Russian Chemical Reviews **64**(6) 569–598 (1995) ©1995 Russian Academy of Sciences and Turpion Ltd

UDC 541.15

Current state of radiation processing

A K Pikaev

Contents

I.	Introduction	569
II.	Sources of ionising radiation	570
III.	Radiation modification of materials	572
IV.	Radiation polymerisation	575
V.	Radiation degradation	579
VI.	Radiation sterilisation of medical articles	580
VII.	Use of radiation for the protection of the environment	581
VIII.	Radiation treatment of food products	585
IX.	Radiation-physical processing	587
X.	Other applications	588
XI.	Technological dosimetry of ionising radiations	588
XII.	Conclusion	589

Abstract. A review of common trends in the development of modern radiation processing is presented. The sources of ionising radiation and the most important processes practically induced under the influence of this radiation are discussed. It is shown that radiation methods can be used successfully for the modification of materials, for the sterilisation of medical articles, for the solution of ecological problems, for the treatment of food products, in radiation engineering, etc. Special attention is paid to processes at the pilot plant and industrial scales. The bibliography includes 548 references.

I. Introduction

The aim of radiation technology is to study, develop, and improve the methods, apparatus, and assemblies used to apply ionising radiations. Radiation methods are used to generate or to improve new properties in materials, new methods of exploiting them, new means of production, etc., and also to solve ecological problems, some problems in nuclear technology, and various other problems. Radiation processing is a relatively new field of study. The first radiation processes (radiation sterilisation of medical items and radiation cross-linking of the polyethylene insulation of wires) were introduced into industrial practice in the mid-1950s,[1] so that the introduction and development of radiation technology as a separate science has now been going on for 35–40 years.

In spite of the shortness of its past history this field of study has already achieved some definite successes. This is shown by the very abundant scientific and technical literature, which includes thousands of original papers and reviews, many patent disclosures and claims, specialised monographs,[1–64] and pamphlets in the 'Radiation-chemical technology' series,[65–87] and representative meetings of specialists held in various countries (in particular, international conferences on radiation technology organised every 2–3 years).[88–96]

Radiation technology still occupies a relatively modest place in the overall volume of industrial and agricultural production. The rate of growth of production by radiation methods is increasing continuously: ~15%–20% per annum. Thus, in foreign countries industrial products worth about 10^{10} US dollars are produced every year by radiation methods. In the not too distant future this could make the industrial production by radiation processes comparable in importance with conventional processes.

Radiation technology can be divided into radiation-chemical, radiation-physical, and radiation-biological processing. Modern radiation-chemical technology is being developed mainly along the following directions: (1) the radiation modification of materials (mainly polymeric); (2) radiation polymerisation, including radiation hardening and radiation graft polymerisation; (3) radiation degradation (mainly of polymeric materials); (4) ecology. The main aims of radiation-biological technology are the radiation sterilisation of medical articles and the radiation treatment of food products. The radiation-physical technology includes the radiation doping of semiconductors, ion implantation, the radiation treatment of articles used in electronic technology, etc. However, the boundary between these divisions of radiation technology is not sharp. A topic common to all these divisions is the construction of radiation apparatus (the production and assembly of sources of ionising radiation and of radiation equipment and the technological dosimetry of ionising radiations).

Regions of radiation-biological technology such as the radiation sterilisation of medical articles and preparations and the radiation treatment of food products are usually classified with the radiation-chemical technology. An important part of these problems is the radiation stability of the polymeric materials from which the medical articles and the medicinal preparations are manufactured, the qualitative and quantitative determination of the composition of the substances formed in the food products during their irradiation, and the identification of the irradiated products. Problems common to radiation-chemical and radiation-physical technology include the increase in the

A K Pikaev Institute of Physical Chemistry of the Russian Academy of Sciences, Leninskii prosp. 31, 117915 Moscow. Fax (7-095) 335 17 78

Received 17 February 1995
Uspekhi Khimii **64**(6) 609–639 (1995); translated by J I Carasso

corrosion resistance of metals and alloys during ion implantation, the radiation doping of semiconductors, etc.

This paper is a review of the current state of radiation processing, with special emphasis on processes realised under pilot plant and under industrial scales. It was written mainly from data published in the last 10–15 years.

II. Sources of ionising radiation

The following sources of ionising radiation are commonly used in radiation processing: ^{60}Co (and more rarely ^{137}Cs) sources of γ radiation, electron accelerators, $^{90}Sr + ^{90}Y$ sources of β radiation, ion implanters, and (very rarely) nuclear reactors.

1. ^{60}Co sources of γ radiation

γ Irradiators are used mainly in the radiation sterilisation of medical equipment and (to a smaller extent) in the radiation treatment of food products. More than 180 industrial γ irradiators based on ^{60}Co are currently operating over the world. The activity of ^{60}Co in one γ irradiator can be as high as 10 MCi. The largest foreign producer and supplier of industrial γ irradiators based on ^{60}Co is the Canadian 'Nordion International Inc.' company. Modern industrial irradiators are housed in specially equipped structures and are usually automated.

2. Electron accelerators

The total number of electron accelerators currently used in radiation processing (including research assemblies) is greater than 1000. The energy of the electron beams generated by electron accelerators is 0.15–10 MeV. Beams with an energy lower than 0.15 MeV are very seldom used because of their unacceptably low penetrating power. At energies greater than 10 MeV the irradiated objects begin to show a significant amount of induced radioactivity.

Industrial electron accelerators can be divided into three groups.[97]

(1) Low-energy accelerators, with an electron energy of 0.15–0.5 MeV and beam powers up to 300–350 kW. The characteristics of accelerators produced in various countries are summarised in Table 1.[1,98] More than 400 of these machines are currently operating over the world: more than 250 of them are used in industry. They are used mainly for hardening coatings, and for treating surfaces and thin-film items.

Low-energy accelerators can themselves be divided into three subgroups:[100] with a scanning beam, with an extended cathode, and with a multiple cathode. The first subgroup includes, for example, accelerators of the 'Aurora' type, the second includes accelerators of the 'Electrocurtain' type, and the third accelerators of the 'Broad Beam' type. We note that in recent years

Table 1. Characteristics of low-energy electron accelerators.

Type of accelerator	Producer	Energy/MeV	Power/kW	Beam width/m
ESH	Polymer-Physik (Germany)	0.15–0.28	Up to 56	0.22–2.5
EPS	Nissin High Voltage Co., Ltd. (Japan)	0.3 0.3 0.3	7.5 19.5 30	0.45 1.2 1.8
Aurora-2	NIIEFA (Russia)[a]	0.3–0.5	25	0.5–2.0
EOL-400	Radiotechnical Institute (Russia)	0.4	14	Up to 2.0
Electrocurtain	Energy Sciences Inc. (USA)	0.15–0.3	Up to ~100	0.5–2.0
BroadBeam	RPC Industries (USA)	0.15–0.3	Up to 360	0.3–2.5
LEA[b]	Institute of Surface Modification (Germany)	0.15–0.2	Up to 60	Up to 1.5
Elektron-16	NIIEFA (Russia)[a]	0.25–0.3	30	Up to 2.0
TUR-M	NTTs 'Energiya' (Russia)	0.15–0.28	10	Up to 1.8
Astra-11	NPO 'Astrofizika' (Russia)	0.2–0.3	25	0.6[c]
Tapir	'Tekra' Company (Russia)	0.3	30	1.2–2.1
Kangaroo	"	0.25	5	0.36
Finback whale[d]	"	0.3	150	6.0[e]

[a] Efremov Research Institute for Electrophysical Instrumentation, S. Petersburg.
[b] From Ref. 99.
[c] An appropriate distribution of moduli having these parameters can be used to establish a production line of any width.
[d] Project aimed at producing an accelerator with several exit windows. The quoted parameters are for a machine with 12 windows.
[e] Cross-sectional area of the beam, m^2.

Table 2. Parameters of moderately powerful electron accelerators.

Type of accelerator	Producer	Energy/MeV	Maximum power/kW
ELT electron transformer[a]	Institute of nuclear physics of the Siberian section of the Russian Academy of Sciences	1.5 – 2.2	15
ELV electron transformer	Institute of nuclear physics of the Siberian section of the Russian Academy of Sciences and Vladimir Il'ich Moscow works (Russia)	0.2 – 2.5	~100
ILU resonator linear accelerator	"	0.5 – 2.5	30
ICT transformer with insulated core[a]	High Voltage Engineering Corp. (USA)	0.3 – 2.5	125
FDJ transformer with insulated core	Research Institute of Automation for Machine-Building Industry (PRC)	0.3 – 1.2	24
'Elektron' (Cockcroft and Walton type)	NIIEFA (Russia)	0.75 – 2.5	~100
EPS (Cockcroft – Walton type)	Nissin High Voltage Co., Ltd. (Japan)	0.8 – 5.0	~150 – 200
Dynamitron	Radiation Dynamics Inc. (USA)	0.55 – 5.0	~200

[a]Production discontinued.

Table 3. Parameters of the linear accelerators used in radiation technology.

Brand of accelerator	Producer	Energy/MeV	Power/kW
LUE-8-5V	NIIEFA (Russia)	8	5
LUE-8-15S	"	8	15
UELV-10-10 (Elektronika-10-10)	NPO 'Torii' (Russia)	10	10
CIRCE II	MeV Industrie (France)	10	20
CIRCE III	"	5 and 10	20 at 5 MeV; 10 at 10 MeV
EB10	Scanditronix AB (Sweden)	10	30
IMPELA	AECL Accelerators (Canada)	10	50
Rhodotron	Ion Beam Applications S.A. (Belgium)	5 and 10	30 at 5 MeV; 50 at 10 MeV[a]

[a]The stated beam powers are guaranteed: a power of 100 kW can probably be achieved.

multicathode accelerators with powers of up to 400 – 500 kW and beam widths up to 3.2 m have been developed.[100]

(2) Intermediate-energy accelerators, with an electron energy of 0.5 – 5.0 MeV and a beam power of up to 300 – 350 kW. More than 500 of these machines are operating over the world. The parameters of accelerators of this group are shown in Table 2.[1, 49, 50, 101–104]

Accelerators of the 'Dynamitron' type are the most widely used accelerators of this type outside the Russian Federation: about 150 of these machines were functioning in 1990.[105] Among the accelerators produced in Russia the most widely used are those of the ELV type (approximately 70 of these machines having been produced so far)[106] and of the ILU type (23 machines produced so far).[107] The nuclear physics institute of the Siberian Section of the Russian Academy of Sciences has developed an ELV-6M accelerator (electron energy 0.5 – 1.0 MeV and maximum beam power 200 kW) and a 'Torch' accelerator (energy 0.5 – 1.0 MeV, maximum beam power 500 kW).[108] In the USA an electron accelerator of the induction type with a beam energy of up to several megawatts is being developed.[109]

Intermediate-energy accelerators are used in many areas of radiation processing: for cross-linking the polyolefin insulation of cables, for the production of thermally formed articles and of foamed polyethylene, for the vulcanisation of the components of tyres, for the purification of waste water and gas discharges, etc.

(3) High-energy accelerators, with an electron energy of 5 – 10 MeV and a beam power of up to 100 kW. These are mostly linear accelerators: about 30 of these machines are used in

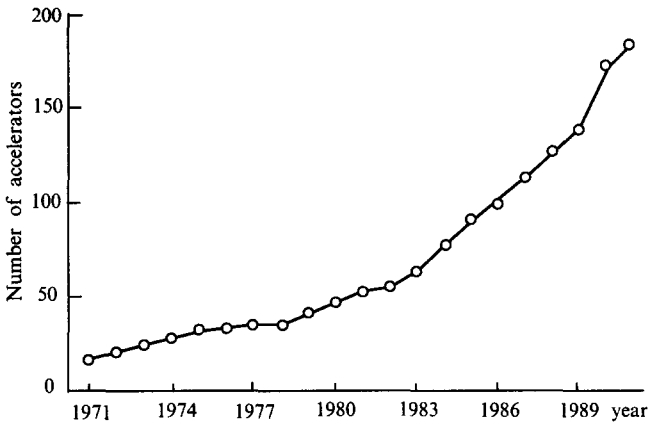


Figure 1. Increase in the production of electron accelerators by the Japanese firm 'Nissin High Voltage Co., Ltd.'

radiation technology. The parameters of some of them are given in Table 3.[1,50,98,110–115] They are used for the radiation sterilisation of medical articles and (to a smaller extent) for the radiation processing of food products.

At the present stage of development of radiation technology electron accelerators are much more generally used than sources of γ radiation. This is because of the greater operational safety and the greater power of the electron accelerators. The rates of development of electron-beam processes are illustrated in Fig. 1, which shows the increase in the number of electron accelerators produced by the Japanese firm 'Nissin High Voltage Co., Ltd.' for radiation technology during the period 1971 – 1991.[104]

3. Other sources

$^{90}Sr + {}^{90}Y$ β sources are used in radiation-physical technology, mainly in the surface treatment of semiconductor devices. Ion beams are also used for the same purpose, and ion implanters are very widespread. For example, about 800 implanters were operating in Japan in 1987.[116] Nuclear reactors were used as sources of ionising radiation only in the radiation doping of semiconductors.[35]

In recent years the possibility of exploiting the breaking (breamsstrahlung) X-radiation with a maximum energy of 5 MeV generated by electron accelerators with a beam power of 200 – 300 kW[113,117–122] is being studied. An electron beam with an energy of 5 MeV and a power of 200 kW can generate a bremsstrahlung X-radiation with a power of ~15 kW when decelerated in a high atomic number metal (for example, tantalum), counting only the radiation in the same direction as the stream of electrons: this is equivalent to the power of γ radiation from a ^{60}Co sample with an activity of ~1 MCi. However, an X-ray beam can be used more effectively (by a factor of approximately 1.5 – 2.5)[118] than γ radiation because ^{60}Co emits its γ quanta isotropically, i.e. in all directions.

Possible applications of the bremsstrahlung X-radiation include the radiation sterilisation of medical items and the radiation treatment of food products. Several equipments based on electron accelerators have already been assembled by using appropriate converters of electron beams into bremsstrahlung X-radiation,[113] and one assembly with an accelerator of the Cockcroft – Walton type (electron energy 5 MeV, beam energy 150 kW) produced by the 'Radia Industry Co., Ltd.' (Japan) has been used on commercial applications[121] since 1992.

III. Radiation modification of materials

The radiation modification of materials is the controlled (and therefore useful) change in their properties produced by using irradiation. The ionising radiation is most often used to modify polymers, because of the high molecular mass of polymers, which allows even relatively small doses to produce marked changes in its properties.

The radiolytic conversion most useful in practice in polyolefins is cross-linking. This is used in various industrial processes, such as the modification of polyolefins [mainly polyethylene and poly(vinyl chloride)], the insulation of cables and wires, the preparation of stronger and heat resistant films, tubes, and manufactured articles, the production of polyethylene foams and (in a much smaller volume) of polypropylene foams, the vulcanisation of elastomers and items made from them (components of tyres, polysiloxane rubbers aimed at the production of thermally stable self-adhesive electrically insulating tapes and rubber-glass cloth, latex from natural raw rubber, rubber gloves, etc.).

1. Production of cables and wires with a radiation-cross-linked insulation

The radiation cross-linking of polyolefins increases their mechanical strength and heat resistance, improves their electrical insulation properties (especially at high temperatures), etc. For these reasons the process discussed in this section is widely used in the production of cables and wires.[1,5,6,10,17,20,50,79,123]

The radiation cross-linking of polyolefin insulation was first achieved in the USA in the 1950s. At present the list of countries in which this process is applied includes Japan, Great Britain, France, Germany, the PRC (China), and several others. In the former Soviet Union 16 industrial lines with electron accelerators of the ELV or ILU type (maximum power ~0.5 MW) were operated.[97,123] Many of these lines were found in the 'Belarus'kabel' plant (Belorussia); their combined maximum annual production was $(160-180)\times10^3$ km of wires with cross-sections between 0.12 and 6.0 mm^2 (see Gofshtein[124]). In Japan ~12% of the insulation produced is radiation-cross-linked.[125]

The radiation method is used to modify mainly polyethylene and poly(vinyl chloride) insulation. Radiation treatment is applied on a smaller scale to insulations of poly(vinylidene fluoride), chlorosulfonated polyethylene, the ethylene – propylene terpolymer, the copolymer of ethylene and tetrafluoroethylene, etc. Radiation-cross-linked polyurethane has recently started to be used as insulation.[126]

The sources of ionising radiation used to irradiate wires and cables are mainly electron accelerators with an energy of 0.3 – 5 MeV and powers of up to 100 – 150 kW. The dose needed to cross-link grades of polyethylene made abroad is 0.2 – 0.4 MGy,[127] whereas the indigenous grade of cable polyethylene requires 0.5 MGy.[123] This dose can be greatly lowered by adding sensitisers to the polyethylene. Typical sensitisers include dipropargyl succinate (which when used as an additive lowers the radiation dose to 0.1 – 0.12 MGy),[128] trimethylolpropane triacrylate and trimethylolpropane trimethylacrylate,[129] alkylamides and some aminoalcohols,[130] etc.

The use of sensitisers is specially valuable with a poly(vinyl chloride) insulation, because when exposed to relatively high doses (60 kGy and above)[131] this polymer undergoes marked structural degradation. Triallyl cyanurate,[132] tetraethyleneglycol dimethacrylate,[133] and other compounds have been proposed as sensitisers for this material.

An important scientific and technical problem, met in conjunction with the use of wires and cables with radiation-cross-linked insulation at high temperatures, is the need to inhibit processes leading to the thermal oxidation of the insulating polymeric material. This thermal oxidation can be suppressed by introducing special substances (antioxidants) into the polymer. In the case of polyethylene effective antioxidants include some phenolic compounds [for example, 1,1,3-tris-(2-methyl-4-hydroxy-5-*tert*-butylphenyl)butane], aromatic amines [for example, *N*,*N*′-diphenyl-*p*-phenylenediamine], and organic substances containing sulfur [for example, 4,4,thio-bis-(6-*tert*-butyl-3-methylphenol)].[134–138]

However, by reacting with the free radicals formed during the irradiation of the polymer the antioxidants increase the dose needed to achieve cross-linking. In this respect organosulfur antioxidants are better than phenolic compounds, since their use induces a much smaller increase in the dose.[137] We note that additives acting simultaneously as sensitisers and as antioxidants have been developed in Russia.[123]

Another important problem is the elimination of fire hazards from cable items having a radiation-cross-linked polymeric insulation. Additives which lower the inflammability (called antipyrenes) include decabromodiphenyl oxide, tetrabromobisphenol, condensed bromacenaphthalene, and aluminium hydroxide.[137,139-141] Condensed bromacenaphthalene (whose molecule contains 1-10 bromacenaphthalene units and 2-4 bromine atoms) is specially effective in the protection of chlorinated polyethylene and of the ethylene-propylene terpolymer.[141,142] Furthermore it is an antioxidant, and ensures radiation stability of the polymer up to 10 MGy. These properties are due to its grafting to the polymer chain during the irradiation.

The radiation cross-linking of polymers has a number of advantages over the chemical reaction, which uses peroxides as initiators.[143] They include better exploitation characteristics of the product, a cheaper process, lower energy losses, and a gain in the working areas. This explains why wires and cables with a radiation-cross-linked polymer insulation are now industrially produced in many countries. They are used in telecommunication systems, in military and in cosmic technology, in electronics and computer instrumentation, in the electric systems of automobiles, in nuclear reactors, etc.[20,131,139-141,144,145]

2. Preparation of densified and thermosetting items

The second radiation-chemical process realised in industry, based on the cross-linking of polymers (mainly polyethylene), is the preparation of densified and thermosetting items. They include thermosetting films, tapes, small bags, small and large tubes, hoses, flaps, and items of a more complex configuration used in the electrical industry, in the automobile and food industries, in electronics, in ship building, and in construction.[79,146-150]

The 'memory' effect (also known as 'shape memorising') provides the basis of the preparation of thermosetting items.[151] Essentially in this effect a polymeric material is irradiated with a dose smaller than the dose corresponding to gel formation, deformed at a temperature higher than the melting point of the crystallites, and then cooled rapidly. After a second heating to the same temperature, it tends to regenerate its initial form (owing to the formation of a three-dimensional network). If this material is stretched over any item it forms a tightly fitting shell after the heating process.

