# FOOD IRRADIATION IN THE UNITED STATES

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## INTRODUCTION

Conceived some thirty years ago, as a practical method of preservation, food irradiation, especially the wholesomeness aspect, has been studied extensively. No other food preservation method has been so thoroughly scrutinized. As the methodology for detecting harmful effects in food have improved, we have become more confident that this is a safe process; and the results of these comprehensive research and development allow us now to predict that in the eighties we will see this new method widely accepted, and irradiated foods move in international trade.

The early man's "wholesomeness studies" of food processes were obtained by observing the effect on humans eating the food. These tests were direct and relevant, although less sophisticated than our wholesomeness testing of irradiated food. The caveman invented the cooking of food and the smoking of meat and fish, as well as sun drying, to prevent the microbial spoilage. Use of salt and oil to preserve food is mentioned by Homer. Recent studies indicate that salt and curing by nitrates and nitrites was used already by the Sumarians some 5000 years ago. In the seventeenth century, following Leeuwenhoek's discovery of the microbes under the microscope, we see the first steps towards heat sterilization, which led to Nicholas Appert's pioneering research in the years 1787-1810. Refrigeration and freezing has long been known to extend shelf-life of food, but not before about 1865 did commercial freezing begin. Today, we see these old methods being improved and modified.

Irradiation, the newest method, is perceived by many to be radically different from the older methods. In the past, when we discovered a new method, we did not stop using the old methods; instead, we used the new method to solve problems we could not, or could barely solve before. That is the way it will be also with food irradiation. It is not a panacea, but sometimes it is the best method.

Let us consider a need to sterilize dryed, powdered, and packaged onions. The alternative to irradiation is often fumigation with ethylene oxide. Before fumigation, we must rehydrate the product by steam, preferably for 24 hours. We then expose it to the ethylene oxide for about 16 hours, remove the ethylene oxide by flushing the product with air; dry it; and regrind it, as the powdered onions will have clumped together. Similarly involved procedures are required for effective sterilization of many other food ingredients, condiments, food colors, food enzymes, as well as dryed animal feed.

Irradiation, on the other hand, is relatively a simple process; it does not require exposure to steam; it can be applied to the product as is without repackaging. It is analogous to x-raying our luggage at the airport. The medical industry is already making extensive use of this method because it is simple, reliable, and less damaging to their product than some of the older methods.

Historical milestones. Before the end of the century, scientific curiousity established that x-rays could kill pathogenic microorganisms(1). In 1909, a patent for destruction of Lasiderma beetles in tobacco by means of x-rays was issued in USA. In 1930, O. Wust obtained a patent in France for food preservation by ionizing radiation, but the scientific evidence for the feasibility of industrial application was still meager. In 1943, Proctor, Van de Graaff, and Fram at MIT reported on the "Effect of x-ray irradiation on the bacterial count of ground meat"(2). In 1947, Brasch and Huber(3) showed that high dose-rates, exclusion of oxygen, and irradiation in frozen state reduced undesirable side reactions. In 1948, The Office of Surgeon General's Medical Nutrition Laboratory initiated some exploratory animal feeding studies on irradiated food, and in September 1950, Swift & Co. initiated a major multigeneration, long-term animal feeding study on irradiated beef(4). These early wholesomeness studies did not find any harmful effect from consumption of irradiated food.

In 1953, a National Academy of Sciences ad hoc committee recommended that Office of the Quartermaster General correlate and support research in this field. In 1954, The Surgeon General and the Quartermaster launched a systematic wholesomeness study of representative foods, shown in Table 1 and 2, with the aim of clearing irradiation of food as a process. In 1964, these studies were completed and The Surgeon General's scientists concluded that(5):

> "Food irradiated up to absorbed doses of 5.6 megarads with Co-60 source of gamma radiation or with electrons with energies up to 10 million volts have been found to be wholesome, i.e., safe and nutritionally adequate."

In 1960, the Atomic Energy Commission (AEC) (now under Department of Energy (DOE)) stepped up its efforts in food irradiation while Department of Army (DA) phased out its wholesomeness studies and stepped up its efforts in engineering and prepared for transfer of the technology to industry. All this changed in 1968 when Food and Drug Administration (FDA) turned down a 1966 petition by DA for irradiated ham. Previously, FDA had approved irradiated potatoes, wheat and bacon. In 1968, FDA revoked the approval for irradiated bacon.

