Food Irradiation: Commercial and Scientific Review

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Abstract
Radiation processing offers the food industry a 'new' process to control food spoilage and pathogenic organisms. The process is based on four decades of extensive research on the underlying aspects of radiation chemistry and radiobiology, concurrent with over 25 years of technical development and commercialization of radiation processing equipment. To date, many countries have approved a wide range of food irradiation applications, but commercial use of the process is just beginning to grow significantly. This paper reviews some aspects of the scientific and commercial background behind this process, focusing on the microbial and chemical safety, and the nutritional issues.

Résumé
Le traitement par radiation offre à l'industrie alimentaire un 'nouveau' procédé permettant de maîtriser les organismes pathogènes qui causent la pourriture. Ce procédé a fait l'objet de quatre décennies de recherche approfondie sur les aspects sous-jacents de la chimie de la radiation et de la radiobiologie. Depuis plus de 25 ans, on effectue des travaux de développement technique et on pratique la commercialisation d'appareils de traitement par radiation. Jusqu'à présent, de nombreux pays ont accepté une large gamme d'applications diverses pour le procédé d'irradiation alimentaire mais l'utilisation commerciale du procédé ne fait que commencer à démarrer. Le présent document fait l'analyse de certains aspects scientifiques et commerciaux reliés à ce procédé et met l'accent sur la sécurité microbienne et chimique ainsi que sur la question de qualité nutritive.

Introduction

Food is essential for human survival, but unfortunately it begins to deteriorate soon after harvest. Much of the spoilage is due to microbial action and insect infestation. Radiation processing in combination with proper storage technology has proven to be effective in controlling microbial and insect causes of spoilage. It is also an effective method of reducing or eliminating pathogenic food-borne organisms such as *Salmonella*. Radiation processing technology, properly and appropriately applied, can contribute to increasing the availability of good-quality foods, and to improving their safety.

Food irradiation attracted many countries during the 1950s push to find peaceful uses for nuclear technology. Food spoilage and food-borne disease was, and remains, a universal problem. Post-harvest losses range from 5% to 50%, depending on the country. Economic and human losses due to pathogenic food-borne *Salmonella* organisms alone are enormous. A recent U.S. Department of Agriculture report [1] estimates economic loss at several billion dollars/year, and, in Canada, a Health Department report [2] estimates 763 deaths per year in Canada are attributable to salmonellosis. A survey in 1968 found that 76 countries had active programs on food irradiation. [3] The need then and now remains the same.

Amongst the most active countries in these early years were: Argentina, Belgium, Canada, Chile, Denmark, the Federal Republic of Germany, France, Greece, Hungary, India, Israel, Italy, Japan, the Netherlands, Pakistan, the Phillipines, South Korea, Thailand, the U.K., the U.S.A., and the U.S.S.R. These countries independently, and often in co-operative projects encouraged or sponsored by international organizations, such as the United Nations and the World Health Organization, generated a vast body of published scientific work. The results addressed the fundamental issues of the safety of irradiated foods and the benefits of using the technology.

Beginning in 1961 and concluding in 1980, five international Joint FA/IAEA/WHO Expert Committees (JEC) were convened to address the issue of irradiated food safety. Each committee, in turn, examined the ever-growing and extensive scientific information

Keywords: irradiation effects, irradiation machines, micro-organisms, foods, nutrition.

available, and recommended additional areas of study. The final JEC, in 1980, recommended that the irradiation of any food up to an overall average dose of 10 kGy is safe. [4] This recommendation was circulated to all 122 member countries of the Codex Alimentarius Commission (CAC), a joint FAO/WHO body established to develop international food standards. After two years of deliberation, the CAC adopted the 1980 JEC recommendation and promulgated a Codex General Standard for Irradiated Foods and a Recommended Code of Practice for the Operation of Radiation Facilities Used for the Treatment of Foods. [5]

Since 1983, many nations have issued first regulations permitting food irradiation; others have broadened existing rules (e.g. U.S. FDA, April 1986[6]), and others, like Canada, are in the process of modifying their regulations to be more consistent with the Codex General Standard. Presently, over 25 countries have approved a wide range of irradiated foods, and commercial implementation is progressing steadily.

Before addressing the commercial part of this subject, it is appropriate to review the principal technical and scientific aspects as they relate to the food irradiation process. These cover the microbiological aspects, chemical effects, and nutritional quality.

The process

Food irradiation consists of exposing foods to a source of ionizing radiation to obtain the dose necessary to achieve the desired effect. Different doses achieve different effects in different foods as can be seen in Table 1. The dose needed may also vary from product to product depending upon the organisms involved and the tolerance of the product. Establishing the correct dose for a given product is a routine matter of product testing with easily established protocols. However, not all foods respond favourably to irradiation. For example, most varieties of grapes will tolerate low doses used to kill or sterilize insects, but when higher doses are applied to prevent mould growth the grapes become softer than is desirable. Similarly, irradiated milk, although effectively pasteurized, tastes differently from heat-pasteurized milk.

In addition to establishing the correct dose, other factors must be addressed, such as the need for temperature control during irradiation, the selection of radiation-compatible packaging materials, and the definition of irradiation procedures that conform to approved food handling practices. These factors are not complex, but because food irradiation is a 'new' process, they are being addressed, in most cases, for the first time for specific products in the context of national requirements. In this regard, the Codex General Standard and Code of Practice provides a measure of standardization.

At this time there is only one source of ionizing radiation readily available, and technologically developed for food irradiation. This is the radioisotope cobalt-60. Cobalt-60 is a deliberately produced isotope that emits ionizing energy in the form of gamma rays; it is not a waste product. These rays are not capable of inducing radiation in the irradiated food. The rays pass through the product depositing energy. The deposited energy kills organisms by mechanisms which are discussed in the next section.

According to AECL marketing data there are, at present, over 125 large cobalt-60 sourced industrial irradiators, over 2000 cobalt-60 sourced cancer treatment machines, and over 300 cobalt-60 sourced research irradiators in use world-wide.

A second source of ionizing enery being developed for food applications uses a machine to produce an accelerated beam of electrons. These electrons can be applied directly, or can be used to generate high energy X-rays. The electrons are less penetrating than gamma rays, but the ionizing effects are essentially the same. The converted X-rays have good penetration, but the costs of conversion are significant in terms of power consumption/loss. Electron beam machines have been in use for cancer treatment and industrial processing of thin films for many years. However, the technology still needs to be developed further and adapted to meet some of the potential food irradiation applications.

Each source technology is best suited to different products, and each will complement the other in commercial application. Cobalt-60 irradiators do an efficient and cost-effective job on bulky, packaged foods, and moderate volumes of high-value granular products such as enzymes. Electron beam machines, when they are developed and commercially available, should be cost-effective for huge volumes of fluid and granular products that can be thinned, and may also be appropriate for the processing of thin packages in in-line configurations.

Presently, there are ten large food irradiators in use world-wide, and several more are under construction. There are about 25 other irradiators that process small quantities, from time to time, in addition to their normal throughput of medical disposable products. There are also plans for an additional six dedicated food irradiators that are likely to be realized in the next few years (AECL data). A large pallet irradiator, similar to AECL installations in Holland and the Federal Republic of Germany, is shown in Figure 1.

Microbiological Aspects

Ionizing radiation affects living cells by creating in the product ions, excited molecules, and free radicals that react with other molecules which, in turn, damage the cells. [8] When enough damage occurs, the cells die or cease to function. The sensitivity of an organism to radiation is usually expressed as a 'D-value.' This is the radiation dose required to inactivate 90% of the

Table 1: Some Examples of Irradiation Applications[1]
(Not Comprehensive – Examples Only)

Food	*Purpose of irradiation*	*Approximate dose needed (kGy)*	*Countries which permit application*
Potatoes and/or onions	Sprout inhibition	up to 0.15	Bangladesh, Brazil Canada, Chile, China Israel, Italy, Netherlands, South Africa, USSR, USA, Yugoslavia
Strawberries[2]	Shelflife extension/mould inhibition	1–4	Brazil, Chile, South Africa
Wheat[3]	Insect disinfestation	up to 0.15	Canada, Chile, USA, USSR
Chicken	Shelflife extension and Salmonella control/elimination	2–7	Bangladesh, Brazil, Chile, France, Israel Netherlands, South Africa
All fruits and vegetables	Disinfestation and shelflife extension	up to 1	USA
Fish (fresh)	Shelflife extension	up to 2	Bangladesh, Brazil
Shell fish (frozen)	*Salmonella* control/elimination	2–7	India
Spices[4]	Microbial reduction, insect disinfestation, sterilization	up to 10, 30 kGy in USA	Bangladesh, Brazil Canada, Chile, India, France, Israel Hungary, Norway South Africa, USA

[1] Data taken from 'Food Irradiation Newsletter' a Joint FAO/IAEA, publication, Vienna, August 1985, [7] and revised by author.
[2] Commercial operation in South Africa
[3] Commercial operation in USSR
[4] Commercial operation in Brazil, France, Israel, Hungary, South Africa, USA

population of that organism in the irradiated sample. Some representative D-values for a range of microorganisms are listed in Table 2. It can be noted that *Clostridium botulinum* Type F spores are the most resistant in that they require a 2.5 kGy dose to achieve a 90% reduction, whereas *Escherichia coli* vegetative organisms can be reduced the same amount with only a .09 kGy dose.

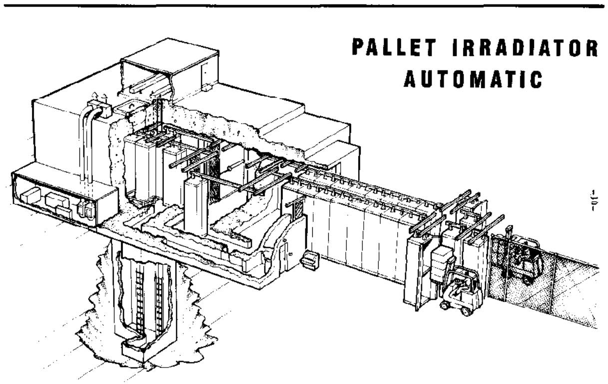

Figure 1 Automatic pallet irradiator

From a practical, processing viewpoint it is important to identify the types of organisms that are the target of irradiation, whether the damage they do is a matter of spoilage or is pathogenic in nature. This enables reasonable estimates to be made of the required doses to achieve the desired result. These estimates, in turn, can then be confirmed by product testing.

Two primary concerns have been raised over the years regarding the application of sub-lethal doses to organisms in food. The question of sub-lethal doses is a very real one, as the current international recommended dose maximum is only 10 kGy. For example, referring to Table 2 and assuming a dose of 10 kGy, it will be noted that the population of *Salmonella typhimurium* would be reduced by a logarithmic factor of 50 and thus effectively eliminated, whereas the population of *Clostridium botulinum* Types A, B, E, and F would only be reduced by logarithmic factors of three to ten. Given enough *Clostridium botulinum* contamina-

Table 2: D-Values for Irradiation of Some Microorganisms[1]

Microorganisms	*D-value (kGy)*
Vegetative Cells	
Escherichia coli	0.09
Pseudomenas	0.05–0.5
Salmonella typhimurium	0.2
Staphylococcus aureus	0.02
Micrococcus radiodurans	1.9–3.0
Vibrio parahaemolyticus	0.05–0.14
Spores	
Clostridium botulinum	
Type A	2.1–2.3
Type B	1.6–3.7
Type E	0.8–1.6
Type F	2.5

[1] Data taken from Banwart, 1979. [9]

tion in the product, it is quite possible that a number of *Clostridium botulinum* organisms would survive (i.e. a sub-lethal dose would have been applied).

The first concern is that the survivors might be mutant and might have increased resistance to radiation and/or would have more harmful characteristics. These mutant organisms could possibly multiply and be spread throughout the world. A second concern is that the survivors, whether mutated or not, would be able to thrive, unbridled by competition from the weaker organisms that were eliminated. If these thriving survivors happened to be pathogenic organisms, the product could appear to be unspoiled, having no deleterious (or undesirable) odours or taste, while in fact it would be microbially unsafe.

Both concerns were well addressed by the JECs and found to be unsupportable. In addition, other authoritative bodies have examined these concerns and supported the findings of the JECs. For example, the Board of the International Committee on Food Microbiology and Hygiene of the International Union of Microbiological Societies addressed these issues at its 1982 meeting and concluded that there was no cause for concern. An excellent summarizing statement, quoted in full below, is taken from the 1986 *Report on the Safety and Wholesomeness of Irradiated Foods*, [10] prepared by the U.K. Advisory Committee on Irradiated and Novel Foods:

5.14 The Panel considered the extensive data on this point and concluded that radiation-induced mutations were not likely to constitute a microbiological hazard. Most mutations in micro-organisms induced by ionizing radiation or by any other means are deleterious to the organism, and will be associated with a decrease in pathogenicity. Furthermore, there is no selective pressure to encourage the enhanced survival in foods of strains of increased virulence. There is no experimental evidence for irradiation producing an increase in pathogenicity, and there are no reports of any greater difficulty in identifying the surviving micro-organisms in irradiated food by standard microbiological techniques than in an unirradiated population. Radiation-resistant mutants of micro-organisms can be selected out under laboratory conditions involving many repeated doses slightly below the lethal dose, but such conditions would not occur in any foreseeable applications of food irradiation.

5.15 We consider that there are considerable benefits from the microbiological effects of food irradiation, both in terms of the extension in shelf life resulting from the reduced number of spoilage organisms in irradiated foods, and in terms of potential health benefits from the fact that food irradiation constitutes an effective addition to the methods of controlling pathogenic organisms in food. We also concur with the Panel that the use of food irradiation is not likely to present any microbiological hazard to the consumer. Although irradiation up to an overall dose of 10 kGy would not kill all pathogenic micro-organisms, and could allow continued growth of surviving pathogens, the same possibilities arise with all of the accepted non-sterilising methods of food processing, and we consider that standard techniques can be applied to determine microbiologically safe conditions for any particular application of food irradiation. Finally, we are satisfied that the ability of ionizing radiation to produce mutations in micro-organisms does not constitute a special microbiological hazard to the consumer.

Chemical Effects

In addition to controlling or eliminating micro-organisms, the ionizing energy is also absorbed by the food itself. The effect on the food is that a few of the molecules are split into new molecules. These new molecules are referred to as radiolytic products. The primary concern that arises from this fact is whether or not these radiolytic products are harmful.

The nature of the radiolytic products depends primarily on the chemical composition of the food itself. The quantity of such products generally increases with radiation dose, but can be modified by factors such as temperature, the presence or absence of air, and the water content of the food at the time of irradiation. However, the amount of energy absorbed by the food during irradiation is much less than that absorbed during heat processes such as canning. It is therefore not surprising that the amount of chemical change is smaller than in comparable heat processes. The 1976 JEC concluded that radiolytic products detected in the wide range of irradiated foods studied did not appear to pose any toxicological hazards in the concentrations at which they were detected [4].

Similarly, other studies of this issue by credible national authorities have reached the same conclusion. One of the most comprehensive of these studies was undertaken by the American Council for Agriculture Science and Technology (CAST), which reported in

July 1986 [11]. Among the many safety issues addressed in their report is the subject of Unique Radiolytic Products (URPS). Scientists in the field define URPS to be compounds that are formed by treating foods with ionizing energy, but which are *not* found normally in any untreated foods, and are *not* formed by other accepted methods of food processing. On the basis of this definition, the CAST report states: 'No unique radiolytic compounds have been found in 30 years of research. Compounds produced in specific foods by ionizing energy have *always* been found in the same foods when processed by other accepted methods, or in other foods.' [11]

The only concerns of substance with regard to radiation-induced chemical changes are *non-toxic* changes that affect the sensory attributes of the food and/or the nutritional quality. As previously discussed, some foods do not respond well to irradiation in that their organoleptic qualities change. This unwanted change is due in large part to the formation of non-toxic radiolytic products that impart different flavours and aromas. The key to avoiding these changes is to ensure that the appropriate radiation dose is applied under the correct conditions to a suitable product. Failure to do so may result in an unmarketable product, even though chemically safe. The second concern, the effect of radiolytic products/chemical change on nutritional quality, is addressed in the following section.

Nutritional Quality

This issue has also been thoroughly researched by reputable authorities, resulting in consistent findings. These can best be summarized by quoting the abstract of the 1978 paper by Dr E.S. Josephson *et al.* 'When foods are exposed to ionizing radiation under conditions envisioned for commercial application, no significant impairment in the nutritional quality of protein, lipid and carbohydrate constituents was observed. Irradiation was no more destructive to vitamins than other food preservation methods. Protection of nutrients is improved by holding the food at low temperature during irradiation and by reducing or excluding free oxygen from the radiation milieu.' [12]

When carbohydrates are irradiated, some splitting of complex compounds into simpler compounds occurs, the main effects of which are hydrolysis and oxidative degradation. Detailed studies have shown these changes to be of no nutritional significance.

The main reactions of irradiation of fats are oxidation, polymerization, decarboxylation, and dehydration. These changes are non-toxic and can be reduced, if desired, by various processing techniques. Regardless of the changes themselves, no significant effect on the digestibility of fat-containing foods has been found.

Proteins are affected similarly to carbohydrates in that complex protein molecules are broken into smaller protein molecules. However, these smaller protein molecules yield the same amino acids upon digestion as the larger unbroken molecules. No effects of significance with respect to nutritional quality have been found.

Vitamins are somewhat different in that some are virtually unaffected even by high radiation doses, whereas others are affected to the same degree as when other processing technologies are used. Two direct quotes from the 1986 CAST report provides a good summary of this aspect:

> Many experiments have been done on the effects of ionizing energy on vitamins. Some vitamins appear to be affected very little by ionizing energy. Vitamin K, for example, appears to be relatively stable. A significant proportion of the vitamin C may be changed to dehydroascorbic acid, but this compound has almost the same vitamin C value as ascorbic acid, which is vitamin C itself. Tocopherols, which are antioxidant compounds with vitamin E activity, seem to be especially sensitive to ionizing energy in the presence of oxygen, as would be expected from their antioxidant properties. Vitamins are sensitive also to processing by heat. Research on vitamin B6 has shown less destruction of this vitamin in products sterilized by ionizing energy than by heat. Vitamin retention in food is greatest when the processing with ionizing energy is carried out at low temperatures in the absence of oxygen.
>
> Exposure of food to ionizing energy is somewhat destructive of vitamins, but no more so than are other food preservation methods used commercially. [11]

A significant summary statement with respect to the absence of deleterious effects on nutritional quality of foods irradiated at low doses for insect disinfestation and shelf-life extension is given in the U.S. Federal Register, which contains the new F.D.A. regulation '21 CFR Part 179 – Irradiation in the production, processing and handling of food: Final Rule':

> 4. Destruction of Nutrients
>
> 12. Several comments stated that destruction of nutrients should be a concern in this rulemaking. The comments stated that many vitamins are light or heat sensitive, and that irradiation will destroy them. One comment stated that nutritional problems may develop for consumers because of nutrient loss when an entire class of foods is irradiated.
>
> 13. The proposal discussed this issue and explained that the available literature indicated that there are no nutritional differences between unirradiated food and food irradiated at levels below 1 kGy (100 krad). The minor ingredients allowed to be irradiated at higher doses are not sources of nutrients. Therefore, the agency believes it is appropriate to conclude that destruction of nutrients

is not an issue in this rulemaking. There have been no additional data submitted to change this conclusion. [6]

Commercialization

If it can be accepted, based on statements from respected scientific and government health authorities the world over who have examined them, that (1) irradiated foods are safe and wholesome, and that (2) facilitative regulations are steadily being developed and promulgated, what are the prospects for increased commercial use of food irradiation technology?

Today, more food is being irradiated and consumed than ever before. The quantity, however, is not huge; the IAEA estimate for 1985 is only 350,000 metric tons. Nevertheless, annual quantities are increasing significantly, as are the number of food irradiators. In the two-year (1986 and 1987) period AECL Radiochemical expects to install three full-scale and five pilot-scale, or small-upgradeable food irradiators. The U.S. Department of Energy has announced plans to construct six strategically located pilot-scale food irradiators. The purpose of these demonstration facilities is to provide the U.S. food industry with readily accessible test facilities that are able to process significant quantities of foods.

For the first time ever, in September 1986, an irradiated fruit was allowed into the U.S.A. for general public consumption. A Puerto Rican mango grower teamed up with the world's leading contract radiation processing firm, Isomedix Inc., to conduct a market trial of irradiated mangoes in Miami. The test was considered a success by all involved, including the retailer who sold the irradiated mangoes faster than locally grown, non-irradiated mangoes. The retailer stated that his customers are more interested in the appearance, quality, and taste of his products than in the way they were treated.

This positive result confirms several North American consumer attitude surveys conducted in the past few years. These studies report that 20–35% of consumers are ready to purchase irradiated foods, 60–70% want more information, and 5–15% are not going to purchase initially. Obviously, 20–35% of consumers is enough to result in good business for the grower, distributor, and retailer. Isomedex Inc. plans to process commercial quantities of mangoes for sale in the U.S. during the 1987 mango season.

