy should or should not be legally permitted in the United States before the Army proceeded further with its food sterilization program.

In the meantime, the Army had awarded a contract to Raltech Scientific Services to conduct the animal feeding, mutagenesis, and teratogenesis parts of a study of the wholesomeness of chicken meat that had been sterilized with ionizing energy (Goresline, 1982; Josephson, 1983). This study, which required 7 years and cost $8 million, was the world's most comprehensive, expensive, and lengthy investigation of wholesomeness of any food that had been treated with ionizing energy. The Army conducted in its own laboratories the portions of the project concerned with induced radioactivity, radiolytic products, antivitamin activity, and microbiology. Subjects investigated in one or more of a total of 20 separate research projects included the possible effects of ionizing energy on the nutritional quality, teratogenicity (promotion of birth defects), toxicity, carcinogenicity (promotion of cancers), reproductive performance, and genetic toxicity (promotion of mutations).

Following the termination by the Army of the contracts with Industrial Biotest Laboratories to assess the wholesomeness of beef, ham, and pork that had been sterilized by ionizing energy, the research and development mission on ionizing energy for food processing was transferred on October 1, 1980, from the Army's laboratories at Natick, Massachusetts, to USDA's Eastern Regional Research Center in Philadelphia, Pennsylvania. USDA monitored the contract with Raltech to completion in 1983 and provided FDA with data on the pathology of several testicular tumors observed in mice receiving the treated meat and others receiving the untreated meat. The tumors eventually were determined to have no relationship to the treatment of the meat. The results of the extensive tests on all aspects of the wholesomeness investigation were summarized by Wierbicki et al. (1986).

As yet, no petition for approval of the process for sterilizing chicken with ionizing energy has been submitted to FDA, but the findings of the extensive investigation on sterilized chicken meat supported FDA's decision to approve the use of ionizing energy at doses ranging from 0.3 to 1.0 kilogray for control of trichina in pork. The findings also supported USDA's submission in 1986 of a petition for approval of doses not to exceed 3 kilograys to destroy disease-causing bacteria in fresh chicken to help reduce the incidence of food-borne illness from *Salmonella, Campylobacter, Yersinia,* and *Listeria* in poultry meat. As of January 1989, FDA had not taken final action on this petition.

Other Nations

Research on the use of ionizing energy for food processing was started in a number of countries during the mid 1950s. Although the United States was recognized initially as the leader, this leadership eventually was lost, and most of the research now is being done elsewhere. Because this report focuses on the United States, the research findings in other countries are not emphasized here. Rather, the current status of knowledge is outlined, with emphasis on the United States. In this section, only brief statistics are given on numbers of nations involved and numbers of approvals for use of ionizing energy. The following section outlines the organizational aspects of international work.

According to Goresline (1973), 33 countries were engaged in research on the use of ionizing energy for food processing in 1966; by 1972, the number had risen to 55. The programs abroad, almost without exception, dealt with doses of ionizing energy below those required for sterilization of the products. The only sterilization efforts of note outside the United States were devoted to developing sterile diets for germ-free laboratory animals and, in the United Kingdom, the Netherlands, and the Federal Republic of Germany, for hospital patients who required sterile diets because of medical suppression of their immune systems for organ transplants or for other reasons. One sign of activity abroad is seen in the list of approvals of the use of ionizing energy for specific foods as published in the *Food Irradiation Newsletter*. According to a recent listing by the International Atomic Energy Agency (IAEA, 1988a), more than 250 separate approvals have been granted worldwide, some of them for multiple products and some for foods in general. Hungary and the Netherlands have the longest lists. Eleven approvals are attributed to the United States; of these, six are for multiple products, and three are updates. See Appendix V, Table V-9, for details.

Japan became the first country to "go commercial" with use of ionizing energy for food processing. In 1973, Japan began commercial treatment of potatoes to inhibit sprouting during storage. The plant put into operation at that time has capacity sufficient to treat up to 10,000 tons of potatoes per month. The largest operation is in the USSR, where 400,000 metric tons of imported grain are being disinfested of insects per year at the port elevator in Odessa. Three companies in the United States are decontaminating a relatively small tonnage of spices. The *Food Irradiation Newsletter* for July 1988 (IAEA, 1988b) listed 20 countries that were processing foods with ionizing energy on a practical scale as of June 1988. See Appendix V, Table V-10, for the details.

Farkas (1988) prepared a summary of facilities on a different basis. He reported that, as of 1985, 44 countries had in operation or planning, design, or construction stages a total of 107 large experimental, pilot-scale, or commercial facilities to be used for processing food or feed with ionizing energy.

International Cooperation

President Eisenhower set the stage for international cooperation in research and development work on the use of ionizing energy in food processing and pest control in his "Atoms-for-Peace" speech to the United Nations General Assembly on December 8, 1953. In 1955, the first "International Conference on the Peaceful Uses of Atomic Energy" was convened in Geneva, Switzerland, under the auspices of the United Nations. In 1956, the Food and Agriculture Organization of the United Nations (FAO) established an Atomic Energy Branch in Rome, Italy, to aid member countries apply ionizing energy to help alleviate serious food spoilage losses. This action was followed by the organization of a European Contact Group on the Use of Isotopes and Radiation in Agricultural Research, which held its first meeting in December 1956 in Wageningen, the Netherlands.

In 1960, the International Atomic Energy Agency (IAEA) established a Unit of Agriculture in Vienna, Austria, to apply the expertise of the Agency to problems in agriculture. In October 1964, a Joint FAO/IAEA Division of Atomic Energy in Food and Agriculture, with headquarters in Vienna, was established, combining the Atomic Energy Branch of FAO and the Unit of Agriculture in IAEA. The Joint Division works very closely with the World Health Organization (WHO) of the United Nations in matters pertaining to the safety for consumption of foods preserved by ionizing energy.

The newly created FAO/IAEA Joint Division's program included fellowships, training courses, exchange professors, panels (acting as executing agent in programs funded by other organizations, such as the United Nations and the World Bank), publications, research contracts, special missions, and in-house laboratory activities. The Food Preservation Section of the Joint Division was placed in charge of all projects involving treatment of food with ionizing energy, including assistance to member countries in food preservation, sponsoring fellowships to train scientific personnel, awarding contracts and processing equipment in support of research, organizing symposia, convening panels of experts, conducting training courses, and publishing the *Food Irradiation Newsletter*.

When in 1968 FDA did not approve the U.S. Army's petition for sterilizing ham with ionizing energy, followed by the recision by FDA and USDA of the prior approval for sterilizing bacon, most of the other countries interested in the use of ionizing energy to preserve food decided that they could no longer look to the United States for world leadership and that they should forge ahead independently (there were a few dropouts, as mentioned previously). In response, an agreement was signed in Paris on October 14, 1970, to establish an International Project in the Field of Food Irradiation (IFIP) and to locate it in Karlsruhe, Federal Republic of Germany. This action was undertaken as a cooperative venture to pool resources because of the high costs of research and the scarcity of facilities and trained personnel in many of the developing countries. IFIP was sponsored by IAEA, FAO, and the Nuclear Energy Agency of the Organization for Economic Cooperation and Development; WHO was associated in an advisory capacity. IFIP's major mission was to conduct an international program of wholesomeness studies on foods processed with ionizing energy. Twenty-four countries, including the United States, contributed funds or services to IFIP.

IFIP was largely instrumental in pulling together the data on wholesomeness considered by the Joint FAO/IAEA/WHO Expert Committee on the Wholesomeness of Irradiated Food at the committee's meeting in Geneva from August 31 to September 7, 1976. IFIP distributed a report dated July 1976 and entitled *Review on International Wholesomeness Testing of Irradiated Food and Feed from 1925 to the Present* that had been prepared for IFIP by J. Barna of the Biology Department of the Central Food Research Institute, Budapest, Hungary. The published version of this report (Barna, 1979) reviewed 1221 studies of wholesomeness of 278 different foods and feeds that had been treated with ionizing energy. Barna concluded that "neither beneficial nor detrimental effects of irradiated food consumption are consequent, unambiguous and reproducible. Neither can specific effects be related to a given food, group of foods, or level of radiation dose." Additionally, IFIP sponsored research on new methods to appraise foods treated with ionizing energy as regards wholesomeness, particularly in developing "time saving methods likely to yield more meaningful results at lower costs" (Anonymous, 1978).

Of major international significance were the 1980 conclusion and recommendations by the FAO/IAEA/WHO Joint Expert Committee on the Wholesomeness of Irradiated Foods. This Committee concluded that any food treated with an average dose of 10 kilograys or less of ionizing energy is wholesome, and recommended that foods treated in this way should be approved without further testing for wholesomeness. The Committee saw no valid scientific grounds for requiring special labeling of foods treated with ionizing energy. This conclusion and the associated recommendations were a sequel to the growing list of approvals, wholesomeness studies, and studies of chemical changes occurring in foods exposed to ionizing energy. The first of these recommendations was implemented by the Food Additives Committee and the Labeling Committee of the Codex Alimentarius Commission and by the Codex Alimentarius Commission itself in 1983. Recommendations by the Joint Expert Committee on foods treated with doses of ionizing energy exceeding 10 kilograys were deferred, pending completion of the wholesomeness study on chicken sterilized by ionizing energy begun by the U.S. Army in 1976 (completed in 1983 under the aegis of USDA) and a study on sterilized ham completed in the Netherlands in 1983.

Clearances of individual foods on a national basis are not, by themselves, sufficient to permit international trade in foods processed by ionizing energy. Agreement on an international basis is required. Action to obtain such agreement for the foods (potatoes, wheat and wheat flour, strawberries, chicken, cod and redfish, onions, papayas, and rice) approved in September 1976 by the Joint FAO/IAEA/WHO Expert Committee began through the framework of the Codex Alimentarius Commission. The Codex Alimentarius Commission's Committee on Food Additives and Processes decided in October 1978 that the Draft General Standard for Irradiated Foods and the Draft Code of Practice for the Operation of Radiation Facilities Used for the Treatment of Foods should be advanced to Step 8 of the 11-step Codex Procedure. These drafts then were submitted to the parent Codex Alimentarius Commission with its 124 member governments for adoption as a Recommended Standard. This process was repeated after the October-November 1980 meeting of the Joint FAO/IAEA/WHO Expert Committee. In 1983, the Codex Alimentarius Commission approved the Joint Expert Committee's recommendation that all foods treated with a maximum overall dose of 10 kilograys are safe to eat and set in motion the procedures for establishing the General Standard for Irradiated Foods and the Code for the Operation of Radiation Facilities. These actions, when completed, should lead to acceptance of foods processed with ionizing energy as items of international trade.

Information Sources

Reports of worldwide activities on food processing with ionizing energy have appeared in issues of the *Food Irradiation Newsletter,* published by the European Information Center for Food Irradiation, Saclay, France, from 1960 through 1971, succeeded by *Food Irradiation Information,* published between 1972 and 1982 by the International Project in the Field of Food Irradiation, Karlsruhe; in the *Food Irradiation Newsletter*, published continuously since March 1977 by the Joint FAO/IAEA Division of Atomic Energy in Food and Agriculture, IAEA, Vienna; in *IAEA Newsbriefs,* published monthly beginning in 1986 by IAEA, Vienna; and in *Proceedings of Symposia* jointly organized by IAEA/FAO/WHO and held in Harwell, England, in 1958; in Brussels, Belgium, in 1961; in Karlsruhe, West Germany, June 6-10, 1966; in Bombay, India, November 13-17, 1972; in Wageningen, the Netherlands, November 21-25, 1977; in Colombo, Sri Lanka, November 24-28, 1980; and in Washington, D.C., March 4-8, 1985.

