Table 27 *(continued)*

Food type (% in diet)[a]	Study type/ duration	Irradiation dose (kGy)[b]	Process conditions	Group	Animals per group	Comments	Author/ reference
Green beans (gb) (35%) synthetic diet	2 years P, F_1–F_3 generations	C = 0 H = 27.9 VH = 55.8	Spent fuel rods; canned gb shipped frozen; irradiated at 60 °F; stored at rt	C, H, VH	10M, 10F for P; 20F for F_1–F_3	NHDIR. 30-year colony at Texas Station[c]. Synthetic diet 4 generations, no significant difference; chicken/ green bean diet 4 generations, no significant difference; congenital blindness not related to diet. Pathology changes not associated with diet. (See also under chicken.)	Richardson, Ritchey & Rigdon (*323*); Rigdon (*324*)
Laboratory diet (100%); autoclaved (auto) or irradiated (irrad)	Lifetime, 3 generations	C = 0 Auto = 0 VH = 44	^{60}Co: paper cartons, plastic bags Auto: 120 °C, 20 min	C, auto, irrad	140M, 140F	NHDIR. Summary of experience with autoclaved or radiation sterilized diets.	Saint-Lèbe (*336*)
Laboratory diet (100%)	200 days	VH = 50	^{137}Cs 1.9 kGy/h; storage NS	0, 20, 30, 90, 200 days	10	NHDIR/PEND. Reversible chromosomal changes.	Rojo & Fernandez (*342*)
Laboratory diet (100%): wheat (53.5%), gram (16%), skimmed milk powder (10%), shrimp (4%), vegetables (2.5%), sesame oil (6%), sucrose (6%), salt (2%); fed after 3–4 weeks storage at 4–6 °C	2 years P, F_1–F_4 generations	C = 0 L = 2 H = 25	^{60}Co 2.4 kGy/h in air at ambient temperature, 25–29 °C	Chow, C, L, H	12M, 24F for repro study	NHDIR. Wistar. No significant differences between controls (stock diet and non-irradiated) and irradiated groups.	Aravindak-shan et al. (*338*)
Laboratory diet (100%): autoclaved at 110 °C, for 10 min (C); autoclaved at 120 °C, for 15 min (auto)	90 days	C = 0 VH = 50	^{60}Co NS	C, auto, VH	15M, 15F	NHDIR. Wistar. Repro: no effect on reproduction parameters. 90 days with F_1. No treatment-related histopathological effects.	van Logten et al. (*340*)

Table 27 *(continued)*

Food type (% in diet)[a]	Study type/ duration	Irradiation dose (kGy)[b]	Process conditions	Group	Animals per group	Comments	Author/ reference
Laboratory diet (100%): casein (8.5%), skimmed milk (9.4%), potato starch (50%), wheat flour (16.5%), sucrose (5%), sunflower oil (6%), choline chloride (0.1%), salt mixture (3.5%) and vitamin mixture (1%)	120 days	C = 0 H = 25 VH = 45	^{60}Co NS stored in PE bags	C, H, VH	50M, 50F	NHDIR. Sprague-Dawley. Investigated effects of diet on liver function.	Metwalli (*339*)
Laboratory diet (100%): wheat (18%), barley (17.5%), rye (14%), oat (14%), maize (4%), sunflower seed (8%), alfalfa meal (2%), fishmeal (5%), casein (5%), skimmed milk powder (4%), yeast (4%), salt (0.5%) and vitamin/ mineral premix (4%)	2 years multigeneration P 24 months F_{1b} 13 months F_{2b} 9 months F_1-F_3 1 month	C = 0 H = 25 VH = 45	50 kCi ^{60}Co 0.5 kGy/h; 7–8 kg PE bags; stored at <10 °C for up to 2 months	C, H, VH	50M, 50F in P; 30M, 30F in F_1-F_3 (300 in P, 5014 in F_1-F_3	NHDIR. Wistar. No adverse or pathological effects in parameters studied: feeding, body weight, reproduction, haemotology, blood chemistry, vitamin metabolism, ophthalmology, parasitology, intestinal flora, health condition and behaviour, findings in mortality, gross pathology, histopathology, oncogenesis, and longevity.	Barna (*335*)
Milk powder (35%) (positive and negative controls for radicals)	3 years P, F_1-F_5 generations	C– = 0 C+ = 25 VH = 45	10 MeV electrons; NS; stored for 10 min	C–, C+, VH	P 120 F_1 72 F_2 54 F_3 72 F_4 60 F_5 78	NHDIR. Sprague-Dawley. High level of radicals present when fed. No indication of toxic or carcinogenic effects.	Renner & Reichelt (*343*)
Mixed: bacon (8.75%), beef (8.43%), haddock (19.15%), ham (4.82%), powdered milk (5.56%), beets (15.45%), green beans (8.39%), cereal (3%) and peaches (20.45%)	2 years P, F_1-F_3 generations	C = 0 VH = 55.8	Spent fuel rods; canned, shipped frozen; irradiated at 60 °F; stored at rt	C, VH	P 20M, 34F F_1 20M, 25F F_2 11M, 12F for C; 15M, 25F for VH F_3 6M, 6F	NHDIR/PEND. Only 2nd-litter animals used in F generation growth studies. Decreased weight gain in females of 4th generation. Increased cytochrome oxidase activity of male rats.	Read et al. (*314*)

Table 27 *(continued)*

Food type (% in diet)[a]	Study type/ duration	Irradiation dose (kGy)[b]	Process conditions	Group	Animals per group	Comments	Author/ reference
Mixed: beef (33% of wet weight), pork (10%), cheddar cheese (20%) and milk powder (12%)	2 years	C = 0 H = 27.9	Spent fuel rods; foods canned, shipped frozen; irradiated at 60 °F; stored at rt	C, H	20M, 20F	NHDIR. Sprague-Dawley. Mix of 5 foodstuffs fed 50:50 with synthetic basal diet.	Teply & Kline (*313*)
Mixed: pork brain (5%) and egg (2.5%)	2 years	C = 0 EH = 93	Spent fuel rods; foods canned separately, shipped frozen; irradiated at 60 °F, stored at rt for 3–9 months	C, EH	20M, 20F	NHDIR. Sprague-Dawley. Brain and whole egg were irradiated separately, then dried.	Teply & Kline (*313*)
Oil, soya (20%)	280 days	C = 0 2.2, 8.8, 44, 88 kGy	1 MeV electrons (van der Graaf); irradiated at 25 °C	C/0 T/1 T/4 T/20 T/40	40	NHDIR/PEND. No toxic effects at 2.2 kGy. Increased mortality at 8.8 kGy at 40 weeks; apparent after 24 weeks at 44 kGy. 88 kGy group had reduced growth and PER at 10 weeks, 18% mortality in 6 months. Mortality attributed to polymerization and autoxidative changes after extreme irradiation of oil.	Lang (*344*)
Oil: beef sterols (bs) and yeast sterols (y) (2.4% in oil; 0.8% in diet)	2 years, P, F_1, F_2 generations	C = 0 H = 27.9 VH = 55.8	Electron radiation; frozen 1/4-inch slabs; GE Labs, Milwaukee, WI	9 groups in 3x3 matrix with (bs) and (y)	15M, 15F for C; 5M, 5F for all other groups	NHDIR/PEND. Sprague-Dawley. Study done in replicate. No carcinogenicity.	Teply & Kline (*313*)
Oil: corn (3%), cottonseed (3%), peanut (3%)	2 years	C = 0 VH = 55.8	Electron radiation; mixture, refrig temp; GE Labs, Milwaukee, WI	C, VH	20M, 20F	NHDIR. Sprague-Dawley.	Teply & Kline (*313*)

Table 27 *(continued)*

Food type (% in diet)[a]	Study type/ duration	Irradiation dose (kGy)[b]	Process conditions	Group	Animals per group	Comments	Author/ reference
Peach (35%)	2 years, P, F_1, F_2 generations	C = 0 H = 27.9 VH = 55.8	Spent fuel rods; canned in syrup, shipped frozen; irradiated (Dugway)	C, H, VH	25M, 25F	NHDIR. Wistar. No diet-related effects.	Tinsley, Bone & Bubl (*327*)
Pork (35%)	8–12 weeks	C = 0 H = 27.9 VH = 55.8	Spent fuel rods; canned meats, shipped frozen; irradiated at 60 °F, stored at rt	C, H, VH	10M	NHDIR/PEND. Sprague-Dawley, males only. Increase in liver cytochrome oxidase in animals fed rt stored pork or beef, whether raw or cooked. (See also under beef.)	Read et al. (*319*)
Pork (35%): cooked prior to mixing in ration	2 years, P, F_1, F_2 generations	C = 0 H = 27.9 VH = 55.8	Spent fuel rods; ground pork canned under vacuum, frozen; irradiated at 60 °F, stored at rt	C, H, VH	6M, 6F	NHDIR. Wistar. No differences in growth, breeding and longevity.	Bubl & Butts (*328*); Bubl (*329*)
Pork (35%): pigs fed conventional diet = C+; pigs fed autoclaved diet = auto; pigs fed 50-kGy irradiated diet = irrad	2.5 years with F_1 generation	C = 0 H = 37 VH = 74	Canned at 70 °C, pasteurized, stored at −40 °C; ^{60}Co, −30 °C, stored at rt	CC+, C auto, auto, C irrad, H irrad VH irrad	P 12M, 24F F_1 50M, 50F	NHDR. SPF-derived Wistar, Riv:TOX. No effect attributable to irradiation. Tumour incidence and appearance comparable in all groups, none of any particular or unusual type.	van Logten (*341*)
Pork ground (p) (35%), bread (br)* (80%), green beans (gb) (35% and 80%) and shrimp (sh) (35% and 80%)	84 days	C = 0 H = 27.9 VH = 55.8	Spent fuel rods; (p), (gb), (sh) (cooked), canned, frozen; irradiated in pool; stored at rt for 3–8 months; (br) 0.25 and 0.5 kGy	C, H, VH	20M, 20F	NHDIR. Albino rats. Interest centred on blood enzymes. No effects related to diets or to amount of (gb) or (sh) in diet.	Brin, Ostashever & Kalinsky (*330*)

Table 27 *(continued)*

Food type (% in diet)[a]	Study type/ duration	Irradiation dose (kGy)[b]	Process conditions	Group	Animals per group	Comments	Author/ reference
Shrimp (35%): control shrimp received frozen, stored frozen; control and irradiated oranges, stored at 34 °F and 70% RH for 60–90 days	2 years, P, F_1–F_3 generations	C = 0 H = 27.9 VH = 55.8	Spent fuel rods; Canned cooked shrimp; irradiated at 60 °F, stored at rt Oranges: surface irradiated with electrons at Michigan State University, MI	C, H, VH	15M, 15F for C; 5M, 5F for all other groups	NHDIR. Sprague-Dawley. Oranges irradiated at 1.4 and 2.79 kGy included in diets of some groups.	Phillips, Newcomb & Shanklin (*331*)
Spice mixture (sm) (25%): pepper (pep) (3.5%), mild paprika (pap) (25%); feeding within 2 weeks of irradiation	15 days teratology	Chow = 0 C = 0 H = 15	^{60}Co NS	Chow C H	pap/pep/sm 13/11/8 12/12/15 14/12/14	NHDIR. CFY albino female rats. No teratological effects in offspring of treatment groups. The slight increase in incidence of hydronephrosis for groups fed irradiated black pepper and paprika not considered related to the diet.	IFIP (*337*)
Strawberry (5%): juice (j) and powder (p); j, frozen, defrosted, homogenized 1:1 H_2O; p, frozen, lyophilized, powdered, stored N_2, canned	84 days	Chow C H	3 MeV electrons; fresh in PE bags; stored frozen	C, M, VH	10M, 10F	NHDIR/PEND. Wistar. Growth retardation in male groups consuming high-dose powder. No significant effects on females and all animals given high-dose juice.	Verschuuren, van Esch & van Kooy (*345*)
Tuna (35%) and control tuna; received frozen, stored frozen	2 years P, F_1, F_2 generations	C = 0 H = 27.9 VH = 55.8	Spent fuel rods; canned; irradiated at 60 °F; stored at rt	3 control groups, 3x3 matrix	10M, 10F (11 groups) 6M, 6F for repro study for P, all groups	NHDIR. Charles-River; Wistar. Groups in 2-year study, no significant difference. Repro: no significant difference in reproduction among groups.	Paynter (*332*)

exp = experiment(s); F = female; F_1, F_2 = first filial generation, second filial generation, etc.; M = male; NHDIR = negative for high-dose irradiation effect; NS = not specified; P = parent generation; PE = polyethylene; PEND = possible effect of nutrition or diet; repro = reproduction study; RH = relative humidity; rt = room temperature.

[a] Based on dry weight unless otherwise indicated.

[b] Food irradiation dose levels: C = control; L = low (<10 kGy); H = high (≥ 10 kGy); VH = very high; EH = extremely high.

[c] Texas Agricultural Experimental Station.

Table 28
Food type – mouse studies

Food type (% in diet)[a]	Study type/ duration	Irradiation dose (kGy)[b]	Process conditions	Group	Animals per group	Comments	Author/ reference
Bacon (35%)	750 days	Chow = 0 C = 0 H = 55.8	Spent fuel rods; canned, frozen; irradiated at 60 °F; stored at 5 °C for first 6 months, then at rt	Chow, C H	0 and 92 150 and 142 147 and 139	NHDIR. C3H and A/Crgl. Fat portion of bacon was separated and added back to laboratory diet. No major differences between experimental and control groups.	McKee et al. (*346*); Dixon et al. (*347*)
Chicken (35%): frozen (f), thermal (t), gamma (g), electron (e)	Reproduction and teratology 20 days	Chow = 0 C = 0 VH = 59	g, ^{60}Co, heated, canned, frozen; e, 10 MeV electrons, heated, vacuum packed in pouch, frozen	Chow, C, VH	60M, 60F for f, 40M, 40F for other groups	NHDIR. CD-1. Temporarily removed from the 730-day carcinogenicity study (for 25 weeks) to serve as P generation.	Raltech Scientific Services (*356*)
Chicken (35%): frozen (f), thermal (t), gamma (g), electron (e)	730 days	Chow = 0 C = 0 VH = 59	g, ^{60}Co, heated, canned, frozen; e, 10 MeV electrons, heated, vacuum packed in pouch, frozen	Chow, C, VH	175M, 175F for f, 115M, 115F for all other groups	NHDIR. CD-1. Questionable incidence of interstitial cell tumours of the testes from (g) and (e) groups; after review of microslides FDA Cancer Assessment Committee (CFSAN) concluded no statistical or biological basis for tumour induction in testes of CD-1 mice.	Raltech Scientific Services (*357*)
Laboratory diet (100%)	60 days	C = 0 VH = 60	^{60}Co NS	C, VH	30–40 M and F	NHDIR. Swiss. Compared haematology.	Maffei, Mazzali & DeSantis (*358*)
Laboratory diet (100%)	730 days P, F_1, F_2 generations	C = 0 VH = 60	^{60}Co 6 kGy/h	C, VH	P 9 F_1 15 F_2 20	NHIR/PEND. Swiss. Decrease in growth and fertility attributed to nutritional deficit (no vitamin supplements).	Biagini et al. (*359*)

Table 28 *(continued)*

Food type (% in diet)[a]	Study type/ duration	Irradiation dose (kGy)[b]	Process conditions	Group	Animals per group	Comments	Author/ reference
Laboratory diet (100%): autoclaved (auto), irradiated	Reproduction lifetime, 3 generations	C = 0 Auto = 0 VH = 44	^{60}Co; paper cartons, plastic bags; auto at 120 °C, for 20 min	C, auto, VH	140M, 140F	NHDIR. Comparison of autoclaved and irradiated diet.	Saint-Lèbe (*336*)
Laboratory diet (100%): diets 1 and 2, autoclaved (auto) or irradiated (I)	Reproduction and teratology 200 days	C = 0 H = 25	^{60}Co; other conditions NS	1-auto 1-I 2-auto 2-I	12M, 24F for diet 1; 12M, 12F for diet 2	NHDIR. LACA and A2G. 2 strains, 4 diets = 8 groups. Comparison of autoclaving/irradiation: with diet 1, autoclaving resulted in higher number of litters; with diet 2, irradiation resulted in higher number of litters. Mice had a strong preference for the irradiated diet compared to the autoclaved diet.	Porter & Festing (*360*)
Mixed: beef (21.8%), tuna (14.3%), corn (30.8%), sweet potato (24.2%), fruit compote (8.9%), on wet weight basis	(12–28 months) 25 24 24 15 24 12 27 28 26 24	C = 0 VH = 55.8	Spent fuel rods; foods canned, frozen; irradiated at 60 °F; stored at rt	C, VH	10 replicates S/3/C5 200/260/200 S/3/C5 222/126/192 3/D 52/280 3 218 3 172 3 144 3 238 3 110 S 213 S 207	NHDIR. Swiss (S), C3H (3), C57 black (C5), DBA (D). Strains acquired from different sources. The strains used had a high incidence of certain tumours. No diet-related effects. Irradiated diet not carcinogenic in mice.	Deichmann (*348*); Radomski et al. (*349*)
Mixed: beef stew, codfish, chicken stew, green beans, peaches, and flour (16.67% each)	2 years	C = 0 VH = 55.8	Spent fuel rods; foods canned, frozen; irradiated at 60 °F; stored at rt	C, VH	Cal A strain: C 106M, 95F; VH 100M, 91F. C3H-NT strain: C 117M, 113F; VH 119M, 109F	NHDIR. Cal A and C3H-NT. Flour irradiated at 0.744 kGy; other components at 55.8 kGy. No signifcant differences between test and control mice of both strains for growth, mortality and reactions, and tumour incidence.	Calandra & Kay (*350*)

Table 28 *(continued)*

Food type (% in diet)[a]	Study type/ duration	Irradiation dose (kGy)[b]	Process conditions	Group	Animals per group	Comments	Author/ reference
Mixed: pork (8.8%), chicken (6%), evaporated milk (19.3%), potatoes (19.3%) and carrots (43%) on wet weight basis	19 months	Chow = 0 C = 0 VH = 55.8	Spent fuel rods; foods canned, frozen; irradiated at 60 °F; potatoes irradiated at 0.1 kGy, stored at 5–10 °C	Chow C, VH	200M, 200F	NHDIR/PEND. Strong A, Dba, Cb. Auricular dilatation with highest incidence in Cb strain. Additional testing suggests lesion due to mineral deficiency (copper).	Monsen (*351–353*)
Mixed: pork (8.8%), chicken (6%), evaporated milk (19.3%) and carrots (43%) on wet weight basis	600 days (II) 300 days (III) 600 days (IV) lifetime (V)	Chow = 0 C = 0 VH = 55.8	Spent fuel rods; foods canned, frozen; irradiated at 60 °F; potatoes irradiated at 0.1 kGy, stored at 5–10 °C	Chow C, VH	II-1200/strain, 3 groups; III-54M, 54F IVa-320, 5 groups; IVb-36M, 36F IVc-42M, 42F IVd-36M, 36F	NHDIR. Cb and Strong A (II), Cb for all others. Repeat of Monsen's study (II); to determine pathogenesis of heart lesions (III); etiology (IV); 100% milk diet (V). No "Monsen heart lesions" found.	Thompson et al. (*354, 355*)
Mixed: pork brain (5%) and whole egg (2.5%)	14 months	C = 0 EH = 93	Spent fuel rods; canned, separately, frozen; irradiated at 60 °F; stored at rt for 3–9 months	C, EH	48	NHDIR. S-P Swiss.	Teply & Kline (*313*)
Oil: concentrate of beef and yeast sterols (2.4%)	15–22 months	C = 0 VH = 55.8	Electron radiation; frozen 1/4-inch slabs, GE Labs, Milwaukee, WI	C, VH	48-S-P Swiss 50-CAF1, JAX 60-C3H JAX	NHDIR. S-P Swiss; CAF1, JAX; C3H JAX. (Dissolved in oil component of diet before mixing.)	Teply & Kline (*313*)
Oil: corn (3%), cottonseed (3%), peanut (3%)	15 months	C = 0 H = 27.9 VH = 55.8	Electron radiation; mixed, stored at refrig. temp., GE Labs, Milwaukee, WI	C, H, VH	50	NHDIR. S-P Swiss. (Mixed equal parts of non-irradiated oil and electron irradiated oil.)	Teply & Kline (*313*)

Table 28 *(continued)*

Food type (% in diet)[a]	Study type/ duration	Irradiation dose (kGy)[b]	Process conditions	Group	Animals per group	Comments	Author/ reference
Wheat flour (50%)	Lifetime P, F_1, F_2 generations	C = 0 VH = 50	^{60}Co 1.8 kGy/h; stored at ambient temp	C, VH	P 2M, 10F F_1 10M, 50F	NHDIR/PEND. C57BL. Wheat flour fed within 1 week after irradiation. Effects on longevity, fertility presumed due to formation of peroxides and radicals (see reference *421*). Reported loss of lipids and carotenoid fractions in irradiated diet.	Bugyaki et al. (*361*)

F = female; F_1, F_2, etc. = first filial generation, second filial generation, etc.; M = male; NHDIR = negative for high-dose irradiation effect; NS = not specified; P = parent generation; PEND = possible effect of nutrition or diet; repro = reproduction study; rt = room temperature.

[a] Based on dry weight unless otherwise indicated.

[b] Food irradiation dose levels: C = control; L = low (<10 kGy); H = high (≥ 10 kGy); VH = very high.

Table 29
Food type – dog studies

Food type (% in diet)[a]	Study type/ duration	Irradiation dose (kGy)[b]	Process conditions	Group	Animals per group	Comments	Author/ reference
Bacon (35%)	2 years	C = 0 H = 27.9 VH = 55.8	Spent fuel rods; canned, frozen; irradiated at 60 °F in pool; stored at rt	C, H, VH	2M, 2F	NHDIR. No differences in growth, weight maintenance, haemoglobin, packed cell volume, white blood cell counts, reproduction and lactation.	Hale, Schroeder & Sikes (*362*)
Beef (35%)	25 weeks	C = 0 H = 27.9 VH = 55.8	Spent fuel rods; canned ground beef, frozen; irradiated at 60 °F; stored at rt	C, H, VH	4M	NHDIR. Beagles. No significant differences in weight gains or blood values attributable to the diet.	Reber et al. (*363*)
Beef (35%)	104 weeks P generation, reproduction	C = 0 H = 27.9 VH = 55.8	Spent fuel rods; canned ground beef, frozen; irradiated at 60 °F; stored at rt	C, H, VH	2M, 2F	NHDIR. Beagles. No diet-related effects.	Reber et al. (*364*)
Beef (35%)	Reproduction and teratology, 3 years	C = 0 VH = 60	11–12 MeV electrons; canned ground beef, frozen; irradiated at 60 °F; stored at rt	C, VH	3M, 15F	NHDIR. Beagles. No effect on growth rate, reproductive performance or general health.	Loosli et al. (*375*)
Beef (35%)	Reproduction, 104 weeks	C = 0 VH = 55.8	Spent fuel rods; canned ground beef, frozen; irradiated at 60 °F; stored at rt	C, VH	3M, 3F	NHDIR. Beagles. No adverse effect.	Clarkson & Pick (*365*)
Beef (35%)	2–3 years	C = 0 H = 27.9 VH = 55.8	Spent fuel rods; raw beef, cellophane packaging, frozen; van de Graaf electrons	C, H, VH	6F	NHDIR. Beagles, No adverse effect.	McCay & Rumsey (*371*)

Table 29 *(continued)*

Food type (% in diet)[a]	Study type/ duration	Irradiation dose (kGy)[b]	Process conditions	Group	Animals per group	Comments	Author/ reference
Beef (35%)	2 years	C = 0 H = 27.9 VH = 55.8	Spent fuel rods; canned, frozen; irradiated at 60 °F; stored at rt	C, H, VH	2M, 2F	NHDIR/PEND. Beagles. No differences in growth. (See also under chicken and pineapple jam.)	Blood et al. (*367*)
Beef stew (35%)	2 years	C = 0 H = 27.9 VH = 55.8	Spent fuel rods; canned, frozen; (Dugway)	C, H, VH	2M, 2F	NHDIR. Beagles. No significant difference between groups.	Deichmann (*366*); Radomski et al. (*326*)
Cabbage (35%)	2 years	C = 0 H = 27.9 VH = 55.8	Spent fuel rods; raw shredded, in plastic bags, in fibre drum, irradiated at 60 °F	C, H, VH	2M, 2F	NHDIR. No differences in growth, weight maintenance, haemoglobin, packed cell volume, white blood cell counts, reproduction or lactation.	Hale, Schroeder & Sikes (*362*)
Chicken (35%)	2 years	C = 0 H = 27.9 VH = 55.8	Spent fuel rods; canned, frozen; irradiated at 60 °F; stored at rt	C, H, VH	2M, 2F	NHDIR/PEND. Beagles. No differences in growth. (See also under beef stew and pineapple jam.)	Blood et al. (*367*)
Chicken (35%): frozen (f), thermal (t), gamma (g), electron (e); or chow (c) 100%	Reproduction, F 36 months, M 40 months	C (c, f, t) = 0 VH = 59	g = ^{60}Co; heated, canned, frozen; e = 10 MeV electrons; heated, vacuum packed in pouch, frozen	C, VH	10M, 20F	NHDIR. Separate studies with gamma- and electron-irradiated chicken meat. No treatment-related effects.	Raltech Scientific Services (*372*)
Chicken stew (35%)	2-3 years	C = 0 H = 27.9 VH = 55.8	Spent fuel rods; canned, frozen	C, H, VH	2M, 2F for C 2M, 3F for H, VH	NHDIR. Beagles. No adverse effect.	McCay & Rumsey (*371*)

Table 29 *(continued)*

Food type (% in diet)[a]	Study type/ duration	Irradiation dose (kGy)[b]	Process conditions	Group	Animals per group	Comments	Author/ reference
Chow (100%): Vetacan (meat feed mixture) (Vc) Vetavit (grain feed mixture) (Vv)	90 days	C = 0 H = 25	^{60}Co	C, H	2 (4 groups)	NHDIR/PEND. 35% destruction of essential amino acids and lipid oxidation in Vc feed and carbohydrates in Vv feed. No noticeable sensory effects on feed, but test animals demonstrated drop in total proteins and creatine in blood serum. No other biological effects noted.	Smid, Dvorak & Hrusovsky (*374*)
Evaporated milk (35%)	2 years	C = 0 H = 27.9 VH = 55.8	Spent fuel rods, canned, frozen; (Dugway)	C, H, VH	2M, 2F	NHDIR. Beagles. No significant difference between groups.	Deichmann (*366*); Radomski et al. (*326*)
Fruit compote (35%)	104 weeks	C = 0 H = 27.9 VH = 55.8	Spent fuel rods; canned; irradiated at 60 °F; stored at rt	C, H, VH	2M, 2F	NHDIR. Beagles. No diet-related effects on food consumption, growth measurements, feed efficiency, reproduction, haemotology or histopathology.	Larson et al. (*368*)
Green beans (35%)	104 weeks	C = 0 H = 27.9 VH = 55.8	Spent fuel rods; canned; irradiated at 60 °F; stored at rt	C, H, VH	2M, 2F	NHDIR. Beagles. No diet-related effects on food consumption, growth measurements, feed efficiency, reproduction, haemotology or histopathology.	Larson et al. (*368*)

Table 29 *(continued)*

Food type (% in diet)[a]	Study type/ duration	Irradiation dose (kGy)[b]	Process conditions	Group	Animals per group	Comments	Author/ reference
Pineapple jam (35%)	2 years	C = 0 H = 27.9 VH = 55.8	Spent fuel rods; canned, frozen; irradiated at 60 °F; stored at rt	C, H, VH	2M, 2F	NHDIR/PEND. Beagles. No differences in growth. Control group for jams was midway between H and VH groups. All dogs in "jam" groups had glycosuria. (See also under beef stew and chicken.)	Blood et al. (*367*)
Pork (35%)	4 years	NS	NS; fresh pork packed in plastic pouches	C, H	8M, 8F	NHDIR. Chow. No significant differences between groups for any parameter.	Cheng & Zhang (*373*)
Pork (35%)	90 weeks	C = 0 H = 27.9 VH = 55.8	Spent fuel rods; canned, frozen; irradiated at 60 °F; stored at rt	C, H, VH	2M, 2F	NHDIR. Beagles. No deviations from normal.	McCay & Rumsey (*369, 371*)
Tuna (35%)	2 years	C = 0 H = 27.9 VH = 55.8	Spent fuel rods; canned, frozen; irradiated at 60 °F; stored at rt	C, H, VH	2M, 2F for C 2M, 3F for H, VH	NHDIR. Beagles. No deviations from normal.	McCay & Rumsey (*370, 371*)

F = female; M = male; NHDIR = negative for high-dose irradiatoin effect; NS = not specified; PEND = possible effect of nutrition or diet; rt = room temperature.

[a] Based on dry weight unless otherwise indicated.

[b] Food irradiation dose levels: C = control; L = low (<10 kGy); H = high (⩾ 10 kGy); VH = very high.

Table 30
Food type – miscellaneous animal studies

Food type (% in diet)[a]	Test species/ study duration	Irradiation dose (kGy)[b]	Process conditions	Group	Animals per group	Comments	Author/ reference
Barley meal (50%)	Japanese quail, 26 days	C = 0 H = 10 VH = 1000	10 MeV electrons, 250 mA, 0.9 cm/s at 40–50 °C	C, H, VH = C^+	30	NHDIR/PEND. Reported decreased lymphocytes, leukocytes, blood serum triglycerides. Authors suggested need for further studies to determine the responsible agent in irradiated barley and whether it leads to a toxic effect.	Koch et al. (*377*); Döllstädt et al. (*378*)
Chicken (35% or 70% of diet); frozen (f), thermal (t), gamma (g), electron (e); or chow (c) 100%	Hamsters, reproduction and teratology, 5 days	C (c, f, t) = 0 VH = 59	g = ^{60}Co; heated, canned, frozen; e = 10 MeV electrons; heated, vacuum packed in pouch, frozen	C, VH	5	NHDIR. No teratogenic response in groups receiving irradiated diet.	Raltech Scientific Services (*379*)
Feed (100%): autoclaved for 10 min at 120 °C (auto); irradiated	Pigs, 16 weeks; 90 days, 3-generation reproduction	C = 0 Auto = 0 VH = 50	^{60}Co; other conditions NS	C, auto, VH	4M, 12F	NHDIR. Phase I of a relay study. No treatment-related effects.	Strik (*380*)
Laboratory diet (100%) with 10% soy bean oil	Chicks, 5 weeks	VH = 30 VH = 60	300 kCi ^{60}Co; soybean oil in glass bottle. 100 kCi ^{60}Co; whole diets in cardboard box	Exp I, 5 groups; Exp II, 9 groups	5	NHDIR/PEND. Growth depression and effects attributed to autoxidation of lipids in irradiated diet.	Takigawa, Danbara & Ohyama (*381*)
Peaches (35%)	Rhesus monkeys, 24 months	C = 0 H = 27.9 VH = 55.8	Spent fuel rods; canned in syrup	C, H, VH	2M, 2F	NHDIR/PEND. Experiment also included animals fed whole and peeled oranges irradiated to 1.5 and 3 kGy with electron source. No diet-related effects.	Blood et al. (*376*)

Exp = experiment; F = female; M = male; NHDIR = negative for high-dose irradiation effect; NS = not specified; PEND = possible effect of nutrition or diet.
[a] Based on dry weight unless otherwise indicated.
[b] Food irradiation dose levels: C = control; L = low (<10 kGy); H = high (≥ 10 kGy); VH = very high or EH = extremely high.