Given the reality that very little co-ordinated consumer education efforts have been made yet in North America, and that an extremely vocal anti-food-irradiation lobby has been actively opposing the process for the past 18 months, the Miami mango test results appear even more positive. Pro food irradiation organizations in Canada and the U.S.A. are being organized, and are just beginning to distribute factual information to the consumer. The U.S. Institute of Food Technologists has included food irradiation in their active program of media/public relations. The U.S. Coalition for Food Irradiation, sponsored by the National Food Processors Association, includes membership from major U.S. food companies. This Coalition has hired a professional Public Relations firm (February, 1986) to assist in providing factual information to consumers, the media, and politicians. In Canada, the newly formed Canadian Advisory Committee on Food Irradiation (June, 1988), initiated by Agriculture Canada, will provide a standing forum for industry, government, and consumer representatives to discuss key issues. A spin-off of this forum will almost certainly be the formation of an industry-led organization to inform the Canadian consumer and the media.

Regardless of commercial progress elsewhere, in particular in large developing countries like China, the world, for the time being, still looks to North America for the lead. The North American food industry is, in general, well informed, and many major companies have active Research and Development programs on food irradiation. However, before these firms make significant moves toward using the technology, they want more proof of consumer acceptance. Over the next few years, a combination of factors will likely result in greater acceptance of food irradiation. The effective banning of ethylene dibromide fumigant in the U.S.A. and Canada, and the likelihood of more countries doing the same, has left many fruit and vegetable producers with no effective alternative except irradiation. Increased, co-ordinated, factual and authoritative consumer education will gradually have a positive effect on consumer attitudes. Additional market trials of significant quantities of irradiated foods will be conducted and will provide hard evidence that the consumer can differentiate between Chernobyl and food irradiation. Some firms (the pioneers) will want to gain a marketing advantage and will decide 'to go for it,' if for no other reason than to capture the business of the 20–35% of consumers that will buy irradiated food now.

The prospects for regulatory and consumer acceptance of irradiated foods world-wide are good, as are the prospects for commercial use. The technology itself is well understood. Good progress has been made in terms of the quantities and range of foods being irradiated. In short, the prospects for the commercialization of food irradiation technology have never been better.

Summary

The scientific work done since the early 1950s is well documented and comprehensive, as it relates to safety and nutritional issues. It has also resulted in a good definition of applications that work and those that don't. However, there are several areas that call for more attention by the scientific community, in particular the generation of additional data on the safety of foods irradiated to doses higher than the 10 kGy Codex-recommended maximum average, and the generation of data on treatments involving irradiation in combination with other technologies and prc :esses.

For the food industry and the consumer, the future commercialization of food irradiation technology is only a matter of how quickly it will come about. The benefits in terms of reduced food losses, improved maintenance of quality, and reduced incidence of pathogenic contamination are too compelling to be ignored or rejected.

Notes and References

1. *Morrison RM, Roberts T.* Food irradiation: New perspectives on a controversial technology. Washington: U.S. Department of Agriculture, 1985.
2. *Todd ECD.* Costs of food borne diseases in Canada. (Presented at the International Consultative Group on Food Irradiation Taskforce Meeting on Decontamination of Foods by Irradiation, Vienna, May 1986. Awaiting publication.)
3. *Urbain WM.* Significant milestones of progress to-date in food irradiation and identification of areas of future advances. (Proceedings of a Symposium on Food Irradiation Processing.) Washington: IAEA/FAO: 509–18.
4. Wholesomeness of irradiated food. (Report of a Joint FAO/IAEA/WHO Expert Committee.) Technical Report Series #659. World Health Organization, 1981.
5. Codex general standard for irradiated foods and recommended international code of practice for the operation of radiation facilities used for the treatment of foods. CAC/Vol XV-Ed 1. FAO and WHO, 1984.
6. U.S. Federal Register, Part III. U.S. Department of Health and Human Services, Food and Drug Administration, 18 April 1986: 13376–99.
7. Food Irradiation Newsletter. Vol. 9, No. 2. Vienna: IAEA, August 1985.
8. *Singh A, Singh H.* Time-scale and nature of radiation-biological damage: Approaches to radiation protection and post-irradiation therapy. Proc. Biophys Mole Biol 1982; 39: 69–107.
9. *Banwart GJ. In*: Basic food microbiology. Westport Connecticut: AVI Publishing Co. Inc., 1979.
10. Report on the safety and wholesomeness of irradiated foods. U.K. Department of Health. Queen's Printer.
11. Ionizing energy in food processing and pest control: Part I Wholesomeness of foods treated with ionizing energy. Report #109. ISSN 0194–4088. Ames, Iowa: U.S. Council for Agriculture Science and Technology, July 1986.
12. *Josephson ES.* Nutritional aspects of food irradiation: An overview. Journal of Food Processing and Preservation 1978; 2.