In order to speculate as to whether such products would be produced commercially, one might attempt to determine what value could be ascribed to their availability. Complete sterilization of meats, fruits, and vegetables could yield products superior to those now available as fully preserved foods, specifically canned or dried products. Such quality improvements could justify added costs and make economics a secondary consideration. For example, the ability to sterilize a truly roasted piece of meat (dry-heat-cooked outside the storage container and then radiation-sterilized after packaging) would represent a substantial quality improvement over conventional thermal processing. Consumer acceptance of such an item might warrant its commercial preparation. Similarly, fruits and vegetables having fresh characteristics would be improvements over the usual canned products. While cost considerations would be significant, improvement of quality in shelf-stable products would be a factor of prime importance.

When products are treated only to extend their normal life, quality improvement, detectable by the consumer, may not result. The results are more likely to be reduction of spoilage losses, extension of the marketing period, and accessibility of hitherto unreachable markets. The value of such benefits is primarily economic and for this reason economics and not product quality improvement will determine their commercial preparation. On this basis one might conclude that the most likely applications will fall in the field of fruits and vegetables where distribution problems exist and losses today are large, and not in meats or poultry where losses are nominal. Which fruits and vegetables, will depend upon individual situations. At present, strawberries and potatoes afford some interesting possibilities.

To sum up the look ahead, we can list two points: Before any commercial use, we must have government clearance for the process, and for less than sterilized products, there must be favorable economics. For sterilized products there must be a clear-cut product quality improvement plus reasonable economics.

How do we proceed? The military program should determine whether government approval can be had. Assuming irradiated foods are cleared, then for less than sterilized foods we shall need suitable radiation sources, and beyond this little else from a technical point of view. For sterilized products, in addition to sources we shall need adequate controls to guarantee delivery of a minimum sterilizing dose for reasons of safety. But most of all for sterilized products we need quality improvement. Perhaps this is available now in pork, chicken, oysters, and shrimp. For other foods we need new knowledge in order to control the undesired sensory changes, particularly flavor. In view of the effort of the past years which has supplied little understanding of the mechanism of these changes, it is clear that what is needed is more basic research. This is a highly important area for the future.

There is one final aspect. Consumer or public attitude toward irradiated foods will be a large if not dominant factor in their success. Even with the assurance of safety based on government approval for irradiated foods, the public will act on its own confidence and understanding. Public consciousness of the hazards of potentially carcinogenic substances in foods, and its awareness of the dangers of radiation *per se* are bound to raise questions regarding safety. The possibilities of confusion between the effects of radiation on the human body and the consumption of irradiated foods will require education to clarify. The seller of irradiated foods will need to secure public confidence through an organized information program.

Prior events actually outside the area of irradiated foods will have great significance in the reaction of the public. We do not know what these will be and any counteraction of them will have to wait until we are ready to sell irradiated foods. It would appear, however, that we shall not be ready to offer irradiated foods for sale for some time to come.

Literature Cited

(1) Dallyn, S. L., Sawyer, R. L., Sparrow, A. H., *Nucleonics* **13**, No. 4, 48 (1955).

(2) Duncan, D. T., Hooker, W. J., Heiligman, F., *Food Technol.* **13**, 159 (1959).

(3) Gernon, G. D., *Food Eng.* **31**, 42 (1959).

(4) Kempe, L. L., "Complementary Effects of Thermal Energy and Ionizing Energy in Microorganisms," Proc. International Conference on Preservation of Foods by Ionizing Radiations, Massachusetts Institute of Technology, Cambridge, Mass., 1959, p. 103.

(5) Nickerson, J. T. R., "Extension of Storage Life of Foods Using Ionizing Energy," *Ibid.*, p. 116.

(6) Proctor, B. E., Nickerson, J. T. R., Licciardello, J. J., Goldblith, S. A., Lockhart, E. E., *Food Technol.* **9**, 523 (1955).

Received for review February 9, 1960. Accepted June 27, 1960. Radiation Processing Section, Nuclear Congress, New York, N. Y., April 1960.

RADIATION PRESERVATION OF FOOD

Current Aspects of the Wholesomeness of Irradiated Food

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Radiation preservation of food represents a rather radical innovation. It was first proposed nearly 15 years ago as a possible supplement to existing food-processing techniques. Its potential application has been under active investigation for over ten years. Throughout this period, the lay press, as well as the technical journals, has shown an exceptional interest in the research results as they were made available. As a result, food irradiation has been alternately heralded as a panacea for the world food problem and as a technological (or economic) impossibility. At present a fair interpretation would appear to be that radiation preservation of food will provide an important supplement to present food-processing practices but will by no means completely supplant any process now in use.

This conclusion is based upon two facets of the over-all problem of suitability: technological feasibility and the health-hazard potential (wholesomeness) of the treated food. Of these, technological development has presented the more formidable problems, particularly from the viewpoint of "commercially sterile" products. However, recent releases to the lay press have stressed the unsuitability of irradiated foods for human use from the whole-

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Radiation processing potentially represents a new approach to food preservation. Recently, confusion has arisen concerning the suitability of irradiated foods for human consumption. This report describes wholesomeness testing and undertakes an analysis of the pertinent data now available. Sixteen foods have been found to be grossly nontoxic to either rats or dogs. Further work is needed to elucidate the heart rupture observed in mice fed highly irradiated foods. Vitamin A, B_1, B_6, C, E, and K are susceptible to extensive radiation destruction. These vitamin losses are dose-related and vary among foods. The resultant deficiency effects may be avoided by consumption of mixed diets of irradiated foods or by appropriate supplementation. No indications of toxicity or nutritional imbalance have been observed during short-term feeding trials with human volunteers.

someness viewpoint. Thus, it would appear timely to evaluate the available data to determine to what degree irradiated foods may be unwholesome.