In addition to polyethylene we can use poly(vinyl chloride), poly(vinylidene fluoride), some rubbers, ethylene-ethyl acrylate and ethylene-vinyl acetate copolymers, etc. to prepare thermosetting items. In most cases electron accelerators are used in the production of thermosetting articles. Electron beams with an energy of 1-3 MeV are used to irradiate tubes, and with films and tapes the beams have an energy of 0.5-1.0 MeV.[147] Assemblies based on transformers with an insulated core and dynamitrons have been developed in the USA; in Russia accelerators of the 'Aurora', 'Elektron', ELV, and ILU type are used. In particular, in Russia a special workshop producing thermosetting polyethylene films and tubes[152] has operated 5 electron accelerators since 1978. The operating speed of this assembly is 1600 t a^{-1}. Two industrial lines have recently been mounted in Syzran' for the production of thermosetting polyethylene tapes: both are fitted with an accelerator of the ELV type (beam power 40 kW).[152] The operating speed of each line is 800 t a^{-1}. In foreign countries thermosetting items are produced by 'Raychem' (USA), 'Nitto' (Japan), and other firms.

The technology of the preparation of thermosetting films differs somewhat from the production technology of small pipes, of tubes, and of flaps. The production of thermosetting films[1,79,146] is shown schematically in Fig. 2. The best dose is 0.12 MGy.[79] Thermosetting pipes, tubes, and flaps can be produced by two methods.[147] In the first the tubes are produced by extrusion; they are then electron irradiated, their diameter is increased by orienting them above the melting point, and they are rapidly cooled, producing a new diameter. In the second method (called the tape method) a polyethylene tape is prepared by extrusion, is irradiated, exposed to oriented heating, and rapidly cooled; tubes are then produced from the heated tapes by winding them on a mandrel. It has been stated that the doses needed for the production of tubes and tapes could be 0.2-0.3 MGy[147] or 0.1-0.12 MGy[79-148] Obviously, the difference is due to differences in the state of the polymeric compositions used in the process.

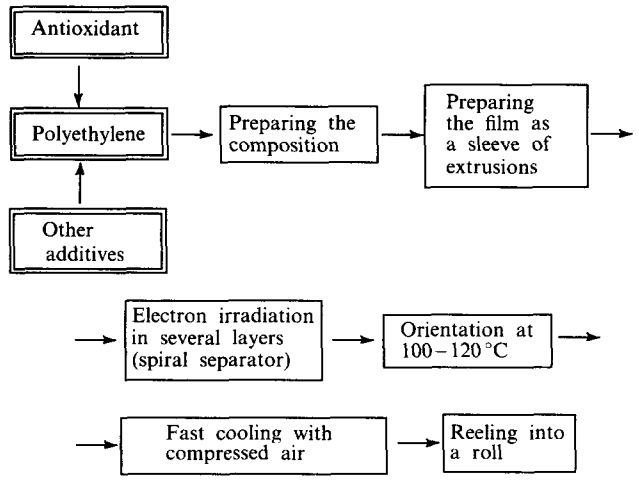


Figure 2. Scheme for the production of thermosetting films.

In the USA thermosetting films are used for packing cooled foodstuffs under vacuum.[146] The 'termoplen' film, produced in Russia, is also a packing material, whereas the 'agroplen' film is used in industrial hothouses to cover the soil before admitting overheated steam in order to eliminate harmful vegetable cultures.[152] Polyethylene tubes made of 'radplast T' are used for the insulation of connected wires and terminals in electric wiring, for the upkeep of damaged insulation, etc. 'Radlen' polyethylene films have been designed to protect gas and petroleum ducts from corrosion.[152]

3. Production of radiation-cross-linked foamed polyethylene

The production technology of radiation-cross-linked polyethylene foams was developed in Japan in the mid-1960s.[153,154] This material is produced in several countries at present.[154-156]

The production of radiation-cross-linked polyethylene foams includes the following main steps: the preparation of the initial composition, the production of the intermediate product (as a sheet) by extrusion at a temperature not above 125-130°C, the irradiation of this sheet by electrons in order to induce cross-linking (dose of 50-70 kGy), the foaming of the cross-linked item at 180-200 °C by the decomposition of a gas former (often known as a porofore) introduced into the composition. A commonly used porofore is diazodicarbonamide $H_2NCON{=}NCONH_2$, which decomposes at ~200 °C (giving 200-250 cm^3 of gaseous products per 1 g of porofore, including CO, CO_2, N_2, and NH_3. Foaming promoters (usually zinc stearate[155]) are added to the composition to lower the decomposition temperature of the porofore. Other additives are also used if necessary: antioxidants, cross-linking sensitisers, dyes, etc. The purpose of the irradiation is to increase the viscosity of the polyethylene melt as a result of cross-linking. An increase in density suppresses the emission of gas from the melt and thus greatly increases the volume of the polymer.

Radiation-cross-linked polyethylene foams have good cushioning and thermal insulation properties, low water absorption, and good elasticity.[154,156,157] In Russia polyethylene foams are produced from low-density polyethylene. It is available as foamed sheets with smooth surfaces (from 0.5 to 1.0 m wide, from 3 to 5 mm thick, up to 50 m in length).[157] These parameters of the radiation-cross-linked polyethylene foams allow them to be used in the building and automobile construction industry, in the production of sporting equipment, as a heating medium and a packing material, etc.

A method of producing cross-linked polyethylene foams with an improved surface was recently reported in Japan.[158] It consists in irradiating polyethylene containing diazodicarbonamide and dicumyl peroxide (initiators of chemical cross-linking) with electrons having an energy of 0.2–0.5 MeV, and then heating it to 220 °C. Cross-linking takes place in the bulk of the polymer as a result of the free radicals formed in the thermal decomposition of the peroxide: because of its low energy the electron beam can induce the radiation cross-linking of polyethylene only in a thin surface layer.

The technology for the preparation of radiation-cross-linked polypropylene foams was developed recently.[144] It is similar to the production technology of polyethylene foams, except for the higher temperature of the process. It was found that the dose should correspond to a gel fraction of 25%–45%. Radiation-cross-linked polypropylene foams have a much higher thermal stability (i.e. a smaller loss in volume when stored at a given temperature) than radiation-cross-linked polyethylene foams. The difficulty in preparing polypropylene foams arises from the rapid decrease in the viscosity of the melt with increase in temperature.[159] This disadvantage can be eliminated by adding polyethylene.[159]

4. Vulcanisation of elastomers and of items made from them

In the case of elastomers we replace the concept of 'cross-linking' by 'vulcanisation'. The radiation-induced vulcanisation of various elastomers and items made from them has found industrial application.

a. Vulcanisation of the components of tyres

It has long been considered (since the late 1950s) that the radiation vulcanisation of automobile tyre casings should be a promising area of application of ionising radiation. However, it was subsequently shown[77] that this process is undesirable because of the complexity of the configuraiton of the tyres, the variety of the chemical nature of tyres, and especially because of the presence of cord, whose strength is degraded by the irradiation. The idea of a combined thermal and radiation vulcanisation of tyres, for example by using ionising radiation for the final vulcanisation of the tyres after a partial thermal vulcanisation,[77] also failed to achieve industrial application because of lack of financial advantage.

A practically more successful approach was a preliminary irradiation of stocks of the individual components of tyres (protectors, carcasses, side walls, etc.) before assembly, formation, and thermal vulcanisation.[160,161] Electron accelerators with energies of 0.8–1.0 MeV were used as the source of radiation. The dose required for the treatment varies from 1 to 200 kGy, depending on the type of radiation. This preliminary treatment allowed the cohesive strength of the raw materials to be increased and some of the natural rubber to be replaced by synthetic rubber while keeping the total time of manufacture of the tyres constant to within ~20%.

The preliminary radiation treatment of the components of tyres has found industrial application in other countries (mainly the USA and Japan). For example, in Japan 9 electron accelerators with a total power of ~0.6 MW were used for this purpose in 1988.[116,162,163]

b. Production of thermally stable self-adhesive electrically insulating materials

In 1971 a radiation method of producing thermally stable self-adhesive electrically insulating tapes and rubber–glass cloths from polyheterosiloxane rubber was developed and introduced into industry.[66,164–166] The production of electrically insulating tape is achieved by using γ radiation from ^{60}Co, and that of rubber–glass cloth by an electron beam generated by an ELV accelerator. Assemblies of this type are now operating in a factory at Kazan'.[66]

The production of electrically insulating tape includes the following steps:[66] the preparation of the initial composition, consisting of polyheterosiloxane rubber with some additives, the addition of pigment to the composition in the rubber mixer at temperatures not above 50 °C, the preparation of stocks of the tape on a polyethylene substrate as rolls 13–15 cm in diameter, their radiation vulcanisation with a ^{60}Co γ source (dose of 0.10–0.13 MGy). Since the preparation of the tape is a batch process, blocks of 25 rolls of the tape are rotated during the irradiation in order to distribute the dose uniformly. The source of γ radiation has a projected activity of 0.75 MCi and an average dose rate of 2.2 Gy s^{-1}.

Siloxane rubber with an additive of a halogenated polymer containing boron is used for the production of the electrically insulating tape.[166] Its vulcanisate has the properties of autohesion and adhesion at room temperature, apparently due to the presence of B–O groups in the polymer chain. Tapes produced by this method are the leading electrically insulating material. They are characterised by a good autohesion, high stability towards water and ice, and long working life (at 250 °C they retain their properties for 200–300 days).[66]

The technological process of preparing self adhesive rubber–glass cloth consists in steeping the glass cloths in a solution of polysilosane, removing the solvent, depositing on the impregnated glass cloth the main layer of rubber mixture, and vulcanising the composite material with an electron beam (using a dose of 50–70 kGy).[66] A ^{60}Co source of γ radiation can also be used for the vulcanisation. In this case the cloth is irradiated in rolls. The operating characteristics of the cloth are approximately the same as in the tapes described above.

c. Other processes based on the vulcanisation of elastomers

Several other processes based on the radiation vulcanisation of elastomers have been described. In Indonesia a pilot plant based on a ^{60}Co γ source (with an activity of 225 kCi) is being operated for the vulcanisation of natural rubber latex.[167] The dose is ~30 kGy (with a dose rate of ~2.8 kGy h^{-1}). The operating speed of the assembly is 1000 t a^{-1}.

The radiation vulcanisation of the latex of natural rubber is one of the stages in the preparation of rubber gloves for handling radioactive preparations.[168] The γ radiation from ^{60}Co is used for this purpose (with a dose of 12 kGy).

It has been reported[169] that the vulcanisation of rubber based on butadiene–styrene copolymer under the influence of electron radiation generated by a linear accelerator can be used in the production of rubber 'cushions' for the tracks of tanks. A technology for the production of medical tubes from siloxane rubber, and roofing and water-repelling material with an atmosphere-resistant layer of ethylene–propylene or butadiene–styrene rubber by using electron radiation to vulcanise these elastomers has been proposed.[170]

5. Other processes based on the cross-linking of polymers

In addition to producing the insulation of wires and cables, thermosetting items, and polyethylene and polypropylene foams the radiation cross-linking of polymers is used to make other products and materials, such as polyethylene tubes for hot water installations,[79,171] matrices of filled polyethylene for concrete and reinforced concrete items,[172] protecting rings of low-pressure polyethylene for rubber packing in water apparatus,[173] insulators of ethylene–vinyl acetate copolymer filled with

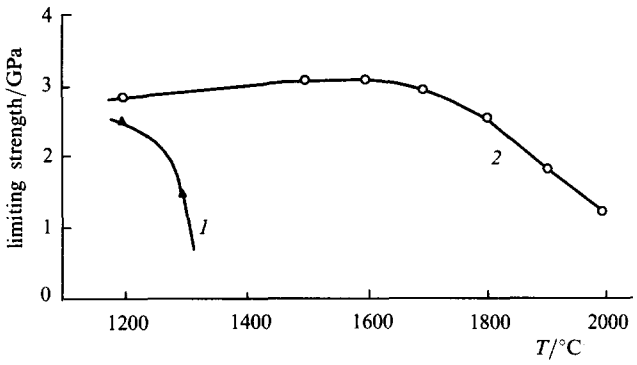


Figure 3. Temperature dependence of the limiting tensile strength of silicon carbide filament prepared by the usual method (*1*) and by using electron-beam treatment (*2*).[176]

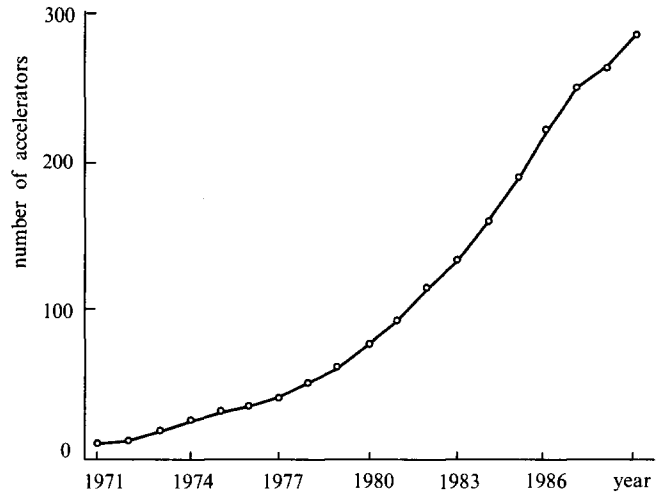


Figure 4. Increase in the number of assemblies with electron accelerators for hardening coatings.

aluminium hydroxide,[174] plastics [for example, of poly(ethylene terephthalate) and nylon] with improved thermal stability for use in modern electronics,[145] etc.

We shall briefly dwell on one new radiation process: the preparation of fibres of silicon carbide SiC.[175–177] This fibre is obtained by heat treatment at 1200 °C of radiation-cross-linked polycarbosilane fibre. It was found that the fibre has a higher thermal stability than the silicon carbide fibre prepared from thermally cross-linked polycarbosilane (see Fig. 3 and Ref. 176). The dose needed to achieve cross-linking is 10 MGy. In Japan a pilot plant is batch operated with an electron accelerator to treat 4.5 kg of polycarbosilane. A project for the commercial establishment of a production rate of 1 tonne of silicon carbide fibre per month in 1996 has been worked out in detail.[176,177]

IV. Radiation polymerisation

Many radiation processes realised on pilot plant and on industrial scales are based on the radiation polymerisation of monomers and their mixtures. These include primarily the radiation hardening of coatings (mainly under the influence of electron beams) and radiation graft polymerisation.

1. Hardening of the coatings

The radiation hardening of coatings has been introduced into industry in many countries.[1,67,98,101,102,116,178–195] In terms of the power of the electron accelerators this process occupies an intermediate place (coming after the radiation cross-linking of the polyolefin insulation of cables and wires). In 1990 ~350 laboratories, pilot plants, and industrial assemblies with electron accelerators for the hardening of coatings were operating throughout the world. Rates of development of this region of radiation technology are illustrated in Fig. 4, which shows the growth of the number of assemblies fitted with an electron accelerator (not including data for the former Soviet Union and for the People's Republic of China).[179]

The wide-ranging interest in radiation hardening was due mainly to its advantages over thermochemical hardening.[1,27,67,196] It was claimed to have a much lower (~85 times) energy consumption,[197] and to offer a gain in working areas, a reasonably high rate, the ability to operate at room temperature, and a lower consumption of reactants. It should specially be stressed that radiation hardening is a cleaner process from an ecological standpoint. Under thermal hardening the organic solvents in the hardened compositions are evaporated into the atmosphere. Industry produces approximately ~20 million tonnes of ordinary compositions every year [177] and, as a result, ~8 million tonnes of organic solvents are introduced into the surrounding medium. Radiation-hardened compositions contain no solvents. Unfortunately, these compositions (together with those obtained by photochemical hardening) account for only 1% of the total production. Obviously, in the interests of the protection of the ecological environment every effort should be made to replace the thermal method of hardening by the radiation (or photochemical) method.

Radiation hardening offers the following advantages over the photochemical hardening under the influence of UV radiation:[179,182] photoinitiators are not required, absence of sensitivity to pigments, uniform hardening even in relatively thick coatings, almost 100% conversion, and the possibility of grafting the monomer to the polymeric substrate. At the same time, the photochemical hardening offers a substantially lower cost (usually by 2–20 times) for the apparatus and instrumentation,[179] less attack on the sample, and lack of an oxygen effect. The high cost of hardening under the influence of electron radiation is often responsible for the preferential application of thermal or photochemical methods. For example, in Japan 29 090 photochemical assemblies were operating in 1988, as opposed to only 60 with electron accelerators.[116]

The doses needed to harden coatings depend on the state of the composition to be hardened and on the irradiation conditions, and usually lie between 20 and 200 kGy.[67] A high operating speed for these relatively high doses can be achieved by using sufficiently powerful electron accelerators. Since the thickness of the coatings is usually small mainly low-energy accelerators are used in this region of technology (electron energy between 0.15 and 0.35 MeV).

The most widely used accelerators are of the 'Electrocurtain' type (see Table 1): in 1991 ca. 200 of these machines were used for radiation hardening.

The power of the electron beams is expressed in kW, but the operating speed of the electron-beam assemblies is often measured in MGy m min^{-1}. For the low-energy accelerators made abroad whose parameters are listed in Table 1 the productivity in these units is 8.2, 3.75–15, and 2–12 respectively for EPS,[198] 'Electrocurtain',[199] and 'Broad Beam'.[100] These machines can be constructed with several accelerator tubes in order to increase the operating speed of the assembly. For example, accelerators of the 'Aurora' type are produced with 1–3 tubes, and accelerators of the 'Electrocurtain' type have between 1 and 4 tubes.[200,201] The power of an accelerator of the 'Electrocurtain' type with four accelerator tubes arranged in series is 100 kW m^{-1} (with an energy of 0.175 MeV).

Assemblies based on accelerators which generate electron beams of higher energy are sometimes used. This happens when the hardening of coatings is combined, for example, with the cross-linking of a polymeric substrate. In particular, electron accelerators of the ELV type (1.2–1.5 MeV energy) are used in

Russia for the production of artificial leather, in which the hardening of the decorative and protective coating is combined with the cross-linking of the polymeric material of the leather (see below).

The basis of hardening compositions are mixtures of unsaturated oligomers (oligoester maleates, oligoester-, polyester, polyurethane and epoxyacrylates and acrylates of organosilicon compounds) and vinyl monomers such as styrene, triethyleneglycoldimethacrylate, hexanediol-1,6-diacrylate, 2-ethylhexyl acrylate, tripropyleneglycol diacrylate, trimethylolpropane triacrylate, and pentaerythritol triacrylate.[67,202–205] In addition to oligomers and monomers the compositions may contain pigments, fillers, inhibitors, stabilisers, and other additives.

Irradiation produces copolymerisation of the oligomer and of the monomer with formation of a stable and insoluble three-dimensional cross-linked polymer. In the great majority of cases this 'thin-layer' radiation polymerisation is a free-radical process, strongly inhibited by the presence of oxygen. If the hardening is carried out in air the oxygen reacts with the free radicals in the surface layer of the coating, suppressing the polymerisation and producing an adhesive and insufficiently hard surface.

