(36) Metta, V. C., Mameesh, M. S., Johnson, B. C., *Federation Proc.* **18,** 537 (1959).

(37) Metta, V. C., Mameesh, M. S., Johnson, B. C., *J. Nutrition* **69,** 18 (1959).

(38) Metta, V. C., Mameesh, M. S., Johnson, B. C., "Nutritive Value of the Major Nutrients of Irradiated Foods and Appraisal of the Toxicity of Irradiated Foods," Progress rept. 15 on Contract DA-49-007-MD-784 with Office of Surgeon General, March 15, 1959.

(39) Metta, V. C., Norton, H. W., Johnson, B. C., *J. Nutrition* **63,** 143–54 (1957).

(40) Monsen, H., "Heart Lesions in Mice Induced by Feeding Irradiated Foods," *Federation Proc.* December 1960 (in press).

(41) Monty, K. J., "Carbonyl Compounds as Inhibitors of Lipid Metabolism and Their Significance in Irradiated Foods," *Ibid.*, December 1960 (in press).

(42) Moore, R. O., "Influence of Irradiated Foods on the Enzyme Systems Concerned with Digestion," Progress rept. 3 on Contract DA-49-007-MD-787 with Office of Surgeon General, Aug. 26, 1958.

(43) Nickerson, J. T. R., Proctor, B. E., Goldblith, S. A., *Food Technol.* **10,** 305–11 (1956).

(44) Plough, I. C., Sellars, J. H., McGary, V. E., Nuss, J., Baker, E. M., Harding, R. S., Taylor, R. L., Weiser, O. L., U. S. Army Medical Nutrition Lab., Denver, Colo., Rept. **204** (May 17, 1957).

(45) Poling, C. E., Warner, W. D., Humburg, F. R., Reber, E. F., Urbain, W. M., Rice, E. E., *Food Research* **20,** 193 (1955).

(46) Proctor, B. E., O'Meara, J. P., *Ind. Eng. Chem.* **43,** 718–21 (1951).

(47) Read, M. S., in "Proceedings of the International Conference on Preservation of Foods by Ionizing Radiations," Department of Food Technology, Massachusetts Institute of Technology, Cambridge 39, Mass., November 1959.

(48) Read, M. S., Kraybill, H. F., Witt, N. F., *J. Nutrition* **65,** 39 (1958).

(49) Read, M. S., Kraybill, H. F., Worth, W. S., Witt, N. F., *Federation Proc.* **17,** 490 (1958).

(50) Read, M. S., Trabosh, H. M., Worth, W. S., Kraybill, H. F., Witt, N. F., *Toxicol. Appl. Pharmacol.* **1,** 417 (1959).

(51) Reber, E. F., Malhotra, O. P., Kreier, J. P., Beamer, P. D., Norton, H. W., "To Determine the Effect of Irradiation upon the Wholesomeness of Food," Progress rept. 8 on Contract DA-49-007-MD-728 with Office of Surgeon General, September 1959.

(52) Reber, E. F., Malhotra, O. P., Kreier, J. P., Norton, H. W., Beamer, P. D., *Toxicol. Appl. Pharmacol.* **1,** 55 (1959).

(53) Richardson, L. R., "A Long-Term Feeding Study on Chicken and Green Beans," Progress rept. 14 on Contract DA-49-007-MD-582 with Office of Surgeon General, Sept. 15, 1959.

(54) Richardson, L. R., Woodworth, P., Coleman, S., *Federation Proc.* **15,** 924 (1956).

(55) Rigdon, R. H., "Pathologic Changes in Rats Fed Chicken and Green Beans," Final rept. Contract DA-49-007-MD-912 with Office of Surgeon General, Nov. 30, 1959.

(56) Schreiber, M., Nasset, E. S., *J. Appl. Physiol.* **14,** 639 (1959).

(57) Sheffner, A. L., Spector, H., p. 161 in "Radiation Preservation of Food," U. S. Government Printing Office, Washington, D. C., **PB151493** (1957).

(58) Teply, L. J., Kline, B. E., *Federation Proc.* **15,** 927 (1956).

(59) Tinsley, I. J., Bubl, E. C., "Growth, Breeding, Longevity, and Histopathology of Rats Fed Irradiated or Control Foods (Tissue Enzyme Studies)," Progress rept. 4 on Contract DA-49-007-MD-580 with Office of Surgeon General, Sept. 15, 1959.

(60) Williams, C., Yen, J., Fenton, F., *Food Research* **23,** 473 (1958).

(61) Witt, N. F., Read, M. S., Worth, W. S., Trabosh, H. M., "Nutritional Adequacy and Probable Toxicity of Foods Preserved by Ionizing Radiations," Progress rept. 12 on Contract DA-49-007-MD-549 with Office of Surgeon General, Sept. 15, 1959.

(62) Worth, W. S., Read, M. S., Kraybill, H. F., U. S. Army Medical Nutrition Laboratory, Denver, Colo., Rept. **210** (Aug. 28, 1957).

(63) Ziporin, Z. Z., Kraybill, H. F., Thach, H. J., *J. Nutrition* **63,** 201 (1957).

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RADIATION PRESERVATION OF FOOD

Commercialization Technology and Economics in Radiation Processing

H. F. KRAYBILL[1] and
D. C. BRUNTON
Curtiss-Wright Corp., Princeton, N. J.

Preservation methods which potentially yield commercially sterile products or substantially extend the shelf life are worthy of investigation. During the last ten years extensive research has been conducted in the United States and Europe on a new concept in food technology, using ionizing radiation. To date, the conventional methods of processing have their limitations. Thermal treatment of food, for example, cannot preserve the product in the raw state and whereas canned food still represents a large volume of the market, such products differ markedly from "garden fresh" fruits or vegetables and fresh meats. To attain the desired degree of bacterial inactivation canned products are frequently overcooked. Freezing, on the other hand, permits the extended storage of foods with retention of original characteristics of texture, flavor, and nutritional properties. In meats, however, there are some color change, "freezer burn," and exudation of fluid (drip). Logistically, in military feeding freezing imposes problems in distribution and economical operation.