Recent sources of general information include an International Atomic Energy Agency training manual (IAEA, 1982a), a three-volume treatise edited by Josephson and Peterson (1982-1983), a collection of research papers edited by Elias and Cohen (1983), a symposium edited by Moy (1985), a monograph by Urbain (1986), a monograph by Farkas (1988), a special report for general readers by the World Health Organization (WHO, 1988), and a booklet for general readers by the American Council on Science and Health (ACSH, 1988). The following older books are also good sources of information: Hannan (1955), U.S. Army Quartermaster Corps (1957), Desrosier and Rosenstock (1960), Brownell (1961), Metlitskii et al. (1967), Frumkin et al. (1973), and Elias and Cohen (1977). Additionally, the National Agricultural Library of USDA in Beltsville, Maryland, maintains a National Food Irradiation Information Center that includes a large collection of books, pamphlets, and papers.

Appendix III: Radiation Chemistry

Free Radicals and Their Reactions

Stable forms of atoms and molecules have an even number of orbital electrons. The electrons are paired, and the two electrons in each pair normally spin in opposite directions. For example, the formula for water, a stable molecule, may be represented by

$$H{:}\overset{\cdot\cdot}{\underset{\cdot\cdot}{O}}{:}H$$

where the dots represent the electrons in the outer orbitals of hydrogen (two) and oxygen (eight). Each of the hydrogen atoms shares two electrons with the oxygen atom.

Free radicals are unstable forms of molecules or atoms, with an uneven number of valence electrons. Free radicals are of widespread occurrence. They may be produced from molecules that split when they are heated, when they are exposed to light or ionizing energy, or when they interact with enzymes or metal ions. Ordinary molecular oxygen in the atmosphere acts as a free radical with two unpaired electrons.

The rate of production of free radicals is greatly increased during the processing of foods with ionizing energy. Using water (a major component of most foods) as an example, a water molecule that has absorbed enough ionizing energy first loses an electron and becomes a free radical with a positive charge:

$$H_2O + \text{ionizing energy} \rightarrow \bullet\, H_2O^+ + e^-$$

where the dot preceding the positive water ion conforms to the usual convention of representing a free radical by including a single dot in its formula, without showing the remaining electrons.

The free electron on the right-hand side of the equation attaches itself quickly to other water molecules to form what is termed a solvated or hydrated electron, denoted by e_s^- or e_{aq}^-. The foregoing equation thus may be written as

$$H_2O + \text{ionizing energy} \rightarrow \bullet\, H_2O^+ + e_{aq}^-$$

The positive water ion breaks up into a hydroxyl radical and a hydrogen ion:

$$\bullet\, H_2O \rightarrow \bullet\, OH + H^+$$

Some water molecules absorb less energy and do not lose electrons, but become highly excited. Some of the excited water molecules split apart to generate a hydroxyl radical and a hydrogen atom:

$$H_2O\ (\text{excited}) \rightarrow \bullet\, OH + \bullet\, H$$

The overall reaction for the interaction of water with ionizing energy may be written as:

$$H_2O + \text{ionizing energy} \rightarrow e_{aq}^-(3),\ \bullet\, OH(3),\ \bullet\, H(0.6),\ H^+$$

where the numbers in parentheses are the yields of the individual species, expressed as the number formed per 100 electron volts of absorbed energy.

In lipids, of which fats are the principal components, absorption of ionizing energy produces lipid radicals:

$$LH_2 \rightarrow \bullet\, LH_2^+ + e^-$$
$$\hookrightarrow \bullet\, LH + H^+$$

where L stands for lipid and H^+ is the hydrogen ion. In proteins, protein radicals are produced:

$$PH_2 \rightarrow \bullet\, PH_2^+ + e^-$$
$$\hookrightarrow \bullet\, PH + H^+$$

where P stands for protein. Positive ions can also fragment into two or more smaller units:

$$HP{-}P'H^+ \rightarrow \bullet\, PH + P'H^+$$

The free radicals from water react with the chemical components dissolved in the water present in foods. For example, in the reaction with protein, •OH can produce a secondary protein radical:

$$\bullet\, OH + PH_2 \rightarrow \bullet\, PH + H_2O$$

Although this protein radical may be identical with the protein radicals described previously, it is said to be secondary because it is formed when a primary free radical (• OH) from water reacts with a protein molecule that is not a free radical. • OH can also add to the aromatic portion of amino acids to give a different kind of free radical known as the OH adduct,

$$\bullet\, OH + PH_2 \rightarrow HO{-}\dot{P}H_2$$

which also is a secondary free radical.

The molecular configurations of primary free radicals produced by absorption of ionizing energy by molecules depend upon the original configurations of the molecules affected. The constituents that split off when primary free radicals are formed depend upon the location of the weakest carbon-hydrogen or carbon-carbon bonds. The secondary free radicals that form when free radicals from water react with organic molecules in foods depend upon the relative reactivities of the organic food components with these free radicals.

Another important factor that affects the chemical nature of free radicals is the presence or absence of molecular oxygen. Molecular oxygen acts as a diradical with two unpaired electrons. In the presence of oxygen, most free radicals react with it to give a variety of peroxy radicals, for example,

$$\bullet\,\mathrm{LH} + \mathrm{O_2} \rightarrow \bullet\,\mathrm{OOLH}$$

In addition to formation of peroxy radicals, an electron transfer process can take place in which a hydrogen ion and a negatively charged oxygen free radical are formed:

$$\bullet\,\mathrm{PH} + \mathrm{O_2} \rightarrow \begin{cases} \bullet\,\mathrm{OOPH} \\ \mathrm{P} + \mathrm{H^+} + \bullet\,\mathrm{O_2^-} \end{cases}$$

The free-radical reactions that occur in the presence of molecular oxygen are thus very different from those that occur in its absence. The difference is of great practical significance with foods in which the products formed in the presence of oxygen contribute to rancidity.

When free radicals react with each other, they either "disproportionate" or "dimerize":

$$\bullet\,\mathrm{RH} + \bullet\,\mathrm{RH} \rightarrow \begin{cases} \mathrm{R} + \mathrm{RH_2} & \text{(disproportionation)} \\ \mathrm{HR{-}RH} & \text{(dimerization)} \end{cases}$$

In the disproportionation process, the two original hydrogen atoms are restored to half of the original material ($\mathrm{RH_2}$) and the other half lacks the two hydrogens (R). In the dimerization process, the two radicals simply join. In both processes, the original free radicals disappear, and the products are stable molecules. Often, some free radicals will disproportionate and others will form dimers in the same system, so that the product is a mixture of three forms (R, $\mathrm{RH_2}$, and HR-RH).

Free radicals may also undergo reactions with reactive solute molecules. An example is the interaction of free radicals with sulfhydryl groups (-SH), as in glutathione (GSH):

$$\bullet\,\mathrm{RH} + \mathrm{GSH} \rightarrow \mathrm{RH_2} + \bullet\,\mathrm{GS}$$

followed by the formation of the oxidized form of glutathione (GSSG):

$$\mathrm{GS}\,\bullet + \mathrm{GS}\,\bullet \rightarrow \mathrm{GSSG}$$

The foregoing reactions are an example of a mechanism by which a reactive radical (• RH) can be transformed into a relatively unreactive radical (GS•), which ends up in a product (GSSG) already present in the food.

A different type of free radical reaction with a solute involves an electron transfer, as in the reaction of peroxy radicals with ascorbate ($\mathrm{AH^-}$ — vitamin C):

$$\bullet\,\mathrm{OORH} + \mathrm{AH^-} \rightarrow \mathrm{HOORH} + \bullet\,\mathrm{A^-}$$

The ascorbate radicals (• $\mathrm{A^-}$) are not very reactive. They eventually disappear by reactions with each other to give ascorbate ($\mathrm{AH^-}$) and dehydroascorbic acid (A):

$$\bullet\,\mathrm{A^-} + \bullet\,\mathrm{A^-} \xrightarrow{\mathrm{H^+}} \mathrm{AH^-} + \mathrm{A}$$

Processing Conditions

In the early days of research on processing food with ionizing energy, when free-radical science was in its infancy, the processing conditions were chosen haphazardly. The advances in knowledge of free-radical reactions in the past 20 years have made it possible to modify the radiolytic effects to some degree to satisfy technological requirements. The nature and extent of the chemical reactions in foods treated with ionizing energy are affected by the conditions discussed briefly in the following paragraphs.

Dose of Ionizing Energy

The amounts of radiolytic products usually increase linearly with the absorbed dose of ionizing energy until the secondary products start to compete with the substrate molecules for the ionizing energy being supplied. The yield of a given radiolytic product can be calculated by the equation:

$$\mathrm{Y} = 10^7 \times \mathrm{G} \times \mathrm{D} \times \rho$$

where Y is the yield of product in moles per kilogram, G is the number of molecules changed per 100 electron volts of energy transferred to the food, D is the dose in grays, and ρ is the specific gravity of the food. Use of this equation to estimate the dose of ionizing energy that has been applied to food is not feasible because the products formed also occur naturally in food or are produced by other methods of processing.

Dose Rate

In general, the direct effects of ionizing energy, that is, the production of free radicals, are much less sensitive to the rate at which the energy is delivered than are the indirect effects, which are the reactions the free radicals undergo. The reason is that high dose rates promote the disappearance of free radicals by recombination because of their high concentration; this suppresses the reaction of free radicals with food components. Losses of certain vitamins and other water-soluble constituents in foods per unit of dose thus would tend to be diminished at high dose rates because the losses are mostly secondary effects that result from the action of free radicals from other sources. The killing of microorganisms, on the other hand, is normally insensitive to the dose rate because the major component in the mechanism of inactivation is the direct action of the ionizing energy.

The dose rate is greater in electron linear accelerators that supply the energy in pulses than it is in radionuclide irradiators. As a consequence, electron linear accelerators would be more suitable than radionuclide sources for delivering the dose needed to inactivate microorganisms while preserving the more susceptible vitamins in foods.

Temperature

The temperature at which products are maintained during processing with ionizing energy is of importance in two principal ways. One is the effect of temperature on the amount of energy that must be absorbed to cause specific reactions to proceed. The other is an indirect effect of temperature on the mobility of free radicals and, hence, on the reactions they undergo. As the temperature decreases, foods become more viscous and eventually become solids when they freeze. The mobility of free radicals consequently decreases. More of the molecular fragments then recombine to form the original molecules instead of moving away and reacting with other entities.

Flesh foods are especially sensitive to processing temperature. When flesh foods are treated at room temperature with the dose of about 40 kilograys of ionizing energy required to produce a sterile product, many reactions occur, and some of the products formed create an unacceptable odor and flavor. As a consequence, current practice is to process meats at low temperatures. The amounts of radiolytic products that can be found in flesh foods by analysis decrease as the temperature is lowered and parallel the sensory and other quality characteristics.

Although the chemical changes in flesh foods are drastically reduced at low temperatures, the killing of microorganisms is much less affected. Hence, the goal of producing a sterile and palatable product can be achieved by proper choice of the temperature and the dose of ionizing energy.

Atmosphere

As mentioned previously in the section on free radicals and their reactions, molecular oxygen acts as a diradical. Oxygen either adds to free radicals (HR•) to give peroxy radicals (HROO•), or it gives oxidized products (R) and superoxide radicals ($\bullet O_2^-$). Peroxy radicals usually abstract hydrogen atoms from molecules and form hydroperoxides (HROOH). Many hydroperoxides are not very stable and are converted into oxidized products.