At that juncture, AEC terminated its food irradiation program, and also DA wanted to terminate its food irradiation program, but was persuaded by scientists and Congress, in 1970, to continue its program. The basis for this request was that in spite of FDA's refusal to approve the petition for ham, nothing in these extensive

wholesomeness studies had shown harmful effects of irradiation.

The 1968 refusal by FDA to approve the petition for irradiated ham resulted in reduction of food irradiation programs throughout the world. Abroad, like in USA, scientists familiar with the problems recognized the merits of food irradiation process and pushed for formation, in 1970, of the International Project in the Field of Food Irradiation (IFIP), sponsored now by 24 countries, including USA, and the Organization for Economic Cooperation and Development (OECD), the International Atomic Energy Agency (IAEA), the Food and Agricultural Organization (FAO), and the World Health Organization (WHO), who is associated in advisory capacity.

TABLE 1. List of 54 Foods Tested on Humans in the Short-Term Toxicological Studies

| 11 Meat Items | 5 Fish Items | 9 Fruit Items | 9 Cereal Product Items | 14 Vegetable Items | 6 Miscellaneous Items |
|---|---|---|---|---|---|
| Bacon | Cod | Dried apricots | Bread | Asparagus | Dessert powder |
| Corned beef | Haddock | Cherries | Crackers | Green beans | Powdered whole milk |
| Ground beef | Salmon | Dried fruit compote | Cereal bar | Lima beans | Peanut butter |
| Beef steak | Shrimp | Melon balls | Flour | Beets | Pineapple jam |
| Chicken | Tuna | Oranges | Macaroni | Brussel sprouts | Strawberry jam |
| Chicken stew | | Orange juice | Nut roll | Cabbage | Sugar |
| Frankfurters | | Peaches | Pound cake | Carrots | |
| Ground ham | | Dried pears | Rice | Cauliflower | |
| Ham steak | | Strawberries | Corn | Celery | |
| Ground pork | | | | Cole slaw | |
| Sausage | | | | Mushrooms | |
| | | | | Peas | |
| | | | | Sweet potatoes | |
| | | | | White potatoes | |

TABLE 2. List of 22 Foods Testing in Long-Term Toxicological Studies During the 1956 - 1965 Period

| 8 Animal Products | 3 Sea Food Items | 4 Fruits |
|---|---|---|
| Ground beef | Codfish | Fruit compote |
| Beef stew | Tuna | Pineapple jam |
| Chicken | Shrimp | Peaches |
| Chicken stew | | Oranges |
| Pork loin | 5 Vegetable Items | |
| Bacon | | 2 Cereals |
| Dried eggs | Green beans | |
| Evaporated milk | Cabbage | Flour |
| | Carrots | Corn |
| | White potatoes | |
| | Sweet potatoes | |

The DA wholesomeness studies were restarted with a more thorough study on individual items and using thorough chemical analysis of the radiolytic products to extrapolate and interpolate the validity of these studies to a broad spectrum of food. The animal feeding studies were contracted out to industrial laboratories. In spite of the fact that these contractors were considered highly qualified, some of the major ones have faulted on their contracts. This has been costly and has also delayed petitioning FDA. Some other contractors have performed well and their results to date will be reported by Major Chapple at this conference. The in-house work at Natick Laboratories in food technology, microbiology and irradiation chemistry has progressed very well. Especially significant for the evaluation of the wholesomeness of irradiated foods has been the thorough analysis of the radiolytic products at Natick, carried out partly in-house and partly through well coordinated contracts with several universities as described by Dr. Taub at this conference.

The international cooperation in food irradiation has been very constructive. Important milestone was the evaluation in 1976 by IAEA/FAO/WHO Joint Expert Committee on Food Irradiation (JECFI) of the data on wholesomeness of irradiated foods, and its recommendation that five irradiated foods be considered unconditionally safe for human consumption and three others receive provisional acceptance. Subsequently, the influential Codex Alimentarius Commission developed General Standards for movement in international trade of these eight irradiated items (poultry, fish, potatoes, onions, wheat, rice, papaya, and strawberries). The standards received final acceptance in December 1979, at Step 8 of the Commission procedures. Simultaneously, the Codex Commission accepted also General Standards for Operation of Food Irradiation Facility for Treatment of Foods in International Trade.