Editor's Note

A fourth paper presented before the Radiation Processing Section, Nuclear Congress, New York, N. Y., April 1960, "Radiation Technology for Nonbiological Materials" by A. J. Restaino, was published in the August 1960 issue of *Industrial and Engineering Chemistry* (page 683).

Radiation preservation has certain advantages, such as the prospect of preserving meat for prolonged periods, a process that is adaptable for continuous processing, the processing of large and small items because of deep penetration of the ionizing radiation, and the possibility of using new transparent plastic film packages because high temperature processing is avoided.

Although Food and Drug Administration clearance on irradiated foods awaits completion of the wholesomeness studies, the technological and economic realization for advancement of this process depends on how competitive this method is with existing methods of

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[1] Present address, Division of Radiological Health, U. S. Public Health Service, Department of Health, Education, and Welfare, Washington, D. C.

This study deals with technical and economic factors in the commercial application of radiation processing to foods, agricultural commodities, and hospital supplies, including specific applications of machine and gamma sources. Currently, low energy source radiation (cobalt-60) is preferred over high energy sources which potentially induce radioactivity. Design and description of radiation facilities for treatment of one or several products are presented. Low-dose treatment at 3×10^5 rads of fish, chicken, and prepackaged, refrigerated meats, at an estimated cost of 0.45 cent per pound, is of considerable interest to less developed countries for control of food spoilage. Trichina destruction in pork at 2×10^4 rads has an estimated cost of 0.15 cent per pound. Sterilization cost for food irradiated at 3 to 4×10^6 rads is estimated at 2 cents and medical supplies at 2×10^6 rads at 0.96 cent per pound.

preservation such as freezing, thermal processing, and dehydration. Reduced costs of radiation and efficiency of utilization in machine sources and in nuclear sources, the availability and low cost per curie for the radioactive isotope, as well as minimal costs for installed radiation facilities, are key factors in commercialization of radiation processing.

Sources of Radiation Energy

For all practical purposes only two general sources of radiation need be considered — electron beam radiation from high energy machines and gamma radiation from radioisotopes. X-radiation obtained when the electron beam strikes a target and a portion of the electron energy is converted to electromagnetic radiation need hardly be considered. When the electron beam energy is low, the conversion efficiency is too low for economic results and when the electron beam energy is high, satisfactory penetration can be obtained without such a conversion. However, high energy electron beams introduce a serious problem—induced radioactivity in the product. The theoretical threshold of such induced activity is 2.2 m.e.v. (the reaction threshold of the γ,n reaction of deuterium), but for practical purposes it is probable that electron beams of up to 8 m.e.v. will be considered to be free of induced activity affects. Even considerably above this energy, the induced activity levels are small and arise from short-lived isotopes. However, such minor effects can be serious, particularly with respect to irradiation of food. Present Food and Drug Administration legislation (the Delaney Food Additives Amendment) precludes the use of a process deemed to induce any radioactivity in the food, on the basis that radioactivity is carcinogenic and no additive of a carcinogenic nature is permitted (*9*).

The penetrating power of electrons is small. For energies from 1 to 5 m.e.v., the effective thickness of a product of unit density for radiation treatment is 0.13 inch per m.e.v. for single-sided irradiation and 0.31 inch per m.e.v. for two-sided irradiation.

Even a 10,000,000-volt machine can be used only on packages a little over 1 inch thick with irradiation from one side. On the other hand, efficiencies of electron machines are attractive. About 80% of the electron beam energy will be absorbed in a material with a thickness 2/3 that of the maximum electron range (*4*, *12*). Considerably higher doses are received in the interior of the sample relative to the surface, so that the net absorption efficiency is about 60%. A further loss of efficiency (even assuming a scanning system designed to fit a given package area) due to geometrical losses and scanning overlap will reduce the net efficiency to approximately 50%. With two-sided irradiation the net efficiency can be raised to about 65% and the package thickness for a 10-m.e.v. beam increased to 3 inches. Two-sided irradiation, of course, creates additional complexity and expense in both the accelerator and the package conveyor.

Available Types of Machine Sources

Cascade generator (or Cockroft Walton machine) Resonant transformer High frequency charging series capacitors	For energies below 5 m.e.v.
Van de Graaf generator Linear accelerator Linac	For higher energies

The low energy machines are capable of large power outputs at low cost per kilowatt, while the high energy machines are substantially more expensive in both capital and operating cost.

The characteristics of radioisotope sources have been reviewed many times. Aside from the use of spent fuel rods, which are generally considered to be inconvenient and expensive except when they can be used in close proximity to the reactor from which they came, three isotopic sources merit serious consideration: Co^{60}, Cs^{137}, and Zr^{95}-Nb^{95}.

One useful figure of merit is a measure of the watt-hours available per curie (the energy per disintegration times the half life). For Co^{60} this is $2.5 \times 5.2 = 13$, and for Cs^{137} it is $0.61 \times 26.6 = 16$. However, it is doubtful if an industrial processor would, at this time, be prepared to amortize his Cs^{137} based on a 26.6-year half life. Consequently it is more practical in considering such a figure of merit to assign to Cs^{137} the same half life as Co^{60}, whereby the figure for Cs^{137} becomes 3.15 and, hence, the relative value of Co^{60} to Cs^{137} is 4.1 to 1. The number of curies required for a plant of a given throughput is in the inverse ratio 1 to 4.1 and the relative initial capital charge for the source is the same ratio multiplied by the ratio of the costs per curies.