Several methods of overcoming the oxygen effect have been suggested.

(1) Irradiation in an atmosphere of inert gas (nitrogen, CO_2, combustion products of natural gas).[67]

(2) Closing the layer to be hardened with a polymeric film (for example, polyethylene or nylon), and removing the film after the irradiation.[206]

(3) Sequential irradiation with an electron beam and with UV light: also called the 'double hardening' method. The light dissociates the peroxidic compounds and induces additional polymerisation as a result of the free radicals created by the process.[184,207]

(4) Using additives which inhibit the oxidation (for example, amines) or which sensitise the hardening (for example, salts of transition metals),[208] or also 'floating' additives (for example paraffin wax).[67,209]

(5) Covering the composition to be hardened with a protective layer of water.[209]

(6) Using special compositions containing oligomers modified by phthalic anhydride, dicyclopentadiene, styrene, etc.[47,210]

(7) Irradiating at very high dose rates ($\sim 10^{11}$ Gy s^{-1}), generated by nanosecond pulses of electrons.[211]

(8) Polymerisation by a cationic mechanism (in this case the oxygen has practically no inhibiting effect).[208,209] This type of hardening is only seldom met.

Methods of suppressing the effect of oxygen were discussed in detail in a review by Fomina et al.[212] In practice only the first three methods have been realised (the second only once). The third method began to be used a few years ago. Nitrogen containing not more than 0.05%–0.1% of oxygen as an impurity is usually used as the inert gas.[209,213]

In recent years the technique of radiation hardening of various polymeric coatings has been developed and brought into industrial practice (paints and varnishes, adhesives, magnetics, metallised materials, printing dyes, etc.) on many surfaces (timber, metallic, ceramic, stone, paper, polymeric, on magnetic disks, etc.).[1] Table 4 shows a list of the materials with radiation-hardened coatings produced in Russia and the Ukraine. The list of the corresponding articles produced by the foreign industry is even wider.[1] In particular, it includes timber parquet tiles and massive rocket bodies.

Table 4. Products with radiation-hardened coating produced in Russia and the Ukraine.

Product	Location of equipment	Operating speed	Ref.
Wooden panels for television sets [a]	L'vov, Simferopol, Samara	11 m^2 min^{-1} (L'vov)	67, 214, 215
Wooden panels for furniture	Kiev, [a] Moscow	950 000 m^2 a^{-1}	67, 216
Artificial leather	Kirov [b]	1.3 $t\,h^{-1}$	217, 218
Gypsum–polymer plates with decorative coatings	Kolomna (Moscow region)	200 000 m^2 a^{-1}	219
Asbestos–cement plates with decorative coatings	Near Moscow	200 000 m^2 a^{-1}	67, 218
Ceramic lining plates with decorative coatings	Dnepropetrovsk	2–5 m^2 min^{-1}	220
Plenkosintokarton [c]	Moscow	—	221, 222
Premelts for the production of laminated glass textolite	"	—	221, 222
Polymeric pressure-sensitive thin-film adhesives	"	—	221, 222

[a] The apparatus is not functioning at present.
[b] The construction of a similar apparatus in Tver has been planned.
[c] A three-layer adhesive composition consisting of a poly(ethylene terephthalate) film and electrically insulating paper.

2. Grafting polymerisation

Radiation grafting polymerisation is used to improve the properties of materials (mainly polymeric). In practice this process is used for finishing textile items, for grafting acrylic acid to polyethylene (in order to increase its adhesion to aluminium), for producing ion-exchange membrane, etc. The most important region of application is radiation biotechnology.

a. Radiation biotechnology

Studies and technological developments in radiation biotechnology are proceeding in two main directions: the production of biocompatible materials and the immobilisation of bioactive substances in polymeric matrices.

Biocompatible materials. Synthetic polymers are often used as biomaterials.[223,224] However, they have several defects: the most important is the presence of toxic impurities (catalysts, stabilisers, plasticisers, dyes), which can be washed out in an aqueous biological environment. On the other hand if the polymer is produced by the radiation method it does not contain these harmful impurities and furthermore it is sterile. Among the most important radiation methods of preparing biocompatible materials we can include graft polymerisation, polymerisation in the bulk, in solution, in an emulsion, or in the solid state, and cross-linking.[223,224] The most widely used of these methods is the first.

One of the main requirements on biocompatible polymers is that they should be hydrophilic. However, hydrogels become mechanically weak when they adsorb large amounts of water (30%–95%), and therefore hydrophobic polymers are used as substrates in their production [silicone rubber, polyethylene, poly(ethylene terephthalate), polytetrafluoroethylene, polyurethanes].

The compounds mainly used to prepare hydrogels include 2-hydroxyalkyl methacrylates $CH_2=C(CH_3)CO_2ROH$ [where R is $-CH_2CH_2-$, $-CH_2CH(CH_3)-$, or $CH_2CH(OH)CH_2-$]; acrylic acid, acrylamide and their derivatives, the derivatives of aminoethyl methacrylate, *N*-vinyl-2-pyrrolidone, penta-2,4-dien-1-ol, *N*-vinyl-*N*-methylacetamide, sodium styrenesulfonate, etc. are used less often. The radiation grafting of these monomers (or of their mixtures) to various substrates produces neutral, anionic, or cationic hydrogels.[223–230] Let us consider some relevant cases.

The production of polyelectrolyte biomaterials having a good blood compatibility has been reported:[231] it uses the radiation grafting of acrylic acid (from an aqueous solution) to polyethylene, followed by the deposition of polyethyleneimine on the resulting copolymer. As reported,[228,232] the radiation grafting of acrylamide to blood vessel substitutes obtained from poly(ethylene terephthalate) fibres markedly improves their properties. Thromboresistant materials have been prepared by the radiation grafting of *N,N*-dimethylacrylamide on polytetrafluoroethylene and on the copolymer of ethylene with polytetrafluoroethylene. It was found that the biocompatibility depends on the dose rate used for the grafting.[233] An improved blood compatibility was obtained also by using other combinations of polymer and of grafted monomer, for example silicone tubes + *N*-vinyl-2-pyrrolidone,[234] polyurethane films and tubes + acrylamide or 2-hydroxyethyl methacrylate,[235,236] silicone rubber (silastic) + *N*-isopropylacrylamide or its copolymers with acrylamide,[237] poly[bis(trifluoroethoxy)phosphazene] or poly[bis(phenoxy)phosphazene] + *N*-vinyl-2-pyrrolidone,[229] or polyethylene tubes + acrylamide,[238] polyamide + a mixture of vinyl monomers (2-hydroxyethyl methacrylate, acrylamide, etc.),[230] and other combinations.

Polymerisation in the bulk and cross-linking are used much less often. Hydrogels obtained by these methods form solid systems or microspheres (without using polymeric substrates).[224] Studies of this type were carried out with 2-hydroxyethyl methacrylate,[239] poly(ethylene oxide),[240] *trans*-1,4-polyisoprene,[241] poly(vinyl alcohol),[242] poly-*N*-vinyl-2-pyrrolidone,[243–246] etc.

The biomaterials prepared in this way were suggested for use in the production of soft contact lenses,[239] of adsorbents for the separation of biologically important substances by the affinity chromatography method,[230] seamless thermosetting compounds for blood vessels,[241] indicators for bilirubin in the urine,[232] surgical dressing,[243,244,246] etc. (Surgical dressing material prepared by radiation cross-linking have been produced on a commercial scale in Poland since 1990 under the trade names HDR^R and AQUA-GEL^R).[244]

However, it should be stressed that these methods did not find wide application in practice. In particular, the use in medical implantation of any material produced by the radiation method has not so far been reported. According to one report[230] this is because of the loss of biocompatibility during lengthy in vivo trials. The explanation of this disappointing result lies in the monitoring (in most cases) of only one property, associated with the biocompatibility, whereas these materials call for a more complex study.

Immobilisation of bioactive substances. The greatest practical applications were achieved by radiation methods of immobilising bioactive substances (antibiotics, antibodies, antigens, anti-cancer preparations, bacterial cells, contraceptives, enzymes, hormones, immunodiagnostic substances, proteins, and others) in polymeric matrices in order to lower their mobility.[223,224,228,243,244,247–257] The main aims of immobilisation are the following:[247] fixing and lowering the solubility of a bioactive substance in order to extend its effectiveness, giving to a material of correct shape and size an enhanced stability towards heat and chemical reactants, and a controlled slow evolution for moderately high and local action. The main regions of application of radiation-immobilised biological materials can be classified into two groups:[250] (1) biochemical processes (of the fermentation type) with the participation of immobilised enzymes, yeasts, bacterial cells, etc.; (2) biomedical applications (systems with a controlled evolution of medicinal substances, immuno-logical systems, artificial organs, etc.), which involve immobilised medicinal preparations, enzymes, antibodies, and cells.

Two main methods of radiation immobilisation have been proposed: the formation of chemical bonds between a bioactive substance and the substrate, and the capture of the material by the polymeric matrix.[248] In the first method the biomolecules react with the functional groups of the polymer, radiation-grafted or radiation-cross-linked, or obtained by radiation polymerisation. It has been reported that heparin, trypsin, chymotrypsin A, L-aspartamine, papain, asparaginase, glucosooxidase, albumin, antibodies, antigens, etc.[251,252,258–260] can be immobilised by this method.

In the second method radiation polymerisation at room temperature or at low temperatures is used to immobilise the bioactive substance, in conjunction with cross-linking of the polymers.[223,247–249,261] The method has been used to immobilise antibiotics, bacterial cells, hormones, haemoglobin, polypeptides, ureases, and various medicinal preparations (pilocarpine, provital, cancer-fighting preparations, etc.). Let us examine some typical examples.

The radiation polymerisation of aqueous solutions of acrylamide in the presence of provital or pilocarpine hydrochloride yielded preparations with controlled additions of medicinal substances used in the treatment of burns and glaucoma respectively.[228] Polyvinylpyrrolidone rods containing prostalgin, prepared by radiation polymerisation and cross-linking, are useful for inducing births.[244] Thin polymeric membranes with a high enzyme activity were synthesised by the radiation hardening of a mixture of a hydrophilic polymer [for example, poly(ethylene glycol) dimethacrylate] and a solution of an enzyme (for example, glucoamylase).[262] Matrices with the cancer-fighting preparation narcyclazine, from which it can be very slowly evolved, were obtained by γ irradiation at -78 °C of a mixture of 2-hydroxyethyl methacrylate and trimethylolpropane trimethacrylate.[263] A promising application of the

chemotherapeutic treatment of cancer consists in implanting the immobilised anti-cancer agent within the tumour: in this way its effect is local and it does not penetrate into the blood stream, thus minimising undesirable side effects.[248,249]

b. Finishing of textile materials

The properties of natural and of artificial fibres and tissues can be improved by radiation grafting.[264–267] In particular, the grafting of *N*-methylolacrylamide significantly improves the crease resistance of tissues made from a mixture of polyester and cotton fibres.[196,265] At the end of the 1960s the firm 'Deering Milliken Corporation' (USA) demonstrated a combined method of finishing these tissues which included the radiation grafting of *N*-methylolacrylamide.[196] To this end they used several electron accelerators: the operating speed of the assembly was 4.5×10^6 m a^{-1}. Articles which do not need to be ironed for long times were produced from the modified tissue. This production was maintained for 10 years, but in the late 1970s the production of textiles by this method was abandoned because of its low profitability and of the introduction of the more economical photochemical method of grafting.[268,269]

Since 1976 a pilot apparatus including an accelerator of the 'Electron' type (energy 0.7 MeV, beam power 7 kW) has been in use for the finishing of tissues by the radiation grafting method at the Glukhovsk cotton and paper concern in the Moscow region.[270] The operating speed of the assembly was 10–100 m min^{-1} (for a dose of 10–20 kGy). One of the processes (the preparation of cotton and paper tissue with antibacterial properties, is achieved by the grafting of methyl-5-vinylpyridinium methylsulfonate followed by the addition of hexachlorophene.[264] Tissues with grafted acrylic acid, treated with a solution of a copper(II) salt, have similar properties. It was reported[271] that the industrial production of tissues having these properties has been prepared: the assembly is fitted with an electron accelerator of the 'Aurora' type.

Yet another pilot assembly (with an 'Aurora' accelerator) for the local finishing of textile materials (for example, polyamides) has long been operating in Dresden.[272,273] Irradiation simultaneously with grafting was carried out on given areas of the textile (outlined by using aluminium 'masks'); under these conditions the grafted and the nongrafted regions had different properties (in particular, a different depth of colour). The operating speed was 50–60 m min^{-1} (for a dose of 100 kGy).

At present, studies of the radiation finishing of cotton–paper materials by using an electron accelerator are also being carried out in India (see, for example, Ref. 274).

c. Other processes based on radiation grafting

Several other processes based on the radiation grafting of monomers to polymers have been developed. They include the preparation of polyethylene with grafted acrylic acid, which has a high adhesion to aluminium, the production of ion-exchange membranes, etc.

In 1968 an industrial assembly for the radiation grafting of acrylic acid to polyethylene, aimed at the preparation of material with a high adhesion to aluminium, began to operate in France.[275] Powdered polyethylene was irradiated with electrons (dose 7–10 kGy) in the air, and acrylic acid was then grafted to it by heating. The operating speed of the assembly was ~20 t d^{-1}. The material prepared in this way is used as a coating for aluminium foil. A technology for the production of grafted polypropylene has also been worked out.[275] Ion-exchange membranes are being manufactured in Japan on a pilot-plant scale by the radiation grafting of acrylic acid on polyethylene films.[276] These membranes are used as separators in alkaline batteries. An apparatus was constructed on the basis of a 'Dynamitron' accelerator (2 MeV energy). A part of the film (for tapes 100–300 m long) was irradiated in a nitrogen atmosphere: grafting was then carried out by inserting the sample for a prescribed time into a solution of acrylic acid saturated with nitrogen, washing the sample, and drying it.

There are reports[196] that battery separators manufactured from polyethylene films with radiation-grafted acrylic acid have been commercially distributed, but at the moment they are being sold only in the USA. The technology of preparing battery separators on the basis of polyethylene with radiation-grafted acrylic acid or acrylonitrile was developed also in Russia.[277,278] In China γ radiation from ^{60}Co is used for the manufacture of these separators (with an annual production of 10 km^2).[279]

The published literature contains a very large amount of other possible (or already feasible) applications of radiation grafting (see, for example, Refs 1 and 271). In the USA the radiation grafting of acrylamide on starch is used to produce flocculants.[196] In France radiation grafting of *N*-vinylpyrrolidone onto silicone rubber is used to prepare soft contact lenses:[196] this product is sold in China.[279] In Japan a pilot plant has been constructed (operating speed 1 t d^{-1}) with a ^{60}Co source of γ radiation (activity 6.5 kCi) for the gas-phase grafting of butadiene to poly(vinyl chloride); the product is characterised by an enhanced impact resistance.[280]

Pikaev et al.[281] have described the technology of the radiation grafting of acrylic acid, acrylonitrile, and of a series of other monomers to butadiene–styrene thermoelastic plastics and to rubbers based on the ethylene–propylene terpolymer which markedly improves the lubrication properties of the products and their adhesion characteristics. To carry out these processes they constructed a pilot plant assembly with a Cockcroft and Walton electron accelerator as the source of ionising radiation. The operating speed of the assembly was 4.2 t a^{-1} with a dose rate of 2.2 Gy h^{-1}.

Radiation gas-phase grafting polymerisation can be used to encapsulate fertilisers in order to extend their lifetime.[86] This is achieved by grafting acrylamide and then vinylidene chloride on the fertiliser (carbamide). The required dose is ~30 kGy.

Other important products obtained by radiation grafting include effective adsorbents for ammonia and acetaldehyde from the gas phase,[282,283] of uranium from sea water,[283] of metals from waste water,[283] water absorbents,[284,285] etc. A method of creating barrier layers from polysiloxane on polymeric packing materials by radiation grafting has recently been developed.[286] These layers protect the packed material from the penetration of oxygen, oil, etc. The grafting of phenylacetylene to polyethylene increases the thermal stability and improves the electric conduction properties of the polymer.[287] The radiation stability of polyethylene is substantially increased by the grafting of acenaphthene.[288] The ethylene–propylene terpolymer and chlorosulfonated polyethylene with radiation-grafted condensed bromoacenaphthalene have a relatively high radiation stability and fire resistance.[141]

3. Production of modified porous materials

The radiation method of modifying various porous materials (wood, cement, asbestos–cement materials, etc.) is now relatively widespread.[86] The method consists in impregnating these materials with monomers or oligomers and polymerising them under the influence of ionising radiation (usually γ radiation from ^{60}Co). It is most often used with wood and plastic materials.

a. Wood and plastics materials

The polymerisation of monomers impregnated in wood greatly improves the properties of the latter: its mechanical strength is increased, its stability towards decay is also increased, and the water absorption is decreased.[76] Methyl methacrylate is often used as the monomer. The dose required for the polymerisation is 10–20 kGy (depending on the dose rate).[76,289] Styrene, and a mixture of acrylonitrile with methyl methacrylate, butyl methacrylate, etc., are used more seldom.

The dose depends on the nature of the monomer. In the case of styrene it is 250–300 kGy.[76] At these high doses the process is complicated by the decomposition of the wood. For this reason the dose used to prepared wood–plastics materials should not exceed 50 kGy.[76] As a result, when monomers difficult to polymerise are needed (for example, styrene) sensitisers are used

(CCl_4, solutions of metal salts with a variable valency, tributylphosphate, etc.).

A high moisture resistance is achieved in wood by using compositions consisting of a mixture of acrylonitrile and methyl methacrylate with additives of ethylene glycol dimethacrylate and maleic anhydride.[290] The dose needed to polymerise this mixture is ~10 kGy. To polymerise butyl methacrylate with some additives 10–30 kGy are required at a dose rate of 8 kGy h^{-1} (see Khan et al.[291]). Radiation modification is used for both soft and hard timber species.[289,292] In the USA hard species are modified by the radiation method, more than 80% being oak timber.[289]

In many countries wood–plastic composites are prepared by the radiation method.[76] In the USA parquet flooring, sports goods, everyday objects, etc.[289,292] are manufactured. In 1975 a pilot plant with a ^{60}Co source of γ radiation (activity ~100 kCi) was produced in Russia (Solikamsk) and operated for a long time for the production of parquet flooring from birch timber impregnated with methyl methacrylate.[76,293] The operating speed was ~10^5 m^2 a^{-1}. A similar but smaller apparatus was assembled in Hungary (with an operating speed of ~200 t a^{-1}).[290,294]

Wood and plastics materials from wood of tropical origin (bamboo, rubber tree, red liana, etc.) prepared by the radiation method can now find practical application.[290,294–300] The original timber of these woods is not used because of its low stability towards rotting.

b. Other composite materials

Among other porous materials modified by polymers we should discuss the cements.[76,293] Cement–polymer materials prepared by the radiation method have a much higher stability than the initial concretes; they are also characterised by an improved stability towards external interactions. The operating characteristics of wood–textile materials, tufa, gypsum, cardboard, paper, etc. are improved as a result of the modification by polymers.[76,293] According to one report[301] composite materials usable in construction and in the production of ceramic articles can be made from the waste products of the cellulose and paper industry by drying them, introducing mineral additives, unsaturated esters, and vinyl monomers, followed by radiation polymerisation.