For most biological systems, the presence of oxygen increases the effects of ionizing energy by a factor of 2 to 4. In fruits and vegetables, processing with ionizing energy in the presence of oxygen results in destruction of some of the more readily oxidized components. Effects are not pronounced for doses less than 1 kilogray, but they would become substantial for sterilizing doses of 20 to 40 kilograys if oxygen were present.

In fruits and vegetables exposed to the atmosphere, the internal oxygen is used up in chemical reactions when the dose of ionizing energy is about 600 grays (0.6 kilogray), provided that no chain reactions take place and the processing time is short enough to prevent reoxygenation through diffusion of atmospheric oxygen in from the outside. The total amount of oxidized products corresponding to depletion of the internal oxygen is theoretically about 260 micromoles per kilogram. In food items containing fat, the amount of oxidized products is increased because of the greater solubility of oxygen in fats. Most free radicals react readily with molecular oxygen to form peroxy radicals. The peroxy radicals may participate in reactions that contribute to the peroxidation of lipids via formation of hydroperoxides. For example, in lipids,

$$LH_2 + \bullet OOLH \rightarrow \bullet LH + HOOLH$$

Processing fat-containing foods with ionizing energy in the presence of molecular oxygen may cause rancidity. Reactions of molecular oxygen with the free radicals produced from fats by ionizing energy are an important source of certain volatile compounds that are produced in small quantities in flesh foods. If such foods absorb enough ionizing energy in the presence of air, these compounds may be formed in quantities sufficient to cause off-flavors and off-odors. Oxygen can be eliminated from packages of food to be processed by either evacuating them or purging them with an inert gas, such as nitrogen, argon, or carbon dioxide.

In the absence of molecular oxygen, the chemical reactions are governed by reducing species (e_{aq}^{-}, reducing radicals, hydrogen atoms). Dimerization and disproportionation of free radicals are the major reactions in addition to the reduction of oxidizing components, such as metmyoglobin in muscle. If products are processed in hermetically sealed containers that can be used for subsequent storage and distribution, the post-processing autoxidation that normally takes place in food can be prevented.

Physical State

When foods are processed with a given dose of ionizing energy, the effects are much less pronounced if the product is frozen than if it is unfrozen, as has been mentioned previously. If the temperature is in the range of liquid nitrogen (-292°F or -180°C) or below, the free radicals are immobile. As the temperature increases, the mobility and rate of reaction of the free radicals increase, especially when the food is unfrozen.

The water content of the food has a major effect on the formation of radiolytic products. In dry foods, the mobility of free radicals is very low, and free radicals may persist for many days. The presence of water, especially in the liquid phase, increases the mobility of the free radicals and their rate of reaction. Free radicals produced from the water add to the chemical changes. In general, the doses of ionizing energy that can be given without impairment in food quality are much greater for dry or semidry foods than for moist foods.

Phase

Although one phase may be dispersed finely in another phase, as for example the fat in marbled meat, the free-radical chemistry of the two phases is distinct, and one hardly affects the other. The reason is the very short distance that free radicals move before they react (usually less than 1 micron or 0.00004 inch). Only the relatively few radicals that are produced at the interfaces between phases can penetrate into the adjacent phase.

Additives

Most additives are used in minute quantities and therefore have no significant effect on the chemical reactions that occur in foods treated with ionizing energy. Tripolyphosphate, an additive used in small quantities, is relatively unreactive toward free radicals. Its main effect would be exerted indirectly through the pH changes it might produce. Salt, an additive used in relatively large quantities, is remarkably unreactive toward free radicals. Sugars, which are used in relatively large quantities (and are defined by the Food and Drug Administration as food additives), react with $\bullet$OH radicals to give substantial quantities of compounds containing carboxyl groups (-COOH) and other products. The effects of additives used in significant quantities must be evaluated for the individual substances because of their differing chemical nature.

To date, additives have not been found useful for controlling the chemical reactions that occur in foods treated with ionizing energy. For example, adding antioxidants would reduce the rancidity in fat-containing foods processed with large doses of ionizing energy in the presence of atmospheric oxygen. The rancidity could not be eliminated, however, unless the antioxidants were added in unacceptably large quantities. Particularly for solid foods, dispersing an additive well enough in the food to control the chemical reactions would be difficult.

Radiation Chemistry of Food Components

Carbohydrates

Some of the radiolytic products of carbohydrates in foods treated with ionizing energy (Thomas, 1987) are glucuronic, gluconic, and saccharic acids; glyoxal; arabinose; erythrose; formaldehyde; and dihydroxyacetone. Oligosaccharides yield monosaccharides and products similar to those obtained from simple sugars. Polysaccharides (starch, cellulose, or glycogen) yield smaller units, such as glucose, maltose, dextrins, and the radiolytic products of these substances.

Josephson et al. (1974) summarized the main effects of ionizing energy upon carbohydrates as being those of hydrolysis and oxidative degradation. Polysaccharides are depolymerized, and cellulose is made more susceptible to enzyme hydrolysis. Pectin substances lose their gelling powers. In short, complex carbohydrates are converted into simpler compounds by ionizing energy. Although ionizing energy may cause changes in the physical and chemical properties of high-carbohydrate foods, such as grains and some vegetables, these have not been shown to be of nutritional significance.

Simic (1983) and Philips (1972) have reported on the radiation chemistry of carbohydrates in model systems. Philips (1972) and Diehl et al. (1978) pointed out that foods contain many substances, such as amino acids and proteins, that protect carbohydrates against damage from ionizing energy. Therefore, caution must be exercised in extrapolating findings with pure substances and model systems (Thomas, 1987).

Proteins

Food proteins consist of 20 major amino acids that are linked in long-chain molecules. When proteins are subjected to ionizing energy, several types of reactions may occur. Chain scission is one of the principal changes. At the scission point, at least one end of the two resulting products will be altered by loss of an amino ($-NH_2$) group, formation of a carbonyl ($>C=O$) group, or decarboxylation (loss of a $-COOH$ or carboxyl group with formation of carbon dioxide).

Cross-links may be formed between different protein molecules and between different locations on a given protein molecule as a direct effect of the absorption of ionizing energy. Cross-linking as a result of indirect effects is efficient only in the absence of oxygen.

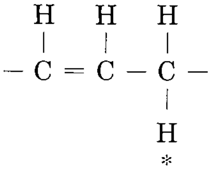
Parts of amino acid molecules can be lost as a direct effect of absorption of ionizing energy. The small quantities of volatile compounds formed from the break-up of individual amino acids include benzene and toluene from phenylalanine, dimethyl sulfide and dimethyldisulfide from methionine, hydrogen sulfide from cysteine, and acetaldehyde from serine. Free radicals derived from water usually alter the amino acids. For example, phenylalanine is altered to tyrosines, tyrosine to dihydroxyphenylalanine, tryptophan to kynurenine, and methionine to methionine sulfoxide.

Metal ions in proteins are usually reduced if they have a lower state of oxidation. For instance, cooked meats, which have a brown-gray color due to oxidation of ferrous iron (valence of 2) to ferric iron (valence of 3), revert back to the natural red color of fresh meats upon absorption of ionizing energy and reduction of iron to the ferrous form. Porphyrin rings, associated with myoglobin, hemoglobin, and cytochromes, may be altered by large doses of ionizing energy to produce yellow and green hues.

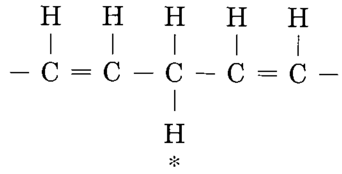
Several general statements may be made about the changes induced in the proteins of meats processed with ionizing energy. First, the amount of amino acids lost is less than 2% for a dose of 100 kilograys (which is more than twice the dose needed for product sterilization). Second, there is some net reduction in molecular weight. Third, damage to porphyrins at doses above 50 kilograys would reduce the shelf-life of meats due to color changes. Fourth, the digestibility and nutritional value is not reduced. And fifth, the texture of meats becomes softer, in part because of degradation of the connective tissue.

Fats

The nature and yields of radiolytic products from fat depend upon the fat percentage, the nature of the fatty acids, the dose of ionizing energy, the temperature, and the presence or absence of molecular oxygen. Autoxidation of fats and processing of fats with ionizing energy yield similar products, which contribute to rancidity. For example, both autoxidation and radiolysis of methyl oleate give 8, 9, 10, and 11 hydroperoxides as a result of peroxy radical reactions. With both processes, the weakest bonds are the target of attack. For example, in the segments of monounsaturated and diunsaturated fatty acids (those with a double bond between adjacent carbon atoms in one or two locations) shown here, the asterisks indicate the hydrogens with the weakest bonds:



$$-\overset{\mathrm{H}}{\mathrm{C}}=\overset{\mathrm{H}}{\mathrm{C}}-\underset{\underset{*}{\mathrm{H}}}{\overset{\mathrm{H}}{\mathrm{C}}}-$$



$$-\overset{\mathrm{H}}{\mathrm{C}}=\overset{\mathrm{H}}{\mathrm{C}}-\underset{\underset{*}{\mathrm{H}}}{\overset{\mathrm{H}}{\mathrm{C}}}-\overset{\mathrm{H}}{\mathrm{C}}=\overset{\mathrm{H}}{\mathrm{C}}-$$

The major products of radiolysis of fats, with or without oxygen present, are hydrocarbons, aldehydes, esters, free fatty acids, dimers, and gaseous hydrogen, carbon dioxide, and carbon monoxide. The only difference with oxygen present is the formation of ketones and larger amounts of dimers. In one study, yields of hydrocarbons ranged from 22 to 90 parts per million in pork processed with 60 kilograys of ionizing energy at -22°F (-30°C).

The yields of radiolysis products increase linearly with the dose of ionizing energy, as illustrated in Fig. III-1. Moreover, the yields of products increase at an increasing rate as the temperature rises, as illustrated in Fig. III-2.

Dimers and polymers of fats are normally induced by heat processing (frying and roasting) and by absorption of ionizing energy as well. Cross-linking in unsaturated fatty acids usually takes place at the weakest carbon-hydrogen bond. For example, in the segment of the monounsaturated fatty acid shown here, R is a second fatty acid that replaces a weakly bonded hydrogen in the original fatty acid molecule:

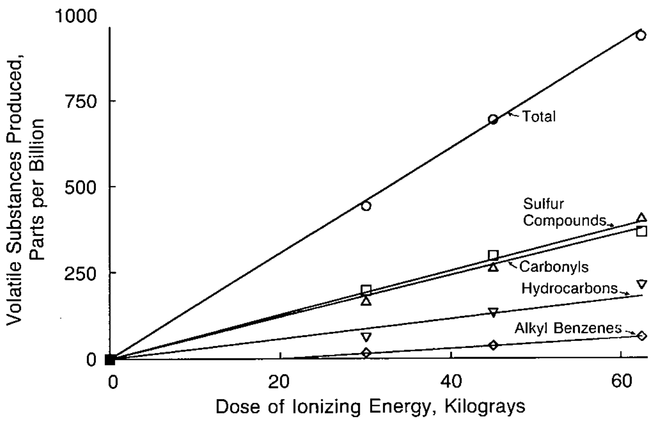
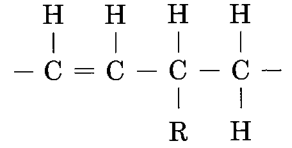


Figure III-1. Quantities of volatile substances produced in beef during processing with different doses of ionizing energy at -301°F (-185°C) (Merritt et al., 1975).



$$\begin{array}{ccccccc} H & & H & & H & & H \\ | & & | & & | & & | \\ -C & = & C & - & C & - & C- \\ & & & & | & & | \\ & & & & R & & H \end{array}$$

Unsaturated fatty acids are more prone to form cross-links and to build up to large molecules or polymers than are saturated fatty acids.