Current prices for both Co^{60} and Cs^{137} are $2.00 per curie (unencapsulated); hence Cs^{137} sources cost four times as much as Co^{60} for the same plant throughput. The raw material for cesium sources is the waste fission products from spent reactor fuel rods and the cost per curie is the processing cost for recovery, concentration, extraction, and encapsulation and hence is very dependent on the quantities in demand. It is difficult to expect at any time a price below $0.25 per curie for Cs^{137}. With Co^{60}, on the other hand, the cost depends on the cost of the neutrons used and when Co^{60} can be made from waste neutrons—e.g., as a by-product in power reactor operations—the cost as in the case of Cs^{137} is very dependent on the quantities in demand. It is anticipated that the price per curie for Co^{60} will decrease in the future at least as rapidly as Cs^{137}. In addition, the greater penetrating power of Co^{60} (in the ratio 4 to 3) is an advantage in most large installations. It is therefore concluded that Co^{60} is a more economical source of radiation than Cs^{137} and likely to remain so.

The case of the fission product pair Zr^{95}-Nb^{95} is of special interest. Zr-Nb has a half life of only 65 days but is about 100 times more plentiful than Cs^{137} in fresh spent fuel rods. Consequently, it is anticipated that Zr-Nb

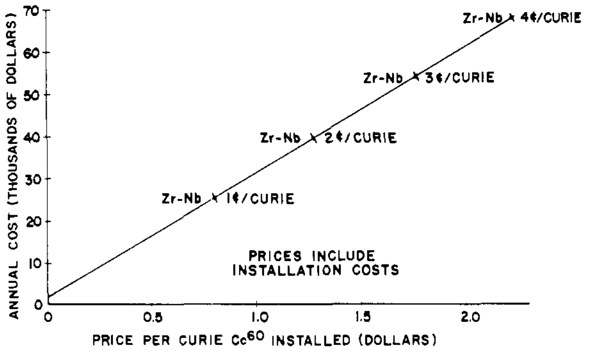

Figure 1. Annual source cost for Co^{60} and Zr^{95}-Nb^{95} considered on basis of plant operating continuously

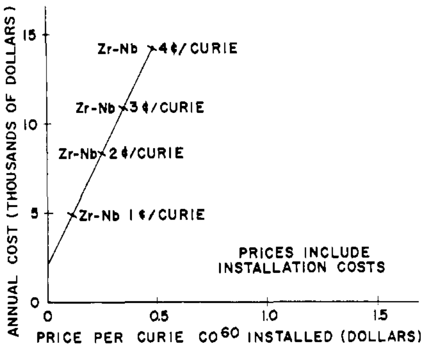

Figure 2. Annual source costs for Co^{60} and Zr^{95}-Nb^{95} considered on basis of plant operating seasonally

65 days, installed capacity 2 kw.

can be made available at a few cents per curie. A particular area of interest for such a short-lived source is in the processing of seasonal products such as fruits and vegetables, whereby a source would be installed for the harvesting season of a given product and permitted to decay to a negligible value during the remainder of the year.

It is instructive to compare the source costs for Co^{60} and Zr-Nb for a typical installation of, say, 2-kw. capacity (140,000 curies of Co^{60}) considered, first, as a plant operating continuously throughout the year and, secondly, as a plant operating for a season of 65 days. The results are shown in Figures 1 and 2. Figure 1 applies to a 2-kw. plant operating continuously, whereas Figure 2 applies to a seasonal operation of 65 days. For a given price per curie for Co^{60}, the annual cost is made up of the number of curies required per year for source replenishment times the price, together with shipping and installation charges and an interest charge of 6% on the capital investment. On the same basis the annual cost for Zr-Nb is computed assuming prices of 1, 2, 3, and 4 cents per curie. Hence, for example, 2 cents per curie Zr-Nb requires the same annual expenditure as Co^{60} at $1.27 per curie in continuous operation and as Co^{60} at $0.26 per curie for the seasonal operation. There have been estimates on Zr-Nb sources from $0.02 to 0.04 per curie (*10*). On this basis Zr-Nb is not expected to be competitive with Co^{60} for continuous operations (assuming Co^{60} prices to become $0.50 to $1.00 per curie) but Zr-Nb shows a distinct advantage for seasonal operations. Another advantage of Zr-Nb is the low capital investment to the user, where it holds a decided advantage even over machine installations.

Potential Areas of Radiation Processing Hospital Supplies, Agricultural Products, and Foods

Concomitant with the extensive research and development work on foods have been the important investigations on radiation processing of pharmaceuticals, hospital supplies, and nonfood agricultural products. As many important developments have evolved in this area with the process proved technically and economically feasible, commercialization on such products may precede that of food applications. In addition, the requirement for extensive wholesomeness clearance studies on foods with ultimate Food and Drug Administration approval does not provide for as early marketing of irradiated foods as might be the case, for example, in radiotreatment of surgical supplies, cotton, hemp, or tobacco.

Radiotreatment of Thermolabile Drugs, Hospital Equipment, and Exported-Imported Agricultural Commodities. Parenteral pharmaceutical products such as antibiotics, hormones, steroids, multivitamin preparations, sulfonamides, alkaloids, and blood plasma have been radiosterilized successfully. However, clinical trials and toxicity tests must be applied, because these products are essentially new, demanding a careful study of properties of the irradiated product. Antibiotics, for example, show no loss of potency on storage after irradiation. Antibiotics are labile to thermal processing. Bone and tissue grafts can be satisfactorily radiation-sterilized, stored, and successfully used in surgery, but this application does not represent an important large use (*5*). Horne (*6*) has suggested that radiomodified drugs might find an important use, for example, in inactivation of virus vaccine such as Salk poliomyelitis virus, which is now inactivated with formaldehyde. By current methods, formol inactivation of virus results in at least 95% loss in antigenicity or vaccinogen power as the infectivity is destroyed. Primarily because of radiosensitivity of the nucleic acids, infectivity of viruses would be destroyed but there would also be substantial loss in antigenicity. It is possible that future successes may come in this area by combination of radiation treatment with chemicals or by operating at low temperatures.