Wholesomeness Testing

Before considering the research program concerning wholesomeness of radiation-preserved foods, it is necessary to examine the meaning and magnitude of the term "wholesomeness." Wholesomeness encompasses two major areas of interest: potential toxicity and nutritional adequacy. These two components are difficult to separate experimentally, inasmuch as there is no finite line which may be drawn between marginal toxicity and low-level nutritional sufficiency. The best approach available is to provide experimental animals with a diet containing all of the known nutritional requirements for adequate growth and development. To this ration may be added the material under question in as large a quantity as the animal will tolerate. Differences in response between animals fed the control and the experimental diets may then be ascribed to potential toxicity. In the case of food, of course, isolation of the offending compound(s) from the treated food must also be undertaken to establish conclusively the existence and identity of a toxicity syndrome. After it has been shown that a particular food is not toxic under these conditions in two or more species of animals, attention may be given to the question of nutritional adequacy. Here, standard techniques may be employed: growth; availability and utilization of the fat, protein, and carbohydrate components; and vitamin analyses. As long as no serious changes are discovered by these tests, it may be safely assumed that the treated food is wholesome.

The Army Research Program

The early experiments employing ionizing radiations for preserving food were very encouraging. The small samples employed did not undergo great alterations in color, texture, etc., so that the process held considerable promise for producing sterile products which, although raw, possessed remarkable keeping qualities. There was little reason to suspect that wholesomeness might be affected. The Department of Defense soon became interested in the potential application of radiation preservation to the serious problem of supplying front-line troops with attractive, nutritious, easily transported foods. A research program was therefore established to study the technological problems involved. It rapidly became apparent, however, that the large energies required for food sterilization caused demonstrable changes in the appearance and chemical composition of many products. Furthermore, it was possible that similar changes might also occur in the wholesomeness characteristics. Therefore, a special program was established to investigate this area simultaneously with the product development research.

It was readily apparent that the wholesomeness testing of radiation-preserved food items would be costly in both time and money. Although many private companies were interested in the results, the cost prevented them from undertaking adequate testing programs to establish wholesomeness. Therefore, the burden of such testing has, by necessity, fallen to the Government, particularly through the Office of the Surgeon General, U. S. Army. This program was initiated in 1953. In the succeeding years, it has been expanded to include 31 research organizations. By and large, most of these research contracts have been established with scientists in well-recognized universities throughout the United States. A few contracts have also been undertaken by private research foundations and government laboratories. During this period over $5,000,000 has been expended for wholesomeness testing alone.

The wholesomeness investigations have not been unilaterally undertaken by the Army. Throughout the planning of the national program, many interested government agencies were consulted. In particular, the Food and Drug Administration contributed greatly in establishing the research approach to be employed. As a result, it is believed that the resultant data may be used by FDA in considering the suitability of radiation-preserved foods for human consumption in the United States. In this way it is hoped that excessive duplication of effort will be avoided in making the transition to commercial application.

In undertaking research concerning the wholesomeness of gamma-irradiated foods, it must be kept in mind that blanket "clearance" of all foods may not be obtained by testing one individual irradiated food. The radiation-induced reactions in any system are dependent upon the components of that system. Many compounds preferentially absorb the incident radiation energy so as to protect the other components of that system. Because each individual food may be considered to be a unique chemical system, it is necessary to test each food (or at least a representative number of foods) for wholesomeness in order to obtain the desired answer. Furthermore, as the radiation dosage increases, the types of chemical products will change. It is conceivable that a product which is biologically unsuitable at one level might be harmless following treatment with a higher dosage of radiation because of the subsequent radiation destruction of the harmful by-product. Therefore, all investigations must include more than one radiation dosage. These have been selected on the basis of applicability to practical expectation. The lower dosage of 2.79 megarads (1 rad = absorption of 100 ergs of energy per gram; 1 megarad = 1,000,000 rads) was chosen as an estimate of the treatment likely to be necessary for commercial dosage; a second dosage twice as high (5.58 megarads) was included to accentuate radiation-induced changes. This was fortunate, inasmuch as present estimates suggest that 4.8 megarads may actually be necessary for commercial sterilization.

In the beginning, the studies were undertaken using individual foods stored frozen after irradiation to minimize storage-accentuated alterations. The growth of rats served as the index to toxicity. Subsequently, the program was expanded to include 2-year feeding studies with cooked, irradiated food products which had been stored for 6 to 9 months at room temperature after irradiation. These experiments employ rats, dogs, mice, and monkeys as the test animals, with growth, reproduction, life span, and disease incidence as the primary criteria. Although the experiments are still in progress, they are in most cases sufficiently close to completion for tentative conclusions to be drawn. Additional research concerning radiation-induced vitamin destruction has been included in the program, as have extensive investigations concerning the possibility of increased cancer incidence (carcinogenicity) in animals fed the irradiated foods.

Once a food has been found to be wholesome in experimental animals, human testing may be undertaken. The latter utilizes the services of volunteer subjects who live under a controlled regimen. During the test periods, the volunteers consume irradiated foods first for 15-day periods and later for intervals up to 6 months.

When all of these investigations have been completed, the Armed Services will be in a position to evaluate the wholesomeness of irradiated foods for military use. The accumulated data will also be given to the Food and Drug Administration for its consideration. Thus, final conclusions concerning the wholesomeness of irradiated foods probably will not be completed for another three to five years.