Antioxidants can reduce the quantity of radiolytic products in oxygenated foods because of their efficiency in inhibiting reactions with peroxy radicals. The relative efficiency of antioxidants in inhibiting the oxidation of fats during treatment with ionizing energy is the same as their relative efficiency in inhibiting autoxidation, namely,

alpha-tocopherol > propyl gallate > BHA,

where BHA is the usual acronym for butylated hydroxyanisole.

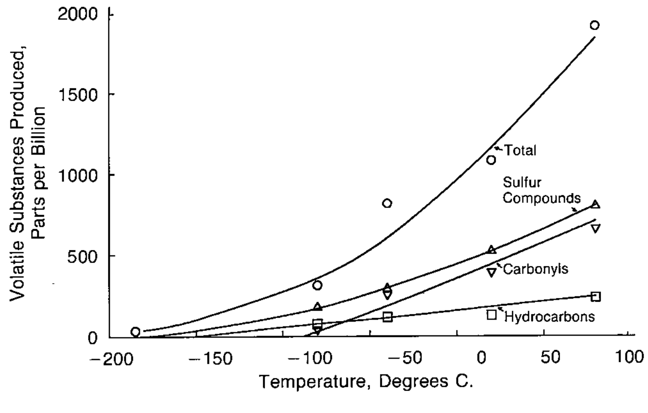


Figure III-2. Quantities of volatile substances produced in beef upon absorption of 45 kilograys of ionizing energy at different temperatures (Merritt et al., 1975).

Treatment of fats with ionizing energy does not contribute to formation of either aliphatic (saturated) or aromatic (unsaturated) carbon ring products. Processing of fats by heat, however, catalyzes the formation of both types of products, of which substituted cyclohexenes and pyrroles are the most abundant. Processing fat-containing foods by heat produces the same kinds of decomposition products noted in Fig. III-2, plus additional products, including the ring compounds, particularly as the temperature is raised above the boiling point of water.

Studies of the effects of ionizing energy on fats lead to the following general conclusions: (1) The volatile hydrocarbons of five- to eight-carbon chain length that are formed when meats are treated with ionizing energy are derived from fats, and their yield is proportional to the content of fat. (2) The composition of the hydrocarbons depends upon the composition of the fat, which differs among animal species and generally among foods. (3) The maximum dose level in fat-containing foods to be processed in the presence of atmospheric oxygen will be limited by the induced rancidity. (4) Depending primarily upon the temperature and the concentration of molecular oxygen during processing with ionizing energy and the dose of ionizing energy absorbed, the volatile compounds formed in small amounts in fats under the influence of ionizing energy may result in off-flavors and off-odors. If the food is stored in contact with air, the oxidative processes can continue for extended periods after exposure of the food to ionizing energy.

Vitamins

The chemical changes in vitamins induced by ionizing energy are governed by their individual reactivities to both primary and secondary free radicals. Vitamins such as A, C, E, B-12, thiamine, and quinones are very reactive with a variety of organic radicals, including peroxy radicals. Conversely, vitamins such as niacin, pyridoxine, riboflavin, D, pantothenic acid, and biotin are relatively unreactive toward many radicals and are fairly stable.

Studies of vitamins allow the following general conclusions: (1) Vitamins sensitive to heat are also sensitive to ionizing energy. (2) Vitamins are best preserved if ionizing energy is applied in the absence of gaseous oxygen and when foods are dry or frozen. (3) The rate of depletion of vitamins during processing with ionizing energy increases with the temperature. (4) For a given dose of ionizing energy, the loss of vitamins is greater with radionuclide sources than with electron beam sources.

General Conclusion

The current understanding of the chemical effects of ionizing energy on the composition of foods is such as to encourage the application of the technology. Although detectable, the chemical changes are small. For each kilogray of ionizing energy absorbed by 1 kilogram (2.2 pounds) of food, approximately 2 chemical bonds are broken in each million chemical bonds present. The products that have been found by analysis are the same types of compounds already present in foods and produced by other accepted means of processing.

The degree of predictability provided by current understanding is sufficient to provide a valuable supplement to the cumbersome and expensive animal feeding studies generally used to investigate the safety and nutritional value of foods treated with ionizing energy. The Food and Drug Administration (FDA, 1984) has gone even further in stating "that scientists should focus on the safety of the radiolytic products to evaluate the safety of irradiated food," pointing out that the traditional animal feeding studies are inappropriate.

Further research and development will lead to optimization of the conditions for processing and to improved quality and quality control for foods treated with ionizing energy. Similar efforts are now underway for heat-processed foods, 179 years after the discovery by Nicholas Appert that foods could be sterilized by heating.

Appendix IV: Poultry

Production, Marketing, and Distribution

Originally, most chickens and turkeys were produced in small barnyard flocks, and most of the carcasses were marketed as "New York dressed" (blood and feathers removed). Today, virtually all poultry offered to consumers are eviscerated. Per capita consumption of poultry meat is now about 78 pounds (35 kilograms) per year.

Chicken broilers are marketed predominantly by integrated firms that control both production and marketing. They own the hatchery, the feed mill, and the processing plant, and they contract with a producer to grow the birds. The firm supplies the chicks and feed, and the producer provides the house and labor for a certain contract fee per pound of broiler.

Integrated operations offer an opportunity for improved quality assurance. The firm provides technical service to the producer on production management, including disease control. The firm often monitors the feed for composition and *Salmonella* contamination. Large firms generally have central quality assurance staffs that monitor the processed birds or other processed items from the microbiological standpoint.

At present, more than 50% of the chicken meat eaten is cut up or further processed. Precooked battered and breaded patties and chicken parts have been adapted to microwave oven usage. The products marketed in the fast food industry are increasingly popular.

Some integrated firms in the turkey industry are involved in all phases of production and processing, but the turkey industry is integrated to a lesser extent than the broiler industry. Feed companies often provide financing for large production operations.

As late as the 1950s, most turkeys were marketed in the whole carcass form and were consumed primarily during the Thanksgiving and Christmas holidays. At present, turkey is eaten throughout the year, and more than 50% is consumed as further processed items, such as turkey rolls, turkey steak, turkey salami, turkey bologna, smoked turkey breasts, and turkey ham.

Bacterial Contamination and Shelf Life

In addition to the microorganisms in the intestinal tract, live poultry are contaminated with a variety of microorganisms on the skin, feathers, and feet (Ayres et al., 1950). Birds reared on the range probably have a greater variety of external microbial contaminants than those raised in confinement. Wet and muddy range conditions may greatly increase the bacterial contamination (Wilkerson et al., 1961).

Most turkeys and virtually all chicken broilers are now produced in environmentally controlled confinement houses. Thus, the poultry industry today has better control of the microbial environment around the growing birds than it did 25 years ago.

During the 1950s, bacterial counts on live poultry were found to range from 600 to 8,000 per square centimeter of skin area (Walker and Ayres, 1956). Ayres et al. (1980) isolated and identified a number of genera of bacteria from live poultry, as shown in Table IV-1. Some of these bacteria can cause human disease; others may cause spoilage in stored poultry. The predominant spoilage microorganisms are members of the *Pseudomonas-Acinetobacter-Moraxella* group.

The numbers of microorganisms tend to increase throughout the successive processing operations. Counts of bacteria in scald water are relatively low, but generally increase with each bird scalded (Gunderson et al., 1954; Walker and Ayres, 1956, 1959; Nagel et al., 1958). Both the dilution effect of the scald water overflow required by U.S. Department of Agriculture regulations and its temperature (136 to 140°F or 58 to 60°C) probably contribute to the relatively low counts of bacteria found in this water.

Transfer to the eviscerating line, opening of the body cavity, and drawing the viscera all increase the bacterial contamination of the carcass, but the final wash reduces it, as shown in Table IV-2. The effect of chilling the carcasses in ice slush on the numbers of bacteria on the skin varies with the degree of agitation of the water during chilling (Kotula et al., 1962; Casale et al., 1965; Brewer et al., 1961; May, 1974). Generally, counterflow and other types of continuous chillers decrease bacterial numbers during chilling. Counterflow chillers, however, cannot be depended upon to reduce the numbers of *Salmonella* because the primary contamination with these bacteria is in the

Table IV-1. Genera of bacteria isolated from poultry (Ayres et al., 1980)

Pseudomonas	*Paracolobacterium*	*Gaffkya*	*Corynebacterium*
Alcaligenes	*Proteus*	*Sarcina*	*Microbacterium*
Achromobacter	*Salmonella*	*Neisseria*	*Arthrobacter*
Flavobacterium	*Haemophilus*	*Brevibacterium*	*Bacillus*
Escherichia	*Micrococcus*	*Streptococcus*	*Actinomyces*
Aerobacter	*Staphylococcus*	*Lactobacillus*	*Streptomyces*

Table IV-2. Total counts of bacteria per square centimeter of poultry skin surface area at different work stations in a poultry processing plant (May, 1961)

	Number of bacteria per square centimeter		
Work station	Lowest	Usual range	Highest
After pick and wash	160	270 - 4,300	4,800
Feet and preen removal	270	460 - 3,800	6,500
Transfer to evisceration line	320	530 - 15,000	17,000
Opening body cavity	1,100	1,100 - 18,000	24,000
Draw viscera	1,100	1,200 - 16,000	28,000
Government inspection	840	1,400 - 17,000	23,000
Giblet removal	1,800	2,000 - 16,000	17,000
Lung removal	1,200	1,400 - 15,000	21,000
Crop removal	1,000	1,400 - 8,300	27,000
Final wash	54	360 - 4,900	7,000
House inspector	72	340 - 5,400	6,800

digestive tract. In contrast, total bacterial counts increase on carcasses in vat type chillers with no agitation.

Bacterial contamination increases during cutting and filleting of poultry meat. Counts may increase as much as six to eight fold (May, 1962). Contaminated cutting surfaces, such as a cutting board, may greatly increase total bacterial counts.

The shelf life of chilled fresh poultry is generally considered to be 8 to 10 days; however, it may be 3 to 7 days longer if the birds are processed under well controlled sanitary conditions, and it may also be shorter if the conditions are less sanitary. An off-odor and the presence of slime on the skin surface are the common subjective measures of deterioration. *Pseudomonas* species are most frequently associated with spoilage, and the numbers of these bacteria may reach approximately 100 million per square centimeter of skin surface before an off-odor and slime conditions are evident (Ayres et al., 1950).

Several factors may influence the shelf life of a refrigerated poultry carcass. Temperature is one of the most important. For example, Shannon and Stadelman (1957) found that the average shelf life was 13.8 days at 32°F (0°C) and 2.1 days at 68°F (20°C). Some processors use a deep-chill technique in which tray-packed parts are chilled rapidly to the freezing point (about 28°F or -2°C) and held at the freezing point. This technique increases the shelf life dramatically.

Other processing techniques have improved the shelf life. For example, chlorination of contact water increases the shelf-life of fresh broilers 2 to 5 days (Dawson et al., 1956). Dipping carcasses in a 5% solution of potassium sorbate increases the shelf life of poultry about 4 days (Dawson et al., 1979; Cunningham, 1979). Succinic and lactic acid are also effective. At one time, broad-spectrum antibiotics were proposed as a means of extending the shelf life. These antibiotics were effective in controlling the bacteria, but their use is not permitted at present because of residues in the products, buildup of populations of antibiotic-resistant bacteria, and growth of yeasts when bacterial growth is inhibited (Ayres et al., 1980).

Concentrations of carbon dioxide up to 25% in the atmosphere surrounding poultry carcasses increase their shelf life and reduce the development of adverse colors. Carbon dioxide "snow" (dry ice) is used commercially by some processors in place of ice to market fresh poultry.