In 1977, the cooperation in the field of radiation chemistry was expanded by formation of CORC (Coordinated Radiation Chemistry) program under the auspices of the International Project in the Field of Food Irradiation, as described by Dr. Elias at this conference. The radiation chemistry data, together with the animal feeding study data, will be used to seek a significant expansion of the acceptance of irradiated food in international trade. For this purpose, JECFI will consider, in Nov 1980, acceptance of food irradiation as a process for all major categories of foods irradiated with a dose less than 10 kGy.

Hygenization of food. Major benefits of food irradiation will derive from hygenization of food, i.e., freeing it from food spoilage and pathogenic microorganisms, parasites, and insects. In modern society, the quality of life has improved greatly because of higher hygenic standards than before in production, processing and distribution of food. The high hygenic standards have improved the health of the consumer (with its many associated

benefits); they have extended the storage life of the food; and they have increased radius of distribution. Still, advanced societies, like USA, could do even better. In a 1976 report from Comptroller General to the US Congress(6), it is estimated that two million cases of salmonellosis occur annually, resulting in losses of at least $300 million. Other reports have estimated the cost closer to $1500 million.

Microbial reduction. Besides salmonella, irradiation can be used to reduce or eliminate other food borne pathogens such as E. coli, Staphylococcus aureus, Clostridium perfringens and Yersinia enterocolitica. The resistance of microorganisms depends on the medium and the temperature. The vegetative organisms are often two or three times more resistant in dry, or frozen state, than in water, and they are more resistant when irradiated anaerobicly, i.e., in vacuum or in inert atmosphere like $N_2$, than when irradiated in oxygen atmosphere. Tables 3 to 7 give a rough guide to resistance of the microorganisms. Table 8 lists some of the applications and the corresponding dose range.

TABLE 3. Viruses (Ref. 8 to 12)

| Microorganism | Irradiation Medium and Temperature | Dose in kGy for Reducing the Number by $10^6$ |
|---|---|---|
| Foot-and-mouth disease virus (FMDV) Types O, A and C | Calf kidney-cells lactalbumin | 36 |
| FMDV Type D | As above - wet | 30 |
| FMDV Type O | Frozen -60°C | 36 |
| FMDV Type O | 20% peptone | 36 |
| FMDV Type O | 0.1% peptone | 10 |
| Teschen disease virus | 20% peptone | 26 |
| Vesicular stomatitis virus | 20% peptone | 12.3 |
| Rinderpest virus | Frozen | Expected |
| Swine fever virus | Frozen | less than 36 |
| African swine fever | Frozen | |
| Adenovirus | Eagle's minimum | 25-30 |
| Coxsachievirus | essential medium | 25-30 |
| Echovirus | plus 2% fetal | 26-33 |
| Poliovirus | bovine serum pH=7 | 26-31 |
| Herpes simplex virus | | 26 |
| Influenza virus A | | 28 |
| Reovirus I | | 26 |
| Simian virus | | 24 |
| Rabies virus | 10% brain emulsion | 6 |

Reduction of parasites. Irradiation can be used to eliminate parasites. Trichinella spirales in meat can be sterilized, and thus the major pathological symptoms eliminated by a dose of only 0.15 kGy. Complete inhibition of maturation is obtained by a dose of 0.3 kGy (48). However, to kill Trichinella spiralis, Cysticereus

TABLE 4. Salmonella (Ref. 16 to 22)

| Microorganism | Temperature | Dose in kGy Reducing the Number by Factor $10^6$ |
|---|---|---|
| Salm. heidelberg | Chicken 0°C | 3.6 |
| Salm. heidelberg | Chicken -18°C | 6.0 |
| Salm. oranienberg | Chicken 0°C | 3.8 |
| Salm. oranienberg | Chicken -18°C | 5.5 |
| Salm. typhimurium | Beef 5°C | 3.5 |
| Salm. typhimurium | Beef -18°C | 6.0 |
| Salm. thompson | Chicken 0°C | 3.8 |
| Salm. thompson | Chicken -18°C | 5.0 |
| Salm. newport | Chicken 0°C | 3.0 |
| Salm. newport | Chicken -18°C | 5.0 |
| Salm. gallinarum | Egg | 2.6 |
| Salm. gallinarum | Egg Frozen | 3.4 |
| Salm. senftenberg | Egg | 3.0 |
| Salm. senftenberg | Fish-meal | 7.2 |
| Salm. pullorum | Shrimp 5°C | 4.5 |
| Salm. choleraesuis | Oysters 5°C | 4.5 |
| Salm. enteritidis | Oysters 5°C | 3.0 |
| Salm. paratyphia A | Shrimp 5°C | 5.1 |
| Salm. paratyphia B | Crabmeat 5°C | 6.0 |
| Salm. paratyphia | Beef Liver 5°C | 1.8 |
| Salm. paratyphia | Horse Meat Frozen | 6.4 |
| Salm. typhosa | Crabmeat 5°C | 6.0 |
| Salm. typhosa | Corned Beef 25°C | 2.4 - 4.8 |
| Salm. wichita | Shrimp 5°C | 6.0 |
| Salm. meleagridis | Meat | 2.3 |
| Salm. meleagridis | Horse Meat Frozen | 5.6 |
| Salm. anatum | Fish-meal | 4.8 |
| Salm. tennesee | Fish-meal | 4.8 |
| Salm. pigmented str. | Fish-meal | 6.6 |
| Salm. derby | Pork 100°C | 2.0 |
| Salm. weltevreden | Pork 100°C | 2.8 |
| Salm. saint paul | Beef Liver 100°C | 3.0 |
| Salm. manchester | Beef Liver 100°C | 2.2 |

TABLE 5. Vegetative Bacteria (Ref. 23 to 29)

| Microorganism | Temperature | Dose in kGy Reducing the Number by Factor $10^6$ |
|---|---|---|
| Yersinia enterocolitica | Ground Beef 0°C | 1.2 |
| Yersinia enterocolitica | Ground Beef -30°C | 2.3 |
| Escherichia coli | Beef +25°C | 2.1 |
| Staphylococcus aureus | Beef | 1.9 - 3.4 |
| Staphylococcus aureus | Broth | 2.7 - 3.1 |
| Staphylococcus albus | Broth | 2.4 - 3.1 |
| Streptococcus faecalis | Broth | 5.5 |
| Streptococcus faecium | Broth | 1.4 - 19 |
| Streptococcus pyogenes | Oysters | 6.0 |
| Shigella sonnei | Crabmeat | 1.6 |
| Shigella paradysenteria | Oysters | 1.6 |
| Shigella dysenteria | Oysters | 2.4 |
| Mycobacterium tuberculosis | Broth +20°C | 1.4 |
| Aerobacter aerogenes | Broth +20°C | 1.5 |
| Aerobacter cloacae | Broth +20°C | 1.6 |
| Salmonella (diff. str.) | Dif. Med. Unfrozen | 2.3 - 6 |
| Proteus vulgaris | Oyster | 1.2 |
| Serratia marcescens | Broth | 0.8 - 1.3 |
| Pseudomonas fluorescens | Beef | 0.8 |
| Pseudomonas aerogenes | Broth | 1.3 |
| Pseudomonas aeruginosa | Broth | 0.4 |
| Pseudomonas geniculata | Broth | 0.8 |
| Brucella abortus | Beef | 2.0 |
| Vibro parahaemolyticus | Phds. Butter | 0.8 |
| Vibro parahaemolyticus | Crabmeat | 0.5 - 0.96 |
| Lactobacillus hetero-fermentative | Broth | 3.3 - 4.8 |
| Lactobacillus homo-fermentative | Broth | 4.9 - 6.6 |
| Leuconostoc sp. | Broth | 1.2 - 3.4 |
| Sarcina flava | Broth | 2.0 |
| Moraxella-Acinetobacter | Beef | <55 |
| Micrococcus radiodurans | Broth | <60 |