Of more immediate application is the radiosterilization of surgical materials such as surgical sutures, tubing for intravenous feeding, bandages, forceps, hypodermic needles, and talc. Some of these products are now marketed as radiation-sterilized materials—for example, sutures sterilized by radiation have a substantial portion of the market in this country, while catheters similarly sterilized are on the market in the United Kingdom. Packages sealed ready for shipment and clinical use are guaranteed sterile, because radiation-sensitive tapes affixed to packages indicate that the product has passed through the sterilization chamber. Pathogens such as staphylococcus have been reported, for example, in talc which escaped commercial steam sterilization, which could not occur in radiation processing. Indeed, commercial radiation sterilization of surgical supplies now being utilized has been shown to be competitive with steam sterilization.

Continuous sterilization of hospital equipment such as blankets, linens, and mattresses is being considered. Because of the incidence of staphylococcus infections in hospitals through general contamination of furniture and equipment, it is envisioned that a gamma-radiation facility which would also accommodate large items might be an important advance in central hospital sterilization operations.

Methods for treatment of agricultural commodities, foods and nonfoods, are continually being developed for control of parasites and insect pests in imported, exported, and domestic products. Radiation treatment with radiation doses below 50,000 rads has been recommended for these applications (*3*). The opening of the St. Lawrence Seaway has stressed the need for more and better facilities and methods for deinfestation of imported and exported products such as cotton, hemp, broom corn, and tobacco, to name but a few items of interest.

Table I. Effect of Chemical Treatment and Gamma Sterilization on Insect Population

[Chemical treatment that induces 90% sexual sterility and gamma-radiation sterilization where sterile males dominate a natural male population in ratio of 9:1. (*8*)]

Generation	Constant Release of Gamma-Sterilized Males	Chemical Sterilization
Parent	1,000,000	1,000,000
F_1	500,000	50,000
F_2	131,578	2,500
F_3	9,535	125
F_4	50	5
F_5	1	1

Table II. Radiation Processing of Seafoods

Items	Recommended Radiation Treatment, Rads	Average Days of Shelf-Life Extension over Untreated Controls at 35° F.[a]
Cod, butterfish	Raw at 2.5×10^5	35
Haddock, pollock	Raw at 6.0×10^5	30
Crabmeat	Raw at 5×10^5	50
Crabmeat	Cooked at 4×10^5	40
Oysters	Blanched, breaded, 5×10^5	60

[a] Shelf life of refrigerated raw fish 7 to 10 days.

Certain types of radiation facilities have been designed for radiation treatment of grains in silos or at the dock side, among which a gravity flow process with Co^{60} source or an electron beam machine on an air stream within the discharge chute appears feasible. A mobile source has many advantages for this purpose, as it can handle a variety of products at different locations with shift labor being involved due to seasonal demands. A short-half-life radioisotope such as Zr^{95}-Nb^{95} with low cost per curie built into a megacurie course that can handle a throughput of at least 200 tons per hour has been proposed because of reduced amortization on a low cost investment. Thus far, however, chemical fumigation with methyl bromide, cyanide, etc., appears to have a slight financial advantage. The fact that reinfestation may occur in warehouses or silos, which would necessitate repeated radiation treatments, imposes a cost which swings the advantage again toward the use of chemicals. The same criteria can be applied to treatment of spices.

In the exporting or importing of some products such as tobacco, cotton, hemp, and broom corn special fumigation facilities are maintained at ports of entry and embarkation for control of crop pests. It is believed that radiation facilities in new locations for radiotreatment of these commodities would be feasible economically; otherwise replacement of the capital investment in old fumigation equipment in existing sites would be prohibitive.

Whereas direct irradiation of products—for example, destruction of cigarette beetles in tobacco—has been proposed for elimination of this insect in stored tobacco, an indirect method based on the release of irradiated sterile male insects has come under consideration. The very successful elimination of the screw worm fly on the island of Curaçao and the gulf states of this country has been described by Knipling (*8*). Christenson (*2*) has had some initial success in his investigations on the irradiation of the fruit fly in Hawaii and Mexico, which again involves the continuous release of millions of irradiated sterile male fruit flies, with the end result being control and/or disappearance of subsequent generations of insects which cause heavy crop losses. It is hoped that future research will establish this unique procedure as effective in control of crop-damaging insects and insects that are vectors of diseases such as the mosquito. The effectiveness of the sterile male method is illustrated in Table I.

Horne, Turner, and Willis (*7*) have demonstrated that gamma radiation at a minimum dose of 2 megarads can successfully inactivate *B. anthracis*, which is a problem in the importation of goat hair. Baled goat hair imported into countries such as Australia and Great Britain constituted a health hazard from this pathogen for factory workers where goat hair was used in manufacture of carpets and other fabrics. Recently a factory in Australia has installed a gamma-radiation facility with a source strength 150,000 curies for processing goat hair and wool. This is the world's first commercial installation of radiation processing with Co^{60}.

Radiopasteurization and Radiosterilization of Foods. Extensive research and development work has been conducted for the past eight years relative to this new concept in food preservation. The program supported largely in this country by the Department of the Army has also stimulated work in Europe. Some major obstacles still prevail in the technology; the development of irradiated sterilized beef is not as yet satisfactory from a palatability standpoint. Pork and pork sausage, chicken, and fishery products respond favorably to radiation processing. Thermal processing yields products which are uniformly acceptable; however, radiation processing currently differs in this respect, in that palatability is related to specific chemical constitution of the food.