Pasteurization of poultry carcasses by dipping them in hot water has also been tested (Pickett and Miller, 1966). Immersion of whole turkey carcasses for 20 seconds in water at 160°F (71°C) was found to kill 89% of the surface organisms. This technique has not gained wide acceptance because of the skin discoloration it sometimes produces.

Disease-Causing Bacteria

Salmonella are disease-causing bacteria that can exist in the digestive tracts of poultry and other birds, rodents, insects, wild animals, livestock, and humans. Infections with *Salmonella* are a major world health problem (Todd, 1980).

Poultry meat and eggs are often mentioned as important sources of *Salmonella* in the food supply. Poultry meat was indicated to be responsible for 12% of the reported food-borne disease outbreaks in the United States from 1966 to 1974 according to Horwitz and Gangorosa (1976). Several types of *Salmonella* have been identified in poultry processing plants (Bryan, 1968). The incidence of *Salmonella* in poultry as marketed in the United States ranged from 3 to 35% in reports reviewed by Ayres et al. (1980). Campbell et al. (1983) found in surveys of poultry processing plants that the proportion of chicken carcasses positive for *Salmonella* as the carcasses left the chillers was 21% in 1969 and 12% in 1979, indicating a probable downward trend. The variability among plants was so great, however, that the difference was not statistically significant. Cunningham and Cox (1987) reported that contamination of poultry with *Salmonella* was relatively low as the birds entered processing plants, but that *Salmonella* were spread during processing. In an attempt to find ways to reduce the contamination of its products, the poultry industry has increased its funding of research.

Poultry may become infected with *Salmonella* on the farm through feed, drinking water, and bird droppings. The infection of flocks may decrease considerably during growth. Dougherty (1976) found that 38% of the chicks tested were infected, but that only 3% of the broilers were infected at the time of marketing. During transportation to the processing plant, *Salmonella* may be spread through the droppings in the cages on the trucks. Additionally, loaders may be a source of contamination.

At the processing plant, the processes of feather picking, eviscerating, cutting, chilling, and packaging all provide opportunity for contaminating previously uncontaminated carcasses or parts of carcasses with *Salmonella.* See Table IV-3 for points of potential cross-contamination in poultry processing plants.

Scalding with steam is generally more effective in reducing *Salmonella* contamination than is scalding with hot water. Chilling has been found to reduce the total numbers of *Salmonella,* but at the same time it may spread the contamination.

Sanitation programs developed by many firms have substantially reduced the level of *Salmonella* contamination in processed poultry products. These programs generally start at the farm with careful monitoring of the feed, and continue with a management program to maintain cleanliness and to lower the incidence of disease in the flock. Within the plant, periodic samplings of carcasses and equipment are helpful in detecting contamination and the need for additional attention.

Complete eradication of *Salmonella* from the production and processing aspects of the poultry industry would be difficult. Proper treatment of packaged poultry with ionizing energy as it leaves the processing plant for marketing would assure *Salmonella*-free products and would eliminate most of the problem for consumers. Recontamination is possible, however, particularly in the home or restaurant, where mechanical transfer may occur from kitchen counters, cutting boards, knives, and the hands of cooks. Poultry that arrives contaminated may serve as a source to contaminate other foods by the same mechanisms. *Salmonella* in untreated raw poultry and other foods can be killed by proper cooking, but some foods are not cooked, and those that are cooked are not always heated enough to kill all the contaminating organisms.

Poultry products have been associated with outbreaks of food poisoning due to *Staphylococcus aureus,* but humans are the main reservoir of this organism (Bryan, 1968). Healthy poultry tissues do not support prolonged growth of staphylococci, but bruised tissues may often be contaminated. The U.S. Department of Agriculture thus requires that all bruises be removed from processed poultry. *Staphylococcus aureus* is easily spread on the hands of workers, in various processing operations, and in the chill water. This organism is sometimes a problem when turkey or chicken salad has been kept at temperatures in excess of 40°F (4.5°C) but less than 140°F (60°C) for extended periods before consumption.

Clostridium perfringens is also found in the intestinal tract of humans and other animals, including poultry. This bacterium is readily spread by poultry processing operations and has been isolated from various stages of processing. It has been found in both raw and cooked turkey products (Bryan and McKinley, 1974). Contaminated products can be made safe for consumption by cooking them to a minimum internal temperature of 165°F (74°C) and cooling them immediately after cooking.

Table IV-3. Some points of potential cross contamination in poultry processing plants (May, 1974)

1. Receiving and hanging
   - Bird to bird in coops
   - Air in holding sheds
   - Coops
   - Hands of hangers
   - Dust and air in hanging area
   - Shackles and rail dust
2. Killing
   - Bird to bird
   - Air
   - Killing machine or knife
   - Shackles and rail dust
3. Scalding and defeathering
   - Scald water
   - Picking fingers
   - Condensate
   - Air
   - Bird to bird
   - Pinners' hands
   - Hock cutter
   - Belt for rehang
   - Shackles and rail dust
   - Rehang operators' hands
4. Evisceration
   - Employees' and inspectors' hands
   - Knives and other cutting instruments
   - Machine contact surfaces (oil sac, lung machines, head cutters, etc.)
   - Air
   - Shackles and rail dust
   - Bird to bird
   - Noncutting instruments (lung guns, lung rakes, head pullers, etc.)
   - Belts and chutes
   - Giblet flumes and water
   - Hang back racks
5. Chilling
   - Chill water
   - Ice
   - Bird to bird
   - Air
   - Elevators
   - Belts and chutes
   - Giblet to giblet, neck to neck
6. Grading
   - Employees' hands
   - Belts
   - Shackles and rail dust
   - Bird to bird
   - Air
7. Ice packing
   - Employees' hands
   - Packing bins
   - Bird to bird
   - Air
   - Ice
   - Packing material
   - Giblet or neck to carcass (or vice versa)
8. Cut-up
   - Employees' hands
   - Knives
   - Saws or power knives
   - Bird to bird
   - Part to part
   - Air
   - Belts, bins, pans, etc.
   - Shackles and rail dust

Campylobacter fetus, subspecies *jejuni,* was rarely associated with human infections before the last 10 years. Today, *Campylobacter jejuni* has become a common cause of acute bacterial gastroenteritis in humans. The organism has been isolated frequently from commercially processed poultry (Blankenship et al., 1983; Oosterom et al., 1983), where it occurs primarily in the digestive tract. Scalding reduces the contamination of carcasses, but the bacterial numbers increase during defeathering and evisceration. Spin chilling greatly reduces the total numbers of *Campylo-*

bacter jejuni on carcasses, but it is not a method for complete decontamination.

Yersinia enterocolitica, another possible cause of gastroenteritis, may be transmitted to foods and water through fecal contamination. This organism has been isolated from both turkey and chicken (Stern and Pierson, 1979). Although there have been no widespread isolations from poultry, the potential for contaminating poultry exists.

Listeria monocytogenes recently has become of concern in a number of animal products, but no outbreak of human listeriosis originating from poultry meat has been reported. The potential exists if poultry meat is improperly handled, however, as indicated by the fact that Bailey and Fletcher (1987) detected *Listeria monocytogenes* in 42.5% of the broiler chickens they tested.

Appendix V: Tables

Table V-1. Doses of ionizing energy suitable for various applications to food (Adapted and updated from Ley, 1971)

Application	Dose range, kilograys
Sterilization to allow long-term unrefrigerated storage of meats, meat products, poultry, shellfish, finfish, and other products	20-72
Sterilization of spices, dehydrated vegetable seasonings, and related products	10-30
Extension of refrigerated storage of meats, poultry, fish, shellfish, and other products at 32-39°F (0-4°C)	0.75-3
Inactivation of bacterial pathogens, such as *Salmonella, Campylobacter, Yersinia,* and *Listeria,* from meats, poultry, eggs, fish, shellfish, and animal feeds	1-10
Reduction of molds and yeasts on fruits and vegetables	1-5
Inactivation of parasites in meats and fish	0.1-10
Inactivation of insects in cereals, vegetables, fruits, and other products	0.1-2
Inhibition of sprouting of potatoes, onions, and other bulb, tuber, and root crops	0.05-0.15
Delay of ripening and senescence of fresh fruits and vegetables	0.25-1
Sterilization of laboratory animal diets	20-50

Table V-2. Useful depth of penetration of accelerated electrons in water[a] (Brynjolfsson, 1963)

Energy, millions of electron volts	Useful depth when irradiated from one side		Useful depth when irradiated from two sides	
	Centimeters	Inches	Centimeters	Inches
1	0.28	0.11	0.72	0.28
2	0.56	0.22	1.44	0.57
3	0.88	0.35	2.12	0.83
4	1.23	0.48	2.96	1.17
5	1.56	0.61	3.84	1.51
6	1.92	0.76	4.68	1.84
7	2.24	0.88	5.50	2.17
8	2.56	1.01	6.44	2.54
9	2.89	1.14	7.22	2.84
10	3.20	1.26	8.06	3.17

[a] The depth at which the dose is equal to the dose at the surface.

Table V-4. Effects of ionizing energy on some food and sewage-borne parasitic protozoa (King and Josephson, 1983)

Organism	Dose, kilograys	Effect
Entamoeba histolytica	0.6 to 1.4	Partial inhibition of growth *in vitro*
	0.25	100% destruction of viable cysts
	2.0	Trophozoites killed
Toxoplasma gondii	0.1	Loss of lethal infectiousness
	0.3	Parasites killed

Table V-3. Dosimeters and their effective ranges[a]

Dosimeter	Effective range, grays
Alanine	1 x 10^{0} - 1 x 10^{7}
Ferrous sulfate (Fricke dosimeter)	3 x 10^{1} - 4 x 10^{4}
Super Fricke (oxygen-saturated)	3 x 10^{1} - 2 x 10^{5}
Radiochromic dyes	5 x 10^{1} - 1 x 10^{7}
Photographic films	2 x 10^{-4} - 1 x 10^{7}
Thermoluminescence materials (calcium fluoride, lithium borate, lithium fluoride)	2 x 10^{-4} - 1 x 10^{5}
Glass	1 x 10^{2} - 5 x 10^{6}
Ethanol-chlorobenzene	1 x 10^{2} - 1 x 10^{7}
Ferrous-cupric	6 x 10^{2} - 8 x 10^{5}
High dose ferrous-cupric (6 times normal concentration)	8 x 10^{3} - 8 x 10^{6}
Ceric sulfate	1 x 10^{2} - 2 x 10^{7}
Potassium dichromate	1 x 10^{1} - 1 x 10^{5}
Oxalic acid	7 x 10^{3} - 5 x 10^{7}
Polymethylmethacrylate	
Perspex HX	1 x 10^{3} - 1 x 10^{7}
Red perspex	1 x 10^{3} - 5 x 10^{6}
Polyvinylchloride films	5 x 10^{3} - 7 x 10^{6}
Blue cellophane	5 x 10^{3} - 1 x 10^{7}

[a] Compiled from published sources by Robert D. Jarrett, Sr., U.S. Department of Agriculture, Hyattsville, Maryland.