TABLE 6. Spores (Ref. 30 to 42)

| Microorganism | Temperature | Dose in kGy Reducing the Number by Factor $10^6$ |
|---|---|---|
| Bacillus subtilis | Dried Broth ($N_2$) | 18 |
| Bacillus subtilis | Dried Broth ($O_2$) | 12 |
| Bacillus pumilus | Buffer | 18 |
| Bacillus stearo-thermophilus | Broth | 18 |
| Bacillus cereus | Physiol. NaCl Sol. | 14 |
| Bacillus anthracis | Physiol. NaCl Sol. | 12 |
| Bacillus globigii | | 18 |
| Cl. sporogenes | Buffer | 13 |
| Cl. welchii | Broth | 8 - 22 |
| Cl. botulinum 33A | Beef - frozen | 24.5 |
| Cl. b. 36A,33A,40B, 41B,53B | Phos. buffer | 20 - 19 |
| Cl. b. 77A,12885A, 9B,62A | Phos. buffer | 15 - 13 |
| Cl. b. E, 51B | Phos. buffer | 8 - 10 |
| Cl. b. 33A-36A | Bacon 15°C | 12.5 |
| Cl. b. 62A(most resist.) | Ham 15°C | 15.5 |
| Cl. b. 12885A | Pork 15°C | 21.5 |
| Cl. b. mix. of 10 most resist str. | Ham -30°C | 18 |
| Cl. b. mix. of 10 most resist str. | Beef -30°C | 20 |
| Cl. b. 77A | Corned beef -30°C | 12 |
| Cl. b. 41B | Pork sausage -30°C | 13.5 |
| Cl. b. 53B | Codfish cake -30°C | 16 |
| Cl. b. E, Beluga, incub. 8°C | Haddock | 9.7 |
| Cl. b. E, Beluga, incub. 20°C | Haddock | 17.1 |
| Cl. b. F.Eklund, 83F - 80°C | Phos. buffer | 13.0 |

TABLE 7. Fungi (Ref. 43 to 47)

| Microorganism | Temperature | Dose in kGy Reducing the Number by Factor $10^6$ |
|---|---|---|
| Trichoderma viride | Citrus fruit | 1.0 |
| Trichoderma viride | Water | 1.6 |
| Phomopsis citri | Citrus fruit | 1.2 |
| Phomopsis citri | Water | 1.5 |
| Penicillum italicum | Citrus fruit | 1.7 |
| Penicillum italicum | Water | 2.1 |
| Penicillum expansum | Prunus fruit | 2.3 |
| Penicillum expansum | Water | 2.1 |
| Penicillum digitatum | Citrus fruit | 1.9 |
| Penicillum digitatum | Water | 2.8 |
| Penicillum camembertii | Water | 1.2 |
| Penicillum notatum | Water | 1.8 |
| Geotrichum candidum | Citrus fruit | 2.5 |
| Geotrichum candidum | Water | 2.9 |
| Monilinia fructicola | Prunus fruit | 3.0 |
| Monilinia fructicola | Water | 3.1 |
| Botrytis cinerea | Prunus fruit | 3.2 |
| Botrytis cinerea | Water | 3.8 |
| Diplodia natalensis | Prunus fruit | 4.5 |
| Diplodia natalensis | Water | 4.5 |
| Rhizopus stolnifer | Prunus fruit | 4.1 |
| Rhizopus stolnifer | Water | 6.5 |
| Alternaria citri | Citrus fruit | 7.4 |
| Alternaria citri | Water | 9.0 |
| Cladosporum herbanum | Prunus fruit | 6.1 |
| Cladosporum herbanum | Water | 7.5 |
| Gilbertella persicaria | Water | 8.0 |
| Saccharomyces cerevisiae | 0.85 NaCl ½% gel. | 3.0 |
| Saccharomyces cerevisiae | Water | 2.5-3.6 |
| Candida species | Broth | 7.5 |
| Torulopsis candida | Broth | 3.6 |
| Aspergillus niger | Water | 2.7 |
| A. flavus (spores) | Water | 2.5 |

TABLE 8. Uses of ionizing radiation

| | | |
|---|---|---|
| 1. | Inhibition of sprouting in potatoes and onions | 0.03 - 0.1 |
| 2. | Sterilization of insects and parasites | 0.03 - 0.2 |
| 3. | Killing of insects and parasites | 0.5 - 5 |
| 4. | Reducing by $10^6$ the number of vegetative bacteria, molds and fungi | 1 - 10 |
| 5. | Reducing by $10^6$ the number of dryed or frozen vegetative bacteria, fungi, and spores | 2 - 20 |
| 6. | Reduction by $10^6$ the number of viruses | 10 - 40 |
| 7. | Sterilization of food | 20 - 45 |

and lipolytic enzymes in meats, poultry, and fish. We prevent oxidation by vacuum packaging the product in durable materials that are impermeable to oxygen and that withstand bacteria and insects. This way, we have produced at Natick a long series of highly acceptable meat, poultry, and fish products that are stable for several years at room temperature (53). Irradiation can also be used to reduce the microflora in raw meat, poultry, and fish products. The raw products should preferably be vacuum packed to prevent oxidation and recontamination. Use of low doses will reduce off-flavor caused by irradiation. On the other hand, the low dose makes it necessary to store the product at refrigerated temperatures or in frozen state.

Chemiclearance and the magnitude of radiolytic changes. Irradiation damage to a molecule is approximately proportional to its molecular weight. The DNA molecule in microorganisms is the largest molecule there is, about $10^8$ daltons. It is also essential for survival of the microorganisms. That is the reason that these organisms, like any other live form, are so sensitive to radiation.. Food nutrients, such as proteins, lipids and carbohydrates, are digested into amino acids, fatty acids, and monosaccharides, with molecular weights about 150-250 before absorbed in the lymphatic system. The damage to these molecules is thus about a million times smaller than to the DNA molecules. A sterilizing dose that causes about $10^{-12}$ reduction of Cl. botulinum will cause a total number of all changes in these macro nutrients when irradiated in frozen or dry state that amount to about 0.24% in proteins, 0.3% in carbohydrates, and 0.4% in all lipids. Specific changes in the molecules are an order

bovis (49) and many other parasites, a dose of 3 to 10 kGy is required. For example, to kill Anisakis larvae in herring (50), a dose of 10 kGy is required.

Reduction of insects. Sterilization of insects is usually obtained by doses in the range of 0.03 - 0.2 kGy (51). However, for some moth species (Sitotroga cerealla), doses in excess of 1 kGy are required. A dose of about 5 kGy is sometimes required for killing the insects (52) and the parasites.

Stabilization of food. Irradiation kills the microorganisms, but does not, otherwise, cause many chemical changes in the food. It thus does not destroy the enzymes in the food and it does not stop, therefore, its decomposition by protolytic and lipolytic enzymes. Also, irradiation does not prevent oxidative reactions, and it does not prevent recontamination by microbes and insects. When meats, poultry, and fish are to be preserved properly for long-term storage, we must use other means to inactivate the enzymes. At Natick, we use mild heat treatment (about 72°C) to inactivate protolytic

or even several orders of magnitude smaller. When irradiated in unfrozen state, the total number of changes may be about 3 times greater. These changes are much too small to be measurable in any protein efficiency study, as confirmed in many experiments. This is especially true when we take into consideration that most of these changes result in products that are commonly found in food, as well as products that result from digestion of the food. We should remember in this context that the changes that occur during storage and especially during thermal processing often result in significant and measurable losses (5-40%) in protein value of the food. In the early experiments, the irradiated food was often improperly packaged in oxygen permeable films. It therefore became oxidized, as evidenced by high peroxide values. Some of the experimentors thought incorrectly that this was due to irradiation. This has caused some confusion. Irradiation makes it possible to extend the storage of food because it reduces or eliminates the microbial problem. Oxidation becomes then often the limiting factor. It therefore becomes important to eliminate oxygen from irradiated foods. Exclusion of oxygen also reduces detrimental oxidative reactions during irradiation.

In proteins, irradiation causes disruption of hydrogen bonds and unfolding of the molecules, similar to the changes caused by mild heat treatment. Relatively frequent, are also reductive deamination and decarboxylation. From alanine, we thus get ethylamine and propionic acid; from glycine we get acetic acid and methylamine, etc.

In polysaccharides, irradiation causes depolymerization and fragmentation into simpler molecules, such as glucose, maltose, maltotrose maltotetrose, maltopentose, carbon dioxide, hydrogen, formic acid, formaldehyde and acetone.

In lipids, irradiation causes abstraction of hydrogen and formation of a double bond, and splitting of the free fatty acids from the triglycerides. It may also cause scission at the carbon-carbon bonds resulting in a spectrum of aliphatic hydrocarbons.

Irradiation can also cause cross-linking, dimerization, and aggregation along with degradation. These changes are very small compared to the cross-linking and aggregation caused by heating. Indications are that these changes are similar in nature to those found in fresh food and in processed and stored food.

In unfrozen state, there are exceptions to the above quantitative estimates. This is especially evident for some of the micro nutrients such as the water soluble C-vitamin and $B_1$-vitamin that act as scavenger for the radiolytic product of water. These vitamins are destroyed about to the same extent as when the food is heat sterilized. The other soluble vitamins, $B_2$, $B_6$, and $B_{12}$, are also good scavengers when they are in pure solution. In food, they are often complexed with other molecules and then more stable. In this context, it should be kept in mind that most vitamins are unstable in long-term storage, and irradiation does not change that fact. The question has been raised if antivitamins (that are often found in food) could be formed. This was checked for vitamins $B_1$ and $B_6$ in meats and no antivitamin activity could be detected.

Energy savings. The energy consumed in the irradiation process is very small compared with other processes. Table 9 shows typical energy values for processing the food. More relevant for national energy savings is to include the energy savings in distribution and in the homes. Table 10 gives a few examples.(54)

Cost of irradiation processing. The irradiation costs, like the costs of many other processes, depend on the scale of production and the product flow plan. It is cheaper to irradiate the finished packaged product as it comes off the production line, than to use central service irradiation facilities, because of the significant cost of loading, shipping and unloading the product. Practice has shown, however, that central service irradiation facilities are needed especially in the beginning, when the quantities to be irradiated are small and the benefits great. Table 11 shows some typical costs of radsterilizing 100 million lbs per year of bacon in a 200 kwatt plant, operated 6000 hours per year at a beam utilization efficiency fo 27%. The capital cost for the 4 MeV accelerator facility is about 1.8 million, for the 20 MeV accelerator facility 2.45 million, and for the Co-60 and Cs-137 facilities about 10 million. These costs are for simple, functionalistic facilities located between the production line and the storage rooms. (55-56)

TABLE 9. Typical Energy Values in KJ/KG Used for Processing of Food

| | |
|---|---|
| Radpasteurization with 2.5 kGy | 21 |
| Radsterilization with 30 kGy | 157 |
| Heat sterilization | 918 |
| Blast freezing chicken from 4.4°C to -23.2°C | 7552 |
| Storing the product at -25°C for 3.5 weeks | 5149 |
| Refrigerated storage for 5.5 days at 0°C | 318 |
| Refrigerated storage for 10.5 days at 0°C | 396 |

TABLE 10. Summary: Energy Use (KJ/KG) Associated with Different Chicken Processing Methods

| | |
|---|---|
| Radsterilization cooked long chicken rolls | 14,260 |
| Radsterilization cooked individual servings | 15,460 |
| Retorted canned chicken meat | 20,180 |
| Frozen cooked long chicken rolls | 27,550 |
| Frozen raw cut-up chicken | 46,600 |
| Refrigerated raw cut-up chicken | 17,760 |
| Refrigerated and radpasteurized raw cut-up chicken | 17,860 |

TABLE 11. Cost of Radsterilizing Bacon*

| Source | 5-Yr Plant Depreciation Costs in ¢ | Operational costs in ¢ per lb | Total Cost in ¢ per lb |
|---|---|---|---|
| Co-60 isotope | 2.03 | 1.2 | 3.23 |
| Cs-137 isotope | 2.03 | 0.32 | 2.38 |
| 10-MeV accelerator | 0.49 | 0.43 | 0.92 |
| 4-MeV accelerator | 0.36 | 0.40 | 0.76 |

*Plant Size: 100,000,000 lb per year

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