Potential Toxicity

Short-term (12-week), single-food rat feeding tests have been completed employing a total of 38 frozen-stored irradiated (2.79 or 5.58 megarads) foods comprising 35% of the dietary solids in each case (*48*, *58*). In these tests, only irradiated jello powder and irradiated peaches were found to exert a significant growth-depressant effect. In the case of the jello powder this was traced to the sucrose component of the product; it is possible that a similar phenomenon occurred with the peaches, as they were obtained from a commercial source and contained a sugar sirup. However, Bubl and coworkers (7) did not confirm the growth-depressant effect in a four-generation study using irradiated peaches stored at room temperature. In addition, a composite diet containing 20% irradiated peach solids (*49*) did not show adverse growth effects in four successive generations of rats.

Several long-term studies concerning the toxicological properties of irradiated foods have been reported. In the earliest of these, Da Costa and Levenson (*14*) found that consumption of an electron-irradiated semisynthetic ration decreased reproduction performance in rats. A later report by Poling and coworkers (*45*), in which irradiated (1.86-megarad) beef was fed as 45% of the solids, noted the same phenomenon but reported that oral supplementation with vitamin E overcame the problem. No other indications of toxicity or nutritional imbalance were observed. Similarly, no adverse effects were noted in 2-year rat-feeding trials with 2.79-megarad-treated mixed organ meats (*7*) or 1.55-megarad-irradiated butterfat (*4*) nor after one year of feeding a 2.79-megarad-irradiated commercial mash to chickens (*10*). A four-generation study utilizing growth, reproduction, life span, and disease incidence as the primary parameters has also been reported (*49*). No signs of toxicity were seen as a result of consumption of a diet compounded from nine individually irradiated frozen-stored food items.

More recent attention has been focused upon toxicity testing of foods stored at room temperature for 6 to 9 months following irradiation. Read *et al.* (*50*) found raw beef or pork treated with 2.79 or 5.58 megarads to be nontoxic for the rat following 12 weeks of feeding. Reber and coworkers (*52*), using dogs, reported no deleterious effects of feeding 37,200 or 74,400 rad-treated flour diets for 24 weeks.

Additional data are also available from the series of contracts sponsored by the Office of the Surgeon General. In these experiments, 22 foods are being tested as 35% of the dietary solids. All foods are fed to rats for 2 years (parent generation) and through three subsequent generations. Each food is tested at two irradiation levels with a nonirradiated vitamin supplement provided with the diet. Growth, reproduction, life span, and carcinogenicity are used as the indexes to toxicity. Using this approach, ten foods have been fed to rats with no grossly toxic manifestations: bacon (*31*), green beans (*53*, *55*), chicken (*53*, *55*), codfish (*1*), dried fruit mixture (*31*), evaporated milk (*15*), sweet potatoes (*1*), white potatoes (*6*), peaches (*9*), and pork loin (*8*). Excepting green beans, chicken, and white potatoes, the histopathology studies that accompany these feeding studies have not been completed.

The counterpart experiments employing dogs as the test animal assess toxicity by analysis of 2-year growth data plus reproductive data from two breeding trials. At the end of the 2-year feeding period, the animals are sacrificed for histologic examination. In experiments of this type, 13 foods have been successfully fed with no gross toxic manifestations: bacon (*18*), green beans (*25*), beef (*51*), carrots (*17*), chicken stew (*29*), codfish (*1*), flour (*51*), mixed dried fruits (*25*), evaporated milk (*15*), sweet potatoes (*1*), pork loin (*29*), shrimp (17), and tuna fish (*29*). Again, the histopathology phase of these studies is still in progress.

To augment these experiments, additional carcinogenicity studies have been undertaken with inbred tumor-susceptible strains of mice in order to assure that radiation treatment does not produce cancer-inducing substances in the foodstuffs. In one of these experiments bacon treated with 5.58 megarads was fed to mice for 2 years (*30*). No significant differences in rate of growth or cancer incidence were found between the irradiated and control diet groups. Additional studies are now in progress using mice fed composite diets of five or six foods from the list under investigation with other animals. None of these experiments has progressed far enough to permit evaluation of the tumor-incidence data. However, an interesting phenomenon completely divorced from carcinogenicity has been observed by Monsen (*40*). Vitamin-supplemented irradiated and control diets compounded from equal proportions (dry solids) of pork loin, chicken, evaporated milk, white potatoes, and carrots have been fed to mice for approximately 20 months. Of the 377 animals started on the irradiated diet, 66 have died of enlargement and rupture of the left auricle of the heart. None of the Cb animals fed the control diet showed this lesion. Furthermore, only seven Strong A mice exhibited these symptoms after consuming the irradiated diet. Subsequent attempts to reproduce the disease with new animals fed the same diet with or without vitamin supplement have failed. However, 77% of the Cb mice fed cooked irradiated milk (with vitamin supplement) showed this lesion within 141 days on the diet, whereas only 16% of the animals fed uncooked irradiated milk were afflicted. Thus, these observations have not yet been explained but the investigations are continuing. This disease has not been reported in long-term dog and rat experiments using diets containing 35% evaporated milk (*15*).

Nutritional Adequacy

The question of nutritional adequacy of irradiated food has received considerable attention. As a result, the literature in this area is voluminous, so that complete discussion of the subject is beyond the scope of the present paper. Comprehensive reviews have been prepared by Read (*47*) and Johnson (*19*). Nevertheless, a general review with a discussion of the most pressing current problems is of interest.

Under the influence of irradiation the carbohydrates are oxidized or depolymerized to form smaller molecules. The degree to which this occurs is relatively slight, so that little or no measurable effect upon the nutritive value of simple sugars, starches, cellulose, etc., has been observed, with either purified compounds or the naturally occurring materials found in foods.

The effects of irradiation upon proteins and amino acids are somewhat more complex. In the case of the amino acids, the primary reactions appear to be deaminations and decarboxylations. This might be anticipated to have considerable nutritional significance, were it not for the fact that protein-bound amino acids are apparently protected from extensive radiation damage. Protein molecules undergo extensive molecular rearrangement, splitting, and/or polymerization, however. These changes may affect the allergenic properties of the treated protein. Thus, gamma irradiation has been found to alter the antigenicity of ovalbumin (*26*) and milk proteins (*21*, *22*). In the latter case, the change in biological properties was accompanied by radiation-related changes in sulfhydryl content, much as was reported by McArdle and Desrosier (*28*) following gamma irradiation of casein solutions. On the other hand, biological assay has shown little change in the nutritional value of irradiated protein. Using the nitrogen balance technique, Calloway, Cole, and Spector (*12*) report that irradiation of turkey with dosages up to 9.3 megarads did not affect the digestibility or biological value of turkey protein. Detailed studies of the digestibility and biological value of pea, lima bean, wheat, corn, milk, and beef protein have also been reported (*33*, *34*, *39*). As may be seen in Figure 1, lima bean protein gave a higher biological value following heating than either the raw or irradiated material; this probably was due to the heat destruction of the trypsin inhibitor in the lima beans. No explanation can be given for the loss in biological value of pea protein following irradiation. However, the similar loss following irradiation of milk protein was stated to be due to the radiation destruction of cystine. These small changes in utilizability of irradiated proteins presumably would be masked during the feeding of a mixed diet of irradiated foods. Such has been shown to be the case in studies employing a diet composed from nine frozen-stored irradiated foods (see Table I).

The irradiation of lipides results in the formation of small amounts of peroxides, polymers, and carbonyl compounds. As is true with proteins, the irradiation of natural food fats yields a smaller amount of these materials than might be anticipated from studies with purified fatty acids. Nevertheless, they exert some effect upon the digestion of irradiated foods. Schreiber and Nasset (*56*) have shown that, in the dog, irradiated lard passes through the stomach and the intestine more slowly than does nonirradiated lard (see Table II). Moore (*42*), using an in vitro technique, has demonstrated that the ability of lipase to hydrolyze lipide emulsions was decreased as radiation level increased (Table III). A tentative explanation is that the emulsions are not as stable following irradiation, so that lipase activity is physically impaired. Recent data by Monty (*41*) indicate that both these effects may be mediated through radiation-produced carbonyls but that the total mechanism is probably more complex than a simple physical effect upon lipide emulsion stability. Thus, the rate of digestion of lipides may be somewhat impaired following radiation sterilization but, as has been repeatedly shown by others, the net nutritive value to the intact host is not altered.

In general, it may be concluded that radiation treatment of food does not seriously alter the nutritional value of the major components (see Tables I and IV). The situation with the vitamins is different, however.

Most of the water-soluble vitamins are sensitive to ionizing radiation when irradiated in pure aqueous solution but the radiosensitivity is considerably less when food items are irradiated, undoubtedly because of the presence of protective compounds in the food. The percentage destruction differs from vitamin to vitamin, thiamine being the most sensitive and niacin the least sensitive. Furthermore, the percentage destruction of a specific vitamin also varies markedly between different foods (see Table V). Because of this variability, consumption of a mixed diet of ir-

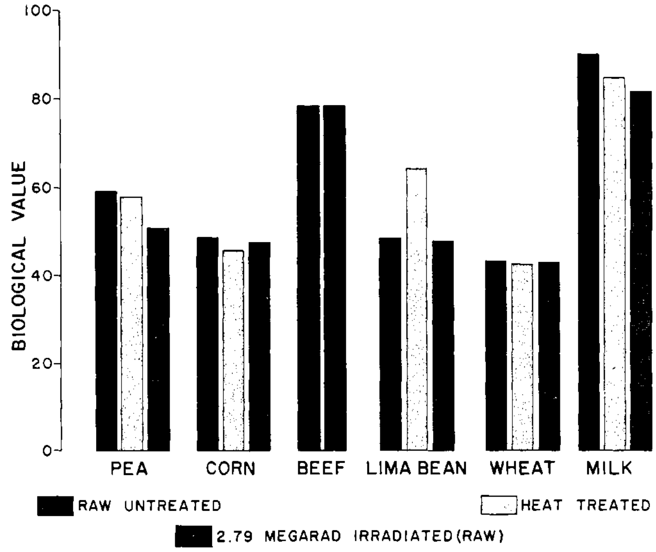

Figure 1. Biological value of proteins treated with heat or ionizing radiations (*33, 34, 39*)

Table I. Availability of Macronutrients in Diets Composed of Nine Frozen-Stored Foods (*11, 62*)

	Nonirradiated, %	*Irradiated (5.58 Megarads), %*
Protein	85.9	87.2
Fat	93.3	94.1
Carbohydrate	87.7	87.9

Table II. Digestion and Absorption of Lard Fed to Dogs (*56*)

(Dogs sacrificed 3 hours after feeding of test meals)

	Non-irradiated, %	*Irradiated (5.58 Mega-rads), %*
Stomach contents	47	65
Small intestine contents	11	8
Absorbed	42	27

Table III. Effect of Substrate Irradiation upon in Vitro Lipase Activity (*42*)

Substrate Emulsion	*Incubation Time, Hr.*	*Radiation Dose, Megarads* 0	2.79	5.58	9.30
		Units of Lipase Activity			
Olive oil	4	35	33	10	..
Corn oil	4	13	10	3	..
Lipomul	5	76	..	66	46

Table IV. Metabolizable Energy Value of Macronutrients Following Radiation Treatment (20)

	Calories per Gram	
	Nonirradiated	Irradiated (2.79 megarads)
Casein	4.56 ± 0.30	4.51 ± 0.22
Lard	8.82 ± 0.31	8.87 ± 0.39
Carbohydrate[a]	3.87 ± 0.20	3.78 ± 0.30

[a] Mixture of sucrose, starch, and dextrin.

Table V. Vitamin Destruction in Foods Exposed to Varying Doses of Gamma Radiation (63)

(Doses stated in megarads)

	Per Cent Destruction					
	Thiamine		Riboflavin		Niacin	
Food	2.79	5.58	2.79	5.58	2.79	5.58
Bacon	..	93	..	7	..	0
Beef	76	85	5	4	2	1
Haddock	68	76	0	4	14	9
Ham (fresh)	87	96	0	0	2	2
Turkey	76	77	27	50	7	0
Beets	52	75	14	10	0	10
Milk (powdered)	0	0	0	0	35	20
Peaches	94	98	0	0	48	56

Table VI. Comparative Effects of Radiation and Heat Treatment on Vitamin Content of Foods

	Per Cent Destruction	
Vitamin	Heat	Irradiation (2.79 megarads)
Thiamine	60–70	55–65
Riboflavin	18–22	6–10
Pyridoxine	28–32	24–25
Niacin	30–35	0–14
Choline	?	0
Folic acid	35	0
Inositol	?	0–5
Vitamin A	20	31–70[a]
Vitamin E	?	61[a]

[a] Dosage. 440,000 rads in dairy products.

Table VII. Ascorbic Acid Destruction in Orange Juice and Strawberries (13, 46)

	Per Cent Destruction	
Dose, Rads	Orange juice	Strawberries
93,000	4	..
279,000	22	63
396,000	26	81
465,000	35	..
698,000	50	..
930,000	59	..

Table VIII. Reproductive Performance of Dogs Fed Irradiated or Nonirradiated Beef Diets (29)

Radiation Dose, Megarads	% Conception	% Weaned
0	82	68
2.79	53	63
5.58	61	50

radiated foods might be anticipated to provide adequate levels of most vitamins, with the possible exception of the most radiosensitive vitamins—e.g., thiamine and pyridoxine. Table VI compares the relative destruction of vitamins by ionizing radiations and cooking. The data have been drawn from a variety of sources and represent only an approximation in both cases. It is readily apparent that, in general, radiation destruction is equal to or smaller than that resulting from cooking. However, the combination of irradiation plus cooking may result in serious losses in vitamin content, requiring vitamin supplementation. Surprisingly, in a study employing baby beef liver, Williams, Yen, and Fenton (*60*) found that subsequent cooking did not result in further destruction of thiamine.

In order to answer these questions more fully, an experiment in our laboratory utilized a composite diet of 15 irradiated foods stored at room temperature after irradiation (*61*). The resultant cooked or raw diets were fed to male rats for 12 weeks. A progressive decrease in growth rate was observed as the radiation level increased. For a given radiation treatment, the animals fed the cooked or the raw diets did not differ significantly in growth. Supplementation with a complete B-complex vitamin premix provided equal growth in all groups. Subsequent tests have shown that thiamine and pyridoxine are the limiting vitamins in this diet; of these, pyridoxine would appear to be the most important. Because the rat does not require ascorbic acid (vitamin C), these experiments did not permit an evaluation of its destruction or availability in irradiated products. This vitamin is one of the most sensitive in aqueous solution; fortunately, it is less sensitive in foods. Nevertheless, ascorbic acid is appreciably destroyed in fruits at even low doses of radiation (Table VII). It is somewhat more stable in milk (*24*), particularly evaporated milk, and in various vegetables (*23*, *43*). There is considerable evidence (*57*) that irradiation of ascorbic acid produces dehydroascorbic acid. The latter, while readily reconverted to biologically active ascorbic acid, is easily oxidized to biologically inactive 2,3-diketogulonic acid. Analogous transformations occur in foods preserved by other methods. Thus, vitamin C destruction during radiation processing varies between food items but, in general, parallels the loss encountered during heat processing. Unlike the other water-soluble vitamins, however, the destruction may be sufficient to be of concern with some fruits now suggested for radiopasteurization.

Considerable information is also available concerning the fat-soluble vitamins A, E, and K. All of these are more sensitive to ionizing radiation than are the majority of the water-soluble vitamins, probably because of their antioxidant properties. For example, vitamin A and carotene are extremely sensitive to radiation in either pure solution or foods. This sensitivity undoubtedly explains the recent report of lower accumulation of vitamin A in the livers of rats fed irradiated carrot diets (*59*).

It was recognized early that vitamin E was extremely labile under the influence of irradiation (*4*, *14*, *45*). As a result, most subsequent experiments have employed an oral supplement of vitamin E administered separately from the diets. In general, this practice has obviated any difficulties in vitamin E nutrition among animals fed irradiated foods. However, it has been reported by McCay (*29*) that dogs fed diets containing irradiated beef show a reduced conception rate and lower weaning percentages than animals fed nonirradiated beef diets (Table VIII). Oestrus was normal in all animals. These symptoms are strikingly similar to those observed in vitamin E–deficient rats. As has been shown with other meat diets (*45*), the vitamin E incorporated in McCay's diets at the time of mixing may have been destroyed during subsequent storage of the diet. Although the symptoms observed by McCay do not parallel precisely those reported for severely E-deficient dogs raised on processed milk diets, the latter cases were apparently complicated by a simultaneous vitamin K deficiency (*2*, *3*). In support of the E-deficiency interpretation is the fact that another dog-feeding experiment using beef, in which vitamin E was provided orally weekly, has not shown similar reproduction failure (*51*). The beef feeding experiments are now being repeated with larger numbers of animals in order to determine the fundamental mechanism involved.

The study of vitamin K in irradiated foods has proved to be most interesting and important. In a series of studies by Richardson and coworkers (*53*, *54*), it has been shown that, in general, natural vitamin K is stable to ionizing radiation in vegetables and some synthetic rations. However, Metta, Mameesh, and Johnson (*37*) have shown that male rats fed a vitamin K–deficient diet containing irradiated beef die of massive hemorrhage. We have confirmed this observation in our laboratory (Table IX) (*61*) and have also demonstrated that the same phenomenon occurs when cooked, nonirradiated pork is fed to male rats under these conditions (Table X). Irradiation of the pork increases the incidence of hemorrhagic diathesis.

The deficiency state created under these conditions is apparently complex. The fact that some control animals (20%) fed the nonirradiated beef also die of hemorrhage indicates that beef is probably a poor source of vitamin K; irradiation of the beef undoubtedly worsens this situation. Synthetic vitamin K_3 is destroyed when it is added to the irradiated beef diet (*38*), much as is seen with nonirradiated pork (Table VI) and as has been observed for vitamin E (*45*). Whether a similar situation also occurs with the naturally occurring forms of vitamin K is not known. However, rats fed a K-deficient diet have been shown in the past to obtain sufficient vitamin by recycling the feces (coprophagy) so as to recover the vitamin synthesized by the gut microflora. Consumption of the irradiated beef does not alter the gut micropopulation (*61*), but the rats apparently do not practice coprophagy (*36*). It is possible that this may be due to the carbonyls produced during irradiation, since *n*-decylaldehyde by itself will achieve the same effect (*35*).

Other factors also are involved. Table V shows that supplementation with bile acids will decrease the incidence of hemorrhagic death, suggesting that lipide emulsification and/or absorption from the intestine may be impaired; with this would go impaired absorption of vitamin K. This possibility is in keeping with the data of Schreiber and Nasset (*56*), which indicate a decreased rate of absorption of irradiated lard in dogs. It has also been shown that vitamins E (*32*) and A (*16*) are involved in the total syndrome. Supplementation with large quantities of either vitamin hastens the onset of hemorrhage; omission of either almost eliminates the appearance of the deficiency. Female rats do not become hemorrhagic on any of these diets (*37*). This is probably due to differences in growth rate, metabolism, and vitamin requirement between male and female rats and probably does not represent a direct protective effect of female sex hormones.

Inasmuch as vitamin K destruction is slight in vegetables, it might be anticipated that consumption of a mixed diet would prevent the appearance of the

Table IX. Deaths of Male Rats Fed Vitamin K–Deficient Diets Containing Cooked Irradiated (5.58-Megarad) or Nonirradiated Beef (*61*)

	Nonirradiated		Irradiated (5.58 Megarads)		
Supplement					
Oral K_3, γ/day	0	0	0	0	4
Bile acids,[a] mg./day	0	83	0	83	0
Number of rats	15	10	10	10	10
Deaths in 70 days	3 (20%)	0 (0%)	10 (100%)	5 (50%)	0 (0%)
Prothrombin times, av. in sec.	30	15	166	60	14

[a] Equal mixture of cholic, deoxycholic, and lithocholic acids.

Table X. Deaths of Male Rats Fed Vitamin K–Deficient Diets Containing Cooked Nonirradiated or 5.58-Megarad Irradiated Pork (*61*)

	Nonirradiated			Irradiated	
Daily vitamin K_3 supplement, γ					
In diet	0	20	0	0	0
Oral	0	0	20	0	20
Number of rats	20	10	10	14	10
Deaths in 70 days	12 (60%)	8 (88%)	0 (0%)	13 (93%)	0 (0%)
Prothrombin time, av. in sec.	85	75	13	140	12

hemorrhagic disease. This has been shown to be the case in the 15-food composite diet study mentioned earlier, in which normal prothrombin times (12 to 13 seconds) were observed in all animals after 12 weeks of feeding.

From the experiments which have been completed with the vitamins, it is apparent that radiation destruction does occur. At least for the water-soluble vitamins, the extent of destruction at sterilization doses roughly parallels heat-induced vitamin losses and is probably not further affected by cooking the irradiated product. The vitamin losses may be overcome by supplementation in a manner analogous to present-day practices in other food-processing industries. The extent of vitamin destruction is also related to radiation dose. Thus, for all vitamins except possibly vitamins A, E, and C, no nutritional problem is now anticipated with radiopasteurized products treated with less than 0.5-megarad doses. In all cases, the significance of the losses will depend upon the type of diet consumed: whether it is a completely irradiated diet such as is envisioned for military survival rations or consists of a mixture of irradiated and nonirradiated foods, much as will be utilized by the average housewife.

Human Feeding Studies

As soon as specific food items have been shown to be grossly nontoxic in 3- to 6-month animal feeding trials, human experiments may be undertaken. The subjects are ten male volunteers who live under closely supervised conditions. Balance studies are performed for nutritional evaluation of the diets as well as a battery of clinical tests to determine the presence of any toxic manifestations. By techniques such as these, 42 frozen-stored irradiated (2.79-megarad) foods comprising successively 35, 60, 80, and 100% of the dietary calories have been fed to the subjects for 15-day periods with no ill effects (*27*). In addition, 23 food products stored at room temperature following irradiation have also been found to be nontoxic during 15-day feeding periods (*5*, *45*). Throughout all these experiments, the per cent availability, energy value, and nitrogen balance data have also indicated that irradiation has no adverse effects from the nutritional viewpoint.

The extrapolation of the hemorrhagic diathesis seen in rats fed irradiated meats to a similar situation in humans is not readily made. The vitamin K requirement is not known for the human nor is the significance of the intestinal micropopulation in satisfying K needs clearly established. However, at no time in any of the human tests did the prothrombin time deviate from normal. This is particularly significant in the one experiment where the subjects were fed 35% pork solids for the 15-day period (*44*). In male rats, a 15-day period is sufficient to induce hemorrhagic death in 10% of the animals and to increase prothrombin times in the remainder.

With the completion of the animal screening program, the lengths of time irradiated foods may be fed to human volunteers may be extended. Present plans indicate that these tests may be extended to 3 to 6 months as soon as sufficient foods are available to permit development of a nonmonotonous diet.

Summary and Conclusions

Wholesomeness is a term denoting health-hazard potential. It encompasses two major areas of research: potential toxicity and nutritional adequacy. The Office of the Surgeon General, U. S. Army, is sponsoring an extensive research program concerning the wholesomeness of radiation-preserved foods. Although final evaluation of all the data will not be completed for three to five years, the present report represents an analysis of the data now available.

Animal tests have uncovered few, if any, indications of toxicity of individual irradiated foods. In general, growth, reproduction, life span, and cancer incidence have not been significantly altered as a result of consumption of the treated product as long as adequate vitamin supplementation has been provided. Further research is required, however, to elucidate the heart rupture problem occurring in mice fed composite diets of irradiated foods.

The nutritional value of irradiated foods appears to be similar to that of cooked foods. Fats, carbohydrates, and proteins are not significantly altered in so far as nutritional properties are concerned. As with cooking, thiamine and pyridoxine are susceptible to radiation destruction. Vitamin C also is labile. The fat-soluble vitamins E and K are particularly susceptible to destruction by radiation, but the resultant problems in reproduction and bleeding may be overcome by supplementation with vitamins E and K, respectively. Consumption by animals of mixed diets of irradiated foods largely eliminates the problem of vitamin destruction in individual foods.

Interpretation of the data with respect to human consumption is difficult, particularly because human requirements for some vitamins (notably E and K) have not been clearly established. However, short-term (15-day) feeding trials with human subjects have shown no wholesomeness difficulties arising from consumption of diets containing up to 100% of the calories from gamma-irradiated foods. Vitamin supplementation, such as is practiced with other processing methods, would further decrease potential problems. Similarly, consumption of a mixed diet of irradiated and nonirradiated foods would provide an adequate nutritious diet. The latter is most nearly analogous to the anticipated practice of the average housewife, inasmuch as not all foods may be satisfactorily preserved with ionizing radiations.

Acknowledgment

This manuscript was prepared while the author enjoyed a visiting professorship in the Department of Biochemistry and Nutrition, Virginia Polytechnic Institute, Blacksburg, Va. The author gratefully acknowledges the encouragement and assistance rendered by the staff members of that department in preparing this paper for publication.

Literature Cited

(1) Alexander, H. D., Salmon, W. D., "Long-Term Rat and Dog Feeding Tests on Irradiated Sweet Potatoes and Codfish," Progress rept. on Contract DA-47-007-MD-543 with Office of Surgeon General, Sept. 15, 1959.
(2) Anderson, H. D., Elvehjem, C. A., Gonce, J. E., Jr., *J. Nutrition* **20,** 433–41 (1940).
(3) Anderson, H. D., Elvehjem, C. A., Gonce, J. E., Jr., *Proc. Soc. Exptl. Biol. Med.* **42,** 750–5 (1939).
(4) Becker, R. R., Kung, H. C., Barr, N. F., Pearson, C. S., King, C. G., *Food Technol.* **10,** 61–4 (1956).
(5) Bierman, E. L., Plough, I. C., Sellars, J. H., McGary, V. E., Nevels, E. M., Baker, E. M., Harding, R. S., Richmond, J., Bowman, B. O., U. S. Army Medical Nutrition Lab., Denver, Colo., Rept. **224** (July 1, 1958).
(6) Brownell, L. E., Burns, C. H., Abrams, G. D., "Growth, Reproduction, Mortality, and Pathologic Changes in Rats Fed Gamma-Irradiated Potatoes," Terminal rept. on Contract DA-49-007-MD-581 with Office of Surgeon General, February 1959.
(7) Bubl, E. C., Butts, J. S., *Federation Proc.* **15,** 930–2 (1956).
(8) Bubl, E. C., Butts, J. S., Bone, J. F., "Growth, Breeding, Longevity, and Histopathology of Rats Fed Irradiated or Control Foods," Progress rept. on Contract DA-49-007-MD-580 with Office of Surgeon General, March 15, 1959.
(9) *Ibid.*, "Peaches," September 1959.
(10) Burns, C. H., Brownell, L. E., Eckstein, H. C., *Federation Proc.* **15,** 910–17 (1956).
(11) Cahall, H. K., Krzywicki, H. J., Read, M. S., Kraybill, H. F., U. S. Army Medical Nutrition Lab., Denver, Colo., Rept. **201** (March 18, 1957).
(12) Calloway, D. H., Cole, E. R., Spector, H., *J. Am. Dietet. Assoc.* **33,** 1027 (1957).
(13) Clarke, I. D., *Intern. J. Appl. Radiation and Isotopes* **6,** 175 (1959).
(14) Da Costa, E., Levenson, S. M., U. S. Army Medical Nutrition Lab., Denver, Colo., Rept. **89** (1951).
(15) Deichmann, W. B., "Long-Term Dog and Rat Feeding Experiment Employing Irradiated Milk and Beef Stew (C-ration)," Progress rept. on Contract DA-49-007-MD-785 with Office of Surgeon General, Sept. 15, 1959.
(16) Doisy, E. A., Jr., Matschiner, J. T., "Hemorrhagic Syndrome in Rats Fed Irradiated Beef," Progress rept. 2 on Contract DA-49-007-MD-996 with Office of Surgeon General, Sept. 15, 1959.
(17) Engel, R. W., Watson, D. F., "Long-Term Dog-Feeding of Irradiated and Control Shrimp and Carrots and Nutritive Value of Irradiated and Control Proteins," Progress rept. 5 on Contract DA-49-007-MD-784 with Office of Surgeon General, Sept. 15, 1959.
(18) Hale, M. W., Schroeder, W. F., Sikes, D., "To Determine the Effect of Irradiation on the Wholesomeness of Food," Progress rept. on Contract DA-49-007-MD-780 with Office of Surgeon General, Sept. 15, 1959.
(19) Johnson, B. C., in "Atomic Energy and Agriculture," C. L. Comar, ed., p. 391, Am. Assoc. Advancement of Science, 1957.
(20) Johnson, B. C., Metta, V. C., *Federation Proc.* **15,** 907 (1956).
(21) Kraybill, H. F., Linder, R. O., Read, M. S., Shaw, T. M., Isaac, G. J., *J. Dairy Sci.* **42,** 581–8 (1959).
(22) Kraybill, H. F., Read, M. S., Harding, R. S., Friedemann, T. E., "Biochemical Alteration of Milk Proteins by Gamma and Ultraviolet Irradiation," *Food Research,* **25,** 372–81 (1960).
(23) Krylova, N. N., *Voenno-Med. Zhur.* **1957,** No. 5, 50.
(24) Kung, H. C., Gaden, E. L., Jr., King, C. G., J. Agr. Food Chem. **1,** 142 (1953).
(25) Larson, P. S., Haag, H. B., Finnegan, J. K., Smith, R. B., Jr., Hennigar, G. R., Belter, L. F., Crawford, E. M., "Long-Term Dog Feeding Tests on Irradiated Green Beans and Fruit Compote," Progress rept. 5 on Contract DA-49-007-MD-786 with Office of Surgeon General, Sept. 15, 1959.
(26) Leone, C. A., *Federation Proc.* **16,** 422 (1957).
(27) Levy, L. M., Bernstein, L. M., Francis, E., Harding, R. S., Krzywicki, H. J., McGary, V. E., Nuss, J., Sellars, J. H., Shipman, M. E., U. S. Army Medical Nutrition Lab., Denver, Colo., Rept. **203** (March 25, 1957).
(28) McArdle, F. J., Desrosier, N. W., *Food Technol.* **9,** 527–32 (1955).
(29) McCay, C. M., Rumsey, G. L., "Effect of Irradiated Meat upon Growth and Reproduction of Dogs," *Federation Proc.* December 1960 (in press).
(30) McKee, R. W., Zeldis, L. J., "Influence of Irradiated Lipids on the Incidence of Spontaneous Mammary Carcinoma and Hepatoma in Strains AHe and C_3H Mice," Final rept. on Contract DA-49-007-MD-579 with Office of Surgeon General, Nov. 1, 1959.
(31) Mead, J. F., Griffith, W. H., "Effect of Ionizing Radiation on Nutritive Value and Safety Characteristics of Food," Progress rept. on Contract DA-49-007-MD-579 with Office of Surgeon General, Sept. 15, 1959.
(32) Mellette, S. J., "Mechanism of the Hemorrhagic Phenomenon Produced in Male Rats by Feeding of Irradiated Beef," Progress rept. 3 on Contract DA-49-007-MD-951 with Office of Surgeon General, Sept. 15, 1959.
(33) Metta, V. C., Johnson, B. C., J. Agr. Food Chem. **7,** 131–3 (1959).
(34) Metta, V. C., Johnson, B. C., *J. Nutrition* **59,** 470–90 (1956).
(35) Metta, V. C., Mameesh, M. S., Johnson, B. C., "Fat Carbonyls and Vitamin K Deficiency," Abstract, 135th Meeting, ACS, Boston, Mass., 1959.

(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).

Received for review February 9, 1960. Accepted June 20, 1960. Radiation Processing Section, Nuclear Congress, New York, N. Y., April 1960. The opinions expressed are those of the author and are not necessarily endorsed by the Department of Defense.

RADIATION PRESERVATION OF FOOD

Commercialization Technology and Economics in Radiation Processing

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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**
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> 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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