Table V-5. Effects of ionizing energy on some food and sewage-borne parasitic helminths (King and Josephson, 1983)

Organism	Dose, kilograys	Effect
Fasciola hepatica	0.03	Failure to mature and eventual death in host, decreased infectivity and pathogenicity, development arrested, no adults
	0.2	Inhibited encystation *in vitro*
Hymenolepis nana	0.2 to 0.4	No adults developed, most adults sexually sterile
Trichinella spiralis	2.3 to 7.9	Kills
	0.009 to 0.3	Sterilizes females, inhibits muscle invasion and maturation, kills larvae, eliminates infestation, adults sterile

Table V-6. Components of tinplated cans used successfully as food containers during sterilization with ionizing energy at temperatures below freezing and at high vacuum and for subsequent storage of the food (Killoran, 1976)

Tinplate	No. 25 electrolytic tinplate 95 lb LTU or No. 25 electrolytic tinplate 100 lb MRT-2
Sideseam	Conventional 2-98 solder
Enamel	Epoxy-phenolic with aluminum pigment or epoxy type with aluminum pigment and wax
End sealing compound	Blend of cured and uncured poly (isobutylene-*co*-isoprene) or blend of neoprene and butadiene-styrene elastomers

Table V-7. Flexible packaging materials approved by the Food and Drug Administration for use with prepackaged foods to be processed with ionizing energy (Anonymous, 1988)

Material	Maximum dose of ionizing energy, kilograys
Kraft paper	0.5
Glassine paper	10.0
Wax-coated paperboard	10.0
Nitrocellulose-coated or vinylidene chloride copolymer-coated cellophane	10.0
Polyolefin film	10.0
Polyethylene terephthalate film[a]	10.0
Polystyrene film	10.0
Rubber hydrochloride film	10.0
Vinylidene chloride-vinyl chloride basic copolymer film	10.0
Nylon 11	10.0
Vegetable parchments	60.0
Polyethylene film	60.0
Polyethylene terephthalate film[a]	60.0
Nylon 6 film	60.0
Vinyl chloride-vinyl acetate copolymer film	60.0

[a] The formulation approved for 60 kilograys differs from the one approved for 10 kilograys.

Table V-8. Components of multilayer flexible pouches used successfully for sterilizing food with ionizing energy and for protecting the food from subsequent contamination (Killoran, 1983)

Pouch number	Pouch film components	Film component thickness, microns[a]
1	Polyethylene terephthalate	13
	Aluminum foil	9
	Polyethylene terephthalate	13
	Polyethylene, 0.96 gram per milliliter	80
2	Polyethylene terephthalate	13
	Aluminum foil	9
	Ethylene-butene-1 copolymer-polyisobutylene blend (70-30)	80
3	Polyiminocaproyl	25
	Aluminum foil	9
	Ethylene-butene-1 copolymer, 0.950 gram per milliliter	80
4	Polyethylene terephthalate	13
	Aluminum foil	9
	Polypropylene-ethylene vinyl acetate copolymer (94-6)	80
5	Polyiminocaproyl	25
	Aluminum foil	9
	Polyethylene terephthalate	13
	Polypropylene	80

[a] The 6-micron adhesive between any two layers is epoxy-polyester cured with the reaction product of trimethylolpropane and 2,4-toluene di-isocyanate.

Table V-9. Clearances as of March 22, 1988, for use of ionizing energy on foods (IAEA, 1988a)

Country	Product	Purpose of treatment	Sort of clearance	Dose permitted, kilograys	Date of approval
Argentina	Strawberries	Shelf-life extension	Unconditional	2.5 max.	30 April 1987
	Potatoes	Sprout inhibition	Unconditional	0.03 to 0.15	30 April 1987
	Onions	Sprout inhibition	Unconditional	0.02 to 0.15	30 April 1987
	Garlic	Sprout inhibition	Unconditional	0.02 to 0.15	30 April 1987
Bangladesh	Chicken	Shelf-life extension/ decontamination	Unconditional	Up to 8	28 December 1983
	Papaya	Insect disinfestation/ control of ripening	Unconditional	Up to 1	28 December 1983
	Potatoes	Sprout inhibition	Unconditional	Up to 0.15	28 December 1983
	Wheat and ground wheat products	Insect disinfestation	Unconditional	Up to 1	28 December 1983
	Fish	Shelf-life extension/ decontamination Insect disinfestation	Unconditional	Up to 2.2	28 December 1983
	Onions	Sprout inhibition	Unconditional	Up to 0.15	28 December 1983
	Rice	Insect disinfestation	Unconditional	Up to 1	28 December 1983
	Frog legs	Decontamination	Provisional		
	Shrimp	Shelf-life extension/ decontamination	Provisional		
	Mangoes	Shelf-life extension/ insect disinfestation Control ripening	Unconditional	Up to 1	28 December 1983
	Pulses	Insect disinfestation	Unconditional	Up to 1	28 December 1983
	Spices	Decontamination/ insect disinfestation	Unconditional	Up to 10	28 December 1983
Belgium	Potatoes	Sprout inhibition	Provisional	Up to 0.15	16 July 1980
	Strawberries	Shelf-life extension	Provisional	Up to 3	16 July 1980
	Onions	Sprout inhibition	Provisional	Up to 0.15	16 October 1980
	Garlic	Sprout inhibition	Provisional	Up to 0.15	16 October 1980
	Shallots	Sprout inhibition	Provisional	Up to 0.15	16 October 1980
	Black/white pepper	Decontamination	Provisional	Up to 10	16 October 1980
	Paprika powder	Decontamination	Provisional	Up to 10	16 October 1980
	Arabic gum	Decontamination	Provisional	Up to 10	29 September 1983
	Spices (78 different products)	Decontamination	Provisional	Up to 10	29 September 1983
	(Semi)-dried vegetables (7 different products)				
Brazil	Rice	Insect disinfestation	Unconditional	Up to 1	7 March 1985
	Potatoes	Sprout inhibition	Unconditional	Up to 0.15	7 March 1985
	Onions	Sprout inhibition	Unconditional	Up to 0.15	7 March 1985
	Beans	Insect disinfestation	Unconditional	Up to 1	7 March 1985
	Maize	Insect disinfestation	Unconditional	Up to 0.5	7 March 1985
	Wheat	Insect disinfestation	Unconditional	Up to 1	7 March 1985
	Wheat flour	Insect disinfestation	Unconditional	Up to 1	7 March 1985
	Spices (13 different products)	Decontamination/ insect disinfestation	Unconditional	Up to 10	7 March 1985
	Papaya	Insect disinfestation/ control of ripening	Unconditional	Up to 1	7 March 1985
	Strawberries	Shelf-life extension	Unconditional	Up to 3	7 March 1985
	Fish and fish-products (fillets, salted, smoked, dried, dehydrated)	Shelf-life extension/ decontamination/ insect disinfestation	Unconditional	Up to 2.2	8 March 1985
	Poultry	Shelf-life extension/ decontamination	Unconditional	Up to 7	8 March 1985
Bulgaria	Potatoes	Sprout inhibition	Experimental batches	0.1	30 April 1972
	Onions	Sprout inhibition	Experimental batches	0.1	30 April 1972
	Garlic	Sprout inhibition	Experimental batches	0.1	30 April 1972
	Grain	Insect disinfestation	Experimental batches	0.3	30 April 1972

Table V-9, continued

Bulgaria, continued	Dry food concentrates	Insect disinfestation	Experimental batches	1	30 April 1972
	Dried fruits	Insect disinfestation	Experimental batches	1	30 April 1972
	Fresh fruits (tomatoes, peaches, apricot, cherry, raspberry, grapes)	Shelf-life extension	Experimental batches	2.5	30 April 1972
Canada	Potatoes	Sprout inhibition	Unconditional	Up to 0.1	9 November 1960 14 June 1963
	Onions	Sprout inhibition	Unconditional	Up to 0.15	25 March 1965
	Wheat, flour, whole wheat	Insect disinfestation	Unconditional	Up to 0.75	25 February 1969
	Poultry	Decontamination	Test marketing	Up to 7	20 June 1973
	Cod & haddock fillets	Shelf-life extension	Test marketing	Up to 1.5	2 October 1973
	Spices and certain dried vegetable seasonings	Decontamination	Unconditional	Up to 10	3 October 1984
	Onion powder	Decontamination	Unconditional	Up to 10	12 December 1983
Chile	Potatoes	Sprout inhibition	Experimental batches		31 October 1974
			Test marketing		29 December 1982
			Unconditional	Up to 0.15	
	Papaya	Insect disinfestation	Unconditional	Up to 1	29 December 1982
	Wheat and ground wheat products	Insect disinfectation	Unconditional	Up to 1	29 December 1982
	Strawberries	Shelf-life extension	Unconditional	Up to 3	29 December 1982
	Chicken	Decontamination	Unconditional	Up to 7	29 December 1982
	Onions	Sprout inhibition	Unconditional	Up to 0.15	29 December 1982
	Rice	Insect disinfestation	Unconditional	Up to 1	29 December 1982
	Teleost fish and fish products	Shelf-life extension/ decontamination/ insect disinfestation	Unconditional	Up to 2.2	29 December 1982
	Cocoa beans	Decontamination/ insect disinfestation	Unconditional	Up to 5	29 December 1982
	Dates	Insect disinfestation	Unconditional	Up to 1	29 December 1982
	Mangoes	Shelf-life extension/ insect disinfestation/ control of ripening	Unconditional	Up to 1	29 December 1982
	Pulses	Insect disinfestation	Unconditional	Up to 1	29 December 1982
	Spices and condiments	Decontamination/ insect disinfestation	Unconditional	Up to 10	29 December 1982
China (People's Republic)	Potatoes	Sprout inhibition	Unconditional	Up to 0.20	30 November 1984
	Onions	Sprout inhibition	Unconditional	Up to 0.15	30 November 1984
	Garlic	Sprout inhibition	Unconditonal	Up to 0.10	30 November 1984
	Peanuts	Insect disinfestation	Unconditional	Up to 0.40	30 November 1984
	Grain	Insect disinfestation	Unconditional	Up to 0.45	30 November 1984
	Mushrooms	Growth inhibition	Unconditional	Up to 1	30 November 1984
	Sausage	Decontamination	Unconditional	Up to 8	30 November 1984
Czechoslovakia	Potatoes	Sprout inhibition	Experimental batches	Up to 0.1	26 November 1976
	Onions	Sprout inhibition	Experimental batches	Up to 0.08	26 November 1976
	Mushrooms	Growth inhibition	Experimental batches	Up to 2	26 November 1976
Denmark	Spices and herbs	Decontamination	Unconditional	Up to 15 maximum Up to 10 average	23 December 1985
Finland	Dry and dehydrated spices and herbs	Decontamination	Unconditional	Up to 10 average	13 November 1987
	Sterilization of all foods for patients requiring sterile diets	Sterilization	Unconditional	Unlimited	13 November 1987
France	Potatoes	Sprout inhibition	Provisional	0.075 - 0.15	8 November 1972
	Onions	Sprout inhibition	Provisional	0.075 - 0.15	9 August 1977
	Garlic	Sprout inhibition	Provisional	0.075 - 0.15	9 August 1977
	Shallot	Sprout inhibition	Provisional	0.075 - 0.15	9 August 1977

Table V-9, continued

France, continued	Spices and aromatic substances (72 products including powdered onions and garlic)	Decontamination	Unconditional	Up to 11	10 February 1983
	Gum arabic	Decontamination	Unconditional	Up to 9	16 June 1985
	Muesli-like cereal	Decontamination	Unconditional	Up to 10	16 June 1985
	Dehydrated vegetables	Decontamination	Unconditional	Up to 10	16 June 1985
	Mechanically deboned poultry meat	Decontamination	Unconditional	Up to 5	16 February 1985
	Dried fruits	Insect disinfestation	Unconditional	1 maximum	6 January 1988
	Dried vegetables	Insect disinfestation	Unconditional	1 maximum	6 January 1988
German Democratic Republic	Onions	Sprout inhibition	Test marketing	0.05	1981
	Onions	Sprout inhibition	Unconditional	0.20	30 January 1984
	Enzyme solutions	Decontamination	Unconditional	10	7 June 1983
	Spices	Decontamination	Provisional	Up to 10	29 December 1982
Hungary	Potatoes	Sprout inhibition	Test marketing	0.1	23 December 1969
	Potatoes	Sprout inhibition	Test marketing	0.15 maximum	10 January 1972
	Potatoes	Sprout inhibition	Test marketing	0.15 maximum	5 March 1973
	Onions	Sprout inhibition	Test marketing		5 March 1973
	Strawberries	Shelf-life extension	Test marketing		5 March 1973
	Mixed spices (black pepper, cumin, paprika, dried garlic: for use in sausages)	Decontamination	Experimental batches	5	2 April 1974
	Onions	Sprout inhibition	Test marketing	0.06	6 August 1975
	Onions	Sprout inhibition	Experimental batches	0.06	6 September 1976
	Mixed dry ingredients (for canned hashed meat)	Decontamination	Experimental batches	5	20 November 1976
	Potatoes	Sprout inhibition	Test marketing	0.10	4 May 1980
	Onions	Sprout inhibition	Experimental batches	0.05	15 September 1980
	Onions for dehydrated flakes processing	Sprout inhibition	Test marketing	0.05	18 November 1980
	Mushrooms (*Agaricus*)	Growth inhibition	Test marketing	2.5	20 June 1981
	Strawberries	Shelf-life extension	Test marketing	2.5	20 June 1981
	Potatoes	Sprout inhibition	Test marketing	0.1	13 October 1981
	Potatoes	Sprout inhibition	Test marketing	0.10	2 December 1981
	Spices for sausage production	Decontamination	Test marketing	5	4 January 1982
	Strawberries	Shelf-life extension	Test marketing	2.5	15 April 1982
	Mushrooms (*Agaricus*)	Growth inhibition	Test marketing	2.5	15 April 1982
	Mushrooms (*Pleurotus*)	Growth inhibition	Test marketing	3	15 April 1982
	Grapes	Shelf-life extension	Test marketing	2.5	15 April 1982
	Cherries	Shelf-life extension	Test marketing	2.5	15 April 1982
	Sour cherries	Shelf-life extension	Test marketing	2.5	15 April 1982
	Red currants	Shelf-life extension	Test marketing	2.5	15 April 1982
	Onions	Sprout-inhibition	Unconditional	0.05 + 0.02	23 June 1982
	Spices for sausage	Decontamination	Test marketing	5	28 June 1982
	Pears	Shelf-life extension	Test marketing	2.5	7 December 1982
	Pears	Shelf-life extension	Test marketing	1.0 + $CaCl_2$ treatment	24 January 1983
	Spices	Decontamination	Test marketing	5	1983
	Potatoes (for processing into flakes)	Sprout inhibition	Test marketing	0.1	28 January 1983
	Frozen chicken	Decontamination	Test marketing	4	3 October 1983
	Sour cherries (canned)		Conditional	0.2 average	20 February 1984 23 April 1985
	Black pepper	Decontamination	Conditional	6 minimum	May 1985
	Spices	Decontamination	Conditional	5-6 minimum	25 April 1986
	Spices	Decontamination	Unconditional	8, 6 average	19 August 1986
India	Potatoes	Sprout inhibition	Unconditional	Codex Standard	January 1986
	Onions	Sprout inhibition	Unconditional	Codex Standard	January 1986
	Spices	Disinfection	For export only	Codex Standard	January 1986
	Frozen shrimp and frog legs	Disinfection	For export only	Codex Standard	January 1986

Table V-9, continued

Indonesia	Dried spices	Decontamination	Unconditional	10 maximum	29 December 1987
	Tuber and root crops (potatoes, shallot, garlic and rhizomes)	Sprout inhibition	Unconditional	0.15 maximum	29 December 1987
	Cereals	Disinfestation	Unconditional	1 maximum	29 December 1987
Israel	Potatoes	Sprout inhibition	Unconditional	0.15 maximum	5 July 1967
	Onions	Sprout inhibition	Unconditional	0.10 maximum	25 July 1968
	Poultry and poultry sections	Shelf-life extension/ decontamination	Unconditional	7 maximum	23 April 1982
	Onions	Sprout inhibition	Unconditional	0.15	6 March 1985
	Garlic	Sprout inhibition	Unconditional	0.15	6 March 1985
	Shallots	Sprout inhibition	Unconditional	0.15	6 March 1985
	Spices (36 different products	Decontamination	Unconditional	10	6 March 1985
	Fresh fruits and vegetables	Disinfestation	Unconditional	1 average	January 1987
	Grains, cereals, pulses, cocoa & coffee beans, nuts, edible seeds	Disinfestation	Unconditional	1 average	January 1987
	Mushrooms, strawberries	Shelf-life extension	Unconditional	3 average	January 1987
	Poultry and poultry sections	Decontamination	Unconditional	7 average	January 1987
	Spices & condiments, dehydrated & dried vegetables, edible herbs	Decontamination	Unconditional	10 average	January 1987
	Poultry feeds	Decontamination	Unconditional	15 average	January 1987
Italy	Potatoes	Sprout inhibition	Unconditional	0.075 - 0.15	30 August 1973
	Onions	Sprout inhibition	Unconditional	0.075 - 0.15	30 August 1973
	Garlic	Sprout inhibition	Unconditional	0.075 - 0.15	30 August 1973
Japan	Potatoes	Sprout inhibition	Unconditional	0.15 maximum	30 August 1972
Korea, Republic of	Potatoes	Sprout inhibition	Unconditional	0.15 maximum	28 September 1987
	Onions	Sprout inhibition	Unconditional	0.15 maximum	28 September 1987
	Garlic	Sprout inhibition	Unconditional	0.15 maximum	28 September 1987
	Chestnuts	Sprout inhibition	Unconditional	0.25 maximum	28 September 1987
	Fresh and dried mushrooms	Growth inhibition and insect disinfestation	Unconditional	1.00 maximum	28 September 1987
Netherlands	Asparagus	Shelf-life extension/ growth inhibition	Experimental batches	2 maximum	7 May 1969
	Cocoabeans	Insect disinfestation	Experimental batches	0.7 maximum	7 May 1969
	Strawberries	Shelf-life extension	Experimental batches	2.5 maximum	7 May 1969
	Mushrooms	Growth inhibition	Unconditional	2.5 maximum	23 October 1969
	Deep-frozen meals	Sterilization	Hospital patients	25 minimum	27 November 1969
	Potatoes	Sprout inhibition	Unconditional	0.15 maximum	23 March 1970
	Shrimp	Shelf-life extension	Experimental batches	0.5-1	13 November 1970
	Onions	Sprout inhibition	Experimental batches	0.15	5 February 1971
	Spices and condiments	Decontamination	Experimental batches	8-10	13 September 1971
	Poultry, eviscerated (in plastic bags)	Shelf-life extension	Experimental batches	3 maximum	31 December 1971
	Fresh, tinned and liquid foodstuffs	Sterilization	Hospital patients	25 minimum	8 March 1972
	Spices	Decontamination	Provisional	10	4 October 1974
	Powdered battermix	Decontamination	Test marketing	1.5	4 October 1974
	Vegetable filling endive	Decontamination/	Test marketing	0.75	4 October 1974
	(prepared, cut)	shelf-life extension	Test marketing	1	14 January 1975
	Onions	Sprout inhibition	Unconditional	0.05 maximum	9 June 1975
	Spices	Decontamination	Provisional	10	26 June 1975
	Peeled potatoes	Shelf-life extension	Test marketing	0.5	12 May 1976
	Chicken	Shelf-life extension/ decontamination	Unconditional	3 maximum	10 May 1976
	Shrimp	Shelf-life extension	Test marketing	1	15 June 1976
	Fillets of haddock,	Shelf-life extension	Test marketing	1	6 September 1976

Table V-9 — *continued*

Netherlands, continued	coal-fish, whiting				
	Fillets of cod and plaice	Shelf-life extension	Test marketing	1	7 September 1976
	Fresh vegetables (prepared, cut, soupgreens)	Shelf-life extension	Test marketing	1	6 September 1977
	Spices	Decontamination	Provisional	10	4 April 1978
	Frozen frog legs	Decontamination	Provisional	5	25 September 1978
	Rice and ground rice products	Insect disinfestation	Provisional	1	15 March 1979
	Rye bread	Shelf-life extension	Provisional	5 maximum	12 February 1980
	Spices	Decontamination	Provisional	7 maximum	15 April 1980
	Frozen shrimp	Decontamination	Provisional	7 maximum	9 May 1980
	Malt	Decontamination	Provisional	10 maximum	8 February 1983
	Boiled and cooled shrimp	Shelf-life extension	Provisional	1 maximum	8 February 1983
	Frozen shrimp	Decontamination	Provisional	7 maximum	8 February 1983
	Frozen fish	Decontamination	Provisional	6 maximum	24 August 1983
	Egg powder	Decontamination	Provisional	6 maximum	25 August 1983
	Dry blood protein	Decontamination	Provisional	7 maximum	25 August 1983
	Dehydrated vegetables	Decontamination	Provisional	10 maximum	27 October 1983
	Refrigerated snacks of minced meat	Shelf-life extension	Test marketing	2	12 July 1984
New Zealand	Herbs and spices (one batch)	Decontamination	Provisional	8	March 1985
Norway	Spices	Decontamination	Unconditional	Up to 10	
Philippines	Potatoes	Sprout inhibition	Provisional	0.15 maximum	13 September 1972
	Onions	Sprout inhibition	Provisional	0.07	1981
	Garlic	Sprout inhibition	Provisional	0.07	1981
	Onions and garlic	Sprout inhibition	Test marketing		9 July 1984 29 September 1986
Poland	Potatoes	Sprout inhibition	Provisional	Up to 0.15	1982
	Onions	Sprout inhibition	Provisional		March 1983
South Africa	Potatoes	Sprout inhibition	Unconditional	0.12 - 0.24	19 January 1977
	Dried bananas	Insect disinfestation	Provisional	0.5 maximum	28 July 1977
	Avocados	Insect disinfestation	Provisional	0.1 maximum	28 July 1977
	Onions	Sprout inhibition	Unconditional	0.5 - 0.15	25 August 1978
	Garlic	Sprout inhibition	Unconditional	0.1 - 0.20	25 August 1978
	Chicken	Shelf-life extension/ decontamination	Unconditional	2 - 7	25 August 1978
	Papaya	Shelf-life extension	Unconditional	0.5 - 1.5	25 August 1978
	Mango	Shelf-life extension	Unconditional	0.5 - 1.5	25 August 1978
	Strawberries	Shelf-life extension	Unconditional	1 - 4	25 August 1978
	Bananas	Shelf-life extension	Unconditional		1982
	Litchis	Shelf-life extension	Unconditional		1982
	Pickled mango (achar)	Shelf-life extension	Unconditional		1982
	Avocados	Shelf-life extension	Unconditional		1982
	Frozen fruit juices	Shelf-life extension	Unconditional		1982
	Green beans		Unconditional		
	Tomatoes	Control ripening	Unconditional		
	Soya pickle products		Unconditional		
	Ginger		Unconditional		
	Vegetable paste		Unconditional		
	Bananas (dried)	Insect disinfestation	Unconditional		
	Almonds	Insect disinfestation	Unconditional		
	Cheese powder	Insect disinfestation	Unconditional		
	Yeast powder		Unconditional		
	Herbal tea		Unconditional		
	Various spices		Unconditional		
	Various dehydrated vegetables		Unconditional		
Spain	Potatoes	Sprout inhibition	Unconditional	0.05 - 0.15	4 November 1969

Table V-9, continued

Spain, continued	Onions	Sprout inhibition	Unconditional	0.08 maximum	1971
Thailand	Onions	Sprout inhibition	Unconditional	0.1 maximum	20 March 1973
	Potatoes, onions, garlic	Sprout inhibition	Unconditional	0.15	4 December 1986
	Dates	Disinfestation	Unconditional	1	4 December 1986
	Mangoes, papaya	Disinfestation/ delay of ripening	Unconditional	1	4 December 1986
	Wheat, rice, pulses	Disinfestation	Unconditional	1	4 December 1986
	Cocoa beans	Disinfestation	Unconditional	1	4 December 1986
	Fish and fishery products	Disinfestation	Unconditional	1	4 December 1986
	Fish and fishery products	Reduce microbial load	Unconditional	2.2	4 December 1986
	Strawberries	Shelf-life extension	Unconditional	3	4 December 1986
	Nam	Decontamination	Unconditional	4	4 December 1986
	Moo yor	Decontamination	Unconditional	5	4 December 1986
	Sausage	Decontamination	Unconditional	5	4 December 1986
	Frozen shrimp	Decontamination	Unconditional	5	4 December 1986
	Cocoa beans	Reduce microbial load	Unconditional	5	4 December 1986
	Chicken	Decontamination and shelf-life extension	Unconditional	7	4 December 1986
	Spices & condiments, dehydrated onions and onions	Insect disinfestation	Unconditional	1	4 December 1986
		Decontamination	Unconditional	10	4 December 1986
Union of Soviet Socialist Republics	Potatoes	Sprout inhibition	Unconditional	0.1 maximum	14 March 1958
	Potatoes	Sprout inhibition	Unconditional	0.3 (1 MeV electrons)	17 July 1973
	Grain	Insect disinfestation	Unconditional	0.3	1959
	Fresh fruits and vegetables	Shelf-life extension	Experimental batches	2 - 4	11 July 1964
	Semi-prepared raw beef, pork & rabbit products (in plastic bags)	Shelf-life extension	Experimental batches	6 - 8	11 July 1964
	Dried fruits	Insect disinfestation	Unconditional	1	15 February 1966
	Dry food concentrates (buckwheat mush, gruel, rice, pudding)	Insect disinfestation	Unconditional	0.7	6 June 1966
	Poultry, eviscerated (in plastic bags)	Shelf-life extension	Experimental batches	6	4 July 1966
	Culinary prepared meat products (fried meat entrecot) (in plastic bags)	Shelf-life extension	Test marketing	8	1 February 1967
	Onions	Sprout inhibition	Test marketing	0.06	25 February 1967
	Onions	Sprout inhibition	Unconditional	0.06	17 July 1973
United Kingdom	Any food for consumption by patients who require a sterile diet as essential factor of their treatment	Sterilization	Hospital patients		1 December 1969
United States of America[a]	Wheat and wheat flour	Insect disinfestation	Unconditional	0.2 - 0.5	21 August 1963
	White potatoes	Shelf-life extension	Unconditional	0.05 - 0.1	30 June 1964
	White potatoes	Shelf-life extension	Unconditional	0.05 - 0.15	1 November 1965
	Spices and dry vegetable seasonings (38 commodities)	Decontamination/ insect disinfestation	Unconditional	30 maximum	5 July 1983
	Dry or dehydrated enzyme preparations (including immobilized enzyme preparations)	Control of insects and/or microorganisms	Unconditional	10 maximum	10 June 1985
	Pork carcasses or fresh, non-heat processed cuts of pork carcasses	Control of *Trichinella spiralis*	Unconditional	0.3 minimum 1.0 maximum	22 July 1985
	Fresh foods	Delay of maturation	Unconditional	1	18 April 1986
	Food	Disinfestation	Unconditional	1	18 April 1986

Table V-9, continued

United States of America, continued	Dry or dehydrated enzyme preparations	Decontamination	Unconditional	10	18 April 1986
	Dry or dehydrated aromatic vegetable substances	Decontamination	Unconditional	30	18 April 1986
Uruguay	Potatoes	Sprout inhibition	Unconditional		23 June 1970
Yugoslavia	Cereals	Insect disinfestation	Unconditional	Up to 10	17 December 1984
	Legumes	Insect disinfestation	Unconditional	Up to 10	17 December 1984
	Onions	Sprout inhibition	Unconditional	Up to 10	17 December 1984
	Garlic	Sprout inhibition	Unconditional	Up to 10	17 December 1984
	Potatoes	Sprout inhibition	Unconditional	Up to 10	17 December 1984
	Dehydrated fruits & vegetables	Sprout inhibition	Unconditional	Up to 10	17 December 1984
	Dried mushrooms		Unconditional	Up to 10	17 December 1984
	Egg powder	Decontamination	Unconditional	Up to 10	17 December 1984
	Herbal teas, tea extracts	Decontamination	Unconditional	Up to 10	17 December 1984
	Fresh poultry	Shelf-life extension/ decontamination	Unconditional	Up to 10	17 December 1984

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[a] Sterilization of laboratory animal diets (rats, mice, and hamsters) for microbial disinfection at doses up to 25 kilograys was approved unconditionally on February 19, 1986 (FDA, 1986).

Table V-9a. Clearances as of August 26, 1988, for use of ionizing energy on foods in Taiwan (Yang, 1988)

Product	Purpose of treatment	Sort of clearance	Dose permitted, kilograys	Date of approval
Potatoes, sweet potatoes, onions, garlic, shallots	Sprout inhibition	Unconditional	0.15	January 16, 1985
Papayas, mangoes	Delay ripening	Unconditional	1.5	January 16, 1985
Rice	Control insects	Unconditional	1.0	Jnauary 16, 1985
Small red beans, mungbeans, soybeans	Control insects	Unconditional	0.2	January 16, 1985
Wheat, flour	Control insects	Unconditional	0.4	January 16, 1985
Spices	Control insects, decontamination	Unconditional	30.0	November 30, 1987

Table V-10. Facilities processing foods on a practical basis as of June 1988 (IAEA, 1988b)

Country	Company and city or state	Food	Approximate amount processed per year, metric tons
Argentina	National Atomic Energy Commission (Buenos Aires)	Spices, cocoa powder, spinach	50
Belgium	IRE (Fleurus)	Spices, dehydrated vegetables, frozen food	8,000-10,000
Brazil	EMBRARAD (Sao Paulo)	Spices	200
Chile	CCHEN (Santiago)	Onion, potatoes, dehydrated vegetables, chicken	500
China	Shanghai Irradiation Center (Shanghai)	Potatoes, apples	500
Cuba	Institute of Food Industrial Research (Havana)	Potatoes, onions	500
Finland	KOLMI-SET Oy (Ilomantsi)	Spices	-[a]
France	Conservatome (Lyon)	Spices	2,500
	Caric (Paris)	Spices, poultry	500
	S.P.I. (Vannes)	Poultry, frozen deboned chicken	2,000
	Oris (Nice)	Spices, vegetable seasonings	200
German Democratic Republic	Central Institute for Isotope Radiation Research (Weideroda)	Onions	600
	Queis Agricultural Cooperative (Spickendorf)	Onions	5,000
	VEB Prowiko (Shoenebeck)	Enzyme solution	300
Hungary	AGROSTER (Budapest)	Spices	400
Israel	Sorvan (Yavne)	Spices	120
Japan	Shihoro Agricultural Cooperative (Hokkaido)	Potatoes	15,000-20,000
Korea, Republic of	KAERI (Seoul)	Garlic powder	-
Netherlands	GAMMASTER (Ede)	Spices, frozen food, poultry, dehydrated vegetables, egg powder	18,000
Norway	Institute for Energy Technology (Kjeller)	Spices	-[a]
South Africa	Nuclear Development Corporation	Fruits, potatoes, onions	-[a]
	ISO-STER (Johannesburg)	Spices, dehydrated vegetables	1,000
	High Energy Processing (Pelindaba)	Fruits, spices, potatoes, onions	20,000
Thailand	Office of Atomic Energy for Peace (Bangkok)	Onions, fermented sausages	600
United States	ISOMEDIX (New Jersey)	Spices	<100[b]
	RTI (Radiation Technology, Inc.) (New Jersey)	Spices	500
	Radiation Sterilizer (California)	Spices	1,800
USSR	Odessa Port Elevator (Odessa)	Grain	400,000
Yugoslavia	Ruder Boskobic Inst. (Zagreb)	Spices	-[a]
	Boris Kidric Inst. (Belgrade)	Spices	100

[a] Not reported.

[b] Report direct from ISOMEDIX.

Table V-11. Summary of methods for identifying foods treated with ionizing energy, and the proximity of the methods to usability (Bögl et al., 1988)

	Findings by indicated method											
					Chemical changes							
Food	Viscosity	Thermo- or chemiluminescence	ESR[a]	Conductivity/ impedance	DNA	Protein	Carbohydrates	Volatiles from fatty acids	Enzymic activity	H_2	Microflora	Histology/ morphology
Fruits	—	—	A[b]	—	—	0	—	—	—	0	0	—
Vegetables	—	A[c]	0	—	—	0	—	—	A	—	0	A[d]
Cereals	—	—	—	—	A	0	—	—	A[e]	—	0	—
Bulbs and tubers	—	—	0	C[f]	—	0	—	—	—	—	0	C[g]
Spices, etc.	B[h]	C[h]	A[h]	0	—	0	—	—	0	—	0	0
Fish and shellfish	0	A[i]	B[i]	0	A	A	0	B	0	—	—	0
Meat	0	A[i]	A[i]	0	A	B[j]	0	C[k]	0	—	0	0
Poultry	0	A[i]	B[i]	0	A	B	0	B	0	—	0	0
Others	B[l]	—	—	—	—	A[m]	—	A[m]	A[n]	—	0	—

Legend: 0 = Not promising at present; A = Concept promising; B = Encouraging experiments; C = Ready for international testing; — = Insufficient information.

[a] Electron spin resonance. [b] Stones and seeds. [c] For light-colored products. [d] For mushrooms. [e] Maize peroxidase. [f] For potatoes. [g] Rooting and germination. [h] For some spices. [i] When bone, shell, or calcified cuticle is present. [j] For pork. [k] In-house blind trials done for pork and beef. [l] For thickening agents and emulsifiers. [m] Eggs. [n] For commercial enzyme preparations.

Table V-12. Preference evaluations of meats sterilized by exposure to ionizing energy (Wierbicki, 1975)

Products	Kilograys of ionizing energy at -22°F (-30°C)	Recipe	No. of panelists	No. of tests	Preference rating[a]
Beef	47	Onion gravy	33	2	6.4
Beef	47	Roast au jus	89	4	6.2
Beef	47	Brown gravy	85	4	6.5
Ham	37	Grilled	32	2	8.1
Ham	37	Baked	201	8	7.5
Pork sausage	27	Fried	91	4	7.4
Chicken	45	Breaded-fried	79	2	7.0
Cooked salami	25	Cold	64	2	6.5

[a] Evaluations on a 9-point scale on which 1 = dislike extremely, 5 = neither like nor dislike, and 9 = like extremely.

Table V-13. Preference evaluations of meats sterilized by ionizing energy that were used on the Apollo-Soyuz space mission (Brynjolfsson, 1977)

Product	Kilograys of ionizing energy at -22°F (-30°C)	Recipe	Preference ratings[a]
Ham	37-43	Cold	7.7
Beef steak	37-43	Fried	7.0
Corned beef	25-29	Cold	7.0
Turkey slices	37-43	Cold	6.4

[a] Summary of evaluations by 64 panelists in two tests on each product. Evaluations on a 9-point scale on which 1 = dislike extremely, 5 = neither like nor dislike, and 9 = like extremely.

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