The technical reports that have been published thus far direct attention to radiation processing of foods that would be technically feasible. For commercialization, primary emphasis must be placed upon products which from a survey are considered important in so far as technical and economic feasibility is concerned. Pending final wholesomeness clearance of all foods tested, conceivably obtained at the end of 1960, the following irradiated foods might be suitable for marketing: fishery products (radiopasteurized and radiosterilized); chicken, radiopasteurized; fruits, radiopasteurized; eggs, radiopasteurized for Salmonella destruction; pork, radiopasteurized for shelf-life extension and destruction of trichina parasite; beef, radiopasteurized for shelf-life extension of refrigerated prepackaged meats and destruction of tapeworm parasite; frozen processed foods, radiopasteurized for bacterial control; pet foods, radiopasteurized; and "brown and serve" meats, radiosterilized.

Radiation processing of fishery products, particularly "low fat" type filleted fish and shellfish, is successful from the stand-point of consumer acceptance. Extension of refrigerated storage time by low dose radiation treatment of perishable products such as shelled shrimp, picked crabmeat, blanched oysters, and filleted fish such as cod, pollock, haddock, butterfish, and flounder is most promising. In Table II some fishery products are listed with the radiation dose required for processing and the days extension of shelf life at 35° F.

Fishery products do not present the problem of botulism, trichinosis, or spore-forming radiation-resistant bacteria. Pseudomonas group of microorganisms are the principal ones causing deterioration and off-odor, and these are readily destroyed at 30,000 rads. Hence, shelf life and acceptance of refrigerated fish can be extended several weeks by low irradiation. Fishery products have been treated with radiation doses ranging from 0.5 to 5 megarads, with no off-flavor development. Blanched oysters are of good quality at 5 megarads. Radiopasteurization of crabmeat may be the solution to the problem of maintaining minimal bacterial counts on canned iced product. Heat pasteurization is now resorted to in many cases to effect such control, with adverse effects on texture and flavor.

The shelf life of chicken can be extended as much as 21 days by radiopasteurization at 400,000 rads. The radiation-sterilized product at 4 or 5 megarads is acceptable.

Among the radiosterilized meat products "brown and serve" pork and chicken are superior to products that receive complete thermal sterilization. The increased cost on this product might be warranted on the basis of increased consumer acceptance.

The demand for "Salmonella-free" egg products necessitates processing methods which can easily and cheaply meet this requirement. While fresh eggs cannot be readily irradiated without adverse effects on flavor and texture, frozen and dried egg products can so be treated to eliminate the pathogens. Liquid eggs that are irradiated and subsequently spray dried are rendered "pathogen-free" and "radiation flavor" compounds are volatilized in the drying process. In Table III the recommended radiation doses are given for processing egg solids and liquid eggs to eliminate Salmonella.

Transcontinental shipments of fresh fruits and vegetables are becoming more common and low-dose radiation treatment of such products will contribute markedly to the retardation of rotting and spoilage. Perhaps the first commercial treatment will be centered upon strawberries, which are in great demand in the off-season. In Mediterranean countries radiation treatment of citrus fruits to arrest mold development will have commercial significance for exporting. Bananas, grapes, and tomatoes are treated satisfactorily at low radiation dose and have considerable promise for future marketing.

For public health reasons elimination of the trichina parasite in pork and tapeworm in beef by the economical process of low radiation dose treatment is important and conceivably will replace conventional methods — for example, freezing or smoking of pork for control of trichinosis. This process is on the threshold for early commercialization, and if the meat packers saw an immediate sales advantage in promoting it, this efficient and rapid method would become a reality. A radiation facility has been designed for accomplishing this objective with maximum economy and flexibility.

Processed foods and complete meals that are frozen and available for serving by quick heating present the problem of high bacterial counts. With more emphasis toward strict requirements for minimal bacterial counts on these frozen processed foods, low-dose radiation processing in combination with freezing should facilitate the attainment of low bacterial count.

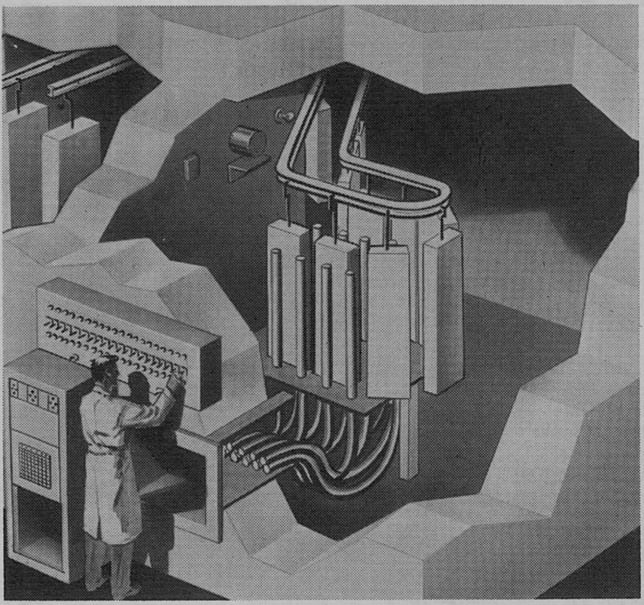

Figure 3. Multi-array gamma irradiator

Table III. Recommended Radiation Dose for Pasteurization of Egg Products[a]

(Radiation dose at 10^5 rads)

	Egg Solids			Liquid Eggs	
	Whole egg	Yolks	Whites	Whole eggs	Whites
S. Senftenberg	4.5	6.5	7.0	1.0	2.3
S. typhimurium	4.5	6.5	7.0	2.5	3.0

[a] For a 10^7-fold reduction in number of Salmonella.