Table 31
Food type – mutagenicity studies *in vitro*

Food type	Species type/ duration	Irradiation dose (kGy)	Process conditions	Comments	Author/reference
Beef, pork, veal	*Salmonella*	50	10 MeV electrons NS	NHDIR. All fried meat samples mutagenic. Irradiation not a factor.	Münzer (*394*)
Cod	*Salmonella*	12	^{60}Co at 4 °C; storage at rt 1, 2, 7, 14, 21 days in plastic film bags	NHDIR. No mutagenic effects.	Joner, Underdal & Lunde (*382*)
2-Dodecylcyclo-butanone (2-DCB) (radiolysis product from palmitic acid moiety in triglyceride)	Rat and human colon cells	Not applicable	Synthesized	PEHDIR. 2-DCB at 0.3–1.25 mg/ml induces DNA strand breaks in rat and human colon cells. Concentrations tested were high compared with actual human intake. *In vivo* test in progress in rats. Chicken meat from Raltech study contained 2-DCB at only 17 µg/g lipid.	Delincée & Pool-Zobel (*427*)
Glucose, peptone	*Escherichia coli*	50	6.5 kCi ^{60}Co	NHDIR. No induction of lysogenic bacteria.	Bugyaki, Lafontaine & Moutschen-Dahmen (*384*)
Growth medium	Human cells	10 20	^{60}Co 4.5 kGy/h; powder form in individual containers at rt; packed in plastic containers, dia. 13 cm	NHDIR. SCE frequencies did not show significant difference.	Vijayalaxmi (*385*)
Herring	*Salmonella*	12	^{60}Co at 4 °C; storage at rt 1, 7, 14 days in plastic film bags	NHCIR/PEND. Saline and ethanol extracts tested in 6 *Salmonella* strains. Saline extracts not mutagenic. Two strains had positive response (twice background) when ethanol extract was concentrated two-fold.	Joner & Underdal (*386*)
Onion powder	*Salmonella*	13.6	^{60}Co ambient, in unsealed plastic pouches in metal cans	NHDIR. No mutagenic effects.	Münzer & Renner (*387*)

Table 31 *(continued)*

Food type	Species type/ duration	Irradiation dose (kGy)	Process conditions	Comments	Author/reference
Paprika	*Salmonella*	50	^{60}Co, aerobic, ambient	NHDIR. No mutagenic effects.	Central Food Research Institute (*388*)
Spice mix	*Salmonella*	15 45	^{60}Co, aerobic, ambient	NHDIR. No mutagenic effects.	Farkas, Andrássy & Incze (*389*)
Strawberry	*Salmonella* Human	15	^{60}Co, 3.6 kGy/h, 400-ml beaker, 25 °C	NHDIR. No signifcant differences using distillates or residue.	Schubert et al. (*390*)
Sucrose solution: concentrated to 20% for shipment to laboratory. Stored at rt or 5 °C for several months, diluted with saline before use	Human	20	^{60}Co, 2% solution, concentrated to 20%	PEHDIR. Chromosomal breaks in human lymphocytes in cell culture. Attributable to radiation-induced chemistry of simple carbohydrate solutions (see reference *383*). Concentration may have increased concentration of oxidized products.	Shaw & Hayes (*391*)
Sucrose solution	*Vicia faba*	20	^{60}Co, 3.3 kGy/h; solution, NS	PEHDIR. Chromosome changes attributable to radiation-induced chemistry of simple carbohydrate solutions (see reference *383*).	Bradley, Hall & Trebikock (*392*)
Sucrose, fructose, glucose, maltose solutions and model mango	*Salmonella*	50	^{60}Co, 17 kGy/h; sealed ampoules, O_2 enriched, 25 °C	PEHDIR. Irradiated simple sugar solutions mutagenic in one of five strains tested. Complex sugar model mango system not mutagenic.	Niemand et al. (*383*)
Sucrose, ribose solutions	*Salmonella*	20	^{60}Co, 4.5 kGy/h; air, N_2 10 min, seal; dry ice; stored 6–8 °C for up to 25 weeks	PEHDIR. Mutagenic effect attributable to radiation-induced chemistry of simple carbohydrate solutions (see reference *383*).	Aiyar & Rao (*393*)

NHDIR = negative for high-dose irradiation effect; NS = not specified; PEHDIR = possible effect of high-dose irradiation; PEND = possible effect of nutrition or diet; rt = room temperature.

Table 32
Food type – mutagenicity studies *in vivo*

Food type (% in diet)[a]	Species type/ duration	Irradiation dose (kGy)	Process conditions	Comments	Author/reference
Beef, ham	*Drosophila*	59 beef, 39 ham	Beef, 3 MCi ^{60}Co, canned, frozen; Ham, 10 MeV electrons, vacuum-packed, frozen	NHDIR. No mutagenic effects. No significant increases in recessive sex-linked lethals, loss of chromosomes or non-disjunction.	Mittler (*395*)
Black beans	Mouse Swiss-55 (10M)	15, 20	^{137}Cs, 4 kGy/h; rt, 5 doses, stored for 2 weeks, boiled	NHDIR. Dominant lethal test. No differences in pregnancy rates, total implants, live and dead implants, sex distribution, or abnormalities.	Bernardes et al. (*414*)
Chicken (35%): chow (c only); frozen (f), stored at 0 °C; thermal (t), stored at 23 °C; gamma (g), stored at 23 °C; electron (e), stored at 23 °C	Mouse (c, 21M; f, 36M; t, 18M; g, 27M; e, 26M)	59	g = ^{60}Co, heated canned, frozen; e = 10 MeV electrons, heated, vacuum-packed in pouch, frozen	NHDIR. Dominant lethal test. Feeding of radiation-sterilized chicken meat did not induce dominant lethal events. Positive control produced negative results, unsuitable for supporting safety.	Raltech Scientific Services (*397*)
Chicken (5, 25, 37.5 or 50% of diet): frozen (f); thermal (t); gamma (g); electron (e)	*Drosophila* (C-, C+, f, t, g, e)	55.8	g = ^{60}Co, heated canned, frozen; e = 10 MeV electrons, heated, vacuum-packed in pouch, frozen	NHDIR. No mutagenic effects. Study noted decreased numbers of offspring in groups raised on irradiated chicken meat. FDA found no evidence of adverse reproductive effects.	Lusskin (*396*)
Glucose powder	Mouse Swiss	20, 50	^{60}Co, 57 Gy/min; polyethylene bags, air, 25 °C	NHDIR. Dominant lethal test. No mutagenic effects.	Varma et al. (*398*)
Glucose powder	*Drosophila*	20, 50	^{60}Co, 57 Gy/min; polyethylene bags, air, 25 °C	NHDIR. No mutagenic effects.	Varma et al. (*399*)
Glucose powder	Mouse Swiss (6 per group)	20, 50	^{60}Co, 57 Gy/min; polyethylene bags, air, 25 °C	NHDIR. Host-mediated assay. No mutagenic effects.	Varma et al. (*400*)

Table 32 *(continued)*

Food type (% in diet)[a]	Species type/ duration	Irradiation dose (kGy)	Process conditions	Comments	Author/reference
Glucose powder	Mouse Swiss	20, 50	^{60}Co, 57 Gy/min; polyethylene bags, air, 25 °C	NHDIR. Micronucleus test in bone marrow cells and chromosomal aberration assay. No evidence of mutagenic effects in somatic or germ cells.	Varma et al. (*401*)
Laboratory diet: Solid cakes	Mouse C57BL	50	^{60}Co; mixed 1:1 with unirradiated food and pressed into new cakes prior to use	NHDIR/PEND. Dominant lethal test. Increased pre-implementation embryonic deaths; not confirmed by cytological analysis.	Moutschen-Dahmen, Moutschen & Ehrenberg (*402*)
Laboratory diet: Pellets, enriched with amino acids and vitamins	Rat SPF Wistar 10–20M, 30–60F	50	C = auto 110 °C, 10 min; Auto = 120 °C, 15 min; H = 10 MeV electrons	NHDIR. Dominant lethal test. No evidence of mutation.	Eriksen & Emborg (*415*)
Laboratory diet: Food pellets	Mouse Swiss (SPF) (10 per group)	0, 7.5, 15, 30	^{60}Co, 8.5 kGy/h; NS	NHDIR/PEND. Host-mediated assay. Significant increase in the mutation frequency induced by the high dose irradiated food (see reference *407*).	Johnston-Arthur et al. (*403*)
Laboratory diet 10% moisture	Rat Wistar (15M)	25	^{60}Co, 2.4 kGy/h; NS, stored for 3–4 weeks at 4–6 °C	NHDIR. Dominant lethal test. No evidence of mutagenic effects.	Chauhan et al. (*404*)
Laboratory diet 10% moisture	Mouse Swiss	25	^{60}Co, 2.4 kGy/h; NS	NHDIR. Dominant lethal test. No effect on post-implantation loss, dead implantations, or pregnancy.	Chauhan et al. (*405*)
Laboratory diet: pellets	Mouse	45	10 MeV electrons; NS; 10 min	NHDIR. Host-mediated assay. No mutagenic effects.	Münzer & Renner (*416*)
Laboratory diet	Mouse BALB/c	28.5	^{60}Co, 11–11.5 h of exposure; 37–38 °C	NHDIR. Bone marrow and male germ cells examined for chromosome aberrations. No mutagenic effects.	Leonard, Wilcox & Schietccatte (*406*)

Table 32 *(continued)*

Food type (% in diet)[a]	Species type/ duration	Irradiation dose (kGy)	Process conditions	Comments	Author/reference
Laboratory diet: pellets	Chinese hamster	45	10 MeV electrons; open aluminium trays	NHDIR/PEND. No increase in chromosomal aberrations; slightly increased incidence of polyploidy.	Renner (*417*)
Laboratory diet: pellets	Mouse (25–100 per group)	0, 7.5, 15, 30	^{60}Co; 250 g pellets in polyethylene sacks; 22–24 °C	NHDIR/PEND. Host-mediated assay for 3 commercial food pellets. Irradiation increased mutation frequency between 10 and 60 fold for the 3 products compared to controls. Subsequent extraction study found mutagenic agent extracted by alcohol. Water extract had a lower effect and ether extract had no effect.	Johnson-Arthur et al. (*407*)
Laboratory diet	Mouse CD1	10, 25, 50	^{60}Co	NHDIR/PEND. Dominant lethal test. Used 4 diets on 2 strains. Some evidence of weakly mutagenic effect with one diet.	Anderson et al. (*408*)
Laboratory feed	Mouse, SPF Ha/ICR (Swiss)	30	10 MeV electrons; NS	NHDIR. Host-mediated assay. No mutagenic effects.	Münzer & Renner (*418*)
Medium	*Drosophila*	30	25 MeV electrons (600 mA) on tungsten converter, 10 kGy/min; medium in lucite vials, used immediately or after 3 weeks	NHDIR/PEND. Offspring tested for dominant, sex-linked, and F_3 lethality. No decrease in F_1 survival or increase in F_3 sex-linked lethality. There was small but consistent increase in sex-linked recessive lethality, but no detectable dose effect. (Low-dose exposures were with X-rays operated at 250 kV_p and 15 mA, 50 Gy/min.)	Rinehart & Ratty (*419*)
Medium, DNA	*Drosophila*	10	14 kCi ^{60}Co; 70-min exposure	NHDIR. No evidence that irradiated medium or DNA is mutagenic.	Chopra (*409*)

Table 32 *(continued)*

Food type (% in diet)[a]	Species type/ duration	Irradiation dose (kGy)	Process conditions	Comments	Author/reference
Medium, sucrose (30%), DNA	*Drosophila*	30	25 MeV electrons (600 mA) on tungsten converter, 10 kGy/min; sucrose solution in lucite vial, used immediately or after 3 weeks; diluted to 10% with medium	NHDIR/PEND. Autoclaved sucrose or DNA medium is mutagenic (irradiated or not). Non-autoclaved sucrose is not mutagenic. (DNA irradiated at low doses with X-rays operated at 250 kV_p and 15 mA, 50 Gy/min.)	Rinehart & Ratty (*420*)
Milk powder (35%)	Mouse, NMRI/Han (750 mice) Rat, Sprague-Dawley (716 rats), P-F_5	45	10 MeV electrons, 10 min	NHDIR. Dominant lethal test, reproduction. High content of radicals in the irradiated food. No harmful effects.	Renner et al. (*421*)
Onion powder (10%)	Chinese hamster Mouse	13.6	^{60}Co; unsealed plastic pouches in metal cans; ambient	NHDIR. Sister chromatid exchange tests negative in hamsters and 3 strains of mice.	Münzer & Renner (*387*)
Paprika	Mouse	50	^{60}Co; aerobic, ambient	NHDIR. Host-mediated assay. No increase in number of revertants.	Central Food Research Institute (*388*)
Paprika (20%) (8.6% moisture)	Mouse Swiss	30	^{60}Co; 3.1 kGy/h; NS; fed 8–18 days after irradiation	NHDIR. Micronucleus test. No differences in the incidence of erythrocytes with micronuclei, and polychromatic:normal ratio comparable among all groups.	Chaubey et al. (*408*)
Spice mix Pepper	Rat CFY	15	^{60}Co; aerobic, ambient	NHDIR. *E. coli* inductest on blood of rats. No induction of lysogenic bacteria.	Farkas & Andrássy (*411*)
Spice mix	Rat CFY	15, 45	^{60}Co; aerobic, ambient	NHDIR. Negative Ames test on irradiated spice extracts and on urine of rats fed irradiated spices.	Farkas, Andrássy & Incze (*389*)

Table 32 *(continued)*

Food type (% in diet)[a]	Species type/ duration	Irradiation dose (kGy)	Process conditions	Comments	Author/reference
Spice mix (25%)	Rat Sprague-Dawley	15	^{60}Co, 0.5 kGy/h; NS; feeding 5–9 days after irradiation	NHDIR. Dominant lethal test. No significant difference between irradiated spice groups and controls.	Barna (*412*)
Strawberry	Mouse	15	^{60}Co; 25 °C	NHDIR. No clastogenic effects.	Schubert et al. (*390*)
Sucrose, ribose solutions	Mouse	50	^{60}Co, 4.5 kGy/h; air, N_2 10 min, seal; dry ice; stored at 6–8 °C up to 25 weeks	NHDIR. Host-mediated assay. No increase in number of revertants.	Aiyar & Rao (*393*)
Wheat (50%)	Mouse (2M, 10F per group in P, 10M, 50F per group in F_1)	0, 50	3.1 kCi ^{60}Co, 1.8 kGy/h; plastic bags	NHDIR/PEND. Chromosomal abnormalities in germ cells presumed due to formation of peroxides and radicals (see reference *421*) with subsequent loss of lipids and carotenoid fractions in irradiated diet.	Bugyaki et al. (*361*)
Wheat (freshly irradiated)	Chinese hamster, 72 h after feeding; Rat, 12 weeks	0, 15, 30	^{60}Co; N_2, air	NHDIR. No difference in polyploids in bone marrow cells or micronuclei in reticulocytes 72 h after diets irradiated in N_2 or air. Analyses of micronuclei in peripheral blood of rat fed wheat flour irradiated at 0.75 kGy done at 6 and 12 weeks.	Tanaka et al. (*413*)

F = female; M = male; NHDIR = negative for high-dose irradiation effect; NS = not specified; PEND = possible effect of nutrition or diet; rt = room temperature.
[a] Based on dry weight unless otherwise indicated.

The United States Army became interested in the feasibility of preserving foods by ionizing radiation from radioisotopes and radioactive by-products from nuclear reactors in the early 1950s (*423*). As part of the Army's overall programme, the Medical Research Branch of the Surgeon General's Office was assigned the task of determining the wholesomeness of radiation-sterilized foods in 1953. This programme supported studies in academic and research institutions as well as in military research institutions, and resulted in many of the feeding studies undertaken in rats, mice, dogs and monkeys. There were initially 49 foods under investigation in short-term studies; 21 were chosen for long-term toxicity studies, including ground beef, pork loin, bacon, shrimp, cod, chicken, tuna, beef stew, chicken stew, carrots, cole-slaw, corn, green beans, potatoes, sweet potatoes, flour, fruit compote, evaporated milk, peaches, oranges and jam.

The high doses used and the quantity of food tested in the animals were greater than those that would normally be encountered and consumed, in order to maximize any potential toxicity. The large group of foods used for the studies reflected the concern at that time that each food item, or a combination of irradiated foods, might respond to irradiation in a unique way (*314, 320*). The research also tried to correct the problem of palatability of diets containing high levels of irradiated food items by taking caloric consumption into account in the statistical evaluation of the results (*320*).

The 1994 WHO publication on the safety and nutritional aspects of irradiated food included a section evaluating the studies in the United States Food and Drug Administration (FDA) electronic database (*10*). Following the 1981 Bureau of Foods Irradiated Food Committee Report, in which it was concluded that, on the basis of studies on the radiation chemistry of foods, an adequate margin of safety can be demonstrated for foods irradiated below 10 kGy and for dry and dehydrated spices that are irradiation sterilized, the FDA reviewed all available animal studies to determine their adequacy and to evaluate the toxicological evidence (*424*). This review of over 400 studies resulted in over 250 being "accepted" or "accepted with reservation", and about 150 being "rejected"; some 20 review articles were not categorized. On the basis of this additional review and evaluation, the FDA confirmed its earlier conclusions regarding the safety of foods permitted by regulation in 1986.

The FDA stated that five of the studies reviewed were considered to have been properly conducted, fully adequate by 1980 standards, and capable of standing alone to support the safety of irradiated foods (*424*). Of those five, two were with foods irradiated to a dose greater than 10 kGy: dried

milk to 45 kGy (*343*) and beef stew and evaporated milk to 27.9 and 55.8 kGy, respectively (*326*).

The Study Group's evaluation of the safety of foods irradiated at doses greater than 10 kGy included some of the studies "rejected" by the FDA reviewers. The studies had been rejected for one or more reasons: the radiation dose was not reported; the number of animals per group was not reported; the number of animals per group was small (less than five); the study was conducted without controls fed a non-irradiated diet; the diet fed was determined to be nutritionally inadequate; and the studies were conducted at a laboratory that was considered by the FDA to be in violation of good laboratory practice (*424*). Nevertheless, their inclusion in the present evaluation provides a broader perspective on the diverse data obtained.

6.3.1 *Subchronic studies*

Many subchronic studies on safety have been conducted in rats (12), mice (1), dogs (2), pigs (1), quails (1) and chickens (1) (Tables 23–26). These studies examined the safety and nutritional adequacy of a variety of dietary items and complete laboratory diets treated with high-dose irradiation. The vast majority of these studies reported no toxic effects in laboratory animals after consumption of high-dose irradiated foods.

The few adverse events in these studies appeared to reflect degradation of essential nutrients in treated diets. In 1963, Malhotra et al. reported that high-dose irradiated beef (55.8 kGy) fed to rats at 35% of the diet resulted in excess mortality from a haemorrhagic syndrome in males that could be prevented by dietary supplementation with vitamin K (*315–317*). They also reported that administration of testosterone increased mortality linearly and that the effect of methionine was protective and decreased mortality linearly; these factors were independent of each other. Other detailed investigations of similar adverse findings in subchronic toxicity studies ultimately demonstrated that they were attributable either to preexisting nutritional deficiencies in the diets or to nutrient degradation not unique to irradiation (*339, 344, 345, 374, 381*).

6.3.2 *Carcinogenicity and chronic toxicity studies*

Several studies on high-dose irradiated diets were conducted using rodents, primarily rats, and following protocols that involved two-year carcinogenicity bioassays and multigeneration reproductive toxicology evaluations. There were 17 such combined studies in rats (Table 23), three in mice (Table 24), and one in pigs (Table 26). Some of the studies were conducted with radiation-sterilized laboratory diets.

Additional carcinogenicity bioassays without reproductive components have been reported for rats and mice (Tables 23 and 24). This large collection of carcinogenicity data is unique in the assessment of all food-related treatments and processes. No irradiation-related increases in tumours occurred in any of the studies that involved administering high-dose irradiated foods or diets to rats or mice. Similarly, no irradiation-induced changes in reproductive function were reported in the multi-generation reproduction phases of the combined carcinogenicity-reproduction studies.

Chronic toxicity studies have been conducted in mice (4), dogs (7) and monkeys (1) (Tables 24–26). In one, an unusual heart lesion (auricular dilatation) was reported in a single mouse strain. This study involved three strains of mice fed three diets: a non-irradiated chow; a synthetic diet constituted from high-dose irradiated components; and a non-irradiated synthetic diet (*351, 352*). Monsen (*351*) reported auricular dilatation in mice fed a composite diet of irradiated pork, chicken, evaporated milk, potatoes and carrots. Thompson et al. at the Medical Research Laboratory tried to repeat Monsen's study and initiated additional tests to determine the pathogenesis of the heart lesions. However, they could not duplicate the effect (*354, 355*). Monsen conducted additional studies (*352, 353*) and reported that the effects were due to deficiency of iron and copper in the diet (*353*). The other chronic studies in mice did not show any adverse effects due to the high-dose irradiated diet or to the high-dose irradiated dietary components.

Chronic studies in dogs, conducted for durations of 2–4 years (Table 25), reported no adverse findings attributable to high-dose irradiated food (Table 29). Blood et al. (*367*) reported that dogs fed an irradiated chicken or beef diet showed no differences in growth compared to controls, but dogs fed an irradiated pineapple jam diet showed some differences and all dogs developed glycosuria as a result of the high-carbohydrate content. The authors noted four cases of primary lymphocytic thyroiditis, two in animals receiving chicken meat, one on the beef diet, and one on the jam diet (*367*). A review of the evidence of the presence of lesions in various organ tissues representing 273 dogs from all studies (*326, 362, 364–366, 368–371*) was made by the United States Armed Forces Institute of Pathology (*425*); thyroiditis in dogs was found to be a nonspecific lesion that had been reported to occur with equal frequency in irradiated and non-irradiated dietary groups. The duration of these dog studies was not adequate to assess carcinogenicity; nonetheless, there were no suggestions of pathological abnormalities in any chronic study conducted with dogs.

In a non-human primate study in which high-dose irradiated peaches (27.9 and 55.8 kGy) were fed to rhesus monkeys for a duration of two years, there were no adverse findings in male monkeys, but female monkeys demonstrated marked variations in acceptance of the semi-liquid irradiated diets. Untoward findings in female monkeys were attributed by the authors to problems consistent with decreased palatability of the diet and consequent rejection of the food (*376*).

The United States Office of the Surgeon General initiated a series of nutritional and toxicological studies on chicken meat sterilized by ionizing radiation in 1976 that was completed in 1984 (*9*). Most of these studies were conducted by Raltech Scientific Services (Raltech) of St Louis, Missouri, with specific portions assigned to other institutions. Responsibility for supervision of the Raltech contract was transferred from the Army to the United States Department of Agriculture in October 1980. The studies included a chronic feeding study in mice (*357*) and dogs (*372*). The chicken meat (deboned, 18% skin and 82% meat) was vacuum packed in cans or retort pouches (26 mm thick), thermally processed at 73–80 °C to inactivate the enzymes, cooled to –40 °C, and irradiated in the frozen state in the absence of air to a minimum dose of 45 kGy and to an average dose of 59 kGy. Samples irradiated by electron accelerator were sterilized by exposure to 10 MeV electrons at –25 °C. Control samples were kept frozen, and thermally treated samples were processed to an internal temperature of 115.6 °C to a sterility level of $F_0 = 6$ (*9*)[1].

As part of the FDA review, scientists from FDA and the National Toxicology Program's Board of Scientific Counselers reviewed the data and agreed that the evidence did not show any treatment-related induction of testicular tumours (*424, 426*).

On the basis of the above studies, the FDA concluded that there were no treatment-related effects in the mouse and dog feeding studies (*424, 426*).

6.3.3 *Reproduction and teratology studies*

The Netherlands National Institute of Public Health and Environmental Hygiene conducted a series of studies to determine the potential formation of toxic compounds in irradiated foods (*340, 341, 380*). In the first study, there were no observable differences between rats fed an irradiated diet (50 kGy) or an autoclaved diet (15 min at 120 °C) and those fed a control diet with respect to growth, feed consumption,

[1] Sterility level F_0 provides a basis for comparing the sterility level achieved by heat treatment at any temperature to that achieved by an equivalent treatment at 121 °C in terms of minutes. $F_0 = 6$ signifies that the heating time at 115.6 °C was sufficient to produce a sterility level equivalent to that achieved by heating at 121 °C for 6 minutes.

reproduction, haematology, urinary and organ histopathology parameters (*340, 380*). The second study was performed with pigs and involved three generations, two litters of piglets per generation, F_a and F_b (*380*). The F_a generation was used for continued breeding and the F_b generation was observed for gross abnormalities and was discarded at weaning age. There were no deviations in feed consumption, growth, haematological, and biochemical parameters in the animals, and the authors concluded that there were no treatment-related effects in the growth and reproduction of pigs fed irradiated or autoclaved feed for three generations. In the third phase of the study, three groups of 15 male and 15 female pigs from the F_{1a} generation fed 50 kGy-irradiated, autoclaved or control feed were slaughtered and processed to ham products (*341, 380*). Six groups each of 50 male and 50 female rats were then fed the following diets: (1) standard diet; (2) 35% ham from control pigs, treated with nitrite at 200 mg/kg; (3) 35% ham from pigs fed the autoclaved diet, treated with nitrite at 200 mg/kg and autoclaved; (4) 35% ham from control pigs, treated with nitrite at 50 mg/kg and irradiated to 37 kGy; (5) 35% ham from pigs fed the 50 kGy-irradiated diet, treated with nitrite at 50 mg/kg and irradiated to 37 kGy; and (6) 35% ham from pigs fed the 50 kGy-irradiated diet, treated with nitrite at 50 mg/kg and irradiated to 74 kGy. The authors concluded that there were no treatment-related effects in: feed consumption, growth, mortality, haematology, biochemistry of blood and urine, organ weights, histopathology and tumour incidence. In addition, the concentrations of nitrosamines in the ham did not change with added nitrite or irradiation dose.

Read et al. (*314*) at the United States Army Medical Research Laboratory in Denver, Colorado, also conducted long-term toxicity studies in rats fed a composite food diet, each irradiated to 55.8 kGy. They reported decreased weight gain in females of the F_3 generation, but urged caution in interpreting the results because of the small number of animals used. They concluded that the variations in reproductive performance did not indicate toxicity, but should be monitored in feeding trials. In addition, they reported increased cytochrome oxidase activity in this study and in an earlier study where rats were fed diets containing 35% beef or pork (*319*). The authors noted that cytochrome oxidase activity was not affected in diets with fruits and vegetables and suggested that the probable cause of the increase was the meat components present in the meat and composite diets, i.e. nutritional components rather than irradiation. A review of the evidence of lesions in various organ tissues representing over 3000 rats did not indicate any gross or histopathological lesions that could be specifically attributed to the irradiated diet (*425*). In a few organs, the differences occurred in both

test and control animals. Because several strains of rats were used, a comprehensive pooled data report was not compiled (A. Brynjolfsson, personal communication).

Several multigeneration reproduction studies were conducted in rats (1), mice (3), dogs (4), and hamsters (1) (Tables 23–26). Minor effects noted in some cases, generally involving small decreases in body weight or body weight gain in the later generations of multigeneration studies, appear to have been related to nutrition and reduced palatability of the diet. Reproductive and teratological end-points demonstrated no effects with any consistent pattern or trend.

6.4 Mutagenicity studies

Data from both *in vitro* and *in vivo* mutagenicity studies are presented in Tables 31 and 32, even though the emphasis in this report has been on high-dose irradiated foods tested directly in animal feeding studies. A few of these *in vitro* studies, but none of the *in vivo* studies, have shown mutagenic effects of certain irradiated substrates. However, the *in vitro* studies are of less relevance, since such data are not as valid as those from animal studies for the purpose of estimating risk to humans on the basis of extrapolation.

In this regard, the possible mutagenic activity of 2-dodecylcyclobutanone (2-DCB), formed radiolytically from food containing fat, has received particular attention. A recent study employing single-cell gel electrophoresis (comet assay) indicated that 2-DCB in the concentration range 0.30–1.25 mg/ml produces some cytotoxicity and an associated but weak effect in DNA at alkali-labile sites (*427*). However, the concentrations used were far greater (about three orders of magnitude) than the 17 µg/g reportedly present in the extracted lipid of chicken meat irradiated to 59 kGy. It should also be noted that the concentration of 2-DCB actually present in high-dose irradiated chicken meat, when calculated on the basis of the total meat content, would be even smaller.[1]

In contrast, studies in *Drosophila* (*396*) and mice (*397*) did not show any mutagenic activity of high-dose irradiated chicken (55.8 kGy and 59 kGy, respectively).

Similarly, Tanaka et al. (*413*) reported no difference from controls in polyploids in bone marrow cells or reticulocytes of Chinese hamsters fed wheat irradiated to doses of 0, 15 and 30 kGy.

[1] *Note added in proof by the Secretariat:* In a subsequent *in vivo* study, as yet unpublished, the researchers claim to have found a small positive effect when six rats were administered an extremely high level of the synthetically prepared 2-DCB. Limitations of the experiment, particularly the exclusive reliance on the unvalidated comet assay technique, call into question the significance of this finding. Another unpublished study found that the Ames test for 2-DCB was negative.

6.5 Human clinical studies

In a series of studies involving young male human volunteers, the United States Army evaluated the wholesomeness of foods treated with high-dose radiation. Subjects consumed irradiated foods for periods of 15 days separated by control and washout intervals. Generally, the experimental protocol called for a variety of foods (54 items) to be sealed in cans, frozen and irradiated to 25–40 kGy using gamma-rays from spent fuel rods in Dugway, Utah, and Arco, Idaho, then thawed and stored at room temperature. Non-irradiated control items were processed and stored similarly, unless freezing was required to avoid spoilage. Irradiated foods were tested for sterility and the presence of bacterial exotoxins prior to human consumption. Individuals and groups served as their own controls during the series of experimental periods.