Radiation polymerisation has been proposed as a means of producing armoured plastics, consisting of a strength material (for example, glass cloth) and a polymeric binder.[302] Plastics of this type are produced by repeating the sequential electron-beam treatment of the cloth and the binder. The technique of polymerising a thin layer of monomeric composite additive on the surface of a moving polyethylene film under an electron beam was developed for the production of adhesion-active materials.[303]

The radiation polymerisation of polymers in porous materials allows us to preserve and strengthen items made of wood, stone, bone, ceramics, etc. having historical value.[304–308] To this end the eroding items (statues, clay vases, dishes, items of furniture, everyday objects, skeletons, gypsum objects, etc.) are saturated with the monomer in a vacuum (or the monomer introduced separately by diffusion), and the monomer is then polymerised by γ radiation from ^{60}Co. This polymerisation gives the item a high mechanical strength which cannot be achieved by ordinary methods. Methyl methacrylate is used most often, vinyl acetate and unsaturated polyester resins are used least often. When the colour of the article has become bleached, a hydrophilic monomer can be used (for example, 2-hydroxyethyl methacrylate) which 'develops' the colouring as a result of polymerisation. This method was developed in Austria, the former Czechoslovakia, France, Germany, Switzerland, the former USSR, and Turkey, and has found some practical applications.

Another application of the radiation polymerisation of monomers impregnated in porous objects has recently been described:[309] the restoration of old books kept in large libraries (like the British Library). A suitable mixture of monomers is deposited on the page, and irradiated when an appropriate degree of impregnation has been reached. The method has been validated on a pilot plant with a ^{60}Co source of γ radiation. The 'Nordion International Inc.' corporation in cooperation with the British Library has planned to assemble an industrial gamma source with an annual throughput of up to 5×10^5 books.

4. Other processes based on radiation polymerisation

There are reports of the practical use of several other processes based on radiation polymerisation. In the People's Republic of China (PRC) the radiation polymerisation method is used on a pilot plant scale to produce polyacrylamide, used in the petroleum industry.[279] The operating speed is 400 t a^{-1}. According to one report[310] polyacrylamide produced by the radiation polymerisation of acrylamide in an ethanol solution can be used as a coating for medical X-ray films: the product is available in China from many producers of photographic film.

Pilot plants with ^{60}Co sources of γ radiation for carrying out emulsion radiation polymerisation have been described.[68,311,312] In 1989 several types of latex were prepared in China by the radiation emulsion polymerisation method with a ^{60}Co γ source (operating speed up to 2000 t a^{-1}).[313] The products are used as a binder in the textile industry and as a thickener in the printing trade.

Various optical items (Fresnel lenses, contact lenses, prisms, etc.) can be obtained by the low-temperature radiation polymerisation of methyl methacrylate, 2-hydroxyethyl methacrylate, and some other monomers.[314,315] The monomer (or sometimes the prepolymer) is placed in a mold and cooled to a temperature close to its glass transition temperature (between −50 and −78 °C). After γ irradiation the resulting polymer is removed from the mold. Because the process has been carried out at a low temperature the compression of the product is relatively small, and the polymer emerges transparent and free from cracks and bubbles even with relatively large items: the method can be used to prepare Fresnel lenses having an area of 1 m^2 (see Kaetsu et al.[315]). The method has been used by the firm 'Nippon Kogaku Co.' (Japan) to produce lenses used in photolithography.[315] It consists of two stages: the preparation of the prepolymer and the polymerisation in the mold at low temperatures. The operating speed is several hundred lenses per annum.

V. Radiation degradation

Radiation degradation is not so widely used as radiation polymerisation. The most important processes based on the radiation degradation of polymeric materials are the production of fodder and of fodder additives from waste products containing cellulose, the control of the molecular mass of polymers, and the decomposition of PTFE and rubbers from butyl rubber.

1. Preparation of fodder for cattle from waste products containing cellulose

Waste products containing cellulose (sawdust, shavings, chaff, fine splinters, etc.) also contain large quantities of polysaccharides; therefore they can be treated as a potential source of fodder for cattle. Irradiation of these materials produces a marked change in their properties: they are amorphised, the recovery of polysaccharides from lignin is improved, the amount of cellular tissue decreases, and monomeric and oligomeric carbohydrates are formed.[41,85,316] For example, wheat chaff contains 36.8% of carbohydrates in the dry residue after γ irradiation to a dose of 1 MGy and acid hydrolysis.[317] It has been shown experimentally that these materials (in particular sawdust, chaff, or shavings) can replace 3%–10% of the normal fodder for oxen, pigs, sheep, and chickens when irradiated to a dose of 0.2–0.6 MGy.[85,316,318]

The dose needed for a substantial improvement in the quality of the fodder from waste products containing cellulose depends on the type of waste and on the class of cattle.[41,85,316,318] It lies between 0.1 and 1.0 MGy. Of course, this large dose can hardly be used economically. But it can be decreased by simultaneously irradiating and heating the waste products or by heating them after irradiation.[85]

A large-scale series of experiments with these fodders has been planned by building a pilot-plant assembly with an ILU electron accelerator.[85,318] Its operating speed is 0.2–0.3 t h^{-1} (see Ershov[85]). The use of the irradiated product as a 5% addition to the feed in an aviary with an annual production rate of ~7 million hens has been reported.

2. Degradation of PTFE waste products

The radiation degradation of polytetrafluoroethylene (PTFE) waste products converts them into a powder or into products having a low molecular mass which are useful in practice.[269] Relatively high doses are required (0.5 MGy or even higher), and at sufficiently high dose rates the heat evolved within the polymer produces a simultaneous thermal degradation (observed at temperatures above 360 °C).[319,320] Under these conditions the nature of the resulting substances depends on the temperature, the dose, and the presence of oxygen. Irradiation in an inert atmosphere produces perfluoroolefins (up to 60%) and perfluoroparaffins. In the presence of oxygen fluoroanhydrides of perfluorocarboxylic acids are formed. The resulting compounds can be used in the synthesis of other substances containing fluorine.

In Russia and in the former German Democratic Republic (GDR) two pilot plants with electron accelerators have been assembled. The annual production of one of these plants is 12 t a^{-1}.[319,320] The Japanese firm 'Sumitomo Heavy Industries, Ltd.' carries out this process on a commercial scale, using a high-power 'Dynamitron' accelerator. In the People's Republic of China three assemblies have been built for the same purpose:[279] the product is used mainly as a high-quality lubricating material.

3. Regeneration of rubbers based on butylrubber

In most cases items made of rubber based on butylrubber cease to perform satisfactorily after a relatively short period of operation. However, many substances present in their composition remain almost unchanged. Therefore it should be possible to exploit them for a second time after a suitable regeneration. One regeneration method which has been used in practice is a radiation treatment which leads to degradation of the polymer.[321–324]

Butylrubber is a copolymer of isobutylene and isoprene. The process consists in breaking up the degraded vulcanised rubber, irradiation (both ^{60}Co γ radiation and an electron beam can be used), crushing, etc. The optimum dose is 50–100 kGy. The product can be added (in 10%–15% quantities) to various rubber mixtures.

The radiation method of regeneration of rubber made from butylrubber is used in the PRC on a commercial scale. The assembly (including an electron accelerator) has a productivity of 200 tonnes per annum,[279] and more than 400 tonnes of rubber were regenerated up to the middle of 1992 in an apparatus using a ^{60}Co source of γ radiation.[324]

4. Other processes

Among the other processes of this group we should include the control of the molecular mass of polymers. It is difficult to obtain a polymer with a prescribed molecular mass by polymerising the monomer: this aim is much more simply achieved by subjecting the polymer to degradation by radiation. The process was realised in practice with poly(ethylene oxide) in the USA[196] and with cellulose (in Russia).[325] In the latter case a pilot plant with an electron accelerator (energy 0.3–0.6 MeV, power 40 kW) was used to irradiate a cellulose bed (1–5 layers, 0.8–1.0 m in width) with a dose of 50 kGy.

Many workers have reported that a previous irradiation of waste products containing cellulose (wood shavings, paper spoilage, waste material from the production of palm oil, etc.) increases the yield of final products even for relatively low doses. We shall quote some examples.

It was stated[78,196] that the irradiation of wood waste in air with a dose of 5–20 kGy increases its storage life and improves the yield of cellulose when the material is subsequently treated by traditional methods (for example, by boiling in acid). Thus, in the case of Christmas tree residues the yield of final product is increased by 5%–9% even for a dose of 5 kGy.[78] The reason for this large effect is not clear.

Brenner[326] has proposed a combined method of treatment of waste paper and other waste containing cellulose aimed at the production of glucose. The method consists in the preparation of a fibrous mass, irradiating it with a dose of 10 kGy, and subjecting it to a brief high-temperature (232 °C) acid hydrolysis. The yield of glucose is 50% of the amount of cellulose in the initial mass, i.e. 10% higher than the amount obtained in treatment without irradiation. A similar effect was observed in the fermentative hydrolysis of previously irradiated sawdust, fine chaff, and other waste products.[327,328]

Let us also consider the methods of increasing the yield of the final products from waste containing cellulose obtained from the irradiation of food products used in the treatment of this waste. It was shown (see, for example, Refs. 85 and 316) that the irradiation of the hydrolysate produced by thermocatalytic hydrolysis of vegetable stocks increases the yield of nutrient yeasts when grown on this hydrolysate. The yield increases by 8%, 16%, and 20% for γ radiation doses of 1, 5, and 10 kGy respectively. This effect is explained by the radiation-chemical decomposition of furfural and other compounds, known to be inhibitors of the growth of yeasts. According to Kume and coworkers[329–331] the irradiation of fermentation media used in treating the waste from the production of palm oil so as to obtain from them fodder for animals and to use them to grow edible fungi (dose 10 or 25 kGy), gives satisfactory results.

VI. Radiation sterilisation of medical articles

The radiation sterilisation of medical articles (in most cases, used only once) is one of the most important industrial processes which uses ionising radiation. It follows from Brinston's paper[332] that in the late 1980s about 30% of the medical production items for once-only usage were sterilised by the radiation method. We note a tendency for an increase in the amount of medical production sterilised by the radiation method. At present the fraction amounts to 40%–50%.[176,177] It has been forecast[332] that in the year 2000 more than 50% of the production of once-only medical items will be sterilised by this method.

γ-Radiation from ^{60}Co and electron beams are used for the sterilisation. The possible advantages of using bremsstrahlung X-radiation generated by powerful electron accelerators have been pointed out. An apparatus of this type based on an accelerator of the Cockcroft and Walton type (electron energy 5 MeV, beam power 150 kW) has already been built[121] (see also Section II.3). In 1992 about 120 large γ sterilisers using ^{60}Co were functioning throughout the world (see also Woods and Pikaev[1]). These assemblies are located in more than 40 countries. Of course, γ radiation from ^{137}Cs is also used for sterilisation, but only relatively seldom.[50]

About 30 sterilisers based on electron accelerators (mainly linear accelerators and accelerators of the 'Dynamitron' type) are operating throughout the world. The energy of their electron beams, used for the sterilisation, is mainly 5–10 MeV. Beams with a lower energy may find application[333,334] in the sterilisation of the packing of medical items. Of course, an assembly with an accelerator of the ILU-6 type (electron energy up to 2.5 MeV, beam power up to 20 kW) has already been tested.[335] It has been suggested that hypodermic syringes should be located in a vertical plane and irradiated from both sides.

It should be noted that in recent years the use of electron accelerators has been increasing as compared with γ sources. This is because of the greater safety offered by working with accelerators as well as because of the greater powers, resulting in shorter times of treatment. Thus, linear electron accelerators specially designed for radiation sterilisation have recently come onto the market (in particular, from the American firm 'Varian Associates Inc.').[336]

Table 5. Characteristics of industrial radiation sterilisers in Russia and the Ukraine with ^{60}Co sources of γ radiation (A) and with linear electron accelerators (B).

A. ^{60}Co source.

Location of the steriliser	Activity/MCi
St. Petersburg	0.93
Belgorod-Dnestrovskii (Ukraine)	0.36
Moscow region	0.12
Kaluzhsk region	0.67
Kazan'	0.17
Tyumen'	0.47
Dimitrovgrad[a]	1.5

B. Linear electron accelerator.

Location of the steriliser	Number and type	Energy/ MeV	Power/ kW
Kurgan[b]	2, LUE-8-5V	8	Both 10
Kostroma[a]	1, UELV-10-10	10	10
Moscow[a]	1, LEU	10	10
Leningrad region[a]	2, LUE-8-15S	8	Both 15

[a] The steriliser is in the building stage.

[b] Improvements are being carried out on the steriliser. Two LUE-8-15S linear electron accelerators will be brought into operation (energy 8 MeV, power 15 kW, annual production from each machine 1400 t).[337]

In Russia the last ten years have seen a large increase in the number of once-only items (mainly syringes). In 1995 it is planned to produce 6×10^9 syringes for once-only use, 190×10^6 containers for the storage of blood, and 320×10^6 blood transfusion units.[337] At the same time we observe an intense development in the radiation sterilisation of these products. In Table 5 we quote some data on the industrial radiation sterilisers in Russia and the Ukraine.[98] In addition to industrial sterilisers, equipment based on linear electron accelerators is located in research institutes. The total number of assemblies, including those functioning in institutes, is ~30 (see Khrushchev et al.[338]).

In addition to medical items for once-only applications (syringes, needles, surgical items, materials and tissues to be implanted, anaesthetic and obstetric kits, equipment for inhalation, dialysis, and blood transfusion, dressings, gloves, Petri dishes, masks, bandages, pipettes, etc.), some pharmaceutical preparations are also subjected to sterilisation by radiation (eye ointments and drops, ointments for burns, salt solutions, veterinary products, etc.), as well as packing materials. In some countries radiation sterilisation is applied to various solid medicinal preparations, ointments, and suspensions of pharmaceutical stock.[339] This method is used also in the sterilisation of tissues and organs of humans and animals needed in implantation surgery.[340,341] The radiation sterilisation of cosmetic materials (bentonite, gelatine, starch, talc, etc.) also offers attractive prospects.[324-344] The sterilising dose adopted in many countries is 25 kGy. In the Scandinavian countries it is much higher (35 kGy for electron radiation and 32 kGy for γ radiation).[57,345] In some countries (in particular the USA and Canada) there is no fixed sterilising dose: it is determined by the initial number of microorganisms in the product to be sterilised, by their nature, and by their sensitivity to the action of the radiation.[346] Therefore it may vary from 10 to ~40 kGy. The dose may be decreased by a careful control of the production conditions of the medical items. In Russia the dose used for sterilisation is 15–25 kGy.[337,338,347]

These doses are relatively high, and therefore in parallel with the sterilisation we must solve the problem of the radiation stability of the preparations and materials from which the item is manufactured. It was found (see, for example, Refs 348 and 349) that many polymers used in the preparation of medical articles are stable enough towards radiation to 'endure' the sterilising dose, but the degradation (especially, post-radiational) of polypropylene, which is widely used as a material for syringes, produces a coloration and makes the material brittle.[350-352] Therefore polypropylene stabilised by various additives has now begun to be used for the production of syringes.

Most of the solid medicinal preparations retain their properties after irradiation with sterilisation doses (see, for example, Ref. 341). This is also true of a series of preparations in the form of concentrated aqueous solutions.[353] However, most medicines in the form of aqueous solutions suffer large changes (dissociation with formation of new substances, changes in pH, etc.). These include some new radiopharmaceutical preparations[354-356] vitamin B_{12},[357] insulin,[357] etc. For these preparations the use of protective additives has been suggested (for example, thiosulfate for a solution of ^{131}I sodium iodide),[354,358] or alternatively irradiation in the frozen state,[357,359-362] when as a result of phase separation only a very small fraction of the energy of the ionising radiation is absorbed by the dissolved substance. Neither of these methods has been applied in practice so far.

An analysis of the economics of these processes has shown that the cheapest method of sterilisation is treatment with steam, and the dearest is the use of ethylene oxide: the radiation method occupies an intermediate place.[363,364] However, at high production rates the radiation sterilisation may compete with the steam method.[364] Obviously, in future the sterilisation with ethylene oxide will continue to be applied in the case of medicinal products unstable towards heat and ionising radiation. For many other items intended for once-only application the radiation method will be the predominant method of sterilisation.

VII. Use of radiation for the protection of the environment

The first studies of the use of ionising radiation for the protection of the environment were carried out in the 1950s.[11] At present studies and technological developments in this region of radiation technology are proceeding in the following main directions:[365] the radiation treatment of natural water, the radiation purification of domestic, industrial, and agricultural waste waters, the radiation treatment of deposits from waste waters, the radiation purification of discharge gases, and the radiation treatment of solid refuse.

1. Natural water

Natural water (from rivers, lakes, reservoirs, artesian wells, etc.), which is used to feed the population, may be contaminated by harmful impurities and contain pathogenic microorganisms and parasites. Often the concentration of these impurities and the level of contamination are small, and relatively low doses are needed for the radiation treatment of the water.

It was found (see, for example, Refs 11, 366, 367) that doses of ~1 kGy are sufficient for the purification and disinfection of natural water (in particular, for the removal of organic compounds of the humin type, which produce colour, smell, etc.). It was recently shown[368] in studies of water strongly coloured by natural organic compounds and by finely divided particles, taken from a river in northwestern Russia, that doses of the order of several kGy can lower the coloration to the required level. The dose required for decoloration depends on the season in which the sample was taken from the river. For example, the dose for autumnal water is higher than for the winter.

One of the important problems still awaiting solution is the purification of natural water from toxic and carcinogenic organic compounds containing chlorine. These substances are introduced into the water from the contaminated surroundings, and are formed during the chlorination of water containing several

organic compounds. It has been shown[365,369–378] that the irradiation of water contaminated with organic substances containing chlorine (1,2-dichloroethane, 1,1,1-trichloroethane, trichloroethylene, tetrachloroethylene, chlorobenzene, 4-chlorophenol, 2,4-dichlorophenol) leads to their decomposition. On the basis of these data we may conclude that small amounts of these substances (10^{-4} mol dm^{-3} and below) may decompose upon exposure to relatively small doses (1 kGy or less). In these systems the use of radiation methods seems promising.

However, it should not be forgotten that in the radiolysis of chlorinated aromatic compounds the dechlorination may be accompanied by the formation of other toxic substances. For example, in the radiolysis of chlorobenzene solutions isomeric hydroxycyclobenzenes [sic. Ed. of Translation] and phenol compounds are formed. Furthermore we observe a marked dependence of the yield of decomposition products upon the strength of the dose (especially at low concentrations).[378]

The irradiation of contaminated water in conjunction with ozonisation produces a synergistic effect (see below). Thus, ozonisation of water contaminated with trichloroethylene and tetrachloroethylene[376,377] also eliminates almost completely the dependence on dose strength in dilute solutions, and also protects the irradiated water from a second appearance of the microorganisms and parasites during its transport along conduits.[377]

Radiation treatment gives good results also in the treatment of ground waters. Firstly, it can be used successfully to regenerate water boreholes contaminated by the products of biological processes.[379–381] Ionising radiation kills the bacteria responsible for the redox reactions of the ions Fe(II), Mn(II), etc., and for the subsequent precipitation of insoluble hydrolysis products, which lead to 'clogging' of the water separators and 'ageing' of the boreholes. The doses needed for this are 0.25–0.4 kGy.[379] This method was widely used in the GDR.[273,379] 372 Boreholes were fitted with ^{60}Co sources of γ radiation (total activity 132 kCi). However, after the union of the German Democratic Republic and the Federal Republic of Germany all sources were removed from the boreholes because in the FRG the irradiation of food products is not allowed, and drinking water is classified as such. Interest in this method has been shown in the Czech state[380] and in the USA.[381]

Secondly, in situ irradiation of contaminated water in underground reservoirs leads to its purification. For example, it has been shown[380] that the concentration of cyanide ions in underground water is much decreased if the reservoir is fitted with a ^{60}Co source of γ radiation and activated carbon is added to it. After a 6 years use of the installation the concentration of cyanide ions in the reservoir had fallen by more than an order of magnitude.[382]

In spite of the promising results of studies and technological developments the purification of natural water to produce drinking water has still not found large-scale application. Of course, in Austria it is planned to build an assembly for the purification of drinking water having a production rate of 1000 m^3 h^{-1} (see Ref. 376). The details of its future operation are being planned with a prototype having an operating rate of 3 m^3 h^{-1}.