Simple Design of a Gamma-Radiation Processing Facility

Designs for gamma-radiation facilities for the processing of pharmaceuticals, hospital supplies, agricultural products, and foods are numerous. A large scale gamma irradiator designed for the Department of the Army (the high intensity food irradiator) is an example of a multimegacurie Co^{60} source which could handle a minimum throughput of 6000 megarad pounds per hour, a short dwell time, and the nonuniformity in dose not to exceed 1.25 (*1*).

For smaller facilities a "multi-array gamma irradiator" presents the utmost in flexibility, because it has the ability to preset configurations of multiple individually projectable and retractable sources. This unique equipment, as shown in Figure 3, can handle kilocurie sources of radioactive isotopes.

With this MAGI equipment radiator tubes can be positioned in any configuration (as plaques horizontal or vertical, cylindrical arrangement). The gamma sources, which are movable and called "rabbits," are air blown from a storage cask through flexible transfer tubes to radiator tubes. When not in operation, the rabbits are retracted back through the transfer tubes to the cask by stainless steel cables. All these movements of the sources into the radiator tubes to provide a source arrangement with a specified field intensity can be controlled remotely from a panel outside the shielded radiation area by manipulating valves and switch controls.

The field strength will be determined by source strength of the rabbits and the number of rabbits projected into the field. Therefore, if each rabbit, for example, has 500 curies and there are 20 radiator tubes, the maximum source strength would be 10,000 curies. Increasing the specific activity and the size of the rabbit and the number of radiator tubes will increase the strength of the gamma source.

Batch or continuous irradiation can be used. By adding a conveyor (track conveyor shown in diagram) system, continuous processing of foods and biological products can be conducted. By allowing material to stand in the radiation cell, batch operations are carried out.

The MAGI with its shielding and conveyor equipment and the wide range in source strength and flexibility due to the unique physical arrangement of sources provides a versatile economic irradiator. This type of gamma ir-

Table IV. Processing Costs for Low-Dose (Pork) and High-Dose (Medical Supplies) Treatment

		Pork	*Medical Supplies*
A. Production requirement, tons/yr.		25,000	25,000
B. Radiation dose, rads		20,000	2,000,000
C. Source strength, curies		20,000	2,000,000
D. Capital costs, dollars			
1. Source cost (assuming 50% efficiency)		40,000	2,000,000[a]
2. Building–equipment costs		100,000	200,000
E. Operating costs, dollars			
1. Source costs		8,000	400,000
2. Maintenance costs		1,000	2,000
3. Amortization and interest on building and equipment		13,000	26,000
4. Power		Negligible	Negligible
5. Labor, dollars			
4 operators at	18,000		
1 supervisor	8,000		
Overhead (100%)	26,000		
		$ 52,000	$ 52,000
6. Total operating cost		$ 74,000	$ 480,000
F. Total processing costs, cents			
1. Per megarad lb. basis		7.4	0.48
2. Per pound product basis		0.15	0.96

[a] Price per curie for large amounts of Co^{60} = $1.00 and for small amounts $2.00/curie.

radiator is well suited for radiopasteurization of food with the requirement of low dose radiation treatment. A mobile MAGI has been designed which is practical for the irradiation of seasonal crops at different locations.

Economics of Radiation Processing

In radiation treatment as in any other process the operating costs are made up of materials consumed, amortization of capital investment, interest charges, maintenance, and labor. In the case of electron machines the material consumed is negligible and the interest charges are small but the maintenance and labor costs are relatively high. With Co^{60} the converse is true. Cobalt-60 is consumed at the rate of 12.4% per year and the interest charges are high because of the larger initial investment, but maintenance and labor are smaller. It is reasonable to assume a 5-year straight-line amortization rate for machines and a 10-year rate on the remainder of an installation, since much of this consists of a concrete shielding structure. The interest rate assumed is 6% on the unamortized portion of the capital investment, since this represents capital borrowed against fixed assets. Because the decay loss on Co^{60} is made up annually, by the 12.4% material charge, the source is essentially a nondepreciating asset and the use charge is the 6% charge on capital investment. It is assumed, further, that sufficient space in the radiator is provided for annual addition of Co^{60}, so that Co^{60} is removed in less than 5 to 10 years. Allowance for such removal adds a 1 to 3% charge, so that the total annual charge for cobalt is 20% of the purchase price. The most difficult cost to estimate is the labor charge, because this depends on the products, the throughput, the location, and the equipment. However, for small to medium capacity installations the labor charge will be the dominating cost of processing. Actual costs can be estimated with reasonable accuracy only for a specific plant in a specific location with a specific product and throughputs. Only in such a context, also, does a comparison of machine costs and isotope costs become significant. Throughputs are defined as megarad pounds per hour, day, or year and, as implied, are the product of the minimum required dose and the number of pounds of material to receive this radiation dose. Radiation source costs are determined by the throughput and efficiency. The latter may be defined as the useful radiation energy absorbed in the product (the minimum dose required times the mass of product receiving this dose) as a percentage of the total radiation emitted by the source.

Cost Factors:

1. Capital costs
   a. Source cost isotope or machine
   b. Building and equipment costs
2. Operation costs
   a. Source costs (for isotopes, decay, and interest for machines, amortization, and interest)
   b. Maintenance cost (source equipment)
   c. Amortization (building, equipment, and interest)
   d. Power
   e. Labor

With this costing basis established, several interesting comparisons may be made—for example, the variation in cost with throughputs from 500 to 50,000 megarad tons per year using Co^{60} sources and the relative cost of Co^{60} and machine sources for different conditions.

The throughput variation or plant capacity may arise because of amount of material processed or the required radiation dose level for a specific application. For example, one might process 25,000 tons of pork per year at 20,000 rads (trichina elimination) or 25,000 tons of medical supplies for sterilization at 2,000,000 rads. The costs for these two radiation treatments are shown in Table IV.

It is obvious in the low-dose case that the labor costs dominate the cost picture and that the radiation source cost is less than 15% of the total cost. In such a case the choice of source—isotope or machine—will be determined by what is most suitable for the job and what will yield the lowest labor cost. The actual cost of the radiation energy is relatively unimportant. In most such cases, Co^{60} will be favored because, with it, product material can readily be handled in bulk form.

However, this is not the case for high dose with large quantities of product. Here the radiation energy cost dominates the cost picture. If, for example, the product were polyethylene sheet with 25,000 tons per year production, a low energy accelerator with a capacity of 30 kw. (or several lower capacity units) would suffice. The capital cost for source would be reduced to $300,000 to $500,000 (including standby units) and the annual operating cost for amortization and maintenance to about $120,000. However, it is assumed that the machines would require at least one machine operator per shift, which would add $48,000, and hence a total operating cost of $246,000 and a cost per pound of 0.49 cent.

Now let us consider an actual example of a proposed application of radiation processing. In choosing this example, every effort has been made to find situations well suited to radiation processing at this time. The example pertains to a radiation processing plant in a warm climate where refrigeration is lacking and transport facilities are inadequate. The extension of shelf life by as little as one day is economically significant. The primary products of interest are whole chicken and fish. The chickens, currently, pass through a central depot at the rate of 20,000 per day. Fish is available for irradiation in substantial quantities. Another product available to radiation processing and with a substantial sale in this area is "purified" bottled water. The purification process must eliminate the hazard from pathogens [particularly *Eberthella typhosa* (typhoid) or *Vibrio comma* (cholera)] and from parasites [*Edameba histolytica* (amebiasis) or liver flukes]. It is considered that a radiation dose of 5×10^5 rads is required for this purpose.

A radiation facility has been designed to handle these three products, simultaneously. A diagrammatic sketch is shown in Figure 4. In the first system, the chicken is carried by a conveyor above and below the plaque source with a radiation dose of 300,000 rads and an efficiency of about 35% (*11*). In the second system, the fish is carried by a conveyor past the ends of the plaque also with a radiation dose of 300,000 rads and an efficiency of 20%. The whole system is surrounded by a water jacket acting as a partial shielding and as a flow chamber for purified water. The water is radiated to a dose level of 500,000 rads with an efficiency of 20%. The total energy balance adds up as follows:

Chicken	35%	Total useful absorption	75%
Fish	20%	Self-absorption in source	10%
Water	20%	Overdose and escape to shielding	15%
Total useful absorption	75%		100%

Therefore the net efficiency of the radiation is 75%.

The amount of Co^{60} required in this case is determined by the requirement to process 20,000 chickens or approximately 1600 pounds per hour. A useful reference figure is that 1 curie of Co^{60} will process 100 megarad pounds per year at 100% efficiency. Therefore at 35% efficiency and a throughput of 480 megarad pounds per hour the source strength required is 120,000 curies. The production and radiation data for this multifood radiation processing plant are shown in Table V.

The cost analysis for radiation processing of chicken, fish, and water is shown in Table VI.

The sale price of chicken in this product area averages about 35 cents per pound and fluctuates rapidly as much as 10 to 15 cents per pound. A quality improvement by better shelf life can easily return 1 to 5 cents per pound and provide a profitable operation, even allowing for much less favorable conditions than assumed above.

It is interesting to consider the alternative of applying an electron machine to this problem. Because the radiation must be carried out on whole chicken, at least a 20-m.e.v. machine and radiation from both sides are required. This immediately involves the touchy question of induced activity. Moreover, present experience indicates that such a machine would cost $500,000 to $1,000,000 and hence present a source expense of three to five times as much. The fact that a machine of such an energy would inevitably have a much greater throughput capacity than required is of no significance in this problem. In addition, maintenance of such a machine at this location would require a full-time resident electronics engineer at an additional expense (including overhead) of $20,000 per year. Hence, the net cost per pound for a machine source, if it could be considered feasible at all, is 1.3 cents per pound. Obviously the Co^{60} source is superior in this situation.

Table VI. Cost Analysis for Radiation Processing of Chicken, Fish, and Water

		Capital Cost	*Operating Cost/Year*
1.	Source cost at $1.40/curie installed	168,000	33,600
2.	Cost of building and equipment	150,000	29,580
3.	Labor		
	8 operators (low wage rate area)	16,000	
	Supervisor	8,000	
	Overhead (100%)	24,000	48,000
	Total annual cost		111,180[a]
4.	Annual production, all products in pounds		2.47×10^7 [b]
5.	Cost per pound for processing		0.45¢

[a] Includes amortization and interest (6% on Co^{60} for 5 yr. and 3% on buildings and equipment for 10 yr.).

[b] Production = 160-hr. week × 50 weeks/yr. × 3090 lb./hr.

Table V. Radiation and Production Data for Multifood Processing Plant

	Items Processed		
	Chicken	*Fish*	*Water*
Efficiency	35	20	20
Total dose, rads	3×10^5	3×10^5	5×10^5
Throughput, M rad lb./hr.	480	280	280
Capacity, lb./hr.	1600	930	560

Total processed (chicken + fish + water) = 3090 lb./hr.