Controlled housing in a metabolic ward was provided during testing and subsequent follow-up evaluations. Particular attention was paid to clinical examinations, cardiac performance, and haematological, hepatic and renal functions.

The first study involved 18 human volunteers. Half the subjects received a diet containing irradiated foods during the initial 15-day experimental period; the remainder received non-irradiated control items. The experimental conditions for the two groups were reversed during subsequent 15-day periods, separated by 5-day washout intervals. The proportion of calories from irradiated food in the experimental diets was increased sequentially from 35%, to 60%, to 80%, and finally to essentially 100% of metabolizable energy by the end of the study (*429*). No toxic effects were observed for any experimental diet, regardless of the proportion of high-dose irradiated food. No clinical changes were detected in any individual from baseline to post-exposure evaluations, or at follow-up examinations up to one year post-exposure.

In a second study, 10 human volunteers consumed a diet in which 32% of calories were derived from irradiated canned pork treated to 30 kGy. The irradiated canned pork was stored at room temperature for one year prior to consumption; control pork was fresh and obtained locally. The irradiated diet contained no vitamin K supplementation (*310*). The study design consisted of two 15-day exposure periods in which half the subjects received irradiated pork and the other half received non-irradiated pork, separated by 5-day washout intervals; the group exposures were reversed during the second 15-day period. There were no adverse clinical effects and no prolongation of prothrombin time for any individual or group following consumption of high-dose irradiated pork.

In a third study, 13 human volunteers consumed a variety of foods irradiated to high doses and stored for three months at room temperature. These foodstuffs were evaluated for acceptability and acute toxicity (*429*). Rotating menus (three daily menus) supplied approximately 80% of calories from irradiated foods. Potatoes, flour and oranges were irradiated to low doses (0.1–1.5 kGy), while major caloric components of the diet were irradiated to high doses of 25–40 kGy. No clinical abnormalities were noted.

In this series of experiments, designed to detect toxic effects after short latency periods and after a one-year latency period, humans consuming high-dose irradiated diets for 15-day intervals showed no toxic effects either during the feeding interval or at subsequent follow-up evaluations. In many of the irradiated foods, the authors noted decreased thiamine and ascorbic acid content and detected the presence of increased "browning reaction" derivatives, fat-soluble carbonyl compounds and thiobarbituric acid reactants (presumably an index of lipid peroxide formation). Significantly, in the study involving 32% calories derived from high-dose irradiated pork stored for one year at room temperature, neither prothrombin time nor any other clinical laboratory parameters was altered. The authors concluded that in all of these studies the digestibility of macronutrients was similar in control diets and in the high-dose irradiated diets. Ideally, human safety studies require double-blind experimental designs to avoid either placebo bias or unintentional experimenter bias. Volunteer participants in these studies, however, reported in journal entries and interviews that control foods and high-dose irradiated foods could be readily distinguished by flavour, odour and texture. Earlier studies on the acceptability of irradiated foods reported that the volunteers noted differences in the colour of strawberries and powdered milk, in the odour of ground beef and in texture changes in fruits and vegetables (*308*). In addition, foods from the cereal product group (bread, crackers, macaroni, pound cake and rice) irradiated to high doses were readily distinguished from the non-irradiated items (*430*). The authors noted that in practice these foods would be irradiated to much lower doses for control of insect infestation, which would result in a minimal difference between the irradiated and non-irradiated items. Significantly, no adverse clinical experiences or reactions associated with consumption of irradiated foods were reported by volunteers. Clinicians detected no adverse findings from physical evaluations or in clinical laboratory values made either during or after these short-term exposures. These studies, however, were not designed to detect long-term nutritional deficiencies or the potential for carcinogenic effects related to the consumption of high-dose irradiated diets.

6.6 Conclusions

Sections 3–5 on chemistry, nutrition, and microbiology addressed many of the early concerns and identified critical elements necessary for good food irradiation practices. This section has presented information from several studies of irradiated foods carried out in the 1950s and 1960s, many of which were processed under conditions that would not be considered as having followed current "good irradiation practice". Nevertheless, this extensive collection of data demonstrates that irradiated foods using a variety of sources under a variety of conditions are toxicologically safe. The carcinogenicity and mutagenicity studies with irradiated food and feed have not demonstrated any treatment-related effect.

Based on the body of toxicological data reviewed here, the Study Group concluded:

- Food irradiation is toxicologically perhaps the most thoroughly investigated food processing technology.
- Animal studies are suitable models and predictions from them are supported by human studies.
- The sensitivity of the methods used to assess safety is adequate, and many studies purposely used higher doses and larger amounts of irradiated food in an attempt to elicit a positive response.
- The large number of toxicological studies, including carcinogenicity bioassays and multigeneration reproductive toxicology evaluations, did not demonstrate any short-term or long-term toxicity related to the process.
- With the exception of a few easily rationalized positive results, the highly diverse and sensitive mutagenicity studies on a variety of foods, including radiation-sterilized chicken, are overwhelmingly negative.
- Foods that are appropriately prepared, packaged and irradiated to high doses under proper conditions to sterilize them should be deemed safe.

7. Packaging considerations

7.1 Introduction

In view of the important role packaging plays in facilitating irradiation processing, in protecting irradiated food from recontamination and in maintaining the quality of the food, it is essential to consider the influence of irradiation on packaging materials. If the packaging is to be effective, then the irradiation should neither compromise the functional properties of the packaging material nor facilitate the migration of any undesirable components from the material into the food.

7.1.1 *Objectives*

The Study Group's objectives were:

- To reassess the safety of flexible packaging developed in the 1950s and 1960s (*431, 432*) and currently employed for radiation sterilization of food in the light of current knowledge.
- To reassess quality assurance methods for flexible packaging, also developed in the 1950s and 1960s, and to recommend improvements that may be needed.
- To assess the suitability of all available packaging materials for use in high-dose applications of food irradiation and, accordingly, to recommend the best candidate materials and processes for the development of future generations of packaging for radiation-sterilized food.

This section focuses on flexible packaging, manufactured from polymers, which is technologically and economically suitable for the purpose of packaging precooked foods to be radiation sterilized.

Products and processes can be assessed by two routes, good engineering practice and strict reliability practice, which are complementary rather than contradictory.

Good engineering practice. Unless proven otherwise, every component or operation is admissible when well accepted and documented practices are followed. Further, any previous data on similar products and processes are regarded as suitable and reliable unless proven otherwise.

Strict reliability practice. Every component or operation is considered apt to fail until assessed otherwise to the desired level of confidence. Further, any previous data on similar products and processes must be strictly assessed to determine their relevancy, accuracy and reliability.

Strict reliability practice is customarily followed for high-technology processes and products, where public acceptance or tolerance of failures is doubtful. Owing to the current status of public acceptance, food irradiation is one such process, and irradiated foods and associated packaging are such products.

7.1.2 *The effects of radiation on macromolecules*

In irradiating prepackaged food, which comprises different types of macromolecules, the goal is to maximize damage to the DNA of contaminating bacteria and to minimize damage to structural polymers of the packaging.

This seemingly self-contradictory goal can be accomplished if at least one of two conditions is met:

- the radiation durability of the two types of macromolecules is substantially different;
- the definition of damage threshold for the two types of macromolecules is substantially different.

The interactions of radiation with materials and the consequent chemical changes are comprehensively discussed elsewhere (*443, 444*); (see also section 3). The information given here addresses the primary processes only briefly and focuses on the final chemical effects, their manifestations and practical implications.

The interactions of ionizing radiation with matter take place via transfer of energy to the electrons in atomic or molecular orbitals, resulting in their displacement. This displacement can eventually result in bond scission, which is the main concern with respect to the damage to polymers. Since most commonly used polymers comprise primarily carbon, hydrogen, nitrogen and oxygen atoms and have molecular orbitals of similar size, their durability to radiation can be classified in a simplified way according to the nature of these orbitals. Those molecular orbitals associated with the polymer backbone play the major role in the resistance of polymers to scission. The radiation durability of these orbitals serves as a general ranking of the radiation durability of polymer families, which in decreasing order is:

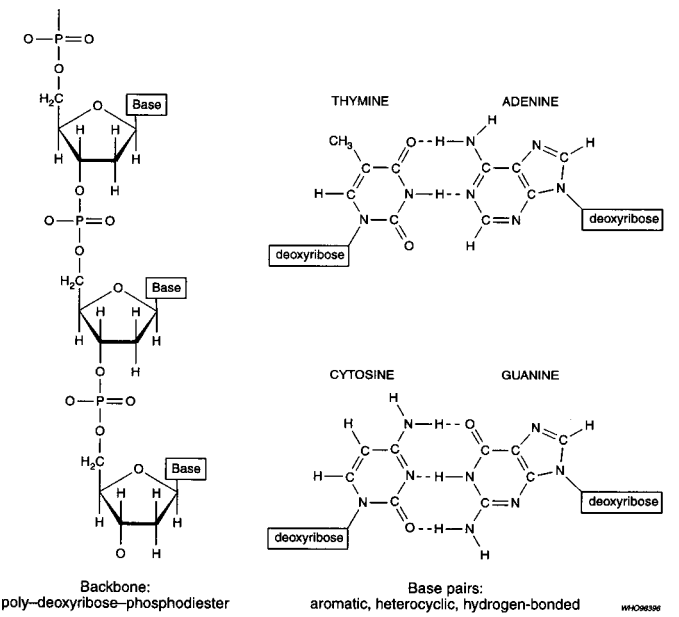
- polymers containing aromatic groups in the backbone, e.g. polyethyleneterephthalate (PET), polyimide (PI), poly[aryl-ether-ketone] (PEEK), etc.
- polymers having an aliphatic-chain backbone with aromatic side groups, e.g. polystyrene (PS), etc.
- polymers having an aliphatic-chain backbone containing ester or amide groups, e.g. polyamides, polyesters, polyurethanes, etc.
- polymers having a simple aliphatic-chain backbone, e.g. polyethylene (PE)
- polymers having an aliphatic-chain backbone with side groups containing various atoms, e.g. polyvinylchloride (PVC), polyvinylalcohol (PVA), polyvinylfluoride (PVF), but with the exception of polytetrafluoroethylene (PTFE), which is relatively sensitive to damage
- polymers having an aliphatic-chain backbone with double-bond side groups, e.g. polymethylmethacrylate (PMMA)

The damage caused by irradiation also depends on the structural robustness of the polymer. Ring structures, ladder structures, crystalline moieties and inter-chain interactions all decrease the mobility of chain segments, thus increasing the probability for recombination of scissioned chains. For packaging to be used in the radiation sterilization

of prepackaged food, the preferred polymers are those comprising groups associated with high radiation durability and characterized by strong inter-chain interactions or high crystallinity.

The primary target in the radiation sterilization of food is the DNA of foodborne bacteria. When this is damaged, the bacterium is eliminated within a few cell divisions. The molecular weight of DNA far exceeds that of all other molecules in the living cell; hence, its energy absorption is the highest. Although this unique molecule (*435*) is highly durable to gross radiation damage, owing to its aromatic groups, heterocyclic rings, hetero-atom rich backbone, and the double-helix structure bridged by a multitude of hydrogen bonds (Figure 18), certain base moieties can be affected, possibly leading to rupture of a sugar–phosphate linkage in a single strand. The radiation durability of DNA, particularly in the low-moisture environment within a spore, means that high doses of radiation are required to achieve sterilization, even after the heat pretreatment given to inactivate proteolytic enzymes. However, it is possible to attain the goal of damaging bacterial DNA without adversely affecting the food or the packaging, since there is a difference in the concept of damage threshold for the two types of macromolecules, (DNA and packaging polymers).

Figure 18
Components of the DNA molecule[a]



[a] Reproduced from Stryer (*435*) with the permission of the publisher.

Minimum damage threshold to the DNA polymer can be taken as "the number of double strand breaks sufficient to reduce the total count of living bacteria from N to $N \times 10^{-12}$ counts/g". However, in practice, only the destruction of spores of proteolytic strains of *Clostridium botulinum* in low-acid shelf-stable food is considered. Maximum damage to the packaging polymer can be taken as "the number of scissions required to change the mechanical properties by 10% and/or to reach the allowed total amount of extractives".[1]

Numerous factors that affect the radiation damage threshold of DNA, such as moisture, dose, dose rate, atmosphere, temperature and pH, also affect the radiation damage threshold of the packaging polymers. The term "damage" is used to describe both degradation of the polymer matrix and the formation of extractives, since both phenomena stem from scission of the polymeric chains and side-groups. The important factors affecting damage to packaging are:

- Total dose. The damage–dose correlation depends on the total dose and, hence, for a reliable selection of packaging polymers it is necessary to determine their actual damage–dose profile (*25, 436, 437*) in the relevant dose range. In polymers that are highly durable to radiation, only negligible changes in properties are measured. However, the accuracy and validity of these measurements are questionable. In accordance with strict reliability practice, a non-finding cannot be regarded as a positive proof unless a reasonable safety margin has been incorporated in testing to compensate for the great uncertainty in the results. The formation of extractives in irradiated polymers is more discernible and may be a better guide in assessing their radiation durability.
- Dose rate affects chemical processes taking place according to second order (and higher) kinetics, such as radical recombination. For the sake of worst-case analysis, packaging polymers should be tested to their damage threshold at a dose rate that is low enough to ensure that the damage is independent of dose rate.
- Atmosphere. Oxygen reacts readily with radicals and other radiation-produced reactive species, thus promoting radiation-generated damage. This means that oxygen must be removed from the food and headspace prior to sealing the packaging: this is usually done with a vacuum pump. Vacuum removal of oxygen assisted by flushing (e.g. with carbon dioxide) may be practised. Food packaging polymers should exhibit both low oxygen content and low permeability to oxygen.

[1] Extractives are molecules capable of diffusing within the polymer that when near or on the surface of the polymer can be transferred into a contacting substance, e.g. solvent or food.

- Thermal and mechanical history. Fabrication of polymer sheets and laminates involves extensive thermal and mechanical processing that can give rise to chemical degradation and latent stresses, affecting the radiation durability of the polymers (*436*). Recycling of materials for use in packaging should therefore receive special attention.
- Irradiation history. Pre-sterilization of food packaging by irradiation should be avoided or at least properly documented and its consequences assessed.

A check list is one of the primary tools in the reliability assessment of polymeric packaging for irradiated food. It should contain each and every factor that could cause concern at the theoretical level. Each factor should be examined singly, and the possibility of synergistic effects from several factors acting together should be investigated. An example of such data compilation is shown in Table 33.

Table 33
Model quality assurance check-list for a candidate polymer

		Data		Durability assessment	
Group	Factor	Full/part/NA	Reliability	Theoretical	Practical
Polymer	Family				
	Producer				
	Specific brand				
	Additives				
	MW distribution				
	Linearity				
	Crystallinity				
	Extractives				
History	Processing				
	Thermal				
	Mechanical				
	Irradiation				
	Recycling				
Irradiation	Dose				
	Dose rate				
	Atmosphere				
Food	Type				
	Absorption (g/g)				
	Swelling (cm/cm)				
Durability	Tear (before/after)				
	Puncture (before/after)				
	Abrasion (before/after)				

MW = molecular weight; NA = not applicable.

7.1.3 *Packaging characteristics*

- Extractives. Molecules of low molecular weight and high diffusivity that can diffuse within the packaging polymer and can be extracted from it into the food. These extractives may be residual compounds from the polymerization process, additives to the polymer or degradation products from the mechanical and thermal processing. For food packaging materials that have already been approved, only molecules either formed or released as a result of irradiation are relevant to the evaluation. The quantity of extractives can be determined by well-accepted protocols, before and after irradiation. Their toxicity is more difficult to assess.
- Packaging integrity. Particular attention should be paid to the packaging walls (e.g. for puncturing), sealing areas, and intra-laminate adhesion. Double packaging may provide extended protection of the layer in contact with the food and may also eliminate the need to use laminates. For sealing, welding appears to be much safer than glueing. The durability of seals needs to be tested with respect to the combined effect of mechanical loads, heat and radiation. Well-established food packaging materials, with documented testing and market experience (including sealing and lamination), are preferred. Some of these have already been radiation-tested for other purposes and thus only the combined effects need to be tested.
- Packaging permeability and swelling tendency. Extremely low permeability and swelling tendency of the food packaging polymers are required for their long-term reliability as oxygen and water barriers. These characteristics should be tested before and after irradiation as part of the polymer screening process.
- Packaging additives. A wide variety of proprietary additives are commonly present in polymer films and their use is not always documented. Of particular interest are aromatic antioxidants that are potentially toxic.
- The food-contacting layer. In the multilayered structures that are likely to be needed to satisfy the demands of radiation processing of prepackaged food (*438*), the layer in contact with the food should be the one most strictly tested as to the formation and migration of potentially toxic compounds.

7.2 The database

7.2.1 *Radiation durability of polymers*

A literature survey was carried out with particular emphasis on high-dose (above 10 kGy) applications relevant to the radiation sterilization of food. Unfortunately, most of the literature relates to lower doses and

to packaging polymers of relatively low radiation durability. A database on radiation durability of polymers has been compiled at the Soreq Nuclear Research Centre, Israel, for use in assessing the durability and functional reliability of polymeric materials in space applications (*439, 440*) and in the packaging of irradiated food (*441*). This database focuses on the reliable selection of highly durable polymers for use in the envelope regions of low-earth-orbit satellites, where the total radiation dose may exceed 50–100 kGy. One of the basic documents in this compilation is the Harwell database on the durability of polymers to ionizing radiation (*442*). The data it provides (Table 34) are regarded only as indicative, since variation in the initial polymer composition may give wide variation in the properties of the same nominal polymer.

For space systems, which are exposed to intense radiation, polymers highly durable to radiation are commonly used (*443–449*). Not surprisingly, most of these polymers are commercially available and some of them are extensively used for food packaging in light of their robustness and long-term reliability. Some of these polymers are listed in Table 35.

An important database on the radiation durability of polymers has been assembled over three decades by researchers at the Institut für Strahlenhygiene des Bundesgesundheitsamtes [Institute for Radiation Hygiene, Federal Office for Health (BGA)], Germany (*450–453*). A compilation of the ionizing radiation effects on some food packaging materials is presented in Table 36 (*452*).

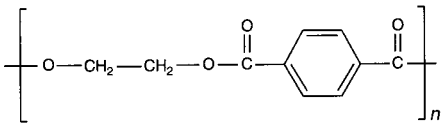
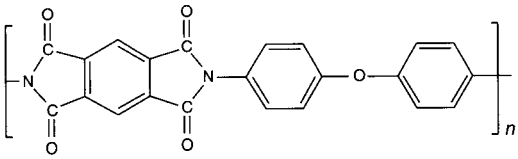
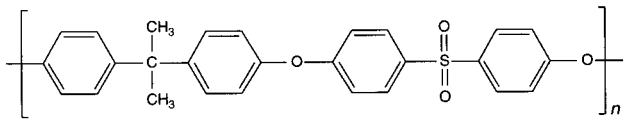
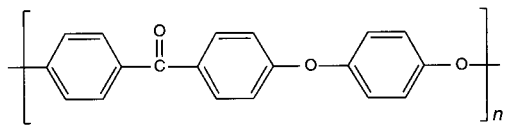
Other data relevant to the irradiation of food packaging materials are also available (*454–457*).

Finally, the data compiled by the United States Army Natick Research, Development and Engineering Center cover all the experimental work and theoretical assessment carried out by or for the United States Army for the purpose of providing reliable and safe radiation-sterilized prepackaged food. Selected documents containing these data are

Table 34
Selected data on the radiation durability of polymers

Polymer	Radiation threshold (kGy)	
	Some damage	Severe damage
Polyethylene	100	2000
Polytetrafluoroethylene	5	40
Fluorinated ethylenepropylene	50	500
Polyvinylidenedifluoride	100	1000
Polystyrene	700	$>10^4$

Table 35
Selected data on the radiation durability of polymers for space applications

Polymer	Radiation threshold (kGy)	
	Some damage	Severe damage
Polyethyleneterephthalate 	$1\text{-}3 \times 10^3$	1×10^5
Polyimide (aromatic) 	$>2 \times 10^3$	$4 \times 10^4\text{-}3 \times 10^5$
Polysulfone 	6×10^3	$>10^4$
Poly[aryl-ether-ketone] 	$>1 \times 10^5$	$>10^5$
Epoxy resins (aromatic)	3×10^5	–
Polyurethane (aromatic)	–	5×10^4
Silicone resins	3×10^5	–

Source of data: Bouquet (*443*), DuPont (*444*), Bouquet et al. (*445*), Meyer et al. (*446*), Bouquet et al. (*447*), Coulter et al. (*448*), Funk & Sykes (*449*).

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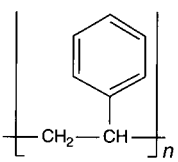
Table 36
Selected data on the radiation durability of food packaging

Polymer	Radiation effects
Low-density polyethylene; medium-density polyethylene; high-density polyethylene	Antioxidants are mandatory for conservation of mechanical properties upon irradiation (10–25 kGy)
	Antioxidants are extracted from these polymers
	The amount of volatile products formed depends on the formulation and processing history of the sample
	More than 100 volatile compounds have been identified, including small amounts of benzene and its derivatives
	Radiation dose for 50% decrease in elongation at break (for high-density polyethylene): 6 kGy without stabilizer, up to 36 kGy with stabilizer
Polypropylene	75% decrease in elongation at break at 10 kGy (irradiated in oxygen)
	Antioxidants are mandatory for conservation of mechanical properties upon irradiation
Polyamide-6	50% increase in acetic-acid extractives at 60 kGy (irradiated in oxygen). Extractives include monomer and oligomers
Polyethyleneterephthalate	Negligible, insignificant or unmeasurable changes in all parameters, including all extractives and permeability, at dose $\geqslant$56 kGy
	Extractives are 30 times lower than with polyamide-6
Polystyrene 	Negligible, insignificant or unmeasurable changes in all parameters, including polar extractives, at dose $\geqslant$56 kGy
	Non-polar extractives (*n*-heptane) increase by 7–18 times.
	Extractives include monomer and oligomers
	No substantial differences in tensile, burst and seal strength are observed at dose $\geqslant$60 kGy
	No significant changes in quantity and composition of extractives are observed at dose $\geqslant$60 kGy
	Polyamide showed marked reduction in tear resistance
Antioxidants (phenol and organo-tin compounds)	Commercially added to polymers with aliphatic backbone[b] to increase ageing resistance
	All additives migrate, and are mostly toxic
	Extractives may be affected by radiation, depending on polymer, radiation mode and extraction liquid

Source of data: Bögl et al. (*450-453*) with the permission of the publisher.
[a] Comprising high-density polyethylene, polyamide-6, polyethyleneterephthalate.
[b] Polyethylene, polypropylene, polyvinylchloride, polystyrene.

WORLD HEALTH ORGANIZATION
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No. 890

HIGH-DOSE IRRADIATION: WHOLESOMENESS OF FOOD IRRADIATED WITH DOSES ABOVE 10 kGy

Report of a Joint FAO/IAEA/WHO Study Group

CORRIGENDUM

Page 136, Table 36, in left-hand column, under chemical structure for polystyrene, and opposite
"No substantial differences in tensile, burst and seal strength are observed at dose ≥60 kGy"

Insert Laminated materials[a]

available (*437, 458–460*). Of special interest is the reasoning used in the development and fabrication of the flexible pouches as described by Pyne et al. (*458*). The food contactant material was primarily selected on the basis of maximal lamination durability of available polymers using available lamination techniques, rather than on maximal radiation durability.

7.2.2 *Extractives*

Only a few articles in the literature address in any substantial way the radiolytic formation of extractives (*461–463*). The data pertain primarily to polymers used in the 1950s–1970s, and to a lesser extent to new polymers that are candidates for the next generation of food packaging (Table 37). The two primary sources of extractives are: trunk polymer fractions and their radiation-generated fragments, which are documented in the literature; and additives and their radiation-generated fragments, which are seldom reported or specified and which remain to be tracked in the course of the quality assurance process.

The literature on materials for space applications provides a useful source of data on extractives in radiation-stable polymers. The primary goals for these materials are high durability, high reliability, insignificant changes of performance upon irradiation, and extreme cleanliness as expressed in terms of outgassing levels (American Society for Testing Materials, standard ASTM E-595). Not surprisingly, many high-quality polymer films manufactured nowadays meet these strict specifications, including films made from polyvinylfluoride (PVF), polyvinylidene-difluoride (PVDF), polyethyleneterephthalate (PET), aromatic polyimide and others. It is noteworthy that the utmost cleanliness of these polymer films does not stem from customers' needs but rather from manufacturing requirements aiming for flawless extrusion into films.

The selection of polymers suitable for the packaging of radiation-sterilized precooked food depends ultimately on minimizing extractives, natural and radiolytically-formed alike. Furthermore, proof derived from analytical and/or animal feeding studies that such extractives are non-toxic is essential and is valid only for the polymers *per se*. If polymers containing additives are considered, their selection should be made only after judiciously taking into account the extractives resulting from the irradiation of the entire system of polymer/additives/food. However, additive-free polymers are preferred.

From the analytical standpoint, the sensitivity of detection has dramatically increased over the past four decades, so that particular attention should be given to newly reported levels of extractives from food packaging. Fortunately, these data are being routinely accumulated by

Table 37
Selected data on extractives in food packaging candidate polymers[a]

Polymer	Extractives	
	Pristine	Radiation induced
Low-, medium- and high-density polyethylene	Antioxidants and other additives	Degraded antioxidants and other additives
		Polyethylene oligomers (small quantities) and their oxygenated derivatives
		100 volatile compounds, including alkanes, alcohols, aldehydes, ketones and acids
Polyamide	Unreacted monomer	Slight increase in extractives as compared to the control
Polyethyleneterephthalate	No detectable extractives	No detectable extractives
		Some inorganic gases, e.g. carbon dioxide
Polystyrene	Polystyrene oligomers (small quantities)	Polystyrene oligomers (small quantities)
Polyimide	* TML < 1% CVCM < 0.1%	* TML < 1% CVCM < 0.1%
Polysulfone	* TML < 1% CVCM < 0.1%	* TML < 1% CVCM < 0.1%
Silicon resins (RTV, spacegrade)	* TML < 1% CVCM < 0.1%	* TML < 1% CVCM < 0.1%

CVCM, condensable volatile cumulative mass on a counter-plate at 25 °C (American Society of Testing for Materials); TML, total mass loss at 125 °C 10^{-6} torr; RTV, room temperature vulcanized rubber.
Source of data: Rojas de Gante & Pascat (*461*), Tripp (*462*) and Killoran (*463*).
[a] Items marked with an asterisk are space-qualification data.

the leading manufacturers of food packaging, as part of their standard quality assurance practices. Extrapolation of their extractives-testing routines to irradiated packaging products seems customary. Further extrapolation may be needed for testing the final packaging products, in particular laminates and pouches, rather than raw films.

From the regulatory standpoint, levels of extractives in food that were tolerated in the 1960s and 1970s may no longer be considered safe. However, the natural levels of potentially toxic materials in commonplace foods can be considered safe, and standards for food packaging safety must be adjusted accordingly. The growing development of new generations of food packaging materials takes these new trends in safety assessment into account.

Animal feeding experiments (*460*) were used to confirm the safety of packaging for radiation-sterilized foods. An extensive and comprehen-

sive study on irradiated chicken (*9*) demonstrated that the consumption of the high-dose, radiation-sterilized food, as a reasonable proportion of the diet, does not pose any health risks. The many subsequent years of hazard-free consumption by human customers have given further support to the safety of this line of products.

An interesting issue arises relating to the trays made of polystyrene (PS) foam (styrofoam) commonly used for prepackaged foods. PS has an aliphatic backbone that is stabilized by the aromatic side groups. It is much more durable to radiation than the widely used PE, but somewhat less durable than PET. It has been tested for radiation-sterilized food packaging at doses up to 56 kGy, but with no safety margin, and small amounts of extractives have been detected (however, doses up to 600 kGy have been applied in tests on its reliability for use in calorimeters for dosimetry). Accordingly, PS is most probably safe for use up to 56 kGy, but a damage–dose profile for PS in the dose range above 60 kGy should be determined.

From a mechanical standpoint, PS trays function faultlessly following food irradiation. One way to circumvent the issue of potential extractives is to laminate styrofoam trays with PET. However, the already available lightweight PET trays would be a more affordable solution for applications involving radiation sterilization of foods in trays.

7.2.3 *Radiation-effected permeability*

There is a considerable body of literature relating to radiation-induced modification of polymer permeability, either through graft-copolymerization or neutron beam-produced tracks. It is recognized that radiation can affect the oxygen permeability of food packaging polymers (*452*). In the case of low-density PE, the oxygen permeability may significantly increase upon irradiation to 25 kGy, in contrast to high-density HDPE or PET in which there is no appreciable increase. However, in practice, the packaging for radiation-sterilized food typically contains a barrier middle layer made of aluminium film. Consequently, the gas permeabilities of the bare polymer films are of minor importance.

Of greater importance is the permeability of the food-contacting layer to migrants that might possibly be extracted into the food. Possible radiation-effected permeabilization of this layer, typically ignored in the literature, needs to be considered. A significant radiation-generated mechanical degradation will most probably precede changes in free volume and in associated permeability. Hence, polymers whose permeability is increased by radiation will be rejected on grounds of mechanical failure. If the selected packaging polymer is free of extractives, either pristine or radiation-generated, the permeabilization

problem is no longer a cause for concern. However, if a compromise is made and the selected polymer is a possible source of extractives, the radiation-effected permeabilization factor may need to be addressed experimentally.

7.2.4 *Food interactions with packaging*

Data are available on food interactions with packaging in the general food packaging literature, but there are few specific studies related to radiation-sterilized foods. Taint-transfer – the transfer of odours from packaging into the food – is an important issue (*464*). The olfactory sense is extremely sensitive in humans and may detect traces of volatile migrants that are at levels lower than all relevant safety thresholds and that might be undetectable by most instruments. These odours compromise the quality of the food, which could present a serious commercial problem and undermine acceptance of irradiated foods by the general public. The taint-transfer of selected polymers is summarized in Table 38. Since the radiation doses in all cases were lower than 4 kGy, the results are only indicative.

7.2.5 *Specific packaging for irradiated food*

The vast majority of the available data relate to packaging materials and methodologies for radiation-sterilized prepackaged foods that were developed by or for Natick in the last four decades. A reasonable proportion has been published or appears in petitions to the FDA. Unpublished material in this comprehensive database, some of which is discussed elsewhere in this section, can be accessed on request.

7.3 Industrial packaging for irradiated food

7.3.1 *Polymers commonly employed*

Most of the polymers covered in the database are commonly employed for various types of food packaging. There has been, however, a distinct shift away from the packaging materials used 20–40 years ago, when

Table 38
Data on the taint-transfer of selected polymers (dose < 4 kGy)

Polymer	Taint-transfer observation
Low-, medium- and high-density polyethylene	No evidence for taint-transfer was found
Polyamide	None
Polyethyleneterephthalate	Some indication of taint-transfer
Polystyrene	Evidence for taint-transfer

most of the relevant research activities took place and the data were compiled. There are two primary reasons for this shift: the availability of a large variety of new polymers and polymer-grades with improved performance of strength, barrier properties and ageing durability; and the increasingly strict demands imposed by customers, and consequently by manufacturers, regarding quality and preservation of packaged food. These demands have fuelled the on-going search for improved packaging materials.

Most materials used for food packaging in the 1950s and 1960s were paper products, cellulose derivatives (cellophane), rubber derivatives, polyethylene, polypropylene and polyvinylchloride. Various types of waxes, rubber products and vinylidene chloride copolymers were used as coating materials to enhance barrier properties. Polyamide films have been used as a barrier constituent of laminates to reduce their permeability. Aluminium foils have also been introduced into food packaging to impart impermeability.

In the course of time, the well-known polymer PET began to be produced in a wide variety of grades that enable facile extrusion, blow-extrusion and heat-sealing. This polymer exhibits excellent mechanical, barrier and durability properties. Furthermore, it has been successfully manufactured to a very high purity and has been found to be practically free of extractives. Demand for PET and its laminates has therefore grown extensively over the last 20 years. The subsequent increase in production capacity has resulted in scaling up the processes and, consequently, a dramatic reduction in product costs and prices. This has further increased its use in food packaging, especially for bottled carbonated drinks; the robustness of PET in withstanding high pressure, rough handling and extraction in aggressive solvents is exemplified by the huge numbers of bottles of such drinks sold daily.

Another newly introduced highly durable, well-known polymer is the aromatic polyimide, which is also produced in a wide variety of grades. Although it is rarely employed for food packaging in view of its relatively high price, it is widely used in the electronics industry because of its electrical properties and its durability to a wide variety of hazards. A variety of polyimide grades has been made available to this industry to satisfy diverse needs: rigid and flexible printed circuit boards, single- and multi-layer printed circuit boards, etc. The space industry also makes extensive use of polyimide in many applications, including as external thermal blankets. In this application, the polyimide films are expected to function reliably, despite high mechanical loads and extensive exposure to photons in the far ultra-violet range and to high doses of ionizing

radiation. The space industry has established the radiation durability of both aromatic polyimide and PET to doses higher than 1000 kGy.

Laminated polymeric packaging materials are widely employed for many foods, e.g. snacks, fish-products, juices, etc., in order to satisfy the combined needs of high mechanical durability and impermeability. Various lamination technologies are in common use, with or without the use of adhesives. Corona pretreatment of the surface (an electric discharge technique that generates plasma, resulting in slight surface oxidation and chain scission) is commonly used to improve printing as well as lamination quality.

Polymer films currently manufactured for high-technology industries meet strict specifications of purity, durability and reliability. The utmost cleanliness of the resin necessary for the extrusion of high-quality films assures migrant-free polymers. Such polymers are crucial not only for space applications, but also for advanced electronics, micro-optics and integrated electro-optical systems. In these systems, any extractives, either "native" or generated by degradation (e.g. laser-generated degradation), are detrimental and could compromise the operation of most devices.

7.3.2 *Polymers highly durable to radiation*

Polymers with high durability to radiation are commonly used in the nuclear and irradiation industries, as well as in space industry systems, including satellites and space vehicles. All these environments are characterized by very high fluxes of ionizing radiation. The total doses accumulated by materials in these environments may exceed MGy and GGy levels in relatively short periods of service time.

In all these environments, polymeric materials are used satisfactorily. Their use in space is steadily increasing, replacing the use of metals and ceramics, because of the severe weight restrictions. The need to reduce weight drives the development of new lightweight, polymer-rich systems and has necessitated the identification of existing polymers that are highly durable to radiation.

Following almost four decades of space research, sufficient knowledge and experience have been gained to direct engineers in their selection of polymers for space applications. The most commonly used highly radiation-durable polymers in space applications are listed in Table 35. Among these, the most adequate for food packaging are the first two, PET and aromatic polyimide, which are widely used and commercially available in the form of films.

7.3.3 *High-barrier packaging polymers and laminates*

The chemical features of high-barrier polymers can in general be characterized as highly aromatic, highly polar, highly linear, and of high molecular weight. The combination of polar and non-polar (hydrophobic) interactions imparts to the polymers not only radiation tolerance but also strong inter-chain interactions that are associated with low permeability.

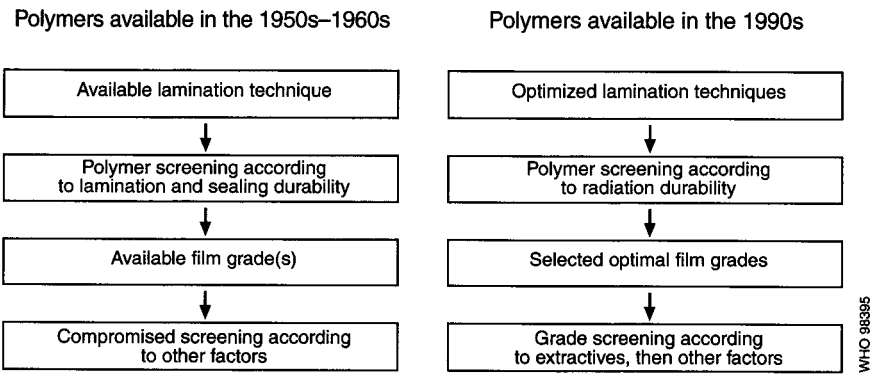
Many foods, like cooked meat, comprise both aqueous (hydrophilic) and fatty (hydrophobic) ingredients, as well as some oleophilic (emulsifying) ingredients. This "cocktail" acts as a swelling agent for polymers; therefore polymers used in packaging must be resistant to it over the desired storage time and temperature range. For military use, and uses of similar complexity, it is difficult to impose limitations on storage duration and temperature. Therefore, packaging barrier material that is most resistant to swelling should be used. Aluminium foil is commonly used for this purpose, typically as a middle layer in a three-layer laminate. Once a puncture-free aluminium foil is laminated into the packaging, the long-term barrier requirements are met. Such laminate technology has been validated over several decades, and is widely utilized for common food products. It has already been successfully used for the packaging of radiation-sterilized prepackaged food, and its use is likely to continue.

Newly developed alternatives to the traditional barrier packaging that offer even more advantages are currently under evaluation for performance, durability under service conditions, and long-term functional reliability (*465*). These include:

- metal-free barrier laminates, having extremely low oxygen and water permeation, made with a glass-like barrier layer produced by plasma-enhanced chemical vapour deposition in the laminate;
- packaging materials containing an oxygen scavenger in the polymeric films, which can react with residual oxygen in the packaging and thus eliminate oxidation-induced food spoilage;
- packaging materials containing antibiotics in the polymeric films, which can prevent or retard growth of residual bacteria and fungi in the food.

The selection of polymers for laminated packaging currently used for radiation-sterilized food was based primarily on long-term stability of the lamination and sealing (*458, 460*), polyethylene being the only choice. While this selection was justified at the time new concerns about dose-safety margin and testing of extractives emerged, leading to further research efforts. Nowadays, numerous flexible and heat-sealable grades of radiation-durable polymers are commercially available to the food,

Figure 19
Comparison of polymer selection in the 1950s–1960s and the 1990s

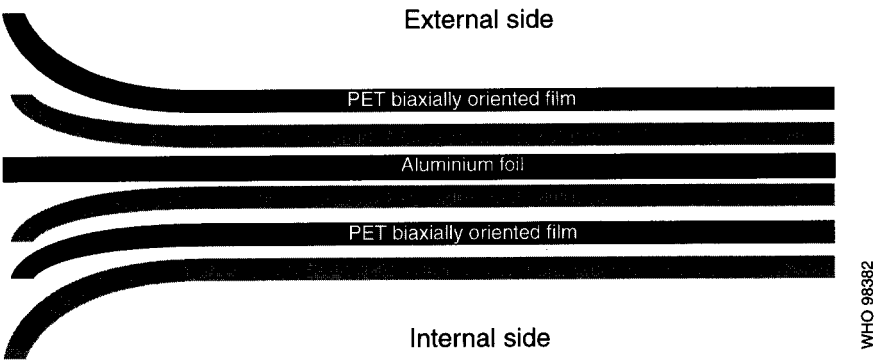


electronic and space industries, so that polymer properties can be selected according to particular needs. This tailoring and optimization can be achieved without compromising either the polymer constitution or consequent radiation durability. Conditions are now such that it should be possible to produce an unquestionably safe and highly durable packaging laminate for high-dose radiation-sterilized prepackaged foods (Figure 19).

7.3.4 *Current practice in high-reliability food packaging*

- The commonly used heat-sealable PET is an amorphous PET copolymer (melting point as low as 80 °C); the PET grade used for bottling soft drinks is partly crystalline, and those used for high-strength films and fabrics are highly crystalline.
- All grades of PET films have been given full approval for use with all types of food by regulatory agencies in many countries.
- Aluminium foils with certified low oil content are available for laminates.
- PET laminations using biaxially oriented films require the use of adhesives. Epoxy adhesives, which are radiation-durable, are rarely used for regular food-packaging laminates owing to their price.
- Heat-sealable PET is adequate for either welding or extrusion lamination, in which molten polymer is applied in the form of a thin film between the layers to be laminated.
- The quality of the raw films is tested by their manufacturers who are required to provide a certificate of compliance certifying their adequacy as a food-grade material.
- Based on these facts, a suggested organization of the laminate for prepackaging foods to be irradiated is shown in Figure 20.

Figure 20
Organization of a laminate for prepackaging food to be irradiated



PET - polyethyleneterephthalate

7.3.5 *Packaging for radiation-sterilized precooked food*

The current practice in packaging for radiation-sterilized precooked foods relates to materials and methodologies that were developed and tested by or for Natick over the last four decades. These foods have been produced for consumption by special groups in the United States and South Africa. The accumulated experience of use, especially by NASA astronauts and their Russian counterparts in joint space flights, is considerable (see Annex 1).

New developments in packaging for radiation-sterilized foods are in progress with the aim of diversifying military ration components and further improving their sensory attributes and overall reliability. These developments include the assessment of improved barrier layers, improved food preparation and packaging technologies, and enhanced quality assurance methodologies. Future packaging trends under assessment include a single-layer food pouch of highly radiation-durable polymers, either in a barrier laminate or used alone. The assessment will be based in part on the physicochemical responses and in part on the analysis of extractives, rather than on mechanical changes. It will include determining damage–dose profiles for many representative polymers as candidates for radiation-processed food packaging.

A commercial company in South Africa (BIOGAM) uses a packaging technology similar to that developed by Natick. Radiation-sterilized foods have been produced for several years and are intended for consumption by South African military personnel as well as by hikers, backpackers and yachtsmen (see Annex 1). The data on the currently

used packaging materials for radiation-sterilized foods in South Africa is proprietary, but can be accessed on request.[1]

7.3.6 *Polymer packaging quality assurance*

Plastics used to be regarded as a cheap alternative to, or imitation of, an expensive high-quality material such as metal, wood or glass; they represented a compromise on quality in order to gain a price reduction. Only in recent decades have the concepts of quality management and quality production pervaded all industries, including the plastics industry. Nowadays, high-quality resins with accurately specified formulation, properties and history are available from leading companies and dealers. Similarly, high-quality films, laminates and pouches made from them are available from leading producers and used by leading food manufacturers.

However, materials of inferior quality might still be encountered that could compromise the quality of radiation-sterilized prepackaged food. The selection of the appropriate polymer must be therefore accompanied by a complete quality assurance procedure that includes the following steps:

- Identification of the polymer.
- Determination of its desired nominal properties and the limits of allowed deviation.
- Quality inspection of the resin manufacturing process and the product testing process.
- Quality inspection of both manufacturing and testing processes for polymer films and laminates, and for the trays, lids and pouches made from these.
- Quality inspection of the food packaging process and the product testing process.
- Quality inspection of the radiation-sterilization process and the product testing process.

All these steps may be excessive for good engineering practice, but are necessary for strict reliability practice.

7.4 Regulatory aspects

Regulations relating to food irradiation and packaging for irradiated foods encompass the following:

- National regulations that permit radiation treatment of specific foods or food products for public consumption.

[1] Ms Ingrid de Bruyn, Atomic Energy Corporation of South Africa, P.O. Box 582, Pretoria 001, South Africa.

- National regulations that permit the use of specific packaging materials for radiation-treated prepackaged food for public consumption.
- Good manufacturing practice methodologies for food production, irradiation, storage and testing.
- Labelling in conformity with the regulations, including the irradiation logo and an appropriate statement.

These legislative aspects are just part of the quality assurance system necessitated by a high-technology product.

A comprehensive, updated database including information on regulatory status is maintained by the Secretariat of the International Consultative Group on Food Irradiation. A listing of national approvals for packaging materials is given in Table 39 (*466*).

The assessment of the currently used packaging for radiation-sterilized food as safe has been validated by extensive animal feeding studies and several decades of human consumption. However, the safety testing of new discrete packaging materials for irradiated foods could be refined. A comprehensive analysis of volatiles and other extractables would be appropriate and practical (*461–463*). Laboratories are now equipped with highly improved analytical methods as compared to the 1950s and 1960s, and extensive databases on the toxicity of molecules are available.

7.5 Safety, reliability and suitability assessment

The process of assessing and validating candidate polymeric packaging materials for radiation-sterilized food comprises two steps:

- Theoretical assessment of the suitability of candidate polymers or laminates for the specific application. The durability, safety and reliability of each candidate material are assessed, and safety margins for the applicable radiation dose are set. Applicable definitions of damage thresholds are also established. Data from manufacturer's data sheet for the candidate materials are compared with the stated requirements. Candidate materials considered suitable for the intended application are then recommended for experimental validation and acceptance tests.
- Experimental validation and acceptance tests are carried out on representative lots of specific materials following common statistical sampling and data analysis techniques:

  Data-based assessment. This method is comprehensive, accurate and reliable for data related to materials that have already been field-tested. These data may also contain some history of product use, history of storage, and a list of products and packaging solutions. Since

Table 39
Packaging materials authorized for use for radiation-treated prepackaged food[a]

No.	Packaging material	Max. dose (kGy)	Country[b]	Date[b]
1	Cardboard	10; 35	UK; Poland	1991[c]
2	Polyethylene coextruded polyvinylacetate	30	USA; Canada	1988
3	Polyethylene-co-vinylacetate	30	USA	1989
4	Fibreboard	10	India	1997
5	Fibreboard, wax coated (boxes)	10	USA; Canada	1989
6	Glassine paper	10	USA	1975
7	Glass	10	India	1997
8	Hessian sacks	10	UK	1991[c]
9	Kraft paper	0.5	USA	1975
10	Nitrocellulose-coated cellophane	10	USA; India	1975
11	Nylon 11	10	USA; India	1975
12	Nylon 6	60; 10	USA; India	1975
13	Paper	10; 35	UK; Poland	1991[c]
14	Paper coated or laminated with wax or polyethylene	10; 35	India; Poland	1990
15	Paper laminated with aluminium foil	35	Poland	1990
16	Polyamide film or polyamide coextruded with polyethylene	35	Poland	1990
17	Polyester-metallized-polyethylene laminate	35	Poland	1990
18	Polyester-polyethylene laminate	35	Poland	1990
19	Polyethylene film (various densities)	60; 35; 10	USA; Poland; India	1975
20	Polyethylene-paper-aluminium laminate	35	Poland	1990
21	Polyethylene-terephthalate	60	USA	1975
22	Polyolefin (low-density as middle or sealant layer)		Canada	1989
23	Polyolefin (high-density as external layer)		Canada	1989
24	Polyolefin film	10	USA	1975
25	Polypropylene sacks	10; 35	UK; Poland	1990[c]
26	Polypropylene – metallized	35	Poland	1990
27	Polystyrene film	10	USA; India	1975
28	Polystyrene foam trays (Styron 685 D)	10	Canada; India	1989
29	Rubber hydrochloride film	10	USA; India	1975
30	Steel, tin plated or enamel lined	10	India	1997
31	Vegetable parchment	60; 10	USA; India	1975
32	Vinylchloride-co-vinylacetate film	60; 10	USA; India	1975
33	Vinylidenechloride-coated cellophane	10	USA	1975
34	Vinylchloride-co-vinylidenechloride film	10	USA; India	1975
35	Wood	35; 10	Poland; India	1990
36	Viscosa	35	Poland	1990

[a] Adapted from reference *466* with permission. Updated by the Secretariat of the International Consultative Group on Food Irradiation, September 1997.
[b] Approvals: USA – 1975; Canada – 1989; Poland – 35 kGy, 1986; United Kingdom – 1991; India – 10 kGy, 1996; earliest date of approval is cited.
[c] For dry herbs.

currently produced raw materials, although compatible with those used in the past, may differ from the original, new acceptance tests would be mandatory if production is reinstated. While this conservative methodology is best for addressing conservative tasks, it is of limited value when the task at hand involves extrapolating to higher

radiation doses, longer storage durations, and stricter damage and safety thresholds.

Extrapolation-based assessment. Radiation sterilization of prepackaged, precooked food is currently restricted to specific consumers, i.e. patients in hospitals that need sterile food, personnel on military or space missions, and individuals engaged in certain outdoor activities. Approval for general public consumption necessitates establishing that the safety of prepackaged foods radiation-sterilized at doses exceeding 10 kGy is not compromised by the packaging. This process again involves a theoretical assessment and an experimental validation.

The theoretical assessment can be an extrapolation (or interpolation) from data that already support the safety assessment. This is indeed the case regarding the radiation stable packaging polymers, as shown throughout this section.

The experimental validation could be relatively straightforward for newer materials. Fully approved and comprehensively tested food-grade, heat-sealable, commercially available polymers like PET (and perhaps polyimide) could be easily adopted. Extrapolation of their approval is straightforward, and requires irradiation followed by post-irradiation testing for certain mechanical properties and extractives.

Since safety has been demonstrated for foods packed in a trilaminate pouch with a low-density PE food-contacting layer, irradiated to doses as high as 105 kGy, products irradiated between 10 kGy and doses consistent with microbial safety and sensory acceptance would be correspondingly safe. If the damage–dose relation of this food-contactant layer is sufficiently linear over an extremely wide dose range (10 times the intended dose), then a judicious extrapolation is justified for a special application requiring a dose higher than tested before.

Many food products are regularly packaged in laminate pouches, made primarily with high-durability polymers, including PET. Some producers of laminate food packaging have extensive experience, well-established quality assurance procedures, and excellent records of regulatory approval of food-grade laminate products. Their procedures can be adapted to ensure retention of the lamination between the PET (or polyimide) layers and the aluminium inner-layer following high-dose irradiation.

7.6 Conclusions

Food packaging technology has made dramatic advances over the last 30 years in all the scientific and technological fields relevant to reliable and safe packaging for prepackaged precooked irradiated foods. The most important advances relate to:

- characterization of physical properties required to protect specific foods
- design of materials and packaging structure to meet specific requirements
- polymeric materials grades, barrier properties and cleanliness
- radiation durability of new polymers, exceeding 10^5 kGy for many of them
- analytical methods for testing of polymer properties and cleanliness
- safety and reliability assessment methodologies

On the basis of existing data and the insights gained from the above advances, the Study Group concluded that:

- The currently used trilaminate pouch developed by Natick with polyethylene as the food-contacting layer (which is approved) is of proven safety, based on experience and long-term wholesomeness testing.
- The concept of double packaging, which provides a single approved layer in contact with the food, overwrapped with a laminated package with the requisite physical properties, should be exploited.
- The concept of chemiclearance should be applied to packaging, since the relationship between polymer structure and resistance to radiation damage (including extractable products) can be established.
- Approving a particular packaging material for use in a radiation sterilization procedure arrived at on the basis of extrapolation above the currently used dose is also possible. It can be done straightforwardly by referencing an established damage–dose response relationship and extrapolating the packaging durability assessment to the projected higher dose. If the extrapolated assessment indicates no compromise in safety or functionality, then the procedure can be considered acceptable.

8. Processing considerations

Processing food by irradiating to high doses is essentially identical to radiation processing of food to any dose up to the currently accepted limit of 10 kGy. However, the accepted and generalized concept of the hazard analysis critical control point (HACCP) system is that the potential hazards associated with a particular technology together with available critical control points should be reconsidered when modifying that technology – even for seemingly minor alterations. Modifications may include a change in established and accepted dose limits and the introduction of new process procedures or applications. The use of high radiation doses to process precooked and prepackaged high-moisture

foods represents a change in the objective as well as in the details of the process. The relevant process parameters include extended residence times of a frozen product in an irradiation facility and higher dose rates in order to reduce treatment times. As a consequence of changing such primary parameters, several other parameters are changed or adapted and need special consideration. Likewise, product handling may be affected by requirements for low temperatures (during pretreatment storage and radiation processing) and for durable barrier packaging. Accordingly, the Study Group reviewed irradiation and HACCP issues relevant to the radiation processing of foods in the dose range above 10 kGy.

8.1 Radiation sources

It is generally accepted and has been adopted as a Codex Alimentarius General Standard (*2*) that only the following radiation sources are suitable for radiation processing of food:

- radioisotope sources: cobalt-60 or caesium-137
- machine sources: electrons up to 10 MeV and X-rays from electrons up to 5 MeV.

The radiation processing industry, which applies this technology for medical sterilization, for paint and ink curing, and for initiating polymerization, has an exceptionally high record of occupational safety. This is due, among other reasons, to the fact that well-trained personnel operate the facilities, that the nature of the irradiated products requires a high level of quality assurance, that irradiation facilities have inherent safety features, and finally that standards and supervision by responsible authorities enforce adherence to good manufacturing procedures.

The radioisotope cobalt-60 is produced intentionally from metallic cobalt-59 which, when inserted into specifically designed nuclear power reactors, absorbs neutrons. The activated metal does not need any waste refinement treatment, and is doubly-encapsulated as rods or discs in stainless steel casings before being released to irradiation facilities. Even for very high specific activities, the unavoidable self-heating could not liquefy the solid metal. Cobalt-60 rods of very high specific activity can be configured in appropriate source frames for use in high-dose and high-dose-rate processing. The technology of cobalt-60 production, handling and use is well established worldwide.

The radioisotope caesium-137 is obtained from spent nuclear fuel elements, but is not readily available in the quantities that would be needed for commercial exploitation.

The quantum energies of the gamma-rays emitted from both of these acceptable radioactive sources, 0.66 MeV for caesium-137 and 1.13 and

1.33 MeV for cobalt-60, are well below the thresholds for photonuclear activation of any chemical element. Consequently, even at the highest imaginable doses, no radioactivity can be induced in the exposed food by these sources.

As indicated above, electrons from machine sources are limited in energy to 10 MeV, and primary electrons for producing X-rays are limited in energy to 5 MeV. For the production of X-rays, converters are used that consist of a material of high atomic number for better efficiency in energy conversion and that have good physical properties such as a high melting point; tantalum and tungsten are the most frequently used materials. Such materials, appropriately cooled, can withstand the high electron beam power needed for X-ray applications.

The possibility that radioactivity might be induced in food processed by electrons or X-rays needs to be considered (*1*). The most important physical processes to be taken into account are: the excitation of isomeric states in nuclei by high energy photons; photonuclear reactions; and the capture of neutrons produced in photonuclear reactions (principally from deuterium). With respect to induced activity, estimates show that only irradiation by X-rays is of concern, since the activity produced by 10-MeV electron irradiation is significantly lower than that produced by 5-MeV X-ray irradiation for equal absorbed doses. In the latter case, neutrons are produced in the food by photonuclear reactions. After "thermalization", they are captured by certain elements in food yielding extremely small amounts of short-lived radionuclides. Since the energy of the X-rays is limited to 5 MeV, which is below the thresholds of photonuclear reactions in heavy metals such as tungsten and tantalum, no neutrons are emitted from the converter target.

The significance of induced activity in food resulting from high-dose irradiation can be assessed by comparing it to the concentration of naturally occurring radionuclides in the food (the most prevalent of which is potassium-40) and the internal body doses resulting from ingestion. Very conservative calculations show that the consumption of food irradiated to doses up to 100 kGy results in doses to the consumer that are at least a factor of 1000 below those from natural activity inherent in the human body, in food, and in the environment. The radiological impact of consumption of food irradiated to high doses would therefore be insignificant.

8.2 Dosimetry

Radiation dosimetry is a well-established technology that can be used over a wide dose range and in any anticipated application. Available ASTM standards, national regulations and certification laboratories

bear witness to the applicability of this standardized measuring technology (*467, 468*). It is based on distinct scientific principles described in several textbooks and monographs that are widely available (*469–471*).

The principles of dosimetry in general and of its application to food irradiation in particular are well established (*472–478*). There are four levels of dosimetry: absolute; reference; routine; and indicator. *Absolute* dosimetry systems are usually operated by metrological institutions and serve the purpose of certifying the physical quantity "absorbed energy dose" and its unit the gray (Gy) with very high accuracy and precision; such efforts are usually coordinated on an international level. The inconvenience of carrying out the required procedures limits their application in industrial radiation processing. Consequently, *reference* dosimetry systems are used and are calibrated against some absolute standard and then linked to the *routine* dosimetry system used in process control. In this way, dose measurements are traceable to national and international standards. Recently, label dosimeters have become available. Such systems change colour or exhibit changes in other easy-to-recognize features after reaching a certain dose level; they are useful in routine dosimetry. *Indicators* must not be confused with label dosimeters; what they have in common is that both are attached to the surface of the products. Indicators cannot "indicate" a dose value; their usefulness is in indicating that the products emerging from the irradiation have been treated.

The challenge of dosimetry for food irradiation is the wide dynamic dose range associated with diverse applications, the dose ranging from a minimum of 10 Gy to more than 50 kGy and the applications ranging from sprout inhibition to insect disinfestation, food sterilization and product modification.

A range of four orders of magnitude is often not a problem for many metrological technologies; however, most established dosimeters are specific to a particular, narrower dose range. This limitation is especially true for dosimeters suitable for routine applications in food irradiation. Consequently, in order for an irradiation facility to provide services for the entire dose range, several dosimeter systems covering overlapping dose ranges must be used. Commercial contractors already provide such services covering any dose range, and they have at hand several dosimetry systems to prove that the dose received complies with customer or regulatory requirements.

Most dosimetry systems, especially routine dosimeters, are sensitive to dose rate, in particular to the dose rates of 10^6–10^8 Gy/s that are associated with electron beam processing facilities. In this connection, it

must be recognized that several radiation effects are also dose-rate dependent, such as the loss of certain micronutrients, so dosimeters suitable for these ranges of dose rates must be used.

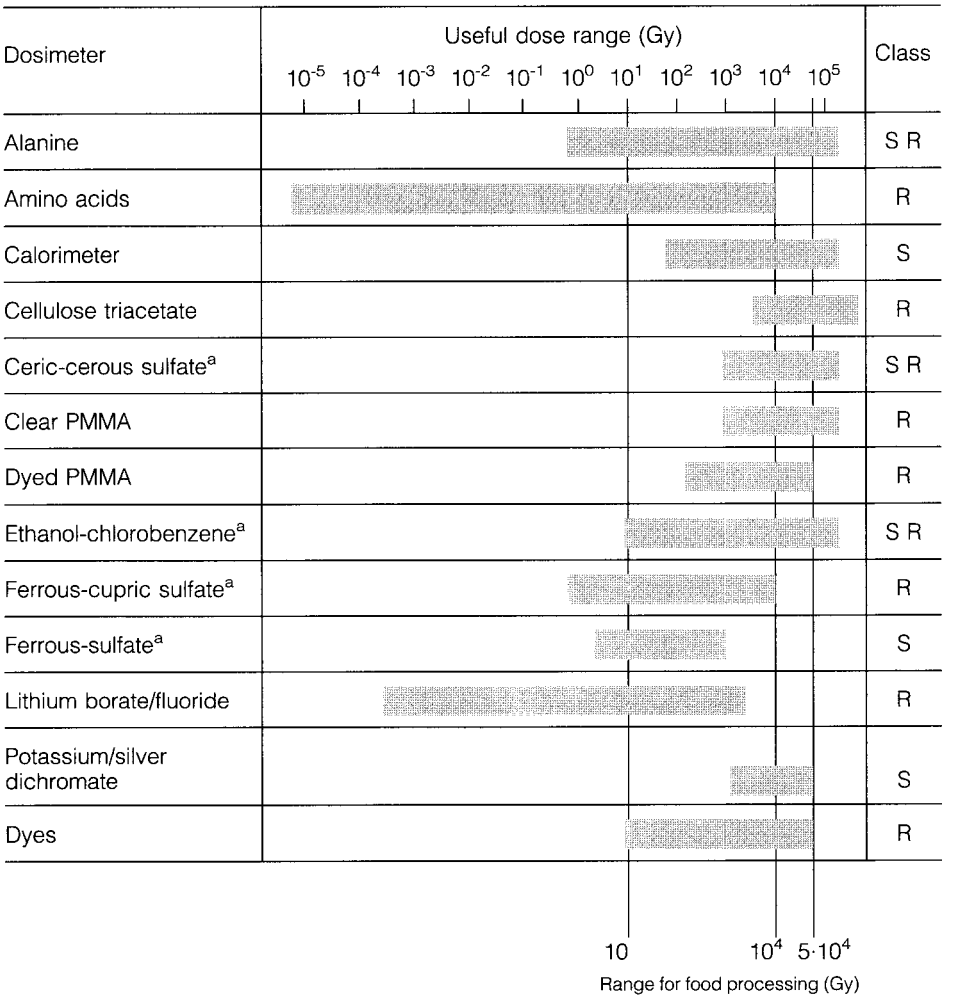
Accordingly, dosimetry and process control – including setting of the target dose – must take into consideration these and other chemical and physical effects (*479–487*). Most dosimeters, for example, are affected by temperature and phase during radiation processing (e.g. the radiation chemistry of liquid and frozen aqueous solutions is completely different); consequently, it must be carefully established that the chosen dosimeter maintains its metrological characteristics at the specified processing temperatures .There are other environmental factors affecting dosimeter performance, including humidity; however, in most instances, shielding the dosimeter against humidity by enclosing it in a plastic film would be sufficient to avoid any problem. It must also be recognized that dosimeters are sensitive to temperature during readout; however, in most cases, simple correction functions apply.

Once the appropriate dosimeter or dosimeters have been chosen, it is typically only necessary to map the dose distribution within a product or product model and to couple that information with the measured time the product remains in the irradiation treatment cell (dwell time) for either continuous or batch operation, in order to obtain the corresponding dose rates. The doses and dwell times used for determining dose rate can be less than for the actual processing, since the operator ultimately relies upon timers and conveyor speed controllers to deliver the desired dose to the product. In this way, the operator ensures that the effect on the dosimeter remains within its working range. Final verification of the dose and dose spread can be made using a dosimeter suitable for the intended range. Various solid state systems (e.g. alanine powders and radiochromic films), solid or liquid calorimeters, and electronic (i.e. charge integrating) devices are available for high-dose operations and can be used as routine secondary dosimeters; they can be referred back to primary standards for certification. All of these approaches have been used successfully in achieving doses of 30–75 kGy both in radioisotope and machine source facilities (Table 40).

8.3 Process control

Food irradiation is a self-limiting process. A dose that is too low would not achieve the intended purpose, prompting the customer to challenge the service provider for not providing the contracted dose and not achieving the desired effect. A dose that is too high would affect the sensory quality of the product, again prompting the customer to challenge the operator for exceeding the contracted dose and spoiling the

Table 40
Examples of routine and reference standard dosimeters

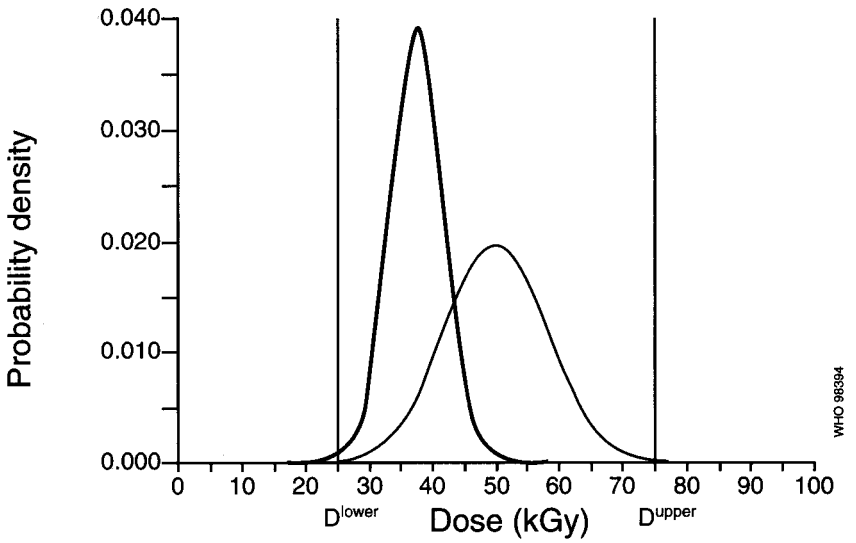


PMMA = polymethylmethacrylate; R = routine; S = reference standard.
[a]Aqueous solution

product quality. Process control is the methodology used to achieve the twin goals of a dose above the minimum required for sterilization and below the maximum imposed by product quality. It also helps to settle disputes between contractor and either regulatory officials or customers and it produces records for later examination and verification (*488*).

In practice, process control relies primarily on past research and practical experiences regarding the effectiveness of the radiation treatment, i.e. the minimum dose necessary to achieve the beneficial effect and – if applicable – the maximum dose tolerable to avoid any

Figure 21
Product dose distributions for two radiation treatments within lower (D^{lower}) and upper (D^{upper}) process limits for absorbed dose



The narrower curve shows the dose distribution that would be chosen for certain products and their quality considerations. Irradiation facility parameters are set so that less than 0.1% of the material to be irradiated receives a dose of less than D^{lower} for effective treatment in both cases; less than 0.1% receives a dose greater than D^{upper} for the wider dose distribution (target minimum dose arbitrarily chosen at 25 kGy)

detrimental effects to the product. In high-dose radiation processing, where the aim is to achieve sterility, factors to be taken into account in determining the minimum effective dose include the expected microbial load, the known radiation sensitivity of the relevant species of microorganisms, and the required reduction factor for that species. Usually the "12D-concept" is applied (see section 5). The required reduction (10^{12}) in the population of the most resistant spores of *Clostridium* spp. translates into a treatment in various foods of 24–42 kGy. In order to guarantee an effective treatment, the operator sets the target minimum dose at a safe level above this minimum value (Fig. 21: lower process limit D^{lower} = minimum effective dose). From sets of dosimeters placed in replicate at the expected minimum dose positions, a statistical distribution is obtained that is characterized by mean value and standard deviation. For quality control procedures, a lower alert limit is used to keep any fluctuations of the dose at the expected position of the minimum dose well above the process limit. The same considerations apply, but inversely, for any upper dose limit (Fig. 21: upper process limit D^{upper} = maximum tolerable dose). This approach

will result in a dose distribution within the irradiated food lot, batch or consignment that clearly falls between the targeted dose limits (Fig. 21). Depending on technical conditions and customer requirements, the resulting dose distribution could either exploit the maximum tolerable value in setting the ratio between maximum and minimum doses or be restricted to a very narrow dose spread.

It should be recognized that the useful dose range in sterilization applications (the range between maximum and minimum doses) will, in many instances, be less than that used in commercial irradiation facilities where the ratio between maximum and minimum dose is less than 3 but often more than 2 (*1*). For comparison, in the Raltech study (*489*), the dose distribution was characterized by a mean dose of 59 kGy, a minimum dose of 47 kGy, and a maximum dose of 71 kGy; the D_{max}/D_{min} ratio was 1.5. This narrower dose spread is achieved by less loading of the carriers (thus limiting the throughput), but assures a safe and acceptable product. It should be emphasized that none of the over 300 000 samples prepared for the Raltech study swelled or was otherwise spoiled.

The most anticipated application of high-dose irradiation of food is to achieve sterility to make the product stable at room temperature. Process control is very critical for delivering the minimum dose required to achieve the desired effect. Unlike medical disposables, the available margin for the maximum tolerable dose might be very narrow for a food whose quality attributes are sensitive to excessively high doses; its flavour, texture and appearance might be compromised. Consequently, the dose distribution in each and every lot being irradiated must be consistent with the technological limits appropriate to that product, and process control procedures must be introduced to keep the dose within the appropriate lower and upper margins.

Good irradiation practice requires that a technically practical narrow range between D_{min} and D_{max} be targeted. Specific requirements for radiation-sterilized products can best be fulfilled in this way, using existing radiation processing facilities.

Besides good irradiation practice, the general rules of good manufacturing practice should also be followed rigorously. In particular, the initial microbial load of the product must be kept as low as possible (*490*) and, therefore, high standards of hygiene in product preparation and handling are required.

From a regulatory standpoint, lower and upper legal dose limits could be set – if appropriate – that accommodate the lower and upper process dose limits. For example, it could be argued that legal limits are inappropriate for sprout inhibition of potatoes: if the process fails

because too low a dose was used, there is no health hazard to the consumer; if the dose used was far too high, the quality of the potatoes is impaired, but again no health hazard would be posed by consuming such potatoes. However, it may be appropriate to set limits when irradiating for specific purposes, e.g. irradiating chicken parts to eliminate pathogenic microorganisms. Consequently, United States regulations currently require a minimum dose of 1.5 kGy in order to fulfil the purpose of the radiation treatment. It is reasonable for authorities to set the lower legal dose limit in high-dose application at or above the lower process limit that had been determined and validated as necessary to sterilize a particular product. Again, however, too high a dose in sterilization treatments could impair the product's quality, but without any toxicological consequences, and would therefore limit its suitability for consumption – so again no legal limits need to be specified.

Process control in radiation processing relies on controlling the minimum and maximum doses throughout a given consignment, batch or treatment. In high-dose processing, the main purpose is to achieve microbial sterility, which to satisfy the 12D-concept requires a minimum dose, depending on the food, of 24–42 kGy. This requirement is met by setting process parameters in such a way that the resulting dose distribution at the expected position of the minimum dose is well above the specified minimum dose (Fig. 21). This minimum is achieved by choosing a tolerable error probability and calculating a tolerance range from the standard deviation of the respective measurements and the tolerance factor determined by number of measurements and applicable error probability. For example, a tolerable error probability of 0.1% would have a tolerance range of about 3.1. It is generally accepted (*1, 2*) that the maximum dose for any treatment under commercial circumstances is about 50% above the average dose and that the ratio between maximum and minimum dose can be kept to less than 3.0; the average dose can be expected to be the mean of the maximum and minimum doses.

With regard to regulatory limitations, there tends to be a misunderstanding of the term "overall average dose". This misunderstanding is evident in connection with its numerical value of 10 kGy for low-dose applications adopted by the Joint Expert Committee in 1980 (*1*) and accepted by Codex Alimentarius in 1983 (*2*). Some regulations specify values lower than 10 kGy for the overall average dose for certain groups of food in order to avoid doses in any part of the food being greater than 10 kGy. The meaning of this quantity can best be understood by bearing in mind that toxicological potential is linked to chemical change and that the formation of radiolysis products is linearly proportional to dose (see section 3) in the dose range of interest (~100 kGy). This linearity implies

that any "over-treatment" is compensated by "under-treatment", so only the average formation of radiolysis products is relevant. Consequently, overall average dose denotes a grand mean of doses applied to the food; regulatory limitations – if needed – can be derived in the light of Fig. 21 and the discussion above.

8.4 Environmental parameter control

Food processing in general requires control not only of process parameters but also of a range of environmental parameters. The basic approach is to isolate the food from the environment by enclosing it within packaging material that provides a barrier to molecular transmission and, in some cases, to light penetration. Since the main intended effect of radiation processing of food to high doses is the elimination of pathogenic and spoilage microorganisms and, hence, the achievement of sterility, the packaging material must prevent any recontamination by ubiquitous microorganisms in the environment, yet not introduce any undesirable effects as a consequence of the irradiation (see section 7).

With the exception of product improvement applications, such as increased juice extraction, high-dose radiation processing will always be primarily part of a "combination treatment" directed towards producing a shelf-stable product. The combination involves: heating to inactivate proteolytic enzymes, which are rather radiation-insensitive and not completely inactivated by even the radiation doses considered at present; vacuum packing to eliminate oxygen and to retain volatile flavorants; and freezing the product and maintaining the frozen state during irradiation, which is most important for minimizing side effects such as the formation of off-flavours. Since the product is stored deep-frozen prior to irradiation, it must be handled as other deep-frozen foods in order to avoid "melt–thaw–freeze" damages and "freezer-burn" caused by recrystallization. Packaging and packing conditions can be selected that permit the use of a "controlled atmosphere" or a "modified atmosphere", which offers the potential of achieving product stabilization with lower doses.

A radiation-sterilized product, heat-treated for enzyme inactivation (which corresponds to being precooked and ready-to-eat), packaged to shield the product from recontamination, and sealed under vacuum in order to suppress oxidative processes, should be very insensitive to post-irradiation environmental factors, in particular humidity and temperature. It should remain stable and retain its qualities for as long as the package retains its integrity (see Annex 1). Radiation-sterilized diets have been used in hospitals in Scotland (*491*) and Washington, United

States (*492*); however, this application was discontinued for practical reasons when more stringent regulations hampered the further use of such products at one hospital and an irradiation facility was no longer available at the other. Samples of irradiated ham prepared for the 1977 joint Apollo–Soyuz space flight and kept at ambient conditions are still intact 20 years later in their original multilayered flexible packages. Since the 1980s, irradiated foods, including bread, breakfast rolls, beefsteak, ham and smoked turkey, have been used regularly on space flights (*493*). South Africa has a conditional clearance for sterile meats for use in producing ready-to-heat-and-eat meals for use by outdoor enthusiasts. Such products are hermetically sealed in mechanically-resistant, oxygen-impermeable, light-shielding plastic pouches that can withstand extreme environmental conditions and exhibit prolonged shelf-life. Several other applications are anticipated, and there are publications in scientific literature describing the sensory and nutritional quality of radiation-sterilized foods (*125, 251, 304, 494, 495*).

8.5 Re-irradiation

Under certain circumstances, it might be justified to process a food commodity that has already been irradiated (*1*). Examples of such situations include: dry products, such as grain, irradiated for insect disinfestation where re-infestation requires repetition of the treatment, as with fumigation; products manufactured from a raw material that had been irradiated for some purpose, such as onions previously irradiated to inhibit sprouting or dried onions prepared from irradiated onions, but where the final product needs to be processed by ionizing radiation for some justified purpose; and an irradiated minor ingredient, such as spices, where the final product containing this ingredient is to be irradiated for a justified purpose. It was concluded that the additional amount of radiolysis compounds in the final products would be insignificant and, hence, that this practice would be acceptable (*1, 2, 490*). This rationale also applies for products, processed to higher doses by ionizing radiation in order to obtain sterility, that contain irradiated ingredients or raw materials; an example is a composite food or meal containing vegetables, meats and spices, all previously irradiated for purposes other than sterilization. The dose and incremental amount of radiolysis compounds would be insignificant and, hence, the use of previously irradiated ingredients in products to be sterilized by irradiation would not need special processing consideration. Situations other than these that require repeated irradiation are not in compliance with good manufacturing practice and should be considered unacceptable. It should be noted that fractionated irradiation – where the full dose is applied in two or more

instalments — is *not* considered to be a repeated irradiation; fractionation could occur when the irradiation is interrupted for technical reasons (e.g. failure of the transport system).

8.6 Conclusions

In view of these considerations, the Study Group concluded that:

- the minimum absorbed dose needed to sterilize a food product can be accurately and reproducibly measured by following standardized dosimetric procedures;
- the ratio of maximum to minimum absorbed dose in any processed food lot, batch or consignment can be accurately and reproducibly defined from the dosimetric measurements;
- the processing and environmental parameters essential for ensuring that the food product is sterilized within the targeted dose range under technologically prescribed conditions can be properly monitored and recorded; and
- the overall handling of the product and process can be sufficiently controlled to ensure that products receive the required sterilizing dose, either in one treatment or in a properly fractionated sequence of treatments, and that they are not re-irradiated unless technically justified.

9. Conclusions

9.1 Wholesomeness: safety and nutritional adequacy

The Study Group concluded that food irradiated to any dose appropriate to achieve the intended technological objective is both safe to consume and nutritionally adequate. This conclusion is based on extensive scientific evidence that this preservation process can be used effectively to eliminate spores of proteolytic strains of *Clostridium botulinum* and all spoilage microorganisms, that it does not compromise the nutritional value of the foods, and that it does not result in any toxicological hazard. Recognizing that, in practice, the doses applied to eliminate the biological hazards would be below those doses that might compromise sensory quality, the Study Group concluded that no upper dose limit need be imposed. Accordingly, irradiated foods are deemed wholesome throughout the technologically useful dose range from below 10 kGy to envisioned doses above 10 kGy.

9.2 Substantial equivalence

In assessing risk, the Study Group concluded that irradiation to high doses is essentially analogous to conventional thermal processing, such as the

canning of low-acid foods, in that it eliminates biological hazards (i.e. pathogenic and spoilage microorganisms) from food materials intended for human consumption, but does not result in the formation of physical or chemical entities that could constitute a hazard. Abundant and convincing data indicate that high-dose irradiated foods do not contain either measurable levels of induced radioactivity or significant levels of any radiolysis products distinct from those found in unirradiated foods. The theoretical maximum levels that might be formed would be so low as to be of no toxicological consequence. Accordingly, none of the toxicological data derived from extensive animal feeding studies reveals any teratogenic, carcinogenic, mutagenic or other harmful effects that are ascribable to high-dose irradiated foods. For these reasons, the application of "risk assessment" in the currently accepted sense[1] is not appropriate to the toxicological assessment of foods preserved by high-dose irradiation. In this context, the concept of "substantial equivalence" may be more appropriate. High-dose irradiated foods are indeed as safe as food materials sterilized by thermal processing, which humans have been eating for more than a century.

9.3 Applications

The Study Group concluded that high-dose irradiation, conducted in accordance with good manufacturing practices and good irradiation practices, could be applied to several types of foods to improve their hygienic quality, to make them shelf-stable, and to produce special products. These foods are envisaged to include, but not be limited to: spices and other dry food ingredients; prepackaged precooked foods that could be stored at ambient temperature for extended periods; and sterilized meals for specific target groups (such as disaster victims, outdoor enthusiasts, and the immunocompromised). Components of all classes of foods whose sensory qualities are not compromised could be irradiated to high doses, either singly or in any combination. Packaging materials that are technically applicable and approved should be used as appropriate.

9.4 Global standardization

The Study Group concluded that appropriate steps need to be taken to establish the technological guidelines implied by these conclusions and to communicate them through Codex Alimentarius standards.

[1] In 1997, the Codex Alimentarius Commission adopted, on an interim basis, the following definition for risk assessment: "A scientifically based process consisting of the following steps: (i) hazard identification; (ii) hazard characterization; (iii) exposure assessment; (iv) risk characterization."

10. Recommendations

1. The substantial benefit to food safety and food availability that would accrue directly from the broad application of food irradiation requires that steps be taken to put this technology into wider practice. These steps will involve standardization, communication and education.

2. WHO, in collaboration with FAO and IAEA, should:
   - coordinate the preparation of documentation and the drafting of appropriate technical language for adoption of standards by the Codex Alimentarius Commission;
   - prepare appropriate brochures and documents that integrate food irradiation into existing guidelines and rules governing the safe production, distribution and handling of food in order to minimize the spread of microbiological contamination and incidence of foodborne illnesses;
   - organize and participate in appropriate training courses and workshops to educate food regulators and food workers about the role food irradiation could, and should, play as a control measure in the framework of the application of the hazard analysis critical control point (HACCP) system.

3. WHO should take the lead in advising international agencies and national ministries of health on the implementation of integrated strategies, including food irradiation, for preventing the transnational spread of pathogens in human food and animal feed, for controlling foodborne illnesses, and for enhancing the availability of safe and nutritious foods.

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References

1. *Wholesomeness of irradiated food. Report of a Joint FAO/IAEA/WHO Expert Committee.* Geneva, World Health Organization, 1981 (WHO Technical Report Series, No. 659).
2. *Codex General Standard for Irradiated Foods and Recommended International Code of Practice for the Operation of Radiation Facilities Used for the Treatment of Food.* Rome, Food and Agriculture Organisation of the United Nations, 1984 (CAV/Vol. XV-Ed. 1).
3. *Wholesomeness of irradiated food. Report of a Joint FAO/IAEA/WHO Expert Committee.* Geneva, World Health Organization, 1977 (WHO Technical Report Series, No. 604).
4. United Kingdom Ministry of Health. *Report of the Working Party on Irradiation of Food.* London, HMSO, 1964.
5. *Radiation processing of foods. Hearings before the Congress of the United States, 9 and 10 June, 1965.* Washington, DC, US Government Printing Office, 1965, pp. 105–106.
6. *Report of the meeting on the wholesomeness of irradiated foods, Brussels, October 1961.* Rome, Food and Agriculture Organisation of the United Nations, 1962.
7. *The technical basis for legislation on irradiated food. Report of a Joint FAO/IAEA/WHO Expert Committee.* Geneva, World Health Organization, 1966 (WHO Technical Report Series, No. 316).
8. *Wholesomeness of irradiated food with special reference to wheat, potatoes and onions. Report of a Joint FAO/IAEA/WHO Expert Committee.* Geneva, World Health Organization, 1970 (WHO Technical Report Series, No. 451).
9. **Thayer DW et al.** Toxicology studies of irradiation-sterilized chicken. *Journal of food protection*, 1987, **50**:278–288.
10. *Safety and nutritional adequacy of irradiated food.* Geneva, World Health Organization, 1994.
11. *Review of data on high dose (10–70 kGy) irradiation of food.* Geneva, World Health Organization, 1995 (unpublished document, WHO/FNU/FOS/95.10; available on request from programme of Food Safety and Food Aid, World Health Organization, 1211, Geneva 27, Switzerland).
12. **Taub IA.** Radiation chemistry and the radiation preservation of food, *Journal of chemical education, 1981,* **58**:162–167.
13. **Basson RA.** Advances in radiation chemistry of food and food components – an overview. In: Cohen AJ, Elias PS, eds. *Recent advances in food irradiation.* Amsterdam, Elsevier, 1983, pp. 7–25.
14. **Diehl JF.** *Safety of irradiated foods*, 2nd ed. New York, Marcel Dekker, 1995, pp. 43–88.
15. **Taub IA, Angelini P, Merrit C Jr.** Irradiated food: validity of extrapolating wholesomeness data. *Journal of food science*, 1976, **41**:942–944.
16. **Farhataziz, Rogers MAJ,** eds. *Radiation chemistry: principles and applications.* New York, VCH Publishers, 1987.
17. **Draganic IV, Draganic ZD.** *The radiation chemistry of water.* New York, Academic Press, 1971.

18. **Buxton GV.** Radiation chemistry of the liquid state: (1) water and homogenous aqueous solutions. In: Farhataziz, Rogers MAJ, eds. *Radiation chemistry: principles and applications.* New York, VCH Publishers, 1987, pp. 321–349.

19. **Holroyd RA.** The electron: its properties and reactions: In: Farhataziz, Rogers MAJ, eds. *Radiation chemistry: principles and applications.* New York, VCH Publishers, 1987, pp. 201–235.

20. **Kestner NR.** Theories of the solvated electron. In: Farhataziz, Rogers MAJ, eds. *Radiation chemistry: principles and applications.* New York, VCH Publishers, 1987. pp. 237–262.

21. **Klassen NV.** Primary products in radiation chemistry. In: Farhataziz, Rogers MAJ, eds. *Radiation chemistry: principles and applications.* New York, VCH Publishers, 1987. pp. 29–64.

22. **Taub IA.** Free radical reactions in food. *Journal of chemical education*, 1984, **61**:313–324.

23. **Dorfman LM, Buhler RE, Taub IA.** Pulse radiolysis studies. I. Transient spectra and reaction rate constants in irradiated aqueous solutions of benzene. *Journal of chemical physics*, 1962, **36**:3051–3061.

24. **Taub IA et al.** Factors affecting radiolytic effects in food. *Radiation physics and chemistry, 1979,* **14**:639–653.

25. **Taub IA.** Reaction mechanisms, irradiation parameters, and product formation. In: *Preservation of food by ionizing radiation*, Vol. 2. Josephson ES, Peterson M, eds. Boca Raton, FL, CRC Press, 1983, pp. 125–166.

26. **Taub IA, Eiben K.** Transient solvated electron, hydroxyl, and hydroperoxy radicals in pulse irradiated crystalline ice. *Journal of chemical physics*, 1968, **49**:2499–2513.

27. **Taub IA, Kaprielian RA, Halliday, JW.** Radiation chemistry of high protein foods irradiated at low temperatures. In: *Proceedings, International Symposium on Food Preservation by Irradiation.* Vienna, International Atomic Energy Agency, 1978, Vol. I, 371–384.

28. **Taub IA, Halliday JW, Sevilla MD.** Chemical reactions in proteins irradiated at subfreezing temperatures, Washington, American Chemical Society. *Advances in chemistry, 1979, Series No. 180,* pp. 109–140.

29. **Taub IA et al.** Chemiclearance: principle and application to irradiated meats. In: *Proceedings of the 26th European Meeting of Meat Research Workers, Colorado Springs, CO, September 1980,* Vol. 1. American Meat Science Association. p. 233.

30. **Kim H-J et al.** Binding-site specificity of the radiolytically induced crosslinking of phenylalanine to glucagon. *Radiation research,* 1984, **98**:26–36.

31. **Kim H-J et al.** Binding-site specificity of the gamma radiation induced crosslinking between phenylalanine and phenylalanine-containing tetrapeptide. *Radiation research,* 1984, **100**:30–40.

32. **Merritt C. Jr.** Qualitative and quantitative aspects of trace volatile components in irradiated foods and food substances. *Radiation research review*, 1972, **3**:353–368.

33. **Shieh JJ et al.** Radiation chemistry of myoglobin, its derivatives, and model compounds in aqueous solution. In: *Radiation biology and chemistry: recent*

developments. Proceedings of the Association for Radiation Research Meeting, 3–5 January 1979, Amsterdam, Elsevier, 1979, p. 179–188.

34. **Whitburn KD, Hoffman MZ, Taub IA.** Formation of a steady state in the radiolysis of ferrimyoglobin in aqueous solution. *Archives of biochemistry and biophysics, 1981,* **208**:319.
35. **Whitburn KD et al.** Globin-mediated redox processes in the interaction of hydroxyl radicals with ferrimyoglobin aqueous solution. *International journal of radiation biology*, 1981, **40**:297–303.
36. **Whitburn KD et al.** Redox transformations in ferrimyoglobin induced by radiation-generated free radicals in aqueous solution. *Journal of biological chemistry.* 1982, **257**:1860–1869.
37. **Whitburn KD, Hoffman MZ, Taub IA.** Simultaneous reaction of hydroxyl radical and aquated electrons with ferrimyoglobin in irradiated solutions. *Journal of food science*, 1983, **48**:1888–1889.
38. **Shieh JJ et al.** Radiation chemistry of meat proteins: myoglobin irradiated in frozen aqueous solutions. In: Tsen CC, Li C, eds. *Proceedings of International Symposium on Recent Advances in Food and Technology, Taipei, January 1980.* Taipei, Hua Shiang Hwan, 1981, p. 277.
39. **Whitburn KS, Hoffman MZ, Taub IA.** Interaction of radiation-generated radicals with myoglobin in aqueous solutions. II: analysis of product yields for hydroxyl radicals with oxymyoglobin under deaerated conditions. *Radiation, physics and chemistry*, 1984, **23**:271–278.
40. **Sevilla C, Swarts S, Sevilla MD.** An ESR study of radical intermediates formed by gamma radiolysis of tripalmitin and dipalmitoyl phosphatidylethanolamine. *Journal of the American Oil Chemists' Society*, 1983, **60**:950–957.
41. Chemical method for detection of 2-dodecylcyclobutanone in irradiated chicken meat. In: *Concerted action of the Community Bureau of Reference on methods of identification of irradiated foods.* Luxemburg, European Commission Report No. EUR 15261 EN, 1994. pp. 74–78.
42. **Boyd D et al.** Synthesis, characterization, and potential use of 2-dodecylcyclobutanone as a marker for irradiated chicken. *Journal of agricultural and food chemistry*, 1991, **39**:789–792.
43. **von Sonntag C.** *The chemical basis of radiation biology.* London, Taylor and Francis, 1987, p. 375–393.
44. **von Sonntag C.** Free radical reactions of carbohydrates as studied by radiation techniques. *Advances in carbohydrates, chemistry and biochemistry*, 1980, **37**: 7–77.
45. **Dauphin JF, Saint-Lèbe LR.** Radiation chemistry of carbohydrates. In: Cohen AJ, Elias PS, eds. *Radiation chemistry of major food components.* Amsterdam, Elsevier, 1983, pp. 131–185.
46. **Raffi JJ. Agnel J-P.** Influence of the physical structure of irradiated starches on their ESR spectra kinetics. *Journal of physical chemistry*, 1983, **87**:2369–2373.
47. **Raffi J et al.** Glucose oligomers as models to elucidate the starch radiolysis mechanism. *Stärke*, 1985, **37**:228–231.
48. **Raffi JJ et al.** Study of γ-irradiated starches derived from different foodstuffs: a way for extrapolating wholesomeness data. *Journal of agricultural and food chemistry*, 1981, **29**:1227–1232.

49. **Raffi J et al.** Gamma radiolysis of starches derived from different foodstuffs. IV: study of radiodepolymerization. *Stärke*. 1981, **33**:301–306.

50. **Raffi J, Michel J-P, Saint-Lèbe L.** Theoretical study of the radiodepolymerization of starch. *Stärke*. 1980, 32:227–229.

51. **Michel J-P, Raffi J, Saint-Lèbe L.** Experimental study of the radiodepolymerization of starch. *Stärke*. 1980, **32**:295–298.

52. **Dizdaroglu M, von Sonntag C.** α-Radiolyse von Cellobiose in N_2O-gesattigter wassriger Losung. Teil I. Identifizierung der Produckte. [α-Radiolysis of cellobiose in N_2O-saturated aqueous solution. Part I. Identification of products.] *Zeitschrift für Naturforschung*, 1973, **28b**:635–646.

53. **Basson RA et al.** Chemiclearance approach to evaluation of safety of irradiated fruits. In: Cohen AJ, Elias DS, eds. *Recent advances in food irradiation.* Amsterdam, Elsevier, 1983, pp. 59–77.

54. **Hart EJ, Anbar M.** *The hydrated electron.* New York, John Wiley and Sons, 1970, p. 110.

55. **Bielski BHJ.** Chemistry of ascorbic acid radicals. In: Sieb PA, Tolbert BM, eds. *Ascorbic acid: chemistry, metabolism and uses. Advances in chemistry series, No. 200.* Washington, DC, American Chemical Society. 1982, p. 81–100.

56. **Laroff GP, Fessenden RW, Schuler RH** The electron spin resonance spectra of radical intermediates in the oxidation of ascorbic acid and related substances. *Journal of the American Chemical Society*, 1972, **94**:9062–9073.

57. **Neta P.** On the ESR spectra of radicals produced by the reaction of $OH^{\bullet}$. with uracils. *Radiation research*, 1973, **56**:201–204.

58. **Ward JF.** Chemical consequences of irradiating nucleic acids. *Journal of agricultural and food chemistry*, 1978, **26**:25–28.

59. **Merritt C Jr, Taub IA.** Commonality and predictability of radiolytic products in irradiated meats. In: Elias PS, Cohen AJ. eds. *Recent advances in food irradiation.* New York, Elsevier, 1983, p. 25–57.

60. **Sevilla MD.** *Commonality of chemical entities in irradiated muscle foods. Final Report.* 1994 (unpublished document; United States Army Contract No. DAAL03-91-0034).

61. **Merritt C. Jr et al.** A quantitative comparison of the yields of radiolysis products in various meats and their relationship to precursors. *Journal of the American Oil Chemists' Society*, 1985, **62**:708–713.

62. **Nawar WW.** Reaction mechanisms in the radiolysis of fats: a review. *Journal of agriculture and food chemistry*, 1978, **26**:21–25.

63. **Raffi J, Agnel J-P, Kassis S-R.** Identification par résonance paramagnétique électronique de céréales irradiées. *Science aliments*, 1987. **4**:657–663.

64. **Fox JB et al.** Gamma irradiation effects on thiamin and riboflavin in beef, lamb, pork and turkey, *Journal of food science*, 1995, **60**:596–598.

65. **Raica N Jr, Scott J, Nielsen W.** The nutritional quality of irradiated foods. *Radiation research reviews*, 1972, **3**:447–457.

66. **Tobback PP.** Radiation chemistry of vitamins. In: Elias PS, Cohen AJ, eds. *Radiation chemistry of major food components.* Amsterdam, Elsevier, 1977, pp. 187–220.

67. **Josephson ES, Thomas MH, Calhoun WF.** Nutritional aspects of food irradiation: an overview. *Journal of food processing and preservation*, 1978, 2:229–313.

68. **Kraybill HF.** Effect of processing on nutritive value of food: irradiation. In: Rechcigl J, ed. *CRC handbook of nutritional value of processed food*, Vol. 1. Boca Raton, FL, CRC Press, 1982, pp. 181–208.

69. **Murray TK.** Nutritional aspects of food irradiation. In: Elias PS, Cohen AJ, eds. *Recent advances in food irradiation.* Amsterdam, Elsevier, 1983, pp. 203–216.

70. **Thayer DW, Fox JB, Lakritz L.** Effects of ionising radiation on vitamins. In: Thorne S, ed. *Food irradiation.* Barking, Elsevier, 1991, pp. 285–325.

71. **Dieh JF, Hasselmann C, Kilcast D.** Regulation of food irradiation in the European Community: is nutrition an issue? *Food control*, 1991, 2:212–219.

72. **Lakritz L et al.** Effect of gamma radiation on levels of alpha-tocopherol in red meats and turkey. *Meat science*, 1995, 41:261–271.

73. **Lakritz L et al.** Effect of gamma radiation on alpha-tocopherol, thiamin, and riboflavin in red meats and turkey. *Abstracts, Institute of Food Technologists Annual Meeting*, 1995.

74. **Al Kahtani HA et al.** Chemical changes after irradiation and post-irradiation storage in tilapia and Spanish mackerel. *Journal of food science,* 1996, 61:729–733.

75. **Kun Fen Lee, Lung Bin Hau.** Effect of gamma-irradiation and post-irradiation cooking on thiamine, riboflavin and niacin contents of grass prawns *(Penaeus monodon). Food chemistry*, 1996, 55:379–382.

76. **Read MS et al.** Successive generation rat-feeding studies with a composite diet of gamma-irradiated foods. *Toxicology and applied pharmacology*, 1961, 3:153–173.

77. **Kraybill HF.** Nutritional and biochemical aspects of food preserved by ionizing radiation. *Journal of home economics*, 1958, 5:695–700.

78. **Thayer DW.** Food irradiation: benefits and concerns. *Journal of food quality,* 1990, 13:147–169.

79. **Underdal B et al.** The effect of ionizing radiation on the nutritional value of mackerel. *Lebensmittel Wissenschaft und Technologie*, 1976, 9:72–74.

80. **Underdal B et al.** The effect of ionizing radiation on the nutritional value of fish (cod) protein. *Lebensmittel Wissenschaft und Technologie*, 1973, 6:90–93.

81. **Metta VC, Johnson BC.** Biological value of gamma irradiated corn protein and wheat gluten. *Journal of agricultural and food chemistry*, 1959, 7:131–133.

82. **Moran ET Jr, Summers JD, Bayley MS.** Effect of cobalt-60 gamma irradiation on the utilization of energy, protein, and phosphorus from wheat bran by the chicken. *Cereal chemistry*, 1968, 45:469–479.

83. **McGinnis J et al.** Improvement in the nutritional value of rye by gamma irradiation. *Federation proceedings*, 1978, 37:759.

84. **Eggum BO.** Effect of radiation treatment on protein quality and vitamin content of animals. In: *Decontamination of animal feeds by irradiation, Proceedings of a Meeting held in Sofia, October 1977.* Vienna, International Atomic Energy Agency, 1979, pp. 55–67.

85. **Ley FJ et al.** Sterilization of laboratory animal diets using gamma radiation. *Laboratory animals*, 1969, 3:221–254.

86. **Reddy SJ, Pubols MH, McGinnis, J.** Effect of gamma irradiation on nutritional value of dry field beans (*Phaseolus vulgaris*) for chicks. *Journal of nutrition, 1979*, **109**:1307–1312.

87. **Daghir NJ, Sell JL, Mateos GG.** Effect of gamma irradiation on nutritional value of lentils (*Lens culinaris*) for chicks. *Nutrition report international*, 1983, **27**:1087–1093.

88. **Diehl JF.** Food irradiation: is it an alternative to chemical preservatives? *Food additives and contaminants*, 1992, **9**:409–416.

89. **Groninger HS, Tappel AL, Knapp FW.** Some chemical and organoleptic changes in gamma irradiated meats. *Food research*, 1956, **21**:555–564.

90. **Josephson ES, Thomas MH, Calhoun WK.** Effects of treatments of foods with ionizing radiation. In: Harris RS, Karmas E, eds. *Nutritional evaluation of food processing*. Westport, CT, AVI, 1975, pp. 393–411.

91. **Thomas MH et al.** Effect of radiation and conventional processing on the thiamin content of pork. *Journal of food science*, 1981, **46**:824–828.

92. **Day EJ et al.** The bioassay of thiamine in beef exposed to gamma radiation. *Journal of nutrition*, 1957, **62**:107–118.

93. **Brasch A, Huber W.** Ultrashort application time of penetrating electrons: a tool for sterilization and preservation of food in the raw state. *Science*, 1947, **105**:112–117.

94. **Wilson GM.** The treatment of meats with ionising radiation. II. Observations on the destruction of thiamine. *Journal of the science of food and agriculture,* 1959, 10:295–300.

95. **Dong FM et al.** Effects of gamma-irradiation on the contents of thiamine, riboflavin, and vitamin B_{12} in dairy products for low microbial diets. *Journal of food processing and preservation*, 1989, **13**:233–244.

96. **Thayer DW et al.** Effect of gamma ray irradiation and frying on the thiamine content of bacon. *Journal of food quality*, 1989, **12**:115–134.

97. **Skala JH, McGown EL, Waring PP.** Wholesomeness of irradiated food. *Journal of food protection*, 1987, **50**:150–160.

98. **Day EJ et al.** Effects of gamma radiation on certain water-soluble vitamins in raw ground beef. *Journal of nutrition*, 1957, **62**:27–37.

99. **Richardson LR, Wilkes S, Ritchey SJ.** Comparative vitamin B_6 activity in frozen, irradiated and heat-processed foods. *Journal of nutrition*, 1961, **73**:363–368.

100. **Brin J et al.** Effects of feeding X-irradiated pork to rats on their pyridine nutrition as reflected in the activity of plasma transaminase. *Journal of nutrition*, 1961, **75**:35–38.

101. **Brooke RO et al.** Preservation of fresh unfrozen fishery products by low-level radiation. 5. The effects of radiation pasteurization on amino acids and vitamins in haddock fillets. *Food technology*, 1966, **20**:99–102.

102. **Mameesh MS et al.** Studies on the radiation preservation of fish. I. The effect of certain vitamins in fresh fillets of cod and dogfish and in smoked fillets of cod and herring. *Fiskeridirektoratets Skrifter*, 1964, **4**:1–10.

103. **Alexander HD et al.** Radiation effects on water soluble vitamins in raw beef. *Federation proceedings*, 1956, **15**:921–923.

104. **Richardson LR, Martin JL, Hart S.** The activity of certain water-soluble vitamins after exposure to gamma radiations in dry mixtures and in solutions. *Journal of nutrition*, 1958, **65**:409–418.

105. **Müller H, Diehl JF.** Effect of ionizing radiation on folates in food. *Lebensmittel Wissenschaft und Technologie*, 1996, **29**:187–190.

106. **Pfeiffer C, Diehl JF, Schwack W.** Effect of irradiation on folate levels and on bioavailability of folates in dehydrated foodstuffs. *Acta alimentaria*, 1994, **23**:105–118.

107. **Galetto W et al.** Irradiation treatment of onion powder: effects on chemical constituents. *Journal of food science*, 1979, **44**:591–595.

108. **Farkas J, Beczner J, Incze K.** Feasibility of irradiation of spices with special reference to paprika. In: *Radiation preservation of food. Proceedings Series.* Vienna, International Atomic Energy Agency, 1973, pp. 389–401.

109. **Diehl JF.** Vitamin A in bestrahlten Lebensmittel. [Vitamin A in irradiated foodstuffs.] *Zeitschrift für Lebensmittel-Untersuchung und -Forschung*, 1979, **168**:29–31.

110. **Knapp FW, Tappel AL.** Comparison of the radiosensitivities of the fat-soluble vitamins by gamma irradiation. *Journal of agricultural and food chemistry*, 1961, **9**:430–433.

111. **Richardson RL, Wilkes S, Ritchey SJ.** Comparative vitamin K activity of frozen, irradiated, and heat-processed food. *Journal of nutrition*, 1961, **73**:369–373.

112. **Metta VC, Mameesh MS, Johnson BC.** Vitamin K deficiency in rats induced by the feeding of irradiated beef. *Journal of nutrition*, 1959, **69**:18–22.

113. **Matschiner JT, Doisy J.** Vitamin K content of ground beef. *Journal of nutrition*, 1966, **90**:331–334.

114. **Hammer CT, Wills FD.** The effect of ionizing radiation on the fatty acid composition of natural fats and on lipid peroxide formation. *International journal of radiation biology*, 1979, **35**:323–332.

115. **Adam S, Paul G, Ehlermann D.** Influence of ionizing radiation on the fatty acid composition of herring fillets. *Radiation physics and chemistry*, 1982, **20**:289–295.

116. **Vaca CE, Harms-Ringdahl M.** Radiation-induced lipid peroxidation in whole grain of rye, wheat and rice: effects on linoleic and linolenic acid. *Radiation physics and chemistry*, 1986, **28**:325–330.

117. **Hafez YS et al.** Effect of gamma irradiation on proteins and fatty acids of soybean. *Journal of food science*, 1985, **50**:1271–1274.

118. **Chiou RY-Y, Shyu S-L, Tsai C-L.** Characterization of gamma irradiated peanut kernels stored one year under ambient and frozen conditions. *Journal of food science*, 1991, **56**:1375–1377.

119. *Report of the FAO/IAEA Consultants' Meeting on Microbiological Aspects of Food Irradiation, Vienna, 16–19 December 1974.* Vienna, International Atomic Energy Agency, 1974.

120. *The Microbiological Safety of Irradiated Food.* Rome, Codex Alimentarius Commission, 1983 (No. CX/FA83/9).

121. **Ingram M, Farkas J.** Microbiology of foods pasteurised by ionising radiation. *Acta alimentaria*, 1977, **6**:123–185.

122. **Farkas J.** Microbiological safety of irradiated foods. *International journal of food microbiology,* 1989, **9**:1–5.

123. **Wierbicki E.** Technological feasibility of preservation of meat, poultry and fish products using a combination of conventional additives, mild heat treatment and irradiation. In: *Combination processes in food irradiation.* Vienna, International Atomic Energy Agency, 1981, pp. 181–203.

124. **Farkas J.** *Irradiation of dry food ingredients.* Boca Raton, FL, CRC Press, 1988.

125. **Taub IA et al.** Effect of irradiation on meat proteins. *Food technology,* 1979, **38**:184–193.

126. **Moseley BEB.** Ionizing radiation: action and repair. In: Gould GW, ed. *Mechanisms of action of food preservation* procedures, London, Elsevier Applied Science, 1989, pp. 43–70.

127. **Grecz N, Rowley DB, Matsuyama A.** The action of radiation on bacteria and viruses. In: Josephson ES, Peterson MS, eds. *Preservation of food by ionizing radiation,* Vol. II. Boca Raton, FL, CRC Press, 1983, pp. 167–218.

128. **Davies R.** The inactivation of vegetative bacterial cells by ionizing radiation. In: Skinner FA, Hugo WG, eds. *Inhibition and inactivation of vegetative microbes.* London, Academic Press, 1976, pp. 279–304.

129. **Licciardello JJ.** Effect of temperature on radiosensitivity of *Salmonella typhimurium. Journal of food science,* 1964, **29**:469–474.

130. **Grecz N et al.** Effect of temperature of liquid nitrogen on radiation resistance of spores of *Clostridium botulinum. Applied microbiology,* 1965, **13**:527–536.

131. **Novanugraha V.** *Simultaneous heating and irradiation of Clostridium sporogenes spores in raw ground beef* [unpublished M.S. thesis]. East Lansing, MI, Michigan State University, 1973.

132. **Matsuyama AT, Thornley MJ, Ingram M.** The effect of freezing on the radiation sensitivity of vegetative bacteria. *Journal of applied bacteriology,* 1964, **27**:110–124.

133. **Anellis A, Berkowitz D, Kemper D.** Comparative resistance of non-sporogenic bacteria to low-temperature gamma irradiation. *Applied microbiology,* 1973, **25**:517–523.

134. **Grecz N, Upadhyay J, Tang T.** Effect of temperature on radiation resistance of spores of *Clostridium botulinum* 33A. *Canadian journal of microbiology,* 1967, **13**:287–293.

135. **Ma K, Maxcy RB.** Factors influencing radiation resistance of vegetative bacteria and spores associated with radappertization of meat. *Journal of food science,* 1981, **46**:612–616.

136. **Thornley MJ.** Radiation resistance among bacteria. *Journal of applied bacteriology,* 1963, **26**:334–345.

137. **Ingram M, Roberts TA.** Microbiological principles in food irradiation. In: *Food irradiation.* Vienna, International Atomic Energy Agency, 1966, pp. 267–285.

138. **Farkas J, Kiss I, Andrássy É.** The survival and recovery of irradiated bacterial spores as affected by population density and some external factors. In: *Radiosterilization of medical products.* Vienna, International Atomic Energy Agency, 1967, pp. 343–354.

139. **Krabbenhoft KL et al.** Chemical sensitization of *Clostridium botulinum* spores to radiation in meat. *Applied microbiology,* 1964, **12**:424–427.

140. **Roberts TA, Ditchett PJ, Ingram M.** The effect of sodium chloride on radiation resistance and recovery of irradiated anaerobic spores. *Journal of applied bacteriology,* 1965, **28**:336–348.

141. **Kiss I et al.** Enhancement of the keeping quality of sliced packaged bread by ionizing radiation. In *Proceedings of the Fourth International Congress of Food Science & Technology, Madrid,* Vol. 5a, *New Preservation Methods.* Valencia, International Union of Food Science and Technology, 1974, pp. 62–63.

142. **Kiss I et al.** Relation between radiation resistance and salt sensitivity of spores of five strains of *C. botulinum* A, B and E. *Applied environmental microbiology,* 1978, **35**:533–539.

143. **Farkas J, Roberts TA.** The effect of sodium chloride, gamma irradiation and/or heating on germination and development of spores of *Bacillus cereus* in single germinants and complex media. *Acta alimentaria,* 1976, **5**:289–302.

144. **Chowdhury MS et al.** Influence of post-irradiation incubation temperature on recovery of radiation-injured *C. botulinum* 62A spores. *Applied environmental microbiology,* 1976, **32**:172–178.

145. **Snyder LD, Maxcy RB.** The effect of a_w of meat products on growth of radiation-resistant *Moraxella-Acinetobacter. Journal of food science,* 1979, **44**:33–36.

146. **Welch AB, Maxcy RB.** Characterization of radiation resistant hemolyticmicrococci isolated from chicken. *Journal of food science,* 1979, **44**:673–675.

147. **Welch AB, Maxcy RB.** Significance of hemolytic activity of some radiation-resistant micrococci in food. *Applied environmental microbiology,* 1979, **38**:902–905.

148. **Morgan BH, Reed JM.** Resistance of bacterial spores to gamma irradiation. *Food research,* 1954, **19**:357–366.

149. **Thayer DW.** Use of irradiation to kill enteric pathogens on meat and poultry. *Journal of food safety,* 1995, **15**:81–192.

150. **Collins CI, Murano EA, Wesley IV.** Survival of *Arcobacter butzleri* and *Campylobacter jejuni* after irradiation treatment in vacuum packaged ground pork. *Journal of food protection,* 1996, **59**:1164–1166.

151. **Grant IR, Patterson MF.** Sensitivity of foodborne pathogens to irradiation in the components of a chilled ready meal. *Food microbiology,* 1992, **9**:95–103.

152. **Tarkowski JA et al.** Low dose gamma irradiation of raw meat. I. Bacteriological and sensory quality effects in artificially contaminated samples. *International journal of food microbiology,* 1984, 1:13–23.

153. **Lambert AD et al.** Microbiological changes and shelf-life of MAP, irradiated fresh pork. *Food microbiology,* 1992, **9**:231–244.

154. **Clavero MRS et al.** Inactivation of *Escherichia coli* O157:H7, salmonellae and *Campylobacter jejuni* in raw ground beef by gamma irradiation. *Applied environmental microbiology,* 1994, **60**:2069–2075.

155. **Grant IR, Patterson MF.** Effect of irradiation and modified atmosphere packaging on the microbiological safety of minced pork under temperature abuse conditions. *International journal of food science and technology,* 1991, **26**:521–533.

156. **Maxcy RB, Tiwari NP.** Irradiation of meats for public health protection. In: *Radiation preservation of food.* Vienna, International Atomic Energy Agency, 1973, pp. 491–504.

157. **Thayer DW, Boyd G.** Gamma ray processing to destroy *Staphylococcus aureus* in mechanically deboned chicken meat. *Journal of food science,* 1992, **57**:848–851.

158. **Patterson M.** Sensitivity of Listeria monocytogenes to irradiation on poultry meat and in phosphate-buffered saline. *Letters in applied microbiology,* 1989, **8**:181–184.

159. **Huhtanen CN, Jenkins RK, Thayer DW.** Gamma radiation sensitivity of *Listeria monocytogenes. Journal of food protection,* 1989, **9**:610–613.

160. **Monk JD et al.** Irradiation inactivation of *Listeria monocytogenes* and *Staphylococcus aureus* in low- and high-fat, frozen and refrigerated ground beef. *Journal of food protection,* 1994, **57**:969–974.

161. **Thayer DW et al.** Effect of heat and ionizing radiation on *Salmonella typhimurium* in mechanically deboned chicken meat. *Journal of food protection,* 1991, **54**:718–724.

162. **Patterson M.** Sensitivity of bacteria to irradiation on poultry meat under various atmospheres. *Letters in applied microbiology,* 1988, **7**:55–58.

163. **El-Zawahry YA, Rowley DB.** Radiation resistance and injury of *Yersinia enterocolitica. Applied environmental microbiology,* 1979, **37**:50–54.

164. **Rashid HO, Ito H, Ishigaki I.** Distribution of pathogenic vibrios and other bacteria in imported frozen shrimps and their decontamination by gamma-irradiation. *World journal of microbiology and biotechnology,* 1992, **8**:494–499.

165. **Hau L-B, Liew M-H, Yeh L-T.** Preservation of grass prawns by ionizing radiation. *Journal of food protection,* 1992, **55**:198–202.

166. **El-Zawahry YA, Rowley DB.** Effect of certain factors on the radiation resistance and recovery of *Yersinia enterocolitica.* Abstracts, Annual Meeting for the American Society of Microbiology, 1978, **78**:190.

167. **Tiwari NP, Maxcy RB.** *Moraxella-Acinetobacter* as contaminants of beef and occurrence in radurized product. *Journal of food science,* 1972, **37**:901–903.

168. **Ito H, Sato T.** Changes in the microflora of Vienna sausages after irradiation with gamma rays and storage at 10 °C. *Agricultural and biological chemistry,* 1973, **37**:233.

169. **Welch AB, Maxcy RB.** Characterization of radiation-resistant vegetative bacteria in beef. *Applied microbiology,* 1975, **30**:242–250.

170. **Anderson AW et al.** Radio-resistant micrococcus. I. Isolation, morphology, cultural characteristics and resistance to gamma-radiation. *Food technology,* 1956, **10**:575–578.

171. **Johnson JL et al.** Nucleic acid homologies among oxidase-negative *Moraxella* species. *Journal of bacteriology,* 1970, **101**:568–573.

172. **Sanders SW, Maxcy RB.** Isolation of radiation-resistant bacteria without exposure to irradiation. *Applied environmental microbiology,* 1979, **38**:436–439.

173. **Herbert RA et al.** Bacteria active in the spoilage of certain seafoods. *Journal of applied bacteriology,* 1971, **34**:41–50.

174. **Duggan DE, Anderson AW, Elliker PR.** Inactivation of the radiation-resistant spoilage bacterium *Micrococcus radiodurans.* I. Radiation inactivation rates in three meat substrates and in buffer. *Applied microbiology,* 1963, **11**:398–403.

175. **Duggan DE, Anderson AW, Elliker PR.** Inactivation-rate studies on a radiation resistant spoilage microorganism. III. Thermal inactivation rates in beef. *Journal of food science,* 1963, **28**:130–134.

176. **Maxcy RB, Rowley DB.** Radiation-resistant vegetative bacteria in a proposed system of radappertized meats. In: *Food preservation by irradiation,* Vol. I. Vienna, International Atomic Energy Agency, 1978, pp. 347–359.

177. **Brooks BW et al.** Red-pigmented micrococci: a basis for taxonomy. *International journal of systematic bacteriology,* 1980, **30**:627–646.

178. **Ito H et al.** Isolation and identification of radiation-resistant cocci belonging to the genus *Deinococcus* from sewage sludges and animal feeds. *Agriculture and biological chemistry,* 1983, **47**:1239–1247.

179. **Setlow JK, Duggan DE.** The resistance of *Micrococcus radiodurans* to ultraviolet radiation. I. Ultraviolet-induced lesions in the cell's DNA. *Biochimica et biophysica acta,* 1964, **87**:664–668.

180. **Moseley BEB, Laser H.** Repair of X-ray damage in *Micrococcus radiodurans. Proceedings of the Royal Society,* 1965, **162**:210–222.

181. **Kitayama S, Matsuyama A.** Possibility of the repair of double-strand scissions in *Micrococcus radiodurans* DNA caused by gamma rays. *Biochemical and biophysical research communications,* 1968, **33**:418–422.

182. **Hansen MT.** Multiplicity of genome equivalents in the radiation-resistant bacterium *Micrococcus radiodurans. Journal of bacteriology,* 1978, **134**:71–75.

183. **Krabbenhoft KL, Anderson AW, Elliker PR.** Ecology of *Micrococcus radiodurans. Applied microbiology,* 1965, **13**:1030–1037.

184. **Davis NS, Silverman GJ, Masurowsky EB.** Radiation-resistant, pigmented coccus isolated from haddock tissue. *Journal of bacteriology,* 1963, **86**:294–298.

185. **Lewis NF.** Studies on a radio-resistant coccus isolated from Bombay Duck (*Harpodon nehereus*). *Journal of general microbiology,* 1971, **66**:29–35.

186. **Cho HD, Kitayama S, Matsuyama A.** Radiation sensitization of *Micrococcus radiodurans* by postirradiation incubation at nonpermissible temperature. *Radiation research,* 1974, **60**:333–341.

187. **Ito H, Iizuka H.** Taxonomic studies on a radio-resistant *Pseudomonas.* XII. Studies on the microorganisms of cereal grain. *Agricultural and biological chemistry,* 1971, **35**:1566–1571.

188. **Engvild KC, Berenstein D.** The radiation-resistant red bacterium from rice. *International journal of radiation biology,* 1975, **28**:191–193.

189. **Oyaizu H et al.** A radiation-resistant, rod shaped bacterium *Deinobacter grandis* gen. nov., sp. nov. with peptidoglycan containing ornithine. *International journal of systematic bacteriology,* 1987, **37**:62–67.

190. **Grant IR, Patterson MF.** A novel radiation-resistant *Deinobacter* sp. isolated from irradiated pork. *Letters in applied microbiology,* 1989, **8**:21–24.

191. **Shapiro A et al.** Minimal requirements in defined media for improved growth of some radio-resistant pink tetracocci. *Applied environmental microbiology,* 1977, **33**:129–133.

192. **Firstenberg-Eden R, Rowley DB, Shattuck E.** Thermal inactivation and injury of *Moraxella-Acinetobacter* cells in ground beef. *Applied and environmental microbiology,* 1980, **39**:159–164.

193. **Firstenberg-Eden R, Rowley DB, Shattuck E.** Factors affecting inactivation of *Moraxella-Acinetobacter* cells in an irradiation process. *Applied environmental microbiology,* 1980, **40**:480–485.

194. **Tan S, Maxcy RB**. Inactivation and injury of a hemolytic radiation resistant *Micrococcus* isolated from chicken meat. *Journal of food science,* 1982, **47**:1345–1349, 1353.

195. **Bruns MA, Maxcy RB**. Effect of selected solutes on growth and recovery of a radiation resistant *Moraxella* sp. *Journal of food science,*1978, **43**:1386–1389.

196. **King BL, Josephson ES**. Action of radiation on protozoa and helminths. In: Josephson ES, Peterson MS, eds. *Preservation of foods by ionizing radiation,* Vol. II. Boca Raton, FL, CRC Press, 1983, pp. 245–267.

197. *Ionizing energy in food processing and pest control. II. Applications.* Ames, IA, Council for Agricultural Science and Technology, 1989, pp. 21–23 (Task Force Report No. 115).

198. *Use of irradiation to control infectivity of food-borne parasites. Proceedings of a Final Research Coordination Meeting, Mexico 1991.* Vienna, International Atomic Energy Agency, 1993, pp. 1–14.

199. **Loaharanu P, Murrell D**. A role for irradiation in control of food borne parasites. *Trends in food science & technology,* 1994, **5**:190–195.

200. **Wilkinson VM, Gould GW**. *Food irradiation. A reference guide.* Oxford, Butterworth-Heinemann, 1996.

201. **Hamed MGE, Elias AN**. Feasibility of using gamma radiation for the control of the trematode *Heterophyes* sp. in the flesh of fish caught from brackish waters. *Egyptian journal of food science,*1974/1975, **2**:135–140 (English abstract).

202. **Murrell KD, Dubey JP**. Epidemiology and control of trichinellosis and toxoplasmosis. In: *Use of irradiation to control infectivity of food-borne parasites. Proceedings of a Final Research Coordination Meeting, Mexico, 1991.* Vienna, International Atomic Energy Agency, 1993, pp. 73–79.

203. **Engel RE, Post AR, Post RC**. Implementation of irradiation of pork for trichina control. *Food technology,* 1988, **42**:71–75.

204. **Schneider CR**. Radiosensitivity of *Entamoeba histolytica* cysts. *Experiments in parasitology,* 1960, **9**:87.

205. **Onyango-Abuje JA, Weinmann CJ**. Effect of gamma irradiation on the infectivity and development of *Hymenolepis nana* oncospheres (*Cestoda: Cyclophyllidea*). *Zeitschrift für Parasitenkunde,* 1974, **44**:111–166.

206. **Villella JB, Gould SE and Gomberg HJ**. Effects of cobalt-60 and X-ray on infectivity of *Ascaris* eggs. *Journal of parasitology,* 1958, **44**:85–92.

207. **Ito H, Iizuka H, Sato T**. A new radio-resistant yeast *Trichosporon oryzae* nov. sp. isolated from rice. *Agricultural and biological chemistry,*1974, **38**:1597–1602.

208. **Stehlik G, Kaindl K**. Microbiological studies on the influence of combined processes of heat and irradiation on the survival of *Saccharomyces cerevisiae* var. *ellipsoideus.* In: *Food irradiation.* Vienna, International Atomic Energy Agency, 1966, pp. 299–305.

209. **Okazawa Y**. *Reports of the Institute of Physical and Chemical Research,* 1971, **47**:211.

210. **McCarthy JA, Damoglou AP**. The effect of substrate on the radiation resistance of yeasts isolated from sausage meat. *Letters in applied microbiology,* 1996, **22**:80–84.

211. **Saravacos GD, Hatzipetrou LP, Georgiadou E.** Lethal doses of gamma radiation of some fruit spoilage microorganisms. *Food irradiation (Saclay)*, 1962, **31**:(1/2) A6.

212. **Fernandez A, Stehlik G, Kaindl K.** *The fungistatic effect of cobalt-60 gamma radiation on different concentrations of grape-juice yeasts. 2. Nonfermenting yeasts.* Seibersdorf, Seibersdorf Reactor Centre, 1967.

213. **Fernandez A, Stehlik G, Kaindl K.** *The fungistatic effect of cobalt-60 gamma radiation on different concentrations of grape-juice yeasts. 1. Juice-fermenting yeasts.* Seibersdorf, Seibersdorf Project Report, 1966.

214. **Eklund MW et al.** Development of yeast in irradiated Pacific crab meat. *Journal of food science*, 1965, **31**:424–431.

215. **Liciardello JJ, Ronsivalli LJ, Slavin JW.** The effect of oxygen tension on the spoilage microflora of irradiated and non-irradiated haddock (*Melanogrammus aegelefinus*) fillets. *Journal of applied bacteriology*, 1967, **30**:239–245.

216. **Malla SS, Diehl JF, Salunkhe DK.** *In vitro* susceptibility of strains of *Penicillium viridicatum* and *Aspergillus flavus* to beta radiation. *Experientia*, 1967, **23**:492–493.

217. **Münzner R.** [Some factors affecting the radiosensitivity of molds.] *Archiv für Mikrobiologie*, 1969, **64**:349–356 (in German).

218. **Sharma A, Padwal-Desai SR, Nair PM.** Aflatoxin producing ability of spores of *Aspergillus parasiticus* exposed to gamma radiation. *Journal of food science*, 1990, **55**: 275–276.

219. **Blank G, Corrigan D.** Comparison of resistance of fungal spores to gamma and electron beam radiation. *International journal of food microbiology*, 1995, **26**:269–277.

220. **Chelack WS et al.** Role of the competitive microbial flora in the radiation induced enhancement of ochratoxin production by *Aspergillus alutaceus* var. *alutaceus* NRRL 3174. *Applied and environmental microbiology*, 1991, **57**:2492–2496.

221. **Sharma A et al.** Influence of inoculum size of *Aspergillus parasiticus* spores on aflatoxin production. *Applied and environmental microbiology*, 1980, **40**:989–993.

222. **van der Riet WB, van der Walt WH.** Effect of ionizing radiation on ascopores of three strains of *Byssochlamys fulva* in apple juice. *Journal of food protection*, 1985, **48**:1016–1018.

223. **Kumee T et al.** Radiosensitivity of *Aspergillus versicolor* isolated from animal feeds and decomposition of sterigmatocystin by gamma irradiation. *Shokuhin shosha*, 1983, **18**:5–9.

224. **Székely JG et al.** Scanning electron microscope observations of growth and ochratoxin A production of *Aspergillus alutaceus* var. *alutaceus* (formerly *A. ochraceus*) on gamma-irradiated barley. *Food structure*, 1991, **10**:295–302.

225. **Webb BD, Thiers HD, Richardson R.** Studies in feed spoilage: inhibition of mould growth by gamma radiation. *Applied microbiology*, 1959, 7:329–333.

226. **Ito H, Iizuka H, Sato T.** Identification of osmiophilic *Aspergillus* isolated from rice and their radiosensitivity. *Agricultural and biological chemistry*, 1973, **37**:789–798.

227. **Paster N, Barkai-Golan R, Padova R.** Effect of gamma radiation on ochratoxin production by the fungus *Aspergillus ochraceus*. *Journal of the science of food and agriculture,* 1985, **36**:445–449.