2. Sewage

It has been found (see, for example, Refs 369, 383–385) that for the radiation treatment of domestic sewage after its biological purification doses from 0.4–0.5 kGy to several kGy are required. For example, the doses needed for disinfection and for the decomposition of harmful impurities (detergents, organic sulfides, dyes, etc.) in the sewage of Tokyo amounted to several kGy.[385] The use of radiation treated water for industrial purposes has been recommended. Kurucz et al.[369] give the same doses, and point out that they are higher for nonchlorinated than for chlorinated water. In the latter case the study was carried out in an apparatus based on an IST electron accelerator (operating rate 460 dm^3 h^{-1}).[369,386]

Industrial sewage differs from contaminated natural water in containing more impurities at much higher concentrations. In most cases higher doses are required for the purification of these effluents (some tens of kGy or more). As a result combined methods of purification have been developed in recent years, in which the radiation treatment is carried out in conjunction with a conventional method (chemical, biological, thermal, flotation, etc.). A brief description of the combined methods is given in Table 6.

Table 6. Combined methods of purifying sewage waters.

Method	Basic processes	Removed impurity[a]	Ref.
Radiation–flotation	Flotation, γ irradiation, secondary flotation	Mercury	387, 388
Radiation–biological	Electron irradiation, additional biological purification	Mixture of isobutyl naphthalenesulphonates	389
Radiation–polymerisation	Irradiation of the sewage containing the monomer	Monomers	26
Thermo–radiation	Irradiation of the waste products while heating	Bacteria, parasites, etc.	390
Radiation–electrodialysis	Combination of radiation and electrodialysis	Various organic substances	391
Radiation–coagulation	Irradiation in the presence of a coagulant	Polyoxyethylene-n-nonyl phenyl ether etc.	392, 393
Radiation–adsorption	Irradiation in the presence of activated carbon	Pesticides	394–396
Oxyradiation	Irradiation of the waste while passing oxygen through the solution	Parasites, bacteria, etc.	397
Ozonoradiation	Irradiation of the waste saturated with ozone	Various organic substances	392, 393, 398

[a]These impurities are quoted as an example.

A radiation-biological method is used to purify the discharge waters of the Voronezh synthetic rubber factory from the emulsifier. The latter material (Nekal) is a mixture of isomeric butyl naphthalenesulfonates of the general formula $C_{10}H_6(R)SO_3Na$, where $R = (CH_3)_3C-$, $(CH_3)_2CHCH_2-$ or $CH_3CH_2CH(CH_3)-$, predominantly the first two butyl groups;[399] the alkyl and the sulfonate group are in the same ring in a pair of positions relative to each other. Nekal is classified as a 'hard' surface-active substance and does not dissociate biologically. However, it was shown[389,399] that the removal of the alkyl of the sulfonate group (or both) from its molecule produces biodegradable substances. Dealkylation and desulfonation take place at relatively low doses. The dose needed to decompose $\sim 100-150$ mg dm^{-3} of Nekal is 2–3 kGy. A study by pulse radiolysis has shown[400] that OH radicals contribute to these processes, and to a smaller extent the hydrated electrons produced in the radiolysis of water also make a contribution.

An apparatus for purifying waste waters has two ELV electron accelerators (0.7 MeV energy, total power 70 kW). The waste water is irradiated as a foam (density 0.02–0.03 g cm^{-3}). The operating rate of the assembly is $\sim 12\,000$ m^3 d^{-1}. After the electron beam treatment the water passes to the biological purification arrangement. The degree of removal of Nekal can be as high as 99.5%. At present this apparatus is used to purify underground water contaminated with Nekal.

We should briefly mention the problem of the disinfection of manure discharge in connection with the building and operation of large pig farms. Many workers[41,401,402] have shown that this problem can be solved in principle by using radiation methods. Four pilot plants (three with electron accelerators, one with a ^{60}Co source of γ radiation) were developed for the disinfection and purification of waste waters in large amounts in the Minsk, Moscow, and Omsk regions and operated for a long time. However, the process was never used in practice.

In our country several projects for the production of large assemblies including electron accelerators (total power ~ 0.9 MW) were considered for the purification of domestic and industrial sewage.[403–405] The largest of these projects was aimed at the radiation treatment of the domestic sewage of one of the towns in the Leningrad region. Its designed operating rate was 110 000 m^3 d^{-1}.[405] However, none of these projects has yet been realised.

3. Sedimentation of sewage

When domestic sewage is allowed to settle (the first stage in their normal purification) deposits containing insoluble solid particles (5%–8%) and water (92%–95%) are formed. In the biological treatment deposits of another type, called the excess active silt (which consist mainly of microorganisms) are formed at the aeration stage. The deposits can be used as fertilisers and as additives to animal fodder. However, they are loaded with bacteria, viruses, and parasites, and they may contain harmful substances. Obviously, they should be disinfected before being used. As can be seen from many published reviews (see Refs 28 and 401) this problem can be solved successively by radiation methods.

It was found that disinfection is achieved at doses of 2–10 kGy. Furthermore irradiation often accelerates the filtration and the sedimentation of deposits, and therefore also their dehydration. At present the technology of the radiation treatment of deposits from sewage waters is being applied in many countries on pilot plant or on industrial scales. The corresponding equipments are based on sources of γ radiation or on electron accelerators. Some data on these assemblies are listed in Table 7. It is intended to build similar apparatus in Canada, Poland, and the Argentine. The system proposed in Canada is based on a ^{60}Co source of γ radiation (with a planned production rate of 80 t d^{-1}).[416,417] The planned production of the Polish system with a linear electron accelerator (energy 10 MeV) is 50–70 t d^{-1} (for a dose of 5 kGy).[418]

Table 7. Apparatus for the radiation treatment of deposits from sewage waters.

Location of apparatus	Period of operation	Source of radiation	Energy/MeV	Power or actvitiy	Operating rate/m^3 d^{-1}	Dose/kGy	Ref.
Heiselbullach (FGR)	1973–1993	^{60}Co and ^{137}Cs	1.25 and 0.66	135 kCi of ^{60}Co + 55 kCi of ^{137}Cs	180 (1981)	2	397, 406, 407
Grosslappen (FGR)	1974– mid-1980s	^{60}Co	1.25	—	30	3	407
Albuquerque (USA)	1978–1985	^{137}Cs	0.66	~ 0.9 MCi	8 [a]	10	408, 409
Baroda (India)	Since 1989	^{60}Co	1.25	150 kCi	110	5	410
Boston (USA)	1976–1980	ICT electron accelerator	0.8	50 kW	379	4	383, 411
Boston (USA)	1980– late 1980s	"	1.5	75 kW	654	4	383, 411
Near Miami (USA)	1984–1985	"	1.5	75 kW	648	4	409, 411
Takasaki (Japan)	Since 1987	Cockcroft–Walton electron accelerator	2.0	60 kW	7.2[a]	5	412, 413
Near Minsk (Belorussia)	In the 1980s	ILU electron accelerator	1.6–2.0	30 kW	~ 150	5	41, 414, 415

[a] Quoted in tonnes per day.

4. Gaseous emissions

At present the most intensively studied area in radiation technology includes the work on one of the most important ecological problems: the purification of gaseous emissions from harmful substances (mainly SO_2 and the nitrogen oxides NO_x, where $x = 1, 2$). Many workers have demonstrated the promise of using electron beams for the purification of these gases. It was clearly shown that the electron-beam treatment of gases containing SO_2 and NO_x removes both impurities at the same time.

A pioneering contribution to this problem was made by Japanese research workers and engineers in the early 1970s.[419,420] It was subsequently found[420–423] that the addition of ammonia to the irradiated gas results in the formation of a powdery product of composition $(NH_4)_2SO_4$ and NH_4NO_3 which can be used as an agricultural fertiliser. At present the process goes under the name of the 'Ebara process', after the Japanese organisation 'Ebara Co.' which built and operated the first pilot plant for the purification of gases.

At present studies and technological developments in this area of work are being carried out in Japan, the USA, Germany, Poland, Russia, Italy, China, Belorussia, and South Korea. The method is realised on a large pilot plant scale. Table 8 shows some information on the pilot and demonstration assemblies. Furthermore, in some countries large experimental plants with electron accelerators are being operated for the development of new methods of radiation purification of gas discharges from various sources.[436]

From the results obtained during studies, technological developments, and extended trials it may be concluded that effectiveness of removing SO_2 exceeds 95%, and in the case of NO_x it can reach 80%–85%.[436] The doses needed for purification are between ~10 and 20 kGy (depending on the concentrations of SO_2 and NO_x); the energy of the electorn beam should lie between 0.3 and 0.8 MeV.

The mechanism of the reactions proceeding during the irradiation of gas discharges containing SO_2 and NO_x has been studied by several workers (see, for example, Ref. 371). The electron beam, interacting with the main components of the gas discharges, produces secondary electrons, ions, free radicals, atoms, and excited particles, which react with SO_2, NO_x, and other possible constituents, as well as taking part in dimerisation, neutralisation, and other reactions. The extent of these processes is not large. For example, in one reported computer modelling[437] 181 reactions of this type were considered. Not only are the nitrogen oxides in these processes oxidised, but they can also be reduced (25%–30%) to N_2O and N_2. Whereas the NO_x is removed entirely by radiation-chemical reactions, the SO_2 is oxidised both in radiation-chemical processes and in thermal reactions involving oxygen and ammonia.[438–440] Up to 70%–90% of the SO_2 can be removed by thermal reactions.[440]

Electron-beam treatment is used also in the purification of exhaust gases from thermal electric power stations operating with coal, fuel oil, etc. and also for the removal of harmful impurities from the exhaust gases from furnaces for the heat treatment of sweepings (SO_2, NO_x, and HCl), from tin treatment plants, (SO_2), and from automobile subways (NO_x). Recently a mobile apparatus with an electron accelerator (0.15–0.3 MeV energy) was constructed in the FRG for the removal of harmful volatile organic compounds from the gases of industrial undertakings, and of nitrogen oxides and benzene from the gases of automobile subways.[441] It was mounted on a trailer, and its operating speed was 1000 $m^3\ h^{-1}$. Sometimes the purification technology differs

Table 8. Large pilot and demonstration scale apparatus with electron accelerators for the purification.

Location	Operating period	Source of gases	Number of accelerators	Energy/MeV	Total power/kW	Additive	Operating rate under normal conditions/$m^3\ h^{-1}$	Ref.
Vakamatsu (Japan)	1977–1978	Furnace for firing iron ore	2	0.75	90	NH_3	10000	421, 423, 424
Indianapolis (USA)	1984–1989	Thermal power station	2	0.8	160	NH_3	16000–32000	425, 426
Karlsruhe (FGR)	1985–1989	Thermal power station	2	0.28–0.3	180	NH_3	10000–20000	426, 427
Kaveshchin (Poland)	Since 1991	Thermal power station	2	0.7	100	NH_3	20000	428, 429
Novosibirsk (Russia)	Since 1991	Tin refining works	1	0.5–0.7	50	None	—	430, 431
Matsudo (Japan)[a]	1992–1995	Furnace for roasting refuse	1	0.95	15	$Ca(OH)_2$	1000	432, 433
Nagoya (Japan)[b]	Since 1993	Thermal power station	1	0.4–0.8	108	NH_3	12000	434, 435
Tokyo (Japan)[c]	Since 1992	Automobile subway	1	0.5	25	—	50000	436

[a] Apparatus designed for the removal of SO_2, NO_x and HCl. [b] The accelerator has three irradiators. [c] The accelerator has two irradiators.

from the Ebara process. Thus, in the purification of gases from the furnace for the heat treatment of sweepings the additive $Ca(OH)_2$ is used; in general this additive is not used in the gases from tin treatment plants (where the SO_2 is removed as sulfuric acid).

In Russia the studies in this area of radiation technology are carried out in several scientific and technological development centres.[442,443] In addition to the equipment already functioning in Novosibirsk (see Table 8) pilot plants are also planned for Moscow, Lipetsk, and Orenburg.[403,430,443] It has been suggested[443] that one of the installations should be fitted with a many-aperture electron accelerator of the 'Finval' type (see Table 1).

However, even the largest of the assemblies built so far allow the removal of the gases produced by only one relatively small generating block (with an electric power of 5–8 MW) of a thermal power station. This limitation is due first of all to the inadequate power of currently available electron accelerators. Accelerators with beam powers of 0.5 MW (in Russia[108]) and even 0.8–1.8 MW (in the USA[109,436]) are now being built. We should stress the importance of a Polish project aimed to build an assembly with a productivity of 270 000 $m^3 h^{-1}$ (for a total electron beam power of 1.2 MW).[444,445]

A lowering of the dose required for the removal of harmful impurities (i.e. an increase in the radiation-chemical yield of the decomposition) should accompany the large-scale applications of the radiation methods of purifying exhaust gases. Different methods of solving this problem have been reported. The effectiveness of the removal of NO_x increases if the technique of repeated (or band) irradiation is used.[434,446,447] As can be seen from Ref. 442 the introduction of an aqueous aerosol into the gas to be purified (in the absence of ammonia) produced a marked lowering of the dose.

Another possible path is to use catalysts as additives. Injecting a solution containing (for example) Mn^{2+} ions into the gas before the electron-beam treatment stage can increase the efficiency of the process. The evidence for this statement[72] is that gases are very effectively purified from SO_2 (oxidation yield up to 10^4 molecules for 100 eV) when passed through a dilute sulphuric acid solution of Mn(II).

Increased efficiency can be achieved also by combining the irradiation with other methods of treatment. It has been reported[448,449] that combining γ irradiation with the application of an electric field produces a marked increase in the radiation-chemical yields of the oxidation of SO_2 in the gas phase (up to 100–150 molecules per 100 eV). According to Zimek et al.[450] the purification efficiency is increased by the simultaneous application of an electron beam and of a stream of microwave energy.

From the economic point of view the Ebara process can compete with the conventional methods of purifying discharge gases.[436,438,451] Its cost effectiveness increases with the SO_2 content of the gases to be purified.

5. Solid waste

There are published reports that radiation methods can find practical applications in the decontamination of waste from hospitals and from airports, in the regeneration of active carbons, and in the purification of contaminated soils. The importance of using γ radiation for the disinfection of hospital waste has been pointed out.[452] At present only one assembly with a ^{60}Co source of γ radiation is being operated (in the state of Arkansas, USA),[453] to treat infected hospital waste. As reported,[452] one relatively small source can disinfect this waste for all the hospitals in a town with a population of 1 million, and a large source can provide for the needs of the hospitals in a town with a population of 5 millions.

The technology of the radiation treatment of hospital wastes has been developed also in Russia.[454] It consists of four stages: (1) the separation of the liquid and the solid phase, (2) the radiation disinfection of the liquid wastes, (3) the radiation disinfection of the solid wastes, (4) the purification of the emitted gases. A suitable assembly with a ^{60}Co source of γ radiation was constructed ('Gammatok-100'); its productivity is 65 $m^3 d^{-1}$. However, the method has not yet been used on a commercial scale.

Another promising application of γ radiation is the treatment of wastes for international airports.[452] 20–30 t (or even more) of waste are produced annually in large international airports. This amount of waste can be treated by a gamma-apparatus of intermediate size. The Canadian company 'Nordion International Inc.' plans to construct an irradiator of this type.[452]

The next possible application is the regeneration of the activated carbon used in the purification of natural and of waste waters by using electron irradiation.[455] Samples of carbon with adsorbed sodium lauryl sulfonate were subjected to radiation treatment. The dose required for regeneration was 1 MGy. An economic assessment showed that the radiation method is ~8–10 times cheaper than the usual high-temperature steam method.

Radiation methods can be used to purify contaminated soil.[456–458] Two methods have been developed. The first consists in mixing the contaminated soil with water and a nonionic surface-actant substance and treating the mixture with γ radiation.[456] This method was used to purify soil contaminated with chlorinated dioxins. In particular it was shown that 2,3,7,8-tetrachlorodibenzo-*p*-dioxin is converted by successive oxidative dechlorination into the nonchlorinated dibenzo-*p*-dioxin, characterised by a negligibly small toxicity. The radiation-chemical yield of the decomposition is $\sim 10^{-6}$ molecules per 100 eV. This means that the breakdown takes place mainly as a result of the 'direct action' of the ionising radiation on the dioxin molecule.

The second method was developed for soil contaminated with volatile organic substances (for example, trichloroethylene).[457,458] It consists in the vacuum extraction of impurities from the soil followed by their electron-beam treatment in the gas phase.

VIII. Radiation treatment of food products

The history of the radiation treatment of food products spans an interval of about 50 years. Many important data on the useful effects of ionising radiation on these products have been obtained. These effects include the suppression of the growth of potatoes and onions during storage, the extension of the storage time of meat and fish in the frozen state, the disinfestation of grain and fruit, the sterilisation of meat products in order to achieve long lifetimes in the non-frozen state, etc.[1] Up to 1994 the irradiation of food products was permitted in 38 countries, and pilot and production plants were operating in 27 countries for the radiation treatment of food products:[459] potatoes, onions, garlic, tomatoes, beans, seasonal vegetables, spices, strawberries, citrus fruit, apples, mangoes, dried fruit, grains, rice, poultry, fermented sausages, shrimps, dried fish, frozen frog's legs, etc. Data for spices and seasonal vegetables (Fig. 5) show that the quantity of products treated by ionising radiation increases from year to year.[459]

Careful chemical and biological studies and also tests on the nourishing properties of the irradiated products reported from specialists in many countries have shown that the radiation treatment has no harmful effect on the products. International organisation have stressed[1] that the irradiation of any foodstuff is safe up to doses of 10 kGy: under these conditions higher doses can be used for food products which account for a small part of the human diet (for example, spices). It has been decided that the following types of ionising radiation can be used: γ radiation from ^{60}Co and ^{137}Cs, bremsstrahlung X-rays generated by electron accelerators with an energy not greater than 5 MeV, and electron radiation with an energy not greater than 10 MeV. The setting of an upper energy level for electrons and X-rays aims to avoid any substantial induced radioactivity. This has been confirmed by many theoretical and experimental studies (see, for example, Refs 460–462).

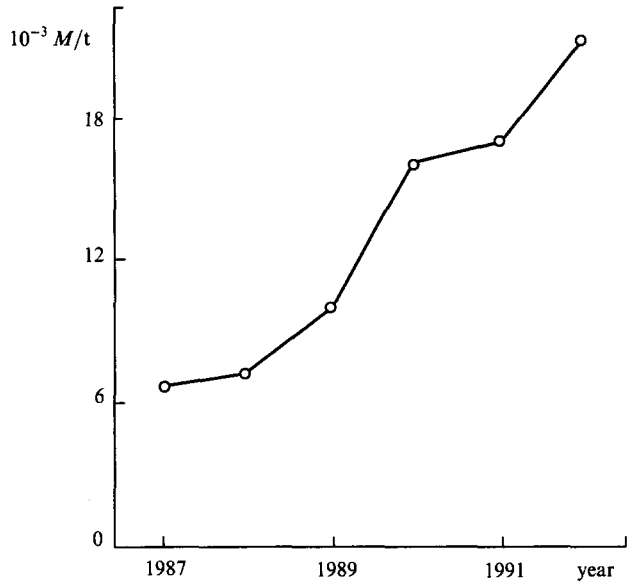


Figure 5. Increase in the number of species and seasonal vegetables (M) treated by radiation.