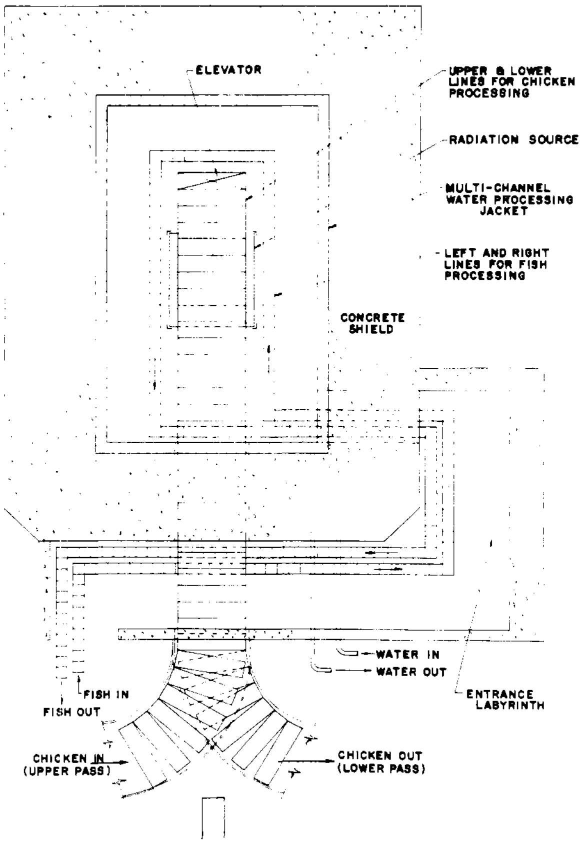

Figure 4. Multifood radiation processing facility

Low-dose radiation processing can be accomplished at reasonable costs. The processing cost for destruction of trichina in pork carcasses at a radiation dose as low as 15,000 rads would be as low as 0.05 cent per pound, according to Murray's data (*11*). Foods treated at sterilization doses of 3 to 5 megarads, however, would entail a higher processing cost above 2 cents per pound. Radiation sterilization, therefore, at the moment does not present the economic potentialities of those currently recognized in radiation processing with low dose treatment.

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Literature Cited

(1) Brunton, D. C., Donovan, J., Voyvodic, L., "Design Experience on a Multi-Megacurie Radiation Facility," Proc. Conf. on Application of Large Radiation Sources in Industry and Especially to Chemical Processes, Warsaw, Poland, September 1959.

(2) Christenson, L. D., *Proc. 10th Intern. Congr. Entomol.* **3,** 11–16 (1958).

(3) Cornwell, P. B., *Intern. J. Appl. Radiation and Isotopes* **6,** 188–93 (1959).

(4) High Voltage Engineering Corp., Burlington, Mass., Bull. P, "Handbook of High Voltage Electron Beam Processing," 1959.

(5) Horne, T., *New Scientist*, No. **15,** 40–1 (1957).

(6) Horne, T., *Pharm. J.* **176,** 27–9 (1956).

(7) Horne, T., Turner, G. C., Willis, A. T., *Nature* **183,** 475–6 (1959).

(8) Knipling, E. F., *Science* **130,** 902–4 (1959).

(9) Kraybill, H. F., "Current Status of Applications in the Pasteurization or Sterilization of Foods by Ionizing Radiation," Proc. Second Annual Texas Conference on Utilization of Atomic Energy, College Station, Tex., November 1959.

(10) Little, Arthur D., Inc., Cambridge, Mass., Report, "Radiation: A Tool for Industry," January 1959.

(11) Murray, G. S., *Intern. J. Appl. Radiation and Isotopes* **6,** 211–215 (1959).

(12) Perry, D. R., *Ibid.,* **6,** 43–5 (1959).

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FRACTIONATION OF CAROTENOIDS

Two New Solvent Systems for the Countercurrent Distribution of Carotenoids

A. LAURENCE CURL

Western Utilization Research and Development Division, Agricultural Research Service, U. S. Department of Agriculture, Albany 10, Calif.

Two new solvent systems for the countercurrent distribution of carotenoids have been discovered. A clean separation of the carotenoid diol, monoepoxide diol, diepoxide diol, and polyol fractions can be obtained in 100 transfers with the system petroleum ether and 73.5% methanol. A good system for the further fractionation of the carotenoid polyols consists of petroleum ether, acetone, methanol, and water (1.25 to 1.00 to 0.10 to 0.65 by volume, respectively). Determination of N_{100} values of individual polyol carotenoids with the latter system has considerable value in showing nonidentity, probable identity, or close relationship, as of stereoisomers.

Earlier work (*2*) shows that carotenoids can be fractionated by means of countercurrent distribution in a Craig apparatus. Two different solvent systems were used: I, petroleum ether and 99% methanol and, II, benzene, petroleum ether, and 87% methanol, 1 to 1 to 1.15 by volume.

More recent investigation has led to the discovery of two other useful solvent systems for the countercurrent distribution of carotenoids. By means of system IV (petroleum ether and 73.5% methanol) the diol-polyol fraction can be much more completely resolved into four fractions in 100 transfers than in 200 transfers with system II. System III (see below) can be used to fractionate further the very complex polyol fraction of fruits such as oranges (*4*) or cling peaches (*1*). Determination of N_{100} values with system III was especially useful in showing nonidentity or possible identity of various carotenoid polyols; with systems I, II, or IV, the N_{100} values are too close to zero.

Experimental

Solvent system IV consisted of petroleum ether, methanol, and water, 10 to 7.35 to 2.65, by volume. System III consisted of petroleum ether, acetone, methanol, and water, 1.25 to 1.00 to 0.10 to 0.65 by volume.

Countercurrent distribution runs were carried out in a 100-tube Craig apparatus in which the volume of the lower layer was 10 ml. The volume of the upper layer added in all cases was also 10 ml. The procedure used was essentially that previously described (*2*). At the end of the run, the contents of the various tubes were transferred to numbered test tubes by means of a glass syringe, and diluted with sufficient acetone to make them homogeneous and to a definite volume (50 ml. with systems III and IV). The depth of color was then measured in an Evelyn photoelectric colorimeter using filter 440. The results obtained were calculated as β-carotene by the use of a conversion table. (The resulting values are roughly approximate for most common carotenoids, and are used here mainly to show the positions of the various fractions.) In the case of some individual constituents, with absorption maxima at somewhat shorter wave lengths than 440 mμ, a 420 mμ filter was