228. **Mohyuddin M, Skoropad WP.** Effects of ^{60}Co gamma irradiation on the survival of some fungi in single samples of each of three different grades of wheat. *Canadian journal of botany,* 1970, **48**:217–219.

229. **Saleh YG, Mayo MS, Ahearn DC.** Resistance of some common fungi to gamma irradiation. *Applied and environmental microbiology,* 1988, **54**:2134–2135.

230. **Anellis A, Koch RB.** Comparative-resistance of strains of *Clostridium botulinum* to gamma rays. *Applied microbiology,* 1962, **10**:26–330.

231. **Grecz N.** Biophysical aspects of Clostridia. *Journal of applied bacteriology,* 1965, **28**:17–35.

232. **Segner WP, Schmidt CF.** Radiation resistance of spores of *Clostridium botulinum* type E. In: *Food irradiation.* Vienna, International Atomic Energy Agency, 1966, pp. 287–298.

233. **Roberts TA, Ingram M.** The resistance of spores of *Clostridium botulinum* type E to heat and radiation. *Journal of applied bacteriology,* 1965, **28**:125–138.

234. **Lawrence CA, Brownell LE, Graikoski JT.** Effect of cobalt-60 gamma radiation on micro-organisms. *Nucleonics,* 1953, **11**:9–11.

235. **Briggs A.** The resistance of spores of the genus *Bacillus* to phenol, heat and radiation. *Journal of applied bacteriology,* 1966, **29**:490–504.

236. **Härnulv BG, Snygg BG.** Radiation resistance of spores of *Bacillus subtilis* and *B. stearothermophilus* at various water activities. *Journal of applied bacteriology,* 1973, **36**:677–682.

237. **Friedman YS, Grecz N.** The role of heat resistance in thermorestoration of hydrated bacterial spores. *Acta alimentaria,* 1973, **2**:209–227.

238. **Grecz N et al.** Gamma radiation studies of *Clostridium botulinum* types A, B and E: biological aspects. In *Radiation preservation of food.* Vienna, International Atomic Energy Agency, 1973, pp. 177–191.

239. **Farkas J, Roberts TA.** The effect of the composition of the recovery medium upon the colony-forming capacity of clostridial spores damaged by gamma-radiation. *Acta alimentaria,* 1982, **11**:393–398.

240. **Grecz N et al.** Bacterial spores: biophysical aspects of recovery from radiation injury. *Journal of food processing and preservation,* 1978, **2**:315–337.

241. **Hashisaka AE et al.** Effects of gamma irradiation at –78 °C on microbial populations in dairy products. *Journal of dairy science,* 1990, **29**:201–204.

242. **Anellis A et al.** Radiation sterilization of prototype military foods: low-temperature irradiation of codfish cake, corned beef and pork sausage. *Applied microbiology,* 1972, **24**:453–462.

243. **Anellis A et al.** Low temperature irradiation of beef and methods for evaluation of a radappertized process. *Applied microbiology,* 1975, **30**:811–820.

244. **Wheaton E, Pratt GB, Jackson JM.** Radioresistance of five strains of *Clostridium botulinum* in selected food products. *Journal of food science,* 1961, **26**:345–350.

245. **Kim J H, Stegeman H, Farkas J.** Preliminary studies on radiation resistance of thermophilic anarobic spores and the effect of gamma radiation on their heat resistance. *International journal of food microbiology,* 1987, **5**:129–136.

246. **Kempe LL.** Combined effects of heat and radiation on food sterilization. *Applied microbiology,* 1955, **3**:346–352.

247. **Kan B, Goldblith SA, Proctor BE.** Complementary effects of heat and ionizing radiation. *Food research,* 1957, **22**:509–518.

248. **Licciardello JJ.** Complementary effect of thermal and ionizing energy. In: Goldblith SA, ed. *Exploration in future food processing techniques.* Cambridge, MA, MIT Press, 1963, pp. 37–45.

249. **Grecz N et al.** Combination treatment of spores of *C. botulinum* with heat plus radiation. In: *Microbiological problems in food preservation by irradiation.* Vienna, International Atomic Energy Agency, 1967, pp. 99–113.

250. **Gombas DE, Gomez RF.** Sensitization of *Clostridium perfringens* spores to heat by gamma radiation. *Applied environmental microbiology,* 1978, **36**:403–407.

251. **Josephson ES.** Radappertization of meat, poultry, fin fish, shell fish and special diets. In: Josephson ES, Petersen MS, eds. *Preservation of foods by ionizing radiation,* Vol. III. Boca Raton, FL, CRC Press, 1983, pp. 231–257.

252. **Ingram M, Thornley MJ.** The effect of low temperatures on the inactivation by ionizing radiations of *Clostridium botulinum* spores in meat. *Journal of applied bacteriology,* 1961, **24**:94–103.

253. **El-Bisi HM, Snyder OP, Levin RE.** Radiation death kinetics of *Clostridium botulinum* spores at cryogenic temperatures. In: Ingram M, Roberts TA, eds. *Botulism.* London, Chapman and Hall, 1966, pp. 89–107.

254. **Grecz N et al.** Effect of irradiation temperature in the range −196 to 95 °C on the resistance of spores of *C. botulinum* 33A in cooked beef. *Canadian journal of microbiology,* 1971, **17**:35–142.

255. **Anellis A et al.** Low-temperature irradiation of beef and methods for evaluation of a radappertization process. *Applied microbiology,* 1975, **30**:811–820.

256. **Esty JR, Meyer KF.** The heat resistance of spores of *B. botulinus* and allied anaerobes. *Journal of infectious diseases,* 1922, **31**:650–663.

257. **Schmidt CF.** Dose requirement for the radiation sterilization of food. In: *Report of the European Meeting on the Microbiology of Irradiated Foods, Paris.* Vol. 2, Appendix II. Rome, Food and Agriculture Organization, 1960.

258. **Ross EW.** Statistical estimation of 12D for radappertized foods. *Journal of food science,* 1974, **39**:800–806.

259. **Ross EW.** On the statistical estimation of inoculated packs. *Journal of food science,* 1976, **41**:578–584.

260. **Anellis A, Rowley DB, Ross EW.** Microbiological safety of radappertized beef. *Journal of food protection,* 1979, **42**:927–932.

261. **Anellis A et al.** Cryogenic gamma irradiation of prototype pork and chicken and antagonistic effect between *Clostridium botulinum* types A and B. *Applied environmental microbiology,* 1977, **34**:631–647.

262. **Anellis A et al.** Gamma irradiation at −30 ± 10 degrees of low level nitrite/nitrate ham. In: Barker AN et al., eds. *Spore research 1976, Vol. 2.* London, Academic Press, 1977, pp. 823–831.

263. **Rowley DB, Brynjolfsson A.** The potential utilization of radiation in the processing of food. *Food technology,* 1980, **34**:75–77.

264. **Thayer DW et al.** Use of irradiation to ensure the microbiological safety of processed meat. *Food technology,* 1986, **40**(4):159–162.

265. Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture. *Shelf-stable foods through irradiation processing.* Vienna, International Atomic Energy Agency, 1995.

266. Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture. *First FAO/IAEA Research Coordination Meeting on Production of Safe Shelf-Stable and Ready-to-Eat Foods Through Irradiation Processing. Belfast, 9–13 September 1996.* Vienna, International Atomic Energy Agency, 1996.

267. **Ingram M, Roberts TA.** Application of the "D-concept" to heat treatments involving curing salts. *Journal of food technology,* 1971, **6**:21–28.

268. **Hauschild AHW.** Assessment of botulism hazards from cured meat products. *Food technology,* 1982, **36**:95–104.

269. **Hauschild AHW, Simonsen B.** Safety assessment for shelf-stable canned cured meats – an unconventional approach. *Food technology,* 1986, **40**(4): 155–158.

270. **Lund BM.** Quantification of factors affecting the probability of development of pathogenic bacteria, in particular *Clostridium botulinum,* in foods. *Journal of industrial microbiology,* 1993, **12**:144–155.

271. **Farkas J, Andrássy É, Horti K.** Combined effects of physical treatments and sporostatic factors on *Clostridium sporogenes* spores. II. Combined effects of gamma radiation, heat treatment, reduced a_w and reduced pH in canned luncheon meat. *Acta alimentaria,* 1992, **21**:49–66.

272. **Lasta JA et al.** *Inhibition of toxigenesis of Clostridium botulinum type A in beef by combined processes.* Final Report, FAO/IAEA Research Co-ordination Meeting on Irradiation in Combination with Other Food Processes for Improving Food Quality. Vienna, International Atomic Energy Agency, 1995.

273. **Sullivan R et al.** Gamma radiation inactivation of coxsackievirus B-2. *Applied microbiology,* 1973, **26**:14–17.

274. **Massa D.** Radiation inactivation of foot and mouth disease virus in the blood, lymphatic glands and bone marrow of the carcasses of infective animals. In: *Food irradiation.* Vienna, International Atomic Energy Agency, 1966, pp. 329–346 (STI/PUB/127).

275. **Goldblith SA.** The inhibition and destruction of the microbial cell by radiation. In: Hugo WB, ed. *Inhibition and destruction of the microbial cell.* London, Academic Press, 1971, pp. 285–305.

276. **Rowley DB, Sullivan R, Josephson ES.** Indicators of viruses in foods preserved by ionizing radiation. In: Berg G, ed. *Indicators of viruses in water and food.* Ann Arbor, MI, Ann Arbor Science Publishers, 1978, pp. 355–382.

277. *Review of data on high dose (10–70 kGy) irradiation of food. International Consultative Group on Food Irradiation, Report of a Consultation, Karlsruhe, 29 August–2 September 1994.* Geneva, World Health Organization, 1995 (unpublished document WHO/FNU/FOS/95.10; available on request from the Programme of Food Safety and Food Aid, World Health Organization, 1211 Geneva 27, Switzerland).

278. **DiGirolamo R, Liston J, Matches J.** Effects of irradiation on the survival of virus in West Coast oysters. *Applied microbiology,* 1972, **24**:1005–1006.

279. **Heidelbaugh ND, Giron DJ.** Effect of processing on recovery of polio virus from inoculated foods. *Food science,* 1969, **34**:239–241.

280. **Ward RL.** Inactivation of poliovirus in wastewater sludge with radiation and thermoradiation. *Applied environmental microbiology,* 1977, **33**:1218–1219.

281. **Adams WR, Pollard E.** Combined thermal and primary ionization effects on bacterial virus. *Archives of biochemistry and biophysics,* 1952, **36**:311–322.

282. **Digioia GA.** Effect of temperature on radiosensitivity of Newcastle disease virus. *Applied microbiology,* 1970, **19**:455–457.

283. **Cliver DO.** Unlikelihood of mutagenic effects of radiation on viruses. In: *Wholesomeness of irradiated food.* Report of a Joint FAO/IAEA/WHO Expert Committee, WHO, Geneva, 1977 (WHO Technical Report Series, No. 604), pp. 43–44.

284. **Larkin EP.** *Thermal inactivation of viruses.* Natick, MA, United States Army Natick Research and Development Command, 1977 (Tech. Report 78/002).

285. **Skulberg A.** The resistance of *Clostridium botulinum* type E toxin to radiation. *Journal of applied bacteriology,* 1965, **28**:239–241.

286. **Wagenaar RO, Dack GM.** Studies on the inactivation of type A *Clostridium botulinum* toxin by irradiation with cobalt-60. *Food research,* 1960, **25**:279–284.

287. **Skulberg A.** Toxins produced by *Clostridium botulinum* and their radiation sensitivity. In: *Radiation sensitivity of toxins and animal poisons.* Vienna, International Atomic Energy Agency, 1970, pp. 19–30.

288. **Rose SA et al.** Studies on the irradiation of toxins of *Clostridium botulinum* and *Staphylococcus aureus. Journal of applied bacteriology,* 1988, **65**:223–229.

289. **Modi NK, Rose SA, Tranter HS.** The effect of irradiation and temperature on the immunological activity of staphylococcal enterotoxin A. *International journal of food microbiology,* 1990, **11**:85–92.

290. **Fenell AJ.** Aflatoxin in groundnuts. IX. Problems of detoxification of the aflatoxins. *Tropical science,* 1966, **8**:61–70.

291. **Miyaki K, Aibara K, Miura T.** Resistance of aflatoxin to chemical and biological changes by gamma irradiation. In: *Microbiological problems in food preservation by irradiation.* Vienna, International Atomic Energy Agency, 1967, pp. 57–64.

292. **Killebrew R et al.** Irradiation with ^{60}Co (gamma rays) of hard flour to destroy fungal spores and toxins. *Transaction of the American Nuclear Society,* 1968, **11**:85–86.

293. **van Dyck PJ et al.** Sensitivity of aflatoxin B_1 to ionizing radiation. *Applied environmental microbiology,* 1982, **43**:1317–1319.

294. **Temcharoen P, Thilly WG.** Removal of aflatoxin B_1 toxicity but not mutagenicity by 1 megarad gamma radiation of peanut meal. *Journal of food safety,* 1982, **4**:199–205.

295. **Aibara K, Miyaki K.** Aflatoxin and its radiosensitivity. In: *Radiation sensitivity of toxins and animal poisons. Proceedings of a Panel, Bangkok.* Vienna, International Atomic Energy Agency, 1970, pp. 41–62 (STI/PUB/243).

296. **Patel UD, Govindarajan P, Dave PJ.** Inactivation of aflatoxin B_1 by using the synergistic effect of hydrogen peroxide and gamma-radiation. *Applied environmental microbiology,* 1989, **55**:465–467.

297. **Baranyi J, Roberts TA.** Mathematics of predictive microbiology. *International journal of food microbiology,* 1995, **29**:490–504.

298. **Farkas J.** Special issue: predictive modelling. *International journal of food microbiology,* 1994, **23**.

299. **McMeekin TA et al.** *Predictive microbiology.* Chichester, Wiley, 1993.

300. International Commission on Microbiological Specifications for Food Modelling microbial responses in foods. In: *Microorganisms in foods. 5. Microbiological specifications of food pathogens.* London, Blackie, 1996, pp. 493–500.

301. **Whiting RC, Buchanan RL.** Predictive modelling. In: Doyle MP, Beuchat LR, Montville TJ, eds. *Food microbiology: fundamentals and frontiers.* Washington, DC, ASM Press, 1997, pp. 728–739.

302. **Thayer DW, Boyd G.** Elimination of *Escherichia coli* O157:H7 in meats by gamma irradiation. *Applied environmental microbiology,* 1993, **59**:1030–1034.

303. **Brynjolfsson A.** Mathematical models for microbial kill by radiation. In: *Proceedings, International Symposium on Food Preservation by Irradiation.* Vienna, International Atomic Energy Agency, 1978, Vol 1, 227–239.

304. **Cohen JS, Mason VC, Wierbicki E.** Flavor and textural changes in radappertized chicken as affected by temperature, NaCl and phosphate addition. *Journal of food science,* 1977, **42**:338–343.

305. **Wierbicki E.** Technology of irradiation preserved meats. In: *Proceedings of the 26th European Meeting of Meat Research Workers, Colorado Springs, CO, Vol. 1.* Chicago, American Meat Science Association, 1980, pp. 194–197.

306. **Raica N.** Data on wholesomeness studies. A progress report. *Food irradiation,* 1965, **5**:A2–A7.

307. **Tinsley IJ, Bone JF, Bubl EC.** The growth, reproduction, longevity, and histopathology of rats fed gamma-irradiated carrots. *Toxicology and applied pharmacology,* 1970, **16**:306–317.

308. **McGary VE, Shipman ME, Bernstein LM.** Acceptability of irradiated foods, dietary procedures. *Journal of the American Dietetics Association,* 1956, **32**:123–127.

309. **McGary VE, Shipman ME.** Acceptability of irradiated foods II. *Journal of the American Dietetics Association,* 1956, **32**:1059–1063.

310. **Plough IC et al.** *An evaluation in human beings of the acceptability, digestibility and toxicity of pork sterilized by gamma radiation and stored at room temperature.* Denver, CO, United States Army Medical Nutrition Laboratory, 1957 (Report 204).

311. **Lehman AJ, Laug EP.** Evaluating the safety of radiation-sterilized foods. *Nucleonics,* 1954, **12**:52–54.

312. **Mead JF, Griffith WH.** *Effect of ionizing radiation on the nutritive and safety characteristics of foods. Final Report.* 1959 (unpublished document; United States Army Contract No. DA-49-007-MD-579).

313. **Teply LJ, Kline BE.** *Possible carcinogenicity of irradiated foods. Reports on rat and mice studies on pork, grain, and egg, mixture of vegetable oils, lard and sterol concentrates, and mixture of ground meat, fish, cheese, and milk powder, in FDA Food Additive Petition, 7M 2056.* 1959 (unpublished document; United States Army Contract No. DA-49-007-MD-583).

314. **Read MS et al.** Successive generation rat feeding studies with a composite diet of gamma-irradiated foods. *Toxicology and applied pharmacology,* 1961, **3**:153–173.

315. **Malhotra OP, Reber EF.** Methionine and testosterone effect on occurrence of hemorrhagic diathesis in rats. *American journal of physiology*, 1963, **205**:1089–1092.

316. **Malhotra OP, Reber EF.** Effect of methionine and age of rats on the occurrence of hemorrhagic diathesis in rats fed a ration containing irradiated beef. *Journal of nutrition*, 1963, **80**:85–90.

317. **Malhotra OP, Reber EF, Norton HW.** Effect of methionine and vitamin K_3 on hemorrhages induced by feeding a ration containing irradiated beef. *Toxicology and applied pharmacology*, 1965, **7**:402–408.

318. **Blood FR et al.** Feeding of irradiated beef to rats. *Toxicology and applied pharmacology*, 1966, **8**:235–240.

319. **Read MS et al.** Short-term rat-feeding studies with gamma-irradiated food products II. Beef and pork stored at elevated temperature. *Toxicology and applied pharmacology*, 1959, **1**:417–425.

320. **Read MS, Kraybill HF, Witt NF.** Short-term rat feeding studies with gamma-irradiated food products. *Journal of nutrition*, 1958, **65**:39–51.

321. **Bone JF.** *The growth, breeding, longevity and histopathology of rats fed irradiated or control foods–(histopathological studies). Final Report.* 1963 (unpublished document; United States Army Contract No. DA 49-193-MD-2064).

322. **Richardson LR.** *A long-term feeding study of irradiated chicken and green beans using the rat as the experimental animal. Contract Report.* 1960 (unpublished document; United States Army Contract No. DA-49-007-MD-582).

323. **Richardson LR, Ritchey SJ, Rigdon RH.** A long-term feeding study of irradiated foods using rats as experimental animals. *Federation proceedings*, 1960, **19**:1023–1027.

324. **Rigdon RH.** *Pathologic changes in rats fed chicken and green beans (Richardson study).* 1959 (unpublished document; United States Army Contract No. 49-007-MD-912).

325. **Phillips AW, Newcomb HR, Shanklin D.** *Long-term rat feeding studies: irradiated chicken stew and cabbage.* Syracuse, NY, Biological Research Laboratories, Syracuse University Research Institute, 1961 (United States Army Contract No. DA-49-007-MD-783).

326. **Radomski JL et al.** Chronic toxicity studies on irradiated beef stew and evaporated milk. *Toxicology and applied pharmacology*, 1965, **7**:113–121.

327. **Tinsley IJ, Bone JF, Bubl EL.** The growth, reproduction, longevity and histopathology of rats fed gamma irradiated peaches. *Toxicology and applied pharmacology*, 1963, **5**:464–477.

328. **Bubl EC, Butts JS.** The growth, breeding and longevity of rats fed irradiated and non-irradiated pork. *Journal of nutrition*, 1960, **70**:211–218.

329. **Bubl EC.** *Short and long-term survival and breeding capacity of rats fed high levels of foodstuffs sterilized by ionizing radiation (ground pork).* 1961 (unpublished document; United States Army Contract No. DA-49-007-MD-580).

330. **Brin M, Ostashever AS, Kalinsky H.** The effects of feeding irradiated pork, bread, green beans, and shrimp to rats on growth and on five enzymes in blood. *Toxicology and applied pharmacology*, 1961, **3**:606–617.

331. **Phillips AW, Newcomb HR, Shanklin D.** *Long-term rat feeding studies – irradiated shrimp and oranges. Final Report.* 1961 (unpublished document; United States Army Contract No. DA-49-007-MD-791).

332. **Paynter OE.** *Long-term feeding and reproduction studies on irradiated corn and tuna fish. Final Report.* Falls Church, VA, Hazleton Laboratories, 1959. (United States Army Contract No. DA-49-007-MD-788).

333. **Becker RR et al.** Nutritional and biochemical effects of irradiation. *Food technology*, 1956, **10**:61–64.

334. **McGown EL, Lewis CM, Waring PP.** *Investigation of possible antithiamine properties in irradiation sterilized chicken. Final Report.* Presidio of San Francisco, CA, Division of Nutrition Technology, Letterman Army Institute of Research, 1979 (United States Army Contract No. DL-47).

335. **Barna J.** *Extract of the final report: multigeneration wholesomeness feeding study on irradiated complete diet fed to rats.* Budapest, Central Food Research Institute, 1972.

336. **Saint-Lèbe L.** Radiation et radappertisation des provendes pour rats et souris apéniques et hétéroxéniques. [Irradiation of commercial diets for axenic and heteroaxenic rats and mice.] *Recueil de medicine veterinaire*, 1979, **155**:805–810.

337. *Teratogenic studies on albino rats fed diets containing either irradiated ground black pepper, mild paprika or spice mixture.* Karlsruhe, International Project in the Field of Food Irradiation, 1979 (Project No. IFIP-R-52).

338. **Aravindakshan M et al.** Multigeneration feeding studies with an irradiated whole diet. In: *Food preservation by irradiation, proceedings series,* Vol. 2. Vienna, International Atomic Energy Agency, 1978, pp. 41–51.

339. **Metwalli OM.** Study on the effect of food irradiation on some blood serum enzymes in rats. *Zeitschrift für Ernährungswissenschaften*, 1977, **16**:18–21.

340. **van Logten MJ, Berkvens JM, Kroes R.** Investigation of the wholesomeness of autoclaved or irradiated feed in rats. Bilthoven, Netherlands National Institute of Public Health, 1978 (Report 33/78 Alg. Tox).

341. **van Logten MJ et al.** Long-term wholesomeness study of autoclaved or irradiated pork in rats. Bilthoven, Netherlands National Institute of Public Health, 1983 (Report No. 617401 001).

342. **Rojo MMI, Fernandez CM.** Inducción y reversión de alteraciones moleculares y citológicas por ingestión de alimento irradiado con dosis esterilizante. [Induction and reversion process of molecular and cytological alterations after highly irradiated food ingestion in mice.] *Nucleotécnica*, 1984, **4**:48–54.

343. **Renner HW, Reichelt D.** Zur Frage der gesundheitlichen Unbedenklichkeit hoher Konzentrationen von freien Radikalen in bestrahlten Lebensmitteln. [Safety of high concentrations of free radicals in irradiated foodstuffs.] *Zentralblatt für Veterinärmedizin, Reihe B*, 1973, **20**:648–660.

344. **Lang K.** Toxicity of irradiated fat. *Food and cosmetics toxicology*, 1963, 1:125.

345. **Verschuuren HG, van Esch GJ, van Kooy JG.** Ninety day rat feeding study on irradiated strawberries. *Food irradiation*, 1966, 7:A17–A21.

346. **McKee RW et al.** *The influence of irradiated lipids on the incidence of spontaneous mammary carcinoma and hepatoma in strains A/HE and C3H mice. Final Report.* Los Angeles, CA, Department of Physiological Chemistry, University of California, 1959 (United States Army Contract No. DA-49-007-MD-570).

347. **Dixon MS et al.** Influence of irradiated bacon lipids on body growth, incidence of cancer, and other pathologic changes in mice. *Journal of food science*, 1961, **26**:611–617.

348. **Deichmann WB**. *Mouse carcinogenicity study.* 1963 (unpublished document; United States Army Contract No. DA-49-007-MD:781).

349. **Radomski JL et al.** A study of the possible carcinogenicity of irradiated foods. *Toxicology and applied pharmacology*, 1965, **7**:122–127.

350. **Calandra JC, Kay JH**. *The carcinogenic properties of irradiated foods.* Chicago, IL, Industrial Bio-Test Laboratories, 1961 (United States Army Contract No. DA-49-007-MD-895).

351. **Monsen H**. Heart lesions in mice induced by feeding irradiated foods. *Federation proceedings*, 1960, **19**:1031–1034.

352. **Monsen H**. *Heart lesions in mice. Final Report.* 1963 (unpublished document; United States Army Contract No. DA–49–007–MD–794).

353. **Monsen H**. *Heart lesions in mice. Addendum.* 1965 (unpublished document; United States Army Contract No. DA-49-007-MD-794).

354. **Thompson SW et al.** Histopathology of mice fed irradiated foods. *Journal of nutrition*, 1965, **87**: 274–284.

355. **Thompson SW et al.** *Histopathology of mice fed irradiated foods. Technical Report No. 279.* Denver, CO, 1963 (Project 3:012501-A-803).

356. **Raltech Scientific Services**. *Mouse teratology study. Final Report.* Washington, DC, National Technical Information Service, 1977 (unpublished document; United States Army Contract No. DAMD 17-76-C-6047; order number PB84–187–048).

357. **Raltech Scientific Services**. *A chronic toxicity, oncogenicity and multigeneration reproductive study using CD-1 mice to evaluate frozen, thermally sterilized, cobalt-60 irradiated, and 10 MeV electron irradiated chicken meat. Final Report.* Washington, DC, National Technical Information Service, 1984 (unpublished document; United States Army Contract No. DAMD 17-76-C-6047; order number PB84-187012).

358. **Maffei G, Mazzali R, DeSantis C.** [Effects on hematological parameters in Swiss albino mice of short-term treatment with an irradiated diet.] *Giornale di medicina militare*, 1967, **117**:369–375 (in Italian).

359. **Biagini C et al.** Accrescimiento e fertilità di topi alimentati per due anni con una dieta irradiata. [Growth and fertility of mice fed an irradiated diet for two years.] *Giornale di medicina militare*, 1967, **117**:347–368.

360. **Porter G, Festing M.** A comparison between irradiated and autoclaved diets for breeding mice, with observations on palatability. *Laboratory animals*, 1970, 4:203–213.

361. **Bugyaki L et al.** Do irradiated foodstuffs have a radiomimetic effect? II. Trials with mice fed wheat meal irradiated at 5 Mrad. *Atompraxis*, 1968, **14**:112–118.

362. **Hale MW, Schroeder WF, Sikes D.** *Growth, reproduction, mortality and pathologic changes in dogs fed gamma-irradiated bacon for two years. Final Report.* 1960 (unpublished document; United States Army Contract No. DA-49-007-MD-780).

363. **Reber EF et al.** The effect of feeding irradiated beef to dogs. I. Growth. *American journal of veterinary research.* 1960, **21**:367–370.

364. **Reber EF et al.** The effects of feeding irradiated beef to dogs. II. Reproduction and pathology. *American journal of veterinary research,* 1962, **23**:74–76.

365. **Clarkson TB, Pick JR.** *The effect of control-ground beef and irradiated 5.58 Mrad ground beef consumption on reproductive performance in the beagle. Final Report.* 1964 (unpublished document; United States Army Contract No. DA-49-193-MD-2098).

366. **Deichmann WB.** *Long-term dog and rat feeding experiment employing irradiated evaporated milk. Final Report.* 1961 (unpublished document; United States Army Contract No. DA 49-007-MD-785).

367. **Blood FR et al.** Feeding of irradiated chicken, beef, and pineapple jam to dogs. *Toxicology and applied pharmacology,* 1966, **8**:241–246.

368. **Larson PS et al.** *Long-term dog feeding tests on irradiated green beans and fruit compote. Final Report.* Richmond, VA, Departments of Pharmacology and Pathology, Medical College of Virginia, 1957 (United States Army Contract No. DA-49-007-MD-786).

369. **McCay CM, Rumsey GL.** *Effect of ionized radiation on the nutritive value of food (pork) as determined by growth, reproduction, and lactation studies with dogs. Final Report.* Ithaca, NY, Department of Animal Husbandry, Cornell University,1960 (United States Army Contract No. DA-49-007-MD-600).

370. **McCay CM, Rumsey GL.** *Effect of ionized radiation on the nutritive value of food (tuna fish) as determined by growth, reproduction, and lactation studies with dogs. Final report.* 1960 (unpublished document; United States Army Contract No. DA-49-007 MD-600).

371. **McCay CM, Rumsey GL.** Effect of irradiated meat upon growth and reproduction of dogs. *Federation proceedings,* 1960, **19**:1027–1030.

372. **Raltech Scientific Services.** *Irradiated sterilized chicken meat: a chronic toxicity and reproductive performance study in beagle dogs.* Washington, DC, National Technical Information Service, 1982 (order number PB84-187020).

373. **Cheng KW, Zhang DJ.** Investigation of the wholesomeness of gamma irradiated fresh pork – long-term animal feeding studies (Abstract). *Radiation physics and chemistry,* 1983, 22:792.

374. **Smid K, Dvorak J, Hrusovsky J.** [Effect of radiation-treated feeds on some biochemical indicators of nutrition level achieved with energy nutrients.] *Veterinary medicine,* 1985, **30**:531–541 (in Czech).

375. **Loosli JK et al.** *Components of ionized irradiated meats injurious to reproduction. Final Report.* Ithaca, NY, Department of Animal Health, Cornell University, 1964 (United States Army Contract No. DA 49-193-MD-2097).

376. **Blood FR et al.** *Long-term monkey feeding experiment on irradiated peaches, whole oranges and peeled oranges.* Nashville, TN, Departments of Biochemistry and Pathology, Vanderbilt University School of Medicine, 1963 (United States Army Contract No. DA-49-007-MD-779 and DA-49-193-MD-2286).

377. **Koch F et al.** Auswirkung der Fütterung van mit 10 kGy bestrahlter Gerste auf hämatologische und lipidstoffwechselparameter wachsender Wachteln. [Effect of feeding 10 kGy irradiated barley on hematological and lipid metabolism parameters in growing quail.] In: *Lebensmittelbestrahlung-2, Gesamtdeutsche Tagung.* Karlsruhe, Bundesforschungsanstalt für Ernährung, 1993, pp. 110–116.

378. **Döllstädt R et al., eds.** Gesundheitliche Verträglichkeit mit sehr hohen Dosen bestrahlen Tierfutters. In: *Lebensmittelbestrahlung-1, Gesamtdeutsche Tagung.* Institut für Sozialmedizin und Epidemiologie des Bundesgesundheitsamtes, 1991, 1:168–177.

379. **Raltech Scientific Services.** *Hamster teratology study on irradiated chicken. Final Report.* Washington, DC, National Technical Information Service, 1978 (United States Army Contract No. DAMD 17-76-C-6047; order number PB84-187048).

380. **Strik JJTWA.** Toxicologisch anderzoek van bestraald dieet bij varkens. [Toxicological investigations on irradiated feed in pigs.] *Tijdschrift voor Diergeneeskunde*, 1986, 111:240–243.

381. **Takigawa A, Danbara H, Ohyama Y.** Gamma ray irradiation to semi-purified diet peroxide formation and its effects on chicks. *Japanese journal of zootechnical science*, 1976, 47:292–302.

382. **Joner PE, Underdal B, Lunde G.** Mutagenicity testing of irradiated cod fillets. *Lebensmittel Wissenschaft und Technologie*, 1978, 11:224–226.

383. **Niemand JG et al.** A study of the mutagenicity of irradiated sugar solutions: implications for the radiation preservation of subtropical fruits. *Journal of agricultural and food chemistry*, 1983, 31:1016–1020.

384. **Bugyaki L, Lafontaine A, Moutschen-Dahmen M.** Have irradiated foods radiomimetic effect? Part I. Experiment on *Escherichia coli* C 600 (2) lvsogene. *Atompraxis*, 1963, 9:194–196.

385. **Vijayalaxmi.** Sister chromatid exchanges in human peripheral blood lymphocytes grown in irradiated medium. *International journal of radiation biology*, 1980, 37:581–583.

386. **Joner PE, Underdal B.** Mutagenicity testing of irradiated herring fillets. *Lebensmittel Wissenschaft und Technologie*, 1980, 13:293–296.

387. **Münzner R, Renner HW.** Mutagenicity testing of irradiated onion powder. *Journal of food science*, 1981, 46:1269–1270, 1275.

388. **Central Food Research Institute.** *Mutagenicity testing of irradiated ground paprika, IFIP-R44.* Karlsruhe, International Project in the Field of Food Irradiation, 1977.

389. **Farkas J, Andrássy É, Incze K.** Evaluation of possible mutagenicity of irradiated spices. *Acta alimentaria*, 1981, 10:129–135.

390. **Schubert J et al.** Irradiated strawberries – chemical, cytogenetic and antibacterial properties. *Journal of agricultural and food chemistry*, 1973, 21:684–692.

391. **Shaw MW, Hayes E.** Effects of irradiated sucrose on the chromosomes of human lymphocytes *in vitro. Nature*, 1966, 211:1254–1256.

392. **Bradley MV, Hall LL, Trebikock SJ.** Low pH of irradiated sucrose in induction of chromosome aberrations. *Nature*, 1968, 217:1182–1183.

393. **Aiyar AS, Rao S.** Studies on mutagenicity of irradiated solutions in *Salmonella typhimurium. Mutation research*, 1977, **48**:17–28.

394. **Münzner R.** Untersuchungen zum mutagenen Potential von gebratenem Fleisch. [Investigations on the mutagenic potential of fried meat.] *Fleischwirtschaft*, 1983, **63**:611–613.

395. **Mittler S.** Failure of irradiated beef and ham to induce genetic aberrations in *Drosophila. International journal of radiation biology*, 1979, **35**:583–588.

396. **Lusskin RM.** *Evaluation of the mutagenicity of irradiated sterilized chicken by the sex-linked recessive lethal test in Drosophila melanogaster. Final Contract Report.* Madison, WI, Raltech Scientific Services, 1979.

397. **Raltech Scientific Services.** *Dominant lethal study. Final Report.* Washington, DC, National Technical Information Service, 1978 (unpublished document; United States Army Contract No. DAMD 17-76-C-6047; order number PB84-187053).

398. **Varma MB et al.** Non-induction of dominant lethal mutations in mice fed gamma-irradiated glucose. *International journal of radiation biology*, 1982, **42**:559–563.

399. **Varma MB et al.** Mutagenic effects of irradiated glucose in *Drosophila melanogaster. Food and chemical toxicology*, 1982, **20**:947–949.

400. **Varma MB et al.** Lack of mutagenicity of irradiated glucose in *Salmonella typhimurium* using host-mediated assay. *Experientia*, 1985, **41**:396–397.

401. **Varma MB et al.** Lack of clastogenic effects of irradiated glucose in somatic and germ cells of mice. *Mutation research*, 1986, **169**:55–59.

402. **Moutschen-Dahmen M, Moutschen J, Ehrenberg L.** Pre-implantation death of mouse eggs caused by irradiated food. *International journal of radiation biology*, 1970, **18**:201–216.

403. **Johnston-Arthur T et al.** Mutagenicity of irradiated food in the host mediated assay system. *Studia biophysica, Berlin*, 1975, **50**:137–141.

404. **Chauhan PS et al.** Studies on dominant lethal mutations in third generation rats reared on an irradiated diet. *International journal of radiation biology*, 1975, **28**:215–223.

405. **Chauhan PS et al.** Dominant lethal mutations in male mice fed gamma-irradiated diet. *Food and cosmetics toxicology*, 1975b, **13**:433–436.

406. **Leonard A, Wilcox M, Schietccatte W.** Mutagenicity tests with irradiated food in the mouse. *Strahlentherapie*, 1977, **153**:349–351.

407. **Johnston-Arthur T et al.** Investigation on irradiated standard diets and their extract components on the possible mutagenic effect in the 'host mediated assay' using *Salmonella typhimurium* G 46 and TA 1530. *Die Bodenkultur*, 1979, **30**:95–107.

408. **Anderson D et al.** Irradiated laboratory animal diets. Dominant lethal studies in the mouse. *Mutation research*, 1981, **80**:333–345.

409. **Chopra VL.** Tests on *Drosophila* for the production of mutations by irradiated medium or irradiated DNA. *Nature*, 1965, **208**:609–700.

410. **Chaubey RC et al.** Cytogenetic studies with irradiated ground paprika as evaluated by the micronucleus in mice. *Acta alimentaria*, 1979, **8**:197–201.

411. **Farkas J, Andrássy É.** Prophage lambda induction (Inductest) of blood of rats fed irradiated spices. *Acta alimentaria*, 1981, **10**:137–142.

412. **Barna J.** Genotoxicity test of irradiated spice mixture by dominant lethal test. *Acta alimentaria*, 1986, **15**:47–56.

413. **Tanaka N et al.** Induction of polyploids in bone marrow cells and micronuclei in reticulocytes in Chinese hamsters and rats fed with an irradiated wheat flour diet. In: Matsuyama A, ed. *Final report of the Food Irradiation Research Committee for 1986–1991.* Tokyo, The Japan Isotopes Association, 1992, pp. 212–220.

414. **Bernardes B et al.** Short term toxicity studies of irradiated black beans (*P. vulgaris*). In: *Wholesomeness of the process of food irradiation.* Vienna, International Atomic Energy Agency, 1981, pp 67–80 (IAEA-TECDOC 256).

415. **Eriksen WH, Emborg C.** The effect on pre-implantation death of feeding rats on radiation-sterilized food. *International journal of radiation biology*, 1972, **22**:131–135.

416. **Münzner R, Renner HW.** Mutagenitätsprüfung von bestrahlten Versuchstierfutter im "host-mediated assay" mit *Salmonella typhimurium* G46. [Mutagenicity testing of irradiated laboratory animal diet by the host mediated assay with *S. typhimurium* G46.] *International journal of radiation biology*, 1975, **27**:371–375.

417. **Renner HW.** Chromosome studies on bone marrow cells of Chinese hamsters fed a radiosterilized diet. *Toxicology*, 1977, **8**:213–222.

418. **Münzner R, Renner HW.** Mutagenitätsprüfung von bestrahlten Versuchstierfutter im "host-mediated assay" mit *Salmonella typhimurium* TA 1530. [Mutagenicity testing of irradiated laboratory animal diet by the host mediated assay with *S. typhimurium* TA 1530.] *Zentralblatt für Veterinarmedizin B*, 1976, **23**:117–121.

419. **Rinehart RR, Ratty FJ.** Mutation in *Drosophila melanogaster* cultured on irradiated food. *Genetics*, 1965, **52**:1119–1126.

420. **Rinehart RR, Ratty FJ.** Mutation in *Drosophila melanogaster* cultured on irradiated whole food or food components. *International journal of radiation biology*, 1967, **12**:347–354.

421. **Renner HW, Grünewald T, Ehrenberg-Kieckebusch W.** Mutagenitätsprüfung bestrahlter Lebensmittel mit dem "dominant lethal test". [Mutagenicity testing of irradiated foodstuffs using the dominant lethal test.] *Humangenetik*, 1973, **18**:155–164.

422. **Ross MA, Garner FM, Hood E.** *Final summary report for rat feeding studies, radiation and sterilization of foods (Project No. 6-60-01-001 02), Nutrition: radiation and sterilization of foods.* Washington, DC, Veterinary Division, Department of Pathology, United States Armed Forces Institute of Pathology, 1964.

423. **Raica N et al.** *Wholesomeness of irradiated food.* Presented at the Proc. International Conference on Radiation Research, United States Army Natick Laboratories, Natick, MA, 14–16 January 1963, pp. 168–184.

424. United States Food and Drug Administration. *Irradiation in the production, processing, and handling of food; final rule.* Federal register, 51 FR 13375-13399, 18 April 1986.

425. **Ross MA, Garner FM, Hood E.** *Report of observations for dog feeding studies, Project No. (6-60-01-001 02), Nutrition: radiation and sterilization of foods.* Washington, DC, Veterinary Division, Department of Pathology, United States Armed Forces Institute of Pathology, 1964.

426. United States Food and Drug Administration. *Irradiation in the production, processing and handling of food; final rule.* Federal register 55 FR 18538-18544, 2 May 1990.

427. **Delincée H, Pool-Zobel BL.** Genotoxic properties of 2-dodecylcyclobutanone, a compound formed on irradiation of food containing fat. *Radiation physics and chemistry,* 1998, **52**:39–42.

428. **Levy LM et al.** *An assessment of the possible toxic effects to human beings of short-term consumption of food sterilized with gamma rays.* Denver, CO, United States Army Medical Nutrition Laboratory, 1957 (Report No. 203).

429. **Bierman EL et al.** *Short-term human feeding studies of foods sterilized by gamma radiation and stored at room temperature.* Denver, CO, United States Army Medical Nutrition Laboratory, 1958 (Report No. 224).

430. **McGary VE et al.** *Acceptability of irradiated food consumed by human subjects.* Denver, CO, United States Army Medical Nutrition Laboratories, 1957 (Report No. 200).

431. **Killoran JJ.** Chemical and physical changes in food packaging materials exposed to ionizing radiation. *Radiation research reviews*, 1972, **3**:369–388.

432. **Agarwal SR, Kumta US, Sreenivasan A.** Assessment of suitability of flexible packaging materials for packaging of irradiated foods. *Journal of food science technology (Mysore)*, 1972, **9**:166–170.

433. **Reichmanis E, O'Donell JH,** eds. *The effects of radiation on high-technology polymers.* Washington, DC, American Chemical Society Symposium Series No. 381, 1989.

434. **Dole M,** ed. The radiation chemistry of macromolecules, Vol. 1–2. New York, Academic Press, 1972.

435. **Stryer L.** *Biochemistry*, 2nd ed. San Francisco, CA, W.H Freeman, 1981, Ch. 24, pp. 560, 566.

436. **Chapiro A.** General consideration of the radiation chemistry of polymers. *Nuclear instruments and methods in physics research,* 1995, **105**: 5–7.

437. **Killoran JJ.** Packaging irradiated food. In: Josephson ES, Peterson MS, eds. *Preservation of food by ionizing radiation,* Vol. II. Boca Raton, FL, CRC Press, 1983.

438. **Chuaqui-Offermanns N.** Food packaging materials and radiation processing of food: a brief review. *Radiation physics and chemistry*, 1989, **34**:1005–1007.

439. **Haruvy Y.** Radiation durability and functional reliability of polymeric materials in space systems. *Radiation physics and chemistry*, 1990, **35**:204–212.

440. **Haruvy Y.** Risk assessment of atomic-oxygen-effected surface erosion and induced outgassing of polymeric materials in space systems. *European Space Agency journal,* 1990, **14**:109–119.

441. **Haruvy Y.** Radiation durability and functional reliability of polymeric materials for packaging of irradiated-food. Inter-Regional Workshop oral presentation *"Proper Use of Ionizing Radiation to Reduce Post-Harvest Food Losses",* ICGFI (FAO, IAEA, WHO), Nethania, Israel, 1989.

442. **Hitchon JW.** Radiation stability of plastics and rubbers. Harwell, Atomic Energy Research Establishment, 1983 (AERE-3251 (Rev.)).

443. **Bouquet FL, Winslow JW.** Radiation effects response data for synthetic organic insulators and dielectrics. *IEEE Transactions on nuclear science,* 1984, **31**(6):1387.

444. **DuPont Bull.** *Kapton–Polymide film, summary of properties.* E–72087, Wilmington, DE, 1985.

445. **Bouquet FL, Hriber VF, Metzler EC.** Radiation effects measurements on spacecraft electrostatic discharge tapes, thermal blankets, and thermo-optical coatings. *IEEE Transactions on nuclear science* 1984, **31**(6):1393.

446. **Meyer K et al.** Ionizing radiation effects on spacecraft polyimide. *IEEE Transactions on nuclear science* 1984, **31**(6):1344.

447. **Bouquet FL, Phillips A, Russell DA.** Simulated space radiation effects on dielectics and coatings. *IEEE Transactions on nuclear science*, 1983, **30**(6):4090.

448. **Coulter DR et al.** *Effects of energetic protons on polymeric materials: experimental studies and degradation models.* Washington, DC, National Technical Information Service, 1986 (United States Army, order number N86281961 XSP), JPL Publication.

449. **Funk JG, Sykes GF Jr.** Space radiation effects on poly[aryl-ether-ketone] thin films and composites. SAMPE, 1988, **19**:19–26.

450. **Bögl KW et al.** *Ionizing radiation for sterilization of drugs and medical products, Vol. I-IX.* Berlin, Institut für Strahlenhygiene des Bundesgesundheitsamtes (Institute for Radiation Hygiene, Federal Office for Health (BGA)), 1978–1993.

451. **Bögl KW et al.** *Detection methods of irradiated products, Vols. 12 and 14.* Berlin, Institut für Strahlenhygiene des Bundesgesundheitsamtes (Institute for Radiation Hygiene, Federal Office for Health (BGA)), 1993.

452. **Bögl KW et al.** *Effects of ionizing radiation on polymers. 1. Food packaging materials, Vol. 5.* Berlin, Institut für Strahlenhygiene des Bundesgesundheitsamtes (Institute for Radiation Hygiene, Federal Office for Health (BGA)), 1992.

453. **Bögl KW et al.** *Effects of ionizing radiation on polymers. 2. Ultra-high molecular weight polyethylene, Vol. 9.* Berlin, Institut für Strahlenhygiene des Bundesgesundheitsamtes (Institute for Radiation Hygiene, Federal Office for Health (BGA)), 1993.

454. **Pyne GO, Schmiege CC.** Survey of packaging requirements for radiation pasteurized foods. USAEC Contract AT(11-1)-989. Chicago, IL, Continental Can Company, 1962 (National Technical Information Service, order number ADA–307021).

455. **Buchalla B, Schuttler C, Bögl KW.** Effects of ionizing radiation on plastic food packaging materials: a review. Part 1. Chemical and physical changes. *Journal of food protection*, 1993, **11**:991–997.

456. **Buchalla R, Schuttler C, Bögl KW.** Effects of ionizing radiation on plastic food packaging materials: a review. Part 2. Global migration and the fate of additives. *Journal of food protection*, 1993, **11**:998–1005.

457. **Welt MA, Welt AM.** Food irradiation and packaging. *Activities report of the R&D Associates,* 1993, **45**: 85–95.

458. **Pyne GO, Spiegl CJ, Long FE.** Study of extractable substances and microbial penetration of polymeric packaging materials to develop flexible plastic containers for radiation sterilized foods. Natick, MA, United States Army

Laboratories, 1969 (Contract No. DA19-129-AMC-162(N), National Technical Information Service order number AD-685-831).

459. **Killoran JJ.** Irradiation of multilayered materials for packaging thermoprocessed foods. In: *Chemistry of food packaging. (Advances in chemistry series, 135)* Washington, DC, American Chemical Society, 1974, pp. 87–94.

460. **Baker RW et al.** Animal feeding study protocol for irradiated sterilized test foods. Madison, WI, Raltech Scientific Services, 1984 (National Technical Information Service order number PB84-186998, 654-837).

461. **Rojas de Gante C, Pascat B.** Effects of β ionizing radiation on the properties of flexible packaging materials. *Packaging technology and science*, 1990, **3**:97–115.

462. **Tripp GE.** Packaging of irradiated foods. *International journal of applied radiation isotopes*, 1959, **6**:199–206.

463. **Killoran JJ.** Chemical and physical changes in food packaging materials exposed to ionizing radiation. *Radiation research reviews*, 1972, **3**:369–388.

464. **Klicast D.** Irradiation of packaged food. In: Johnston DE, Stevenson MH, eds. *Food irradiation and the chemist. Royal Society of Chemistry, Special Publication*, 1990, **86**:140–152.

465. **Hernandez RJ, Giacin JR.** Factors affecting permeation, sorption, and migration processes in package-product systems. In: Taub IA, Singh RP, eds. *Food storage stability*. Boca Raton, FL, CRC Press, 1998, pp. 269–329.

466. *Training manual on operation of food irradiation facilities.* Vienna, International Atomic Energy Agency, 1992.

467. **United Kingdom. Panel on Gamma and Electron Irradiation.** Code of practice for the validation and routine monitoring of sterilization by ionizing radiation. *Radiation physics and chemistry*. 1989, **33**:245–249.

468. **Nam JW.** Standardization of high doses in radiation processing, *IAEA bulletin*, 1988, **4**:41–43.

469. **Chadwick KH, Ehlermann DAE, McLaughlin WL.** Manual of food irradiation dosimetry. Vienna, International Atomic Energy Agency, 1977 (IAEA Technical Report Series No. 178).

470. **McLaughlin WL et al.** Dosimetry for radiation processing. London, Taylor and Francis, 1989.

471. **Mahesh K, Vij DR,** eds. Techniques of radiation dosimetry. New Delhi, Wiley Eastern, 1985.

472. **Regulla DF.** Dosimetry for food irradiation. In: Bögl KW, Regulla DF, Suess MJ, eds. *Health impact, identification, and dosimetry of irradiated foods.* Berlin, Institut für Strahlenhygiene des Bundesgesundheitsamtes (Institute for Radiation Hygiene, Federal Office for Health (BGA)), 1988, **125**:348–370.

473. **Chadwick KH.** Dosimetry concepts for the gamma irradiation of food. In: Bögl KW, Regulla DF, Suess MJ, eds. *Health impact, identification, and dosimetry of irradiated foods.* Berlin, Institut für Strahlenhygiene des Bundesgesundheitsamtes (Institute for Radiation Hygiene, Federal Office for Health (BGA)), 1988 (ISH-Heft 125), pp. 400–405.

474. **Miller A.** Dose distribution and dose limits in food irradiation. In: Bögl KW, Regulla DF, Suess MJ, eds. *Health impact, identification, and dosimetry of irradiated foods.* Berlin, Institut für Strahlenhygiene des Bundesgesundheits-

amtes (Institute for Radiation Hygiene, Federal Office for Health (BGA)), 1988 (ISH-Heft 125), pp. 405–414.

475. **Ehlermann DAE**. Dose distribution and methods for its determination in bulk particulate food materials. In: Bögl KW, Regulla DF, Suess MJ, eds. *Health impact, identification, and dosimetry of irradiated foods*. Berlin, Institut für Strahlenhygiene des Bundesgesundheitsamtes (Institute for Radiation Hygiene, Federal Office for Health (BGA)), 1988 (ISH-Heft 125), pp. 415–419.

476. **Miller A, Chadwick KH**. Dosimetry for the approval of food irradiation processes. *Radiation physics and chemistry,* 1989, **34**:999–1004.

477. **Sharpe PHG**. Dosimetry for radiation processing. *beta-gamma,* 1989, **3**:30–34.

478. **Chadwick KH, Oosterheert WF**. Dosimetry concepts and measurements in food irradiation processing. *International journal of radiation applications and instrumentation,* Part A, **1986, 37**:47–52.

479. **Ehlermann DAE**. Selection of dosimeter systems for radiation processing of food. In: *High dose dosimetry for radiation processing*. Vienna, International Atomic Energy Agency, 1991, pp. 45–54.

480. **Ehlermann DAE**. Dosimetry for food irradiation. *Journal of radiation sterilization*, 1992/1993, 1:101–107.

481. **Ehlermann DAE**. Dosimetry and process control – selected examples with practical relevance. *Radiation physics and chemistry,* 1996, **48**:376–377.

482. **Ehlermann DAE**. Control of food irradiation: a challenge to authorities. *Trends in food science and technology*, 1993, **4**:184–189.

483. *Annual book of ASTM standards,* Vol. 12.02, ASTM E1204-93. Practice for dosimetry in gamma irradiation facilities for food processing. West Conshohocken, American Society for Testing Materials, 1996.

484. *Annual book of ASTM standards,* Vol. 12.02, ASTM E 1204-93. Guide for the selection and calibration of dosimetry systems for radiation processing. West Conshohocken, American Society for Testing Materials, 1996.

485. *Annual book of ASTM standards,* Vol. 12.02, ASTM E1204-93. Practice for dosimetry in electron and Bremsstrahlung irradiation facilities for food processing. West Conshohocken, American Society for Testing Materials, 1996.

486. *Annual book of ASTM standards,* Vol. 12.02, ASTM E1204-93. Practice for dosimetry in an X-ray (Bremsstrahlung) facility for radiation processing. West Conshohocken, American Society for Testing Materials, 1996.

487. *Annual book of ASTM standards,* Vol. 12.02, ASTM E1204-93. Practice for dosimetry in an electron beam facility for radiation processing at energies from 300 keV to 25 MeV. West Conshohocken, American Society for Testing Materials, 1996.

488. **Ehlermann DAE**. Regulations and enforcement. In: *Food irradiation and consumers*. Vienna, International Consultative Group on Food Irradiation, International Atomic Energy Agency, 1994, pp. 71–75 (ICGFI-Document No. 18).

489. **Brynjolfsson A**. Definition and control of processing parameters for radappertization of beef for wholesomeness studies in the United States of America. In:

Radiation preservation of food. Vienna, International Atomic Energy Agency, 1973, pp. 549–560 (STI/PUB/317).

490. Consultation on microbiological quality of food to be further processed, including by irradiation. Geneva, World Health Organization, 1989 (unpublished document WHO/EHE/FOS/89.5; available on request from Programme of Food Safety and Food Aid, World Health Organization, 1211, Geneva 27, Switzerland).

491. **Pryke DC, Taylor RR.** The use of irradiated food for immunosuppressed hospital patients in the United Kingdom. *Journal of human nutrition and diet*, 1995, **8**:411–416.

492. **Dong FM et al.** Irradiated or aseptically prepared frozen dairy desserts: acceptability by bone marrow transplant recipients. *Journal of the American Dietetics Association*, 1992, **92**:719–723.

493. **Klicka MV, Smith MC.** *Food for U.S. manned space flight.* Natick, MA, United States Army Natick Research and Development Laboratories, (TR–82/019, 1982).

494. **Bruhn CM, Schutz HG.** Consumer awareness and outlook for acceptance of food irradiation. *Food technology,* 1989, **43**:9–97.

495. **Ionizing energy in food processing and pest control, Vol II Application.** Ames, Council for Agricultural Science and Technology, 1989 (Task Force Report No. 115): pp. 54–59.

Annex 1
High-dose irradiated foods – practical experience

Introduction

Practical experience in the use of high-dose irradiated foods demonstrates that the important quality attributes of such foods are retained during processing and subsequent storage and confirms that the target average doses used to eliminate any microbiological hazard are effective and sufficient. Early researchers developing these products relied on the evaluations made by technical panels and small consumer panels to refine product formulation and processing, but they had no significant opportunity to validate the laboratory results with large numbers of consumers. Regulatory limitations worldwide have precluded any such large-scale testing, so feedback on the acceptability of the high-dose irradiated foods could only be obtained where special niches of approved use existed. Such special groups for which approval was obtained include: immunocompromised hospital patients; United States and Russian astronauts; and military personnel and outdoor enthusiasts in South Africa.

High-dose irradiated products

Persons with compromised immune systems

Beginning in 1974, the Fred Hutchinson Research Center in Seattle, Washington, offered radiation-sterilized food items to patients with compromised immune systems so as to maintain their nutritional health and to prevent ingestion of foodborne infective agents (*1*). Food not suitable for autoclaving to destroy microbial contaminants, such as breads, pancakes, tortillas, crackers, stuffing mix, pastries, cereals, dry beverages, snacks and candies, nutritional supplements, meats and condiments, were irradiated to achieve sterility. These products were very favourably received by the patients. Because the irradiation source at the University of Washington had decayed to too low a level of activity, the use of irradiation was discontinued in 1988. The additional staff time needed to prepare the extensive documentation required for upgrading the source and for renewing approval for its use was considered prohibitive (S.N. Aker, personal communication).

Deep-frozen meals irradiated to an average dose of 75 kGy have also been produced in the Netherlands for use by hospital patients.

Programmes to inform high-risk individuals about the advantages of irradiation are under way in the United States. As part of the food safety initiative, Iowa State University has developed video-based educational

materials on food irradiation technologies and microbial food safety. These materials are intended for use by health care and other professionals when working with immunocompromised persons and their care givers.

Astronauts

From the inception of the United States space programme, astronauts have consumed irradiated food while in space. Irradiated products were eaten by United States astronauts on the Apollo 17 flight to the moon in December 1972 and on joint space flights with Soviet cosmonauts. Between 1981 and 1986, 228 portions of irradiated meat products and 121 bakery products were consumed (*2*). These irradiated foods were considered highly aceptable (*3*) and were selected because of their higher sensory quality compared to thermally-processed counterparts (*2*). Irradiated beefsteaks were also used on NASA Space Shuttle flights in 1993 (*4*). In addition to steaks, the United States Army Natick Research, Development and Engineering Center produced irradiated smoked turkey slices, corned beef, chicken, burritos, pork chops and pizza for the shuttle flights. In 1996, over 2500 beefsteaks, sliced turkey and other meat products were produced and radiation-processed (*5*). Four new products for NASA were also developed. In sensory panel evaluations, the new irradiated grilled beefsteak, breaded chicken breast, pork chops and corned beef all received scores above that required for shuttle foods.

South Africa

South Africa markets irradiated shelf-stable foods and a variety of other irradiated products including spices and herbs, honey products, torulite yeast, garlic, egg products and fresh vegetables. The type of shelf-stable foods and consumer response to them are of particular interest.

Research into irradiated shelf-stable meat products was initiated during 1977 as a result of a request from the Armed Forces. During the early 1980s, several products were developed in conjunction with food scientists from the Council for Scientific and Industrial Research and from Technicon of Pretoria. Researchers irradiated novel convenience foods that cannot be satisfactorily prepared by alternative methods such as canning or retorting (*6*); 12 dishes were tested, including grilled chicken, curried chicken, bacon, curried beef and a Malaysian dish called bobotie. Between 1982 and 1987, approximately 20 000 portions were produced and evaluated by individuals, expeditions and the Armed Forces. In 1989, approval was obtained from the Department of Health to supply shelf-stable irradiated food to the Armed Forces.

Table A1
Sale in portions (~150 g) of shelf-stable irradiated meat in South Africa

Year	Military	Non-military
1987	18 660	NA
1988	20 000	NA
1989	25 000	2 859
1990	25 000	5 726
1991	415 750	8 286
1992	415 750	9 870
1993	415 750	12 826
1994	236 650	11 867
1995	206 590	22 355
1996	0	25 579
1997	0	37 147

Reproduced from Bruyn (*7*) with permission.

In 1987 and 1988, approximately 20 000 portions of shelf-stable meat items were sold to the military (*7*). The quantity increased to 25 000 per year in 1989 and 1990, then to over 400 000 per year in the period 1991–1993 (Table A1). Annual sales decreased to over 200 000 in 1994 and 1995 owing to restructuring of the military.

The total of about 1.8 million portions (about 3 million kg) of high-dose irradiated foods consumed by the military provides a basis for assessing acceptance by users. Many special forces personnel have relied upon these ration portions for their entire intake of protein for extended periods. There have been no incidences of adverse health responses reported (*7*). Moreover, these foods were found to be "consistently of the highest quality."

In 1989, the sale of shelf-stable meat items to non-military customers began with 2859 portions sold in the first year, increasing to almost 10 000 in 1992 and 25 579 in 1996. Increased sales after 1989 were associated with permission being obtained to sell in selected hiking and outdoor shops and to undertake a marketing programme, which included tasting. High-dose irradiated products were clearly popular among yachtsmen and other outdoor enthusiasts, based on feedback from them. Yachtsmen competing in a race from the Cape to Rio accounted for a large quantity sold in 1996.

A marketing survey among the general population found that, while only 15% initially indicated they were likely to purchase irradiated food, the proportion willing to purchase increased to 54% after receiving visual information. It also found that, after receiving information *and* tasting the food, 76% indicated they would purchase the irradiated shelf-stable product, while only 5% said they probably would not.

Conclusions

The acceptability in niche markets of various high-dose irradiated products, including meat items and whole meals, and the lack of any health problems resulting from their consumption, provide practical evidence of the effectiveness and appropriateness of the radiation-sterilization process.

References

1. **Aker SN**. On the cutting edge of dietetic science. *Nutrition today*, 1984, **19**:24–27.
2. **Bourland CT**. *NASA and food irradiation.* International Conference on Seafood Irradiation, New Orleans, June 16–18, 1992.
3. **Josephson ES**. Radappertization of meat, poultry, finfish, shellfish, and special diets. In: Josephson ES, Peterson MS, eds. *Preservation of food by ionizing radiation*, Vol. 3. Boca Raton, FL, CRC Press, 1983, pp. 231–251.
4. **Bourland CT**. The development of food systems for space. *Trends in food science and technology*, 1993, **4**:271–276.
5. **Loveridge VA**. *Substitution/Introduction of irradiated foods (IF) (Information paper, subject, A94-18).* Natick, MA, United States Army Natick Research, Development and Engineering Center, 1996.
6. **den Drjver L, Sirgel FA, van der Linde HJ**. *Novel convenience foods through radurisation.* Seventh World Conference of Food and Food Technology, Singapore, 1987.
7. **Bruyn I**. *Application of high dose irradiation.* Proceedings of National Seminar on Food Irradiation, Toluca, 1997, pp. 32–40.

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887	(1999) **WHO Expert Committee on Drug Dependence** Thirty-first report (28 pages)	14.–
888	(1999) **Evaluation of certain veterinary drug residues in food** Fiftieth report of the Joint FAO/WHO Expert Committee on Food Additives (102 pages)	20.–

* Prices in developing countries are 70% of those listed here.