At present both γ radiation and electron beams are used for the treatment of food products. The possibility of using bremsstrahlung radiation is being considered. The suggested doses are relatively small:[1] 0.05–0.15 kGy (for inhibiting the growth of potatoes, onions, etc.), 0.15–0.50 kGy (for the disinfestation of grain, fruit, etc.), 0.5–1.0 kGy (to slow the ripening of fruit, vegetables, etc.), 1.5–3.0 kGy (for increasing the lifetime of strawberries and other fruit), 2.0–5.0 kGy (for the destruction of pathogenic parasites and microorganisms in fresh and in frozen poultry, shrimps, frog's legs, etc.), 2.0–10 kGy (to improve the technological properties of several food products), 10–50 kGy (for the decontamination of food additives and ingredients, especially spices), 30–50 kGy (for the sterilisation of meat, meat products, dietary products for the sick, etc.). Some establishments have a relatively high operating speed. let us consider some examples.

In 1973 an apparatus with a ^{60}Co source of γ radiation (activity 0.3 MCi) began to function for the treatment of potatoes (productivity 15 000–20 000 tonnes per season).[463] In 1986 a pilot plant with a ^{60}Co activity of 0.24 MCi was constructed in the GDR for the irradiation of onions (operating speed 18 t h^{-1}).[464] The largest apparatus ever used in this region of radiation technology, with two electron accelerators, was assembled in Odessa in the early 1980s for the disinfestation of imported grain (operating speed 400 000 t a^{-1}).[465] It was planned to build an apparatus of this type in the Rostov region, but the project could not be realised. From 1986 until 1990 the French firm 'Société des Protéines Industrielles' used an electron accelerator (energy 7 MeV, power 5 kW) to treat chicken's fillets (operating speed ~3 t h^{-1}). A more powerful accelerator (energy 10 MeV, power 10 kW) has been in use since 1990: this change has made a 2-fold improvement in the operating speed.[466–467] Since the end of 1991 the 'Vindicator Inc.' company (USA) has treated strawberries and citrus fruit with γ radiation from ^{60}Co.[468,469] In the USA two demonstration equipments with linear electron accelerators were built (energy 5 MeV, power 20 kW, or energy 10 MeV, power 10 kW) to irradiate strawberries, fruit, poultry, and other products.[470] In Poland an apparatus based on a linear electron accelerator of the 'Elektronika' type (energy 10 MeV, power 10 kW) was built for the treatment of spice, mushrooms, etc.[471] In the late 1980s the radiation treatment of spices had been established in 17 countries (for example, in Belgium, France, the Netherlands, the UAR, and the USA).[472] Garden strawberries are another product now being treated in large quantities. This is specially true of France, the Netherlands, the USA, and several other countries. For example, in the UAR 4–8 tonnes of strawberries were irradiated per annum.[473] In the early 1990s the total amount of food products treated by radiation methods was 500 000 t a^{-1}.[468]

An important problem in this field of radiation technology is the identification of food products which have undergone radiation treatment. The identification of irradiated products is essential for the information of the buyer and for proper sales control. This is a difficult problem, because the effects produced by the ionising radiation are usually small; furthermore they lead

Table 9. Chemical changes used to identify irradiated food products.

Change	Product	Ref.
Formation of volatile compounds from lipids	Fish, meat	474–476
Changes in DNA (for example, formation of thymidineglycols)	Meat	474,475
Changes in proteins (for example, formation of *o*-tyrosine)	Meat, prawns	474–477
Formation of hydrocarbons from fatty acids	Meat, prawns, frogs' legs	476,478
Formation of 2-alkylcyclobutanones from fatty acids	Poulty, eggs	476,479
Formation of CO from fatty acids	Meat	476,480
Formation of 2,3-butanediol	Alcoholic drinks	481
Hydroxylation of aromatic compounds	Fruit, vegetables	482
Decomposition of starch	Spices	483,484
Formation of free radicals	Strawberries, fruit, meat with bones, fish and sea foods containing bones, shells, etc., spices	474–477, 485,486

to changes similar to those produced by storage. Useful results have nevertheless been obtained.

A universal method for the detection of irradiated food products has still not been developed, though all types of radiation effects have been examined (chemical, physical, and biological). They include changes in the histological and morphological characteristics, in the physical properties (electric impedance, viscosity, wetting properties, etc.), in the chemical changes in the components of the food products (carbohydrates, lipids, proteins, nucleic acids, vitamins, etc.), and in the formation of free radicals, detected by chemiluminescence, thermoluminescence, and ESR methods.[474-476] Some chemical changes used to identify irradiated food products are shown in Table 9.

Clearly, the most promising are the methods based on the formation of free radicals. These species are retained in bones, shells, membranes, grains, skins, etc.; they can exist for relatively long times, and therefore they can be detected by luminescence methods and by ESR. It has been claimed[476] that routine analyses can already be done by the ESR method (for the analysis of meat including poultry, with bones), by the thermoluminescence method (for spices and herbs), by the gas chromatography method (for meat, including poultry), and by the determination of long-chain hydrocarbons.

The level of industrial application of radiation treatment is strongly dependent on the ratio of consumers to the number of irradiated food items. Many questionnaires have shown that this ratio is usually large (see, for example, Refs 459 and 472).

IX. Radiation-physical processing

The changes in the physical properties of materials (mainly solids) after irradiation have been used as a basis for several practical applications. They include ion implantation, the doping of semiconductors, the modification of semiconductor materials and articles, the preparation of polymeric membranes and resists for photolithography, changes in the colour of glass and of precious stones, the thermal effect of powerful electron beams, etc.

Ion implantation is the introduction of additional atoms into the surface of a solid by bombardment with accelerated ions. Ion energies greater than 1 keV are often used.

Ion implantation is used for the doping of semiconductors, for modifying solid surfaces (to generate anticorrosion coatings on metals and alloys, to clean surfaces, to improve optical surfaces, to deposit films, etc.)[14,29,30,43] We note that for high ion fluxes (greater than $10^{17} - 10^{18}$ cm^{-2}), when the concentration of implanted ions is comparable with the concentration of atoms in the surface layer of the target, new compounds are formed (or, in the conventional language, ion synthesis takes place). For example, when silicon is bombarded with nitrogen, carbon, and oxygen ions the compounds Si_3N_4, SiC, and SiO_2 are formed respectively.[43] This process is used to form protective films and insulating layers in integrated circuits. Ion implantation is also used to produce alloys and solid solutions, including metastable alloys: the process is often called ion metallurgy.

The next region of radiation-physical processing is the radiation doping of semiconductors with the help of nuclear reactions.[35] The reactions can be initiated by thermal neutrons, which are characterised by large ranges, so that by using this method semiconductors can be doped evenly over their entire volume. The most important application of the method is the doping of silicon by phosphorus, based on the $^{30}Si(n,\gamma)^{31}Si$ reaction in a nuclear reactor.[35,487] Silicon-31 has half-life of 2.62 h: by undergoing a β decay it is converted into phosphorus-31.

The first large-scale production of radiation-doped silicon was set up in 1983 in the RBMK-1000 reactors of the Chernobyl atomic power station;[488] 54.5 t of this material were prepared (including 12.8 t in 1991). Methods of producing it in other atomic power stations with reactors of the RBMK type are being examined.[488] The doping of silicon is carried out also in an experimental reactor in Obninsk (with a production rate of several tonnes per annum). In foreign countries radiation-doped silicon is almost wholly produced in research reactors.[488]

Attempts are also being made to dope GaAs, InAs, InP, InSb, etc. by using n,γ reactions.[488] The most widely used of the materials prepared in this way is doped gallium arsenide. We note that doping can be carried out also by using other nuclear reactions. Thus the irradiation of silicon with protons of 20–25 MeV energy in order to dope it with aluminium has been suggested.[489]

X-Radiation, and electron and ion beams, are used in photolithography. The first two forms of radiation offer a high resolution (up to $\sim$0.1 μm) in the preparation of silicon integrated circuits.[490,491] The separation of the device from the SiO_2 in these circuits (as one of the stages in the lithographic process) can be achieved by ion beam etching.[43] Polymers having high radiation-chemical yields in their cross-linking or degradation reactions can be used as resists when ionising radiation is used. For example, chloromethylated polystyrene and poly-α-methylstyrene,[492] and also poly(glycidyl methacrylate),[493] are cross-linked by irradiation and act as negative resists. Poly(methyl methacrylate) and its derivatives, poly-1-butenesulfones, and some polysilanes are decomposing polymers: they behave as positive resists.[491] Polymers usually undergo cross-linking and decomposition simultaneously. It has been suggested[491] that a polymer acts as a negative resist if G (decomposition) $< 4G$ (cross-linking), where G is the radiation-chemical yield, measured as the number of molecules, atoms, bonds, etc. formed (or dissociated) by the absorption of 100 eV of energy of ionising radiation.

The irradiation of high-power semiconductor devices (for example, power diodes and thyristors) with electrons in relatively high doses improves their high-speed performance and some other operational characteristics.[30,494-498] This irradiation is practiced in several countries (Italy, the Czech republic, China, Japan etc.).[279,494,499] For example, in China and in Italy up to 100–150 thousand semiconductor devices are subjected every year to electron-beam treatment.[279,494]

Low-energy focussed electron beams (0.25 eV and below) can be used to heat the irradiated objects to high temperatures. These beams can be used for melting, evaporating, cutting, and welding various materials.[43,500,501] According to several workers (see, for example, Refs 502–504) electron irradiation can be used for the high-temperature synthesis of materials such as portland cement, sodium aluminate, barium and strontium ferrites, lead molybdate, etc. Simultaneous radiation and thermal treatment can lead to reactions with a higher rate, a higher yield, and at a lower temperature. A project has been reported[505] for the construction of an apparatus with an electron accelerator of the ELV type (energy 1.5 MeV, power 20 kW), aimed to treat cement so as to improve its performance. An apparatus has been built in Novosibirsk on the basis of an ELV electron accelerator (energy 1.5 MeV, power up to 100 kW) with the aim of creating a radiation-thermal technology for the production of cement and other similar materials.[506]

The formation of cylindrical tracks in materials (usually in polymeric films) irradiated with beams of heavy ions has been used for the production of membrane filters.[43,507] In most cases poly(ethylene terephthalate) films 1–10 μm thick are used, with ion beam energies (argon, nitrogen, xenon, etc.) above 100 MeV. The damaged parts of the irradiated film are removed by etching with a suitable solvent. This treatment produces pores with a diameter dependent on the mass, charge, and energy of the ions and on the time and temperature of the etching.[507-509] By controlling these parameters pores of a diameter dependent on the mass and charge (from a few nanometers to tens of micrometers) can be prepared. Filters prepared by this method are used in medicine, biology, and in the food industry.[43,507]

The ability of ionising radiation to form colour centres in solids is used in practice. It is used to change the colour of some

glass items, precious stones (for example topaz, diamond, and others), and pearls.[499] One of the metro stations in Prague is decorated with γ-irradiated glass tiles (in which a brownish tint was produced by irradiation).[499] This project required the irradiation of about 10 000 tiles with γ radiation (dose 2.7 kGy).

X. Other applications

Other applications of ionising radiation are known. First we should mention radiation synthesis. This has long been thought to be one of the most promising sections of radiation-chemical technology. Thus it was widely believed that ionising radiation (in particular, the radiation from a nuclear reactor) can be successfully used also for large-scale synthesis. Only a few processes using γ radiation and electron beams have been realised in practice (see Table 10). At present these studies have been almost completely discontinued, and they are carried out only in a few centres on a laboratory scale. For example the preparation of 2,3-dimethyltartaric acid by the γ irradiation of aqueous solutions of pyruvic acid,[515] of 1,2,3,4-butanetetracarboxylic acid by the γ radiolysis of aqueous solutions of succinic acid,[516] and of hexafluoropropylene oxide by the low-temperature liquid-phase oxidation of hexafluoropropylene,[517] etc. have been described.

As reported,[518,519] high-temperature electron-beam treatment can be used to regenerate catalysts and sorbents used in the oil and gas industry. Tests with large samples (up to 2 t) of irradiated catalysts showed that this treatment leads to almost 100% regeneration of the initial catalytic activity.

The possibility of using electron beams for the treatment of mineral deposits[520] and for the gasification of coal[521] has been studied, but these processes are still far from practical realisation. Paths towards the use of radiation from a nuclear reactor for the synthesis of hydrogen from water and CO_2 (through the formation of carbon monoxide and its subsequent conversion) were studied in the 1970s and 1980s, and considered to be an important problem in hydrogen energetics.[522,523] However, studies in this direction were subsequently abandoned.

Some problems in atomic energetics and in radiochemical production are directly related to applied radiation chemistry. They include accounting for special features of radiolytic transformations in aqueous solutions of actinide and of trace elements, establishing the features of the radiolysis of extractants and diluents, studying the radiation-chemical processes in highly radioactive waste, the radiation capacity of heat-transfer agents (in particular, water) and other reactor materials, the radiation corrosion of construction materials, etc. A discussion of these problems goes beyond the scope of the present work. Relevant information can be found in published monographs[1,47,53,60,71,524–528] and reviews.[529–533]

XI. Technological dosimetry of ionising radiations

In the development of the technology of a radiation process the best control of the operation of the assembly and of the creation of a high-quality product requires carrying out various dosimetric measurements, including the determination of the dose and of its strength, establishing the distribution of the dose in the irradiated sample, etc. The absorbed doses used in radiation technology cover a wide range (from ~50 Gy for the inhibition of the growth of potatoes and onions to >1 MGy for experiments with the radiation); the same is true of the strength of the dose. The irradiated samples include gases, liquids, and solids; they can be homogeneous or heterogeneous. It follow that dosimetry in radiation technology is required to solve many complex problems.

A large set of parameters needing to be measured can be 'overlapped' by using a relatively large number of dosimeters. Obviously, for each range of doses characterising the various processes there should be a particular dosimeter. To a large extent

Table 10. Radiation syntheses realised on pilot plant and on production scales.

Country and period of functioning of the apparatus	Process	Type of radiation	Product	Operating rate/t a^{-1}	Ref.
USA, 1962–1970s	$CH_2=CH_2 + HBr$	^{60}Co γ radiation	C_2H_5Br	~450	510
USA, 1960s	Alkanes + SO_2 + O_2	"	Sulfonic acids	—	511
USSR, 1966–1970s	Alkanes + SO_2 + Cl_2	"	Sulfonyl chloride	0.36[a]	27,512
USSR, 1967–1990s	$CH_2=CH_2 + CCl_4$	"	Tetrachloropropane, tetrachloropentane	175	513
USSR, 1974–1980s	$H_2 + Cl_2$ (removal of H_2 from Cl_2 prepared by electrolysis)	Electrons, 0.65 MeV	HCl	—	74
USSR, 1980s	$2\,C_4H_9Br + Sn$	γ Radiation from ^{60}Co	$(C_4H_9)_2SnBr_2$	20	319
USSR, 1980s	Synthesis of organochlorosilanes	Electrons, ~0.3 MeV	$CH_3SiCl_2C_6H_5$, $C_6H_5SiCl_3$, etc.	—	87
Germany, 1980s	Poly(vinyl chloride) + Cl_2	γ Radiation from ^{60}Co	Chlorinated poly(vinyl chloride)	—	514

[a] Quoted in t h^{-1}.

Table 11. Dosimeters for different dose ranges.

Type of dosimeter	Method of measurement	Range of dose/Gy
Alanine	ESR	$1 \times 10^0 - 2 \times 10^5$
Solution of ferrous sulphate (Fricke dosimeter)	Spectrophotometric	$2 \times 10^1 - 2 \times 10^2$
Solution of dichromate	"	$5 \times 10^2 - 1 \times 10^5$
Solution of Ce(IV) sulfate	"	$1 \times 10^2 - 1 \times 10^5$
Solution of chlorobenzene in aqueous ethanol	Titration of H^+ or Cl^- (potentiometric, or high-frequency conductimetric)	$5 \times 10^1 - 1 \times 10^6$
Thermoluminescent, based on LiF	Measurement of the luminescence on heating to 195 °C	$< 1 \times 10^0 - 1 \times 10^3$
Crystalline LiF	Spectrophotometric	$2 \times 10^2 - 2 \times 10^6$
Solutions of dyes	"	$2 \times 10^0 - 2 \times 10^5$
Coloured polymer films and plates	"	$2 \times 10^0 - 2 \times 10^5$
Colourless polymer films and plates	"	$1 \times 10^4 - 4 \times 10^5$
Glucose solution	Polarimetric	$5 \times 10^4 - 2 \times 10^6$
Glass (silicate, activated with nickel)	Spectrophotometric	$1 \times 10^2 - 1 \times 10^4$
Glass (metaphosphate, activated with manganese)	"	$3 \times 10^3 - 1 \times 10^5$
Quartz	"	$1 \times 10^5 - 5 \times 10^7$
Nitrous oxide	Change in pressure, gas chromatographic, mass spectrometric	$5 \times 10^2 - 2 \times 10^4$

this problem is already solved. Table 11 shows the chemical dosimeters available for different ranges of doses.[19,33,50,57,97,534]

Among the recent developments we may quote the dosimetric systems based on aqueous solutions of rhodamine dyes with additions of selenate[535] and of solutions of tetrazolium salts.[536,537] The former system is suitable for dosimetric measurements in the radiation treatment of food products. The latter system can be used, depending on the composition, to determine doses over a wide range of compositions.

In Russia several dosimetric systems have been developed, including practically the whole range of doses used in radiation technology.[33,81,538] They include glucose solutions, plates of poly(methyl methacrylate), polymer films containing a dye, glasses with various additives, etc.

In several radiation processes (for example, the radiation sterilisation of medical products) we use light indicators of the dose in the form of labels attached to the item being irradiated. The labels contain a radiation-sensitive dye or the leuco-base of a dye. The irradiation produces a change in the colour of the indicator. This indicates that the item has been irradiated. Some data on these dose indicators can be found in various publications.[538-545]

A direct determination of the dose can be made with a calorimeter. Several forms of calorimeter, differing in the simplicity of their design and used in routine measurements and for the calibration of chemical dosimeters, have been developed in recent years.[1,545-548] They include water, graphite, and polystyrene calorimeters. The first two consist of Petri dishes filled with water or containing a graphite disk; changes in temperature are measured with thermistors. They can be used to determine doses in the ranges of 1 – 50 and 0.1 – 20 kGy respectively. The polystyrene calorimeter is designed to measure the power of the dose of γ radiation.

In Russia a special equipment including precision calorimeters has been produced for the accurate preliminary testing and calibration of dosimeters.[33,538]

Another important problem is the international comparison of dosimetric mesurements. It is essential, so as to ensure that radiation processes are carried out on a single world dosimetric basis. The International Atomic Energy Agency plays a leading role in this international effort.

XII. Conclusion

This discussion of the present state of radiation technology leads to the following conclusions. In addition to the expanded use of some well known processes, new processes have been developed (for example, the production of silicon carbide fibre). The use of electron accelerators as a source of ionising radiation safer and more power-ful than sources of γ radiation has been greatly developed. Bremsstrahlung X-radiation has begun to be used in radiation technology. It should be noted that the use of ^{137}Cs as a source of γ radiation has almost completely ceased because it is less safe than ^{60}Co. Interest in ion beam problems has increased considerably, especially in Japan, where ion beams are now used in studies of their influence on semiconductors and on constructional materials for cosmic technology, on the radiation defects in materials for thermonuclear reactors, in radiation biotechnology, etc.[176]

At present radiation technology is finding increasing applications in ecology. This is specially seen in radiation methods of purification of rejected gases from SO_2, NO_x, and other harmful impurities. Evidently, a substantial outbreak in the radiation treatment of food products can be expected in the near future. This will be assisted by the recent commissioning of the first appropriate commercial assembly in the USA.[468,469]

In spite of the general commercial recession we find (in Russia) an increase in the production of medical items sterilised by the radiation method. This is accompanied by an extension in the use of electron accelerators. Ecological applications of radiation technology are also being successfully developed. Definite improvements were made also in the region of the radiation hardening of coatings.

More and more countries are now using radiation technology, which is being transferred from the developed to the developing countries. The International Atomic Energy Agency maintains both a financial and a scientific and technical support of the various programmes, and as a result of this support radiation assemblies have been constructed in Bangladesh, Vietnam, Syria, Iran, Peru, Ecuador, Ghana, and other countries. The main field of application of these assemblies is the radiation sterilisation of medical items and the treatment of food products.

One of the main advantages of radiation technology is the lowering in the level of contamination of the environment produced by its use. In particular, no harmful gases (of the ethylene oxide type) are used in radiation sterilisation. As has already been pointed out, the compositions used in radiation hardening, unlike the compositions used for ordinary, thermal hardening, do not contain organic solvents. Undoubtedly, all this will stimulate further developments in radiation technology.

References

1. R J Woods, A K Pikaev *Applied Radiation Chemistry. Radiation Processing* (New York: Wiley, 1994)
2. A M Kabakchi, Ya I Lavrentovich, V V Pen'kovskii *Khimicheskaya Dozimetriya Ioniziruyushchikh Izluchenii* (Chemical Dosimetry of Ionising Radiations) (Kiev: Izd. Akad. Nauk Ukr. SSR, 1963)
3. A Charlesby (Ed.) *Radiation Sources* (Oxford: Pergamon Press, 1964)
4. A Kh Breger, B I Vainshtein, N P Syrkus, V A Gol'din, L V Chepel' *Osnovy Radiatsionno-Khimicheskogo Apparatostroeniya* (Foundations of Radiochemical Apparatus Building) (Moscow: Atomizdat, 1967)
5. E E Finkel', R P Braginskii, S S Leshchenko *Radiatsionnaya Khimiya i Kabel'naya Tekhnika* (Radiation Chemistry and Cable Engineering) (Moscow: Atomizdat, 1968)
6. G N P'yankov, A P Meleshevich, A G Yarmilko, A M Kabakchi, S I Omel'chenko *Radiatsionnaya Modifikatsiya Polimernykh Materialov* (Radiation Modification of Polymer Materials) (Kiev: Tekhnika, 1969)
7. N W Holm, R J Berry (Eds) *Manual on Radiation Dosimetry* (New York: Marcel Dekker, 1970)
8. R Sh Shafeev *Vliyanie Ioniziruyushchikh Izluchenii na Protsess Flotatsii* (Effect of Ionising Radiations on Flotation Process) (Moscow: Nauka, 1971)
9. G G Eichholz (Ed.) *Radiation Engineering* (New York: Marcel Dekker, 1972)
10. R P Braginskii, E E Finkel', S S Leshchenko *Stabilizatsiya Radiatsionno-Modifitsirovannykh Poliolefinov* (Stabilisation of Radiation Modified Polyolefins) (Moscow: Khimiya, 1973)
11. P I Dolin, V N Shubin, S A Brusentseva *Radiatsionnaya Ochistka Vody* (Radiation Purifying of Water) (Moscow: Nauka, 1973)
12. *Manual on Radiation Sterilization of Medical and Biological Materials* (Vienna: IAEA, 1973)
13. H Drawe *Angewandte Strahlenchemie* (Heidelberg: Hüthig, 1973)
14. G Dearnaley, J H Freeman, R S Nelson, J Stephen *Ion Implantation* (Amsterdam: North-Holland, 1973)
15. E R L Gaughran, A J Goudie (Eds) *Sterilization by Ionizing Radiation* Vol. 1 (Montreal: Multiscience, 1974)
16. J E Wilson *Radiation Chemistry of Monomers, Polymers, and Plastics* (New York: Marcel Dekker, 1974)
17. V K Knyazev, N A Sidorov *Obluchennyi Polietilen v Tekhnike* (Irradiated Polyethylene in Engineering) (Moscow : Khimiya, 1974)
18. M A Tumanyan, D A Kaushanskii *Radiatsionnaya Sterilizatsiya* (Radiation Sterilisation) (Moscow: Meditsina, 1974)
19. A K Pikaev *Dozimetriya v Radiatsionnoi Khimii* (Dosimetry in Radiation Chemistry) (Moscow: Nauka, 1975)
20. E E Finkel', R P Braginskii *Nagrevostoikie Provoda i Kabeli s Radiatsionno-Modifitsirovannoi Izolyatsiei* (Heat-Resistant Conductors and Cables with Radiation Modified Insulation) (Moscow: Energiya, 1975)
21. L V Chepel' *Primenenie Uskoritelei Elektronov v Radiatsionnoi Khimii* (Application of Electron Accelerators in Radiation Chemistry) (Moscow: Atomizdat, 1975)
22. F A Makhlis *Radiatsionnaya Khimiya Elastomerov* (Radiation Chemistry of Elastomers) (Moscow: Atomizdat, 1976)
23. E R L Gaughran, R F Morrissey (Eds) *Sterilization by Ionizing Radiation* Vol. 2 (Montreal: Multiscience, 1977)
24. P S Elias, A J Cohen (Eds) *Radiation Chemistry of Major Food Components* (Amsterdam: Elsevier, 1977)
25. *Manual on Food Irradiation Dosimetry* (Vienna: IAEA, 1977)
26. V N Shubin, S A Brusentseva, G K Nikonorova *Radiatsionno-Polimerizatsionnaya Ochistka Proizvodstvennykh Stokov* (Radiation Polymerisation Purification of Industrial Effluents) (Moscow: Atomizdat, 1979)
27. R V Dzhagatspanyan, V I Kosorotov, M T Filippov *Vvedenie v Radiatsionno-Khimicheskuyu Tekhnologiyu* (Introduction to Radiochemical Technology) (Moscow: Atomizdat, 1979)
28. N A Vysotskaya, A F Rekasheva, L G Shevchuk *Radiatsionnaya Obrabotka Osadkov Stochnykh Vod* (Radiation Processing of Waste Water) (Kiev: Tekhnika, 1980)
29. J K Hirvonen (Ed.) *Ion Implantation* (New York: Academic Press, 1980)
30. L S Smirnov (Ed.) *Problemy Radiatsionnoi Tekhnologii Poluprovodnikov* (Problems in the Radiation Technology of Semiconductors) (Novosibirsk: Nauka, 1980)
31. G R Brewer (Ed.) *Electron Beam Technology in Microelectronics Fabrication* (London: Academic Press, 1980)
32. A V Larichev, E D Chistov *Bezopasnost' v Radiatsionnoi Tekhnologii* (Safety in Radiation Technology) (Moscow: Energoatomizdat, 1981)
33. V V Generalova, M N Gurskii *Dozimetriya v Radiatsionnoi Tekhnologii* (Dosimetry in Radiation Technology) (Moscow: Izd. Standartov, 1981)
34. E R L Gaughran, R F Morrisey (Eds) *Sterilization of Medical Products* (Montreal: Multiscience, 1981)
35. L S Smirnov, S P Solov'ev, V F Stas', V A Kharchenko *Legirovanie Poluprovodnikov Metodom Yadernykh Reaktsii* (Doping of Semiconductors by Nuclear Reactions) (Novosibirsk: Nauka,1981)
36. *Training Manual on Food Irradiation Technology and Techniques* (Vienna: IAEA, 1982)
37. E S Josephson, M S Peterson (Eds) *Preservation of Food by Ionizing Radiation* Vols 1-3 (Boca Raton, FL: CRC Press, 1983)
38. P S Elias, J Cohen (Eds) *Recent Advances in Food Irradiation* (Amsterdam: Elsevier, 1983)
39. V P Gordienko *Radiatsionnoe Modifitsirovanie Kompozitsionnykh Materialov na Osnove Poliolefinov* (Radiation Modification of Composite Materials Based upon Polyolefins) (Kiev: Naukova Dumka, 1985)
40. R Bradley *Radiation Technology Handbook* (New York: Marcel Dekker, 1984)
41. V S Vetrov, N A Vysotskaya, A M Dmitriev, V N Kalinin, L G Shevchuk *Radiatsionnaya Obrabotka Otkhodov dlya Sel'skokhozyaistvennogo Ispol'zovaniya* (Radiation Processing of Waste for Use in Agriculture) (Moscow: Energoatomizdat, 1984)
42. D A Kaushanskii, A M Kuzin *Radiatsionno-Biologicheskaya Tekhnologiya* (Radiobiological Technology) (Moscow: Energoatomizdat, 1984)
43. A I Abroyan, A N Andronov, A I Titov *Fizicheskie Osnovy Elektronnoi i Ionnoi Tekhnologii* (Physical Foundations of Electronic and Ion Technology) (Moscow: Vysshaya Shkola, 1984)
44. E P Petryaev, V I Vlasov, I A Savushkin *Radiatsionno-Khimicheskaya Ochistka Stochnykh Vod i Vybrosnykh Gazov* (Radiochemical Purification of Waste Water and Gases) (Minsk: Izd. Universitetskoe, 1985)
45. V A Gol'din, E D Chistov *Ustanovki i Apparaty Radiatsionnoi Tekhnologii* (Plant and Apparatus for Radiation Technology) (Moscow: Energoatomizdat, 1985)

46. W M Urbain *Food Irradiation* (Orlando, FL: Academic Press, 1986)
47. G F Egorov *Radiatsionnaya Khimiya Ekstraktsionnykh Sistem* (Radiation Chemistry of Extraction Systems) (Moscow: Energoatomizdat, 1986)
48. V K Milinchuk, V I Tupikov (Ed.) *Radiatsionnaya Stoikost' Organicheskikh Soedinenii* (Radiation Stability of Organic Compounds) (Moscow: Energoatomizdat, 1986)
49. A E Abramyan *Promyshlennye Elektronnye Uskoriteli* (Industrial Electron Accelerators) (Moscow: Energoatomizdat, 1986)
50. A K Pikaev *Sovremennaya Radiatsionnaya Khimiya. Tverdoe Telo i Polimery. Prikladnye Aspekty* (Recent Radiation Chemistry. Solid and Polymers. Applied Aspects) (Moscow: Nauka, 1987)
51. Farhataziz, M A J Rodgers (Eds.) *Radiation Chemistry. Principles and Applications* (New York: VCH, 1987)
52. D R Randell (Ed.) *Radiation Curing of Polymers* (London: Royal Society of Chemistry, 1988)
53. A K Pikaev, S A Kabakchi, I E Makarov *Vysokotemperaturnyi Radioliz Vody i Vodnykh Rastvorov* (High-Temperature Radiolysis of Water and Aqueous Solutions) (Moscow: Energoatomizdat, 1988)
54. J H Bly *Electron Beam Processing* (Yardley, PA: International Information Associates, 1988)
55. V S Ivanov *Radiatsionnaya Khimiya Polimerov* (Radiation Chemistry of Polymers) (Leningrad: Khimiya, 1988)
56. E Reichmanis, J H O'Donnell (Eds) *The Effects of Radiation on High-Technology Polymers (ACS Symp. Ser. 381)* (Washington, DC: American Chemical Society, 1989)
57. W L McLaughlin, A W Boyd, K N Chadwick, J C McDonald, A Miller *Dosimetry for Radiation Processing* (London: Taylor & Francis, 1989)
58. A Heger, H Dorschner, L Dunsch, B Ihme, K Lunkwitz *Technologie der Strahlenchemie von Polymeren* (München: Hanser, 1990)
59. O Güven *Crosslinking and Scission of Polymers (NATO ASI, Ser. C 292)* (Dordrecht: Kluwer, 1990)
60. V M Byakov, F G Nichiporov *Radioliz Vody v Yyadernykh Reaktorakh* (Radiolysis of Water in Atomic Reactors) (Moscow: Energoatomizdat, 1990)
61. D W Clegg, A A Collyer *Irradiation Effects on Polymers* (London: Elsevier Applied Science, 1991)
62. Y Tabata, Y Ito, S Tagawa (Eds) *Handbook of Radiation Chemistry* (Boca Raton, FL: CRC Press, 1991)
63. A Singh, J Silveman (Eds) *Radiation Processing of Polymers* (Munich: Hanser, 1992)
64. A O Matkovskii, D Yu Sugak, S B Ubizskii, O I Shpotyuk, E Chernyi, N M Vakiv, V A Mokritskii *Vozdeistvie Ioniziruyushchikh Izluchenii na Materialy Elektronnoi Tekhniki* (Action of Ionising Radiation on Materials for Electronic Engineering) (L'vov: Svit, 1994)
65. A Kh Breger *Radiatsionno-Khimicheskaya Tekhnologiya. Ee Zadachi i Metody* (Radiochemical Technology. Tasks and Methods) (Moscow: Atomizdat, 1979)
66. S V Aver'yanov, V A Gol'din *Tekhnologiya Radiatsionnoi Vulkanizatsii Termostoikikh Samoslipayushchikhsya Elektroizolyatsionnykh Materialov* (Technology of Radiation Vulcanisation of Thermostable Self-Adhesive Insulating Materials) (Moscow: Atomizdat, 1980)
67. G V Shiryaeva, Yu D Kozlov *Tekhnologiya Radiatsionnogo Otverzhdeniya Pokrytii* (Technology of Radiation Hardened Covers) (Moscow: Atomizdat, 1980)
68. V I Lukhovitskii, V V Polikarpov *Tekhnologiya Radiatsionnoi Emul'sionnoi Polimerizatsii* (Technology of Radiation Emulsion Polymerisation) (Moscow: Atomizdat, 1980)
69. E D Chistov, A V Larichev *Obespechenie Radiatsionnoi Bezopasnosti v Radiatsionno-Khimicheskoi Tekhnologii* (Radiation Safety in Radiation Chemical Technology) (Moscow: Atomizdat, 1980)
70. N P Syrkus, E S Stariznyi, V A Rudoi, A V Putilov *Radiatsionnaya Tekhnologiya i Kompleksnye Energokhimicheskie Proizvodstva* (Radiation Technology and Combined Power and Chemicals Production) (Moscow: Atomizdat, 1980)
71. S A Kabakchi, A K Pikaev *Metody Rascheta Gazovydeleniya i Vzryvoopasnosti Radiatsionno-Khimicheskikh Apparatov s Vodyanym Teplonositelem ili Biologicheskoi Zashchitoi* (Methods of Calculating Gas Evolution and Evaluating Dangers of Explosion in Radiochemical Plant with Water as Heat Carrier or with Biological Protection) (Moscow: Energoatomizdat, 1981)
72. R B Baranova, L T Bugaenko, V M Byakov, V I Lazarev, E P Petryaev *Vybrosnye Gazy i Ikh Radiatsionno-Khimicheskaya Ochistka* (Waste Gases and Their Radiochemical Removal) (Moscow: Energoatomizdat, 1981)
73. R V Dzhagatspanyan, V A Gol'din, M T Filippov, E L Mendel'son *Tekhnologiya Ochistki Stochnykh Vod* (Technology of the Purification of Waste Water) (Moscow: Energoatomizdat, 1981)
74. R V Dzhagatspanyan, V I Emel'yanov *Tekhnologiya Radiatsionno-Khimicheskikh Protsessov v Gazovoi Faze* (Technology of Radiochemical Processes in the Gas Phase) (Moscow: Energoatomizdat, 1982)
75. V A Gol'din *Metody i Ustroistva dlya Radiatsionno-Tekhnologicheskikh Issledovanii s Izotopnymi Istochnikami Izlucheniya* (Methods and Arrangements for Radiation Technological Research with Isotope Radiation Sources) (Moscow: Energoatomizdat, 1982)
76. E A Borisov, F Z Raichuk, G V Shiryaeva *Tekhnologiya Radiatsionno-Khimicheskogo Proizvodstva Betono-Polimernykh i Drevesno-Plastmassovykh Materialov* (Technology of Radiochemical Production of Concrete–Polymer and Wood–Plastic Materials) (Moscow: Energoatomizdat, 1982)
77. A S Kuz'minskii, T S Fedoseeva, M Ya Kaplunov *Tekhnologiya Radiatsionnoi Vulkanizatsii i Modifitsirovaniya Elastomerov* (Technology of Radiation Vulcanization and Modification of Elastomers) (Moscow: Energoatomizdat, 1982)
78. A P Meleshevich *Metody Radiatsionnoi Khimii v Proizvodstve i Modifikatsii Bumagi* (Methods of Radiation Chemistry in the Production and Modification of Paper) (Moscow: Energoatomizdat, 1983)
79. E E Finkel', V L Karpov, S M Berlyant *Tekhnologiya Radiatsionnogo Modifitsirovaniya Polimerov* (Technology of the Radiation Modification of Polymers) (Moscow: Energoatomizdat, 1983)
80. V A Rudoi, A V Putilov *Radiatsionnaya Tekhnologiya za Rubezhom* (Radiation Technology Abroad) (Moscow: Energoatomizdat, 1983)
81. G Z Gochaliev *Tekhnologicheskaya Dozimetriya. Vybor, Obosnovanie i Primenenie Khimicheskikh Metodov Dozimetrii v RKhT* (Technological Dosimetry. Choice, Basis, and Application of Chemical Methods of Dosimetry in Radiochemical Technology) (Moscow: Energoatomizdat, 1984)
82. R V Dzhagatspanyan, V I Emel'yanov *Tekhnologiya Radiatsionnogo Khlorirovaniya, Sul'fokhlorirovaniya i Sul'fookisleniya Organicheskikh Soedinenii* (Technology of Radiation Chlorination, Sulfochlorination, and Sulfoxidation of Organic Compounds) (Moscow: Energoatomizdat, 1984)
83. E S Stariznyi, N I Rybkin, L I Medvedovskii *Optimizatsionnye Zadachi Radiatsionnykh Konturov* (Optimization Tasks of Radiation Contours) (Moscow: Energoatomizdat, 1985)
84. V N Shubin, Yu I Sharanin, S A Brusentseva, A A Chudin *Radiatsionnoe Obezzarazhivanie Stochnykh i Prirodnykh Vod* (Radiation Disinfection of Waste and Natural Water) (Moscow: Energoatomizdat, 1985)
85. B G Ershov *Radiatsionnaya Tekhnologiya i Kormoproizvodstvo* (Radiation Technology and Feed Production) (Moscow: Energoatomizdat, 1986)
86. M A Bruk *Radiatsionnoe Parofaznoe Kapsulirovanie Tverdykh Tel* (Radiation Vapour-phase Encapsulation of Solids) (Moscow: Energoatomizdat, 1988)
87. V I Vainshtein *Radiatsionno-Khimicheskaya Tekhnologiya Sinteza Kremneorganicheskikh Soedinenii* (Radiochemical Technology of the Synthesis of Organosilicon Compounds) (Moscow: Energoatomizdat, 1991)
88. *Proceedings of the Ist International Conference on Radiation Processing (May, 1976, Dorado Beach, Puerto Rico); Radiat. Phys. Chem.* **9** (1977)
89. *Proceedings of the IInd International Conference on Radiation Processing (October, 1978, Miami, FL, USA); Radiat. Phys. Chem.* **14** (1979)

90. *Proceedings of the IIIrd International Conference. on Radiation Processing (October, 1980, Tokyo, Japan); Radiat. Phys. Chem.* **18** (1981)
91. *Proceedings of the IVth International Conference on Radiation Processing (October, 1982, Dubrovnik, Yugoslavia); Radiat. Phys. Chem.* **22** (1983)
92. *Proceedings of the Vth International Conference on Radiation Processing (October, 1984, San Diego, CA, USA); Radiat. Phys. Chem.* **25** (1985)
93. *Proceedings of the VIth International Conference on Radiation Processing (May-June, 1987, Ottawa, Canada); Radiat. Phys. Chem.* **31** (1988)
94. *Proceedings of the VIIth International Conference on Radiation Processing (April, 1989, Noordwijkerhout, the Netherlands); Radiat. Phys. Chem.* **35** (1990)
95. *Proceedings of the VIIIth International Conference on Radiation Processing (September, 1992, Beijing, PRC); Radiat. Phys. Chem.* **42** (1993)
96. *Proceedings of the IXth International Conference on Radiation Processing Radiat. (September, 1994, Istanbul, Turkey); Radiat. Phys. Chem.* 1995 (in the press)
97. A K Pikaev *Khim. Vys. Energ.* **27** 2 44 (1993)
98. A K Pikaev *Radiat. Phys. Chem.* 1995 (in the press)
99. R Mehnert, P Klenert, L Prager *Radiat. Phys. Chem.* **42** 525 (1993)
100. H Tanaka, in *Proc. Radiation Curing Conf. RadTech Asia '91 (April, 1991, Osaka)* (Tokyo: Organizing Committee, 1991) p. 509
101. A K Pikaev *Radiat. Phys. Chem.* **35** 870 (1990)
102. A K Pikaev, in *RadTech '92 North America UV/EB Conference and Exposition. Conference Proceedings (April, 1992, Boston)* (Northbrook, IL: RadTech International North America, 1992) p. 116
103. W Shiqin, C Dali *Radiat. Phys. Chem.* **42** 559 (1993)
104. I Sakamoto *Radiat. Phys. Chem.* **42** 485 (1993)
105. J McKeown *Radiat. Phys. Chem.* **35** 606 (1990)
106. R A Salimov *Radiat. Phys. Chem.* 1995 (in the press)
107. V L Auslender *Nucl. Instrum. Methods. Phys. Res. B* **89** 46 (1994)
108. N K Kuksanov, B M Korabelnikov, M R Kosilov, P I Nemytov, V V Prudnikov, R A Salimov *Radiat. Phys. Chem.* 1995 (in the press)
109. J Bayliss, R Adler *Radiat. Phys. Chem.* **31** 327 (1990)
110. A K Pikaev *Sovremennaya Radiatsionnaya Khimiya. Osnovnye Polozheniya. Eksperimental'naya Tekhnika i Metody* (Modern Radiation Chemistry. Main Position. Experimental Engineering) (Moscow: Nauka, 1985)
111. T Sadat *Radiat. Phys. Chem.* **35** 616 (1990)
112. M Karlsson *Radiat. Phys. Chem.* **35** 670 (1990)
113. M R Cleland *Radiat. Phys. Chem.* **42** 499 (1993)
114. G R Kerluke, J McKeown *Radiat. Phys. Chem.* **42** 511 (1993)
115. D Defrise, M Abs, F Genin, Y Jongen *Radiat. Phys. Chem.* 1995 (in the press)
116. Y Tabata *Radiat. Phys. Chem.* **35** 36 (1990)
117. J Farrell, S Seltzer, J Silverman *Radiat. Phys. Chem.* **22** 534 (1983)
118. K Yotsumoto, H Sunaga, S Tanaka, T Kanazawa, T Agematsu, R Tanaka, K Yoshida, S Taniguchi, I Sakamoto, N Tamura *Radiat. Phys. Chem.* **31** 363 (1988)
119. M Odera, K Nagakura, Y Tanaka *Radiat. Phys. Chem.* **35** 534 (1990)
120. M R Cleland, C C Thompson, M Strelczyk, D P Sloan *Radiat. Phys. Chem.* **35** 632 (1990)
121. M Takehisa, T Saito, T Takahashi, Y Sato, T Sato *Radiat. Phys. Chem.* **42** 495 (1993)
122. S Uehara, S Taniguchi, M Kashiwagi, K Mizusawa, I Sakamoto, Y Hoshi, K Tomita *Radiat. Phys. Chem.* **42** 515 (1993)
123. E E Finkel', E I Mironov, A S Mitkevich *Vestn. ADS "RadTekh-Evraziya"* **2(4)** 18 (1992)
124. V Z Gofshtein *Vestn. ADS "RadTekh-Evraziya"* **2(4)** 60 (1992)
125. K Ueno *Radiat. Phys. Chem.* **35** 126 (1993)
126. I Uda, K Ueno, S Tada, S Suzuki *Radiat. Phys. Chem.* **35** 148 (1990)
127. E Oda *Radiat. Phys. Chem.* **18** 241 (1981)
128. T Sasaki, F Hosoi, M Hagiwara, K Araki, E Saito, H Ishitani, K Uesugi *Radiat. Phys. Chem.* **14** 821 (1979)
129. J H Bly *Radiat. Phys. Chem.* **18** 1331 (1981)
130. T Sasaki, F Hosoi, N Kasai, M Hagishiwara *Radiat. Phys. Chem.* **18** 847 (1981)
131. R G Mitchell *Radiat. Phys. Chem.* **14** 937 (1979)
132. Z Hell, M Ravlic, L Bogodanovic, J Malec, I Dvornik, F Ranogajec, M Ranogajec *Radiat. Phys. Chem.* **22** 619 (1983)
133. L D Loan *Radiat. Phys. Chem.* **9** 253 (1977)
134. O Gal, L Novakovic, V Markovic, V T Stannett *Radiat. Phys. Chem.* **22** 627 (1983)
135. O S Gal, V M Markovic, L R Novakovic, V T Stannett *Radiat. Phys. Chem.* **26** 325 (1985)
136. L Novakovic, O Gal, V Markovic, V T Stannett *Radiat. Phys. Chem.* **26** 331 (1985)
137. K Ueno, I Uda, S Tada *Radiat. Phys. Chem.* **37** 89 (1991)
138. Yu I Matusevich, A A Baev, V A Timoshuk, O I Shadyro, L P Krul' *Vestn. ADS "RadTekh-Evraziya"* **2(4)** 55 (1992)
139. K Ueno *Radiat. Phys. Chem.* **25** 867 (1985)
140. K Sano, H Ishitani *Radiat. Phys. Chem.* **25** 849 (1985)
141. E Oda, S Fujimura, M Kubo, Y Tsutsumi, T Seguchi, M Hagiwara *Radiat. Phys. Chem.* **37** 83 (1991)
142. E Oda, S Fujimura, M Kubo, Y Tsutsumi, T Seguchi, M Hagiwara, in *Proceedings of the International Symposium on Radiation Degradation of Polymers and Radiation Resistant Materials (July, 1989, Takasaki, Japan)* (Takasaki: JAERI, 1989) p. 233
143. A Barlow, J Biggs, M Maringer *Radiat. Phys. Chem.* **9** 685 (1977)
144. T Sawasaki, A Nojiri *Radiat. Phys. Chem.* **31** 877 (1988)
145. K Ueno *Radiat. Phys. Chem.* **35** 126 (1990)
146. W G Baird *Radiat. Phys. Chem.* **9** 225 (1977)
147. S Ota *Radiat. Phys. Chem.* **18** 81 (1981)
148. L S Aktabaeva, V A Borisov, B M Vanyushkin, V P Dul'nev, V I Popov, N G Kon'kov, in *Doklady III Vsesoyuz. Soveshch. po Primeneniyu Uskoritelei Zaryazhennykh Chastits v Narodnom Khozyaistve (Iyun', 1979, Leningrad)* [Reports at the Third All-Union Meeting on the Application of Accelerators of Charged Particles in the National Economy (June, 1979, Leningrad)] (Leningrad: NIIEFA, 1979) Vol. 2, p. 86
149. I Yu Babkin, Yu D Kozlov, in *Doklady III Vsesoyuz. Soveshch. po Primeneniyu Uskoritelei Zaryazhennykh Chastits v Narodnom Khozyaistve (Iyun', 1979, Leningrad)* [Reports at the Third All-Union Meeting on the Application of Accelerators of Charged Particles in the National Economy (June, 1979, Leningrad)] (Leningrad: NIIEFA, 1979) Vol. 2, p. 21
150. E Jaworska, A Robalewski, H Wincel, in *Industrial Application of Radioisotopes and Radiation Technology* (Vienna: IAEA, 1982) p. 131
151. A Charlesby *Atomic Radiation and Polymers* (Oxford: Pergamon Press, 1960) (Translated into Russian; Moscow: Izd. Inostr. Lit., 1962)
152. V P Perepelkin *Vestn. ADS "RadTekh-Evraziya"* **2 (4)** 26 (1992)
153. S Machi *Radiat. Phys. Chem.* **14** 155 (1979)
154. S Sagane, H Harayama *Radiat. Phys. Chem.* **18** 99 (1981)
155. D A Trageser *Radiat. Phys. Chem.* **9** 261 (1977)
156. I Yu Babkin, S M Berlyant, A A Brainis, K F Koz'menkov, V E Lesnichii, V P Pleshanov, S G Stoenko, A I Larionov, G N Matyushkina, L I Pokrovskii, in *Vsesoyuz. Konf. po Teoreticheskoi i Prikladnoi Radiatsionnoi Khimii, Oktyabr', 1984, Obninsk* (The All-Union Conference on Theoretical and Applied Radiation Chemistry, October, 1984, Obninsk; Ed. A K Pikaev) (Moscow: Nauka, 1984) p. 32
157. *Vestn. ADS "RadTekh-Evraziya"* **2 (4)** 123 (1992)
158. T Kemmotsu, M Okada, T Ono *Radiat. Phys. Chem.* **42** 97 (1993)
159. S Tokunaga, T Kemmotsu, T Ono *Radiat. Phys. Chem.* 1995 (in the press)
160. J D Hunt, G Aliger *Radiat. Phys. Chem.* **14** 39 (1979)
161. C E Snyder *Radiat. Phys. Chem.* **22** 3 (1983)
162. I Sakamoto, K Mizusawa, M Kashiwagi, Y Hoshi *Radiat. Phys. Chem.* **25** 911 (1985)
163. K Mizusawa, J R Klempen, I Sakamoto, M Suzuki, M Kashiwagi, Y Hoshi *Radiat. Phys. Chem.* **31** 267 (1988)
164. N A Pekarskii, V B Osipov, I Ya Poddubnyi, G N Lebedeva, S V Mamikonyan, B M Terent'ev, S V Aver'yanov, E D Chistov, V A Gol'din, Z Z Safin, G I Marfin *At. Energ.* **36** 155 (1974)

165. S V Aver'yanov, L A Aver'yanova, V A Gol'din, N A Pekarskii, in *Voprosy Atomnoi Nauki i Tekhniki (Ser. Radiatsionnaya Tekhnika)* [Problems of Atomic Science and Engineering (Ser. Radiation Technology)] (Moscow: Energoatomizdat, 1985) Vol. 3, No 31, p. 48
166. S V Aver'yanov, L A Aver'yanova, V A Gol'din *Vestn. ADS "RadTekh-Evraziya"* **2 (4)** 67 (1992)
167. M Ridwan *Radiat. Phys. Chem.* **25** 887 (1985)
168. K Makuuchi, F Yoshii, I Ishigaki, K Tsushima, M Mogi, T Saito *Radiat. Phys. Chem.* **35** 154 (1990)
169. J Silverman, in *Proceedings of the International Conference on the Evolution in Beam Applications (November, 1991, Takasaki, Japan)* (Tokyo: JAERI, 1992) p. 225
170. M Ya Kaplunov, N I Vinokurov *Vestn. ADS "RadTekh-Evraziya"* **2 (4)** 73 (1992)
171. L V Chepel', V G Danilov, O V Mamitsova, A I Tikhonov, in *Vtoraya Vses. Konf. po Teoreticheskoi i Prikladnoi Radiatsionoi Khimii, Oktyabr', 1990, Obninsk (Tez. Dokl.)* [The Second All-Union Conference on Theoretical and Applied Radiation Chemistry, October, 1990, Obninsk (Abstracts of Reports)] (Moscow: NIITEKhim, 1990) p. 306
172. Yu I Orlovskii, V P Gordienko, B P Ivashkevich, in *Radiatsionnaya Khimiya i Tekhnologiya Monomerov i Polimerov* (Radiation Chemistry and Technology of Monomers and Polymers) (Kiev: Naukova Dumka, 1985) p. 205
173. V V Smirnov, V P Sel'kin, B V Ratner, G Z Gochaliev *Vestn. ADS "RadTekh-Evraziya"* **2 (4)** 44 (1992)
174. V S Ivanov, N A Kalinina, I I Migunova, G N Aleksandrov, V I Irkhin, A V Kuznetsov, A I Shchelokov, V A Gol'din, F Z Raichuk, N P Syrkus *Vestn. ADS "RadTekh-Evraziya"* **2 (4)** 32 (1992)
175. T Seguchi, N Kasai, K Okamura, in *Proceedings of the International Conference on Evolution in Beam Applications (November, 1991, Takasaki, Japan)* (Tokyo: JAERI, 1992) p. 702
176. S Machi *Radiat. Phys. Chem.* **42** 13 (1993)
177. S Machi, R Iyer *IAEA Bull.* **36** (1) 3 (1994)
178. V P Thalacker *Radiat. Phys. Chem.* **35** 18 (1990)
179. U V Liuppi *Radiat. Phys. Chem.* **35** 30 (1990)
180. T Czvikovszky *Radiat. Phys. Chem.* **35** 41 (1990)
181. S V Nablo *Radiat. Phys. Chem.* **35** 46 (1990)
182. I Sakamoto, Y Hoshi *Radiat. Phys. Chem.* **33** 403 (1989)
183. Ma Zue Teh, Yan Qi, Xu Mao Jun, in *Proceedings of the Conference on Radiation Curing, Asia (CRCA'88) (October, 1988, Tokyo)* (Tokyo: Organizing Committee, 1988) p. 42.
184. A Berejka, W Radak, in *Proceedings of the Conference on Radiation Curing, RadTech Asia '91 (April, 1991, Osaka)* (Osaka: Organizing Committee, 1991) p. 5
185. U V Läuppi, in *Proceedings of the Conference on Radiation Curing, RadTech Asia '91 (April, 1991, Osaka)* (Osaka: Organizing Committee, 1991) p. 23
186. P A Dworjanin, J L Garnett, in *Proceedings of the Conference on Radiation Curing, RadTech Asia '91 (April, 1991, Osaka)* (Osaka: Organizing Committee, 1991) p. 29
187. A K Pikaev, in *Proceedings of the Conference on Radiation Curing, RadTech Asia '91 (April, 1991, Osaka)* (Osaka: Organizing Committee, 1991) p. 35
188. C J Kallendorf, in *RadTech '92 North America UV/EB Conference and Exposition. Conference Proceedings (April, 1992, Boston)* (Northbrook, IL: RadTech International North America, 1992) p. 129
189. J L Garnett, in *RadTech '92 North America UV/EB Conference and Exposition. Conference Proceedings (April, 1992, Boston)* (Northbrook, IL: RadTech International North America, 1992) p. 122
190. N Imai, in *RadTech Asia '93 UV/EB Conference and Exposition. Conference Proceedings (November, 1993, Tokyo)* (Tokyo: RadTech Japan, 1993) p. 1
191. K Lawson, in *RadTech Asia '93 UV/EB Conference and Exposition. Conference Proceedings (November, 1993, Tokyo)* (Tokyo: RadTech Japan, 1993) p. 7
192. H Scheidt, in *RadTech Asia '93 UV/EB Conference and Exposition. Conference Proceedings (November, 1993, Tokyo)* (Tokyo: RadTech Japan, 1993) p. 19
193. S J Bett, J L Garnett, N J W Gamage, in *RadTech Asia '93 UV/EB Conference and Exposition. Conference Proceedings (November, 1993, Tokyo)* (Tokyo: RadTech Japan, 1993) p. 24
194. A K Pikaev, in *RadTech Asia '93 UV/EB Conference and Exposition. Conference Proceedings (November, 1993, Tokyo)* (Tokyo: RadTech Japan, 1993) p. 32
195. A J Berejka *Radiat. Phys. Chem.* **42** 147 (1993)
196. A S Hoffman, in *Radiation Research. Biomedical, Chemical, and Physical Perspectives. Proceedings of the 5th Interenational Congress on Radiation Research, July, 1974, Seattle* (Eds O F Nygaard, H I Adler, W K Sinclair) (New York: Academic Press, 1975) p. 65
197. W J Ramler *Radiat. Phys. Chem.* **9** 69 (1977)
198. K Mizusawa, T Kimura, S Uehara, in *Proceedings of the Conference on Radiation Curing, RadTech Asia '91 (April, 1991, Osaka)* (Osaka: Organizing Committee, 1991) p. 501
199. P M Fletcher, in *Proceedings of the Radiation Curing Conference RadTech Asia '91 (April, 1991, Osaka)* (Osaka: Organizing Committee, 1991) p. 515.
200. U V Läuppi, J R Seidel, B Hugelin *Radiat. Phys. Chem.* **22** 823 (1983)
201. W A Frutiger, S V Nablo *Radiat. Phys. Chem.* **25** 683 (1985)
202. E Haering, in *Industrial Application of Radioisotopes and Radiation Technology* (Vienna: IAEA, 1982) p. 235
203. T Czvikovszky *Radiat. Phys. Chem.* **26** 547 (1985)
204. H E Huber *Beta-Gamma* (1) 3 (1992)
205. E Takacs, I Czajik, T Czvikovszky *Radiat. Phys. Chem.* **35** 76 (1990)
206. B J Twomey *Radiat. Phys. Chem.* **14** 69 (1979)
207. Yu V Vishev, in *Radiatsionnaya Khimiya i Tekhnologiya Monomerov i Polimerov* (Radiation Chemistry and Technology of Monomers and Polymers) (Kiev: Naukova Dumka, 1985) p. 85
208. T A Bol'shakova, G V Shiryaeva, N V Fomina *Vestn. ADS "RadTekh-Evraziya"* **1 (3)** 18 (1992)
209. I Czajik, E Takacz, T Czvikovszky *Radiat. Phys. Chem.* **33** 457 (1989)
210. N G Videnina, in *Radiatsionnaya Khimiya i Tekhnologiya Monomerov i Polimerov* (Radiation Chemistry and Technology of Monomers and Polymers) (Kiev: Naukova Dumka, 1985) p. 92
211. V N Chmukh, in *Vses. Konf. po Teoreticheskoi i Prikladnoi Radiatsionnoi Khimii, Oktyabr' 1984, Obninsk (Tez. Dokl.)* [All-Union Conference on Theoretical and Applied Radiation Chemistry, October, 1984, Obninsk (Abstracts of Reports); Ed. A K Pikaev] (Moscow: Nauka, 1984) p. 379
212. N V Fomina, T A Bol'shakova, G V Shiryaeva, N A Slovokhotova, L A Onosova *Intensifikatsiya Radiatsionnoi Tonkosloinoi Polimerizatsii na Vozdukhe. Obzornaya Informatsiya* (Intensification of Radiation Thin-Layer Polymerisation in Air. Summarised Information) (Moscow: NIITEKhim, 1988)
213. G V Shiryaeva, V V Bydanova, V G Bondarev, V I Troenko, V P Koryagin, G I Mandych, V N Solod, in *Radiatsionnaya Khimiya i Tekhnologiya Oligomernykh Sistem* (Radiation Chemistry and Technology of Oligomer Systems) (Moscow: NIITEKhim, 1983) p. 70
214. I Yu Babkin, Yu D Kozlov, V V Krayushkin, A V Larichev, V E Lesnichii, V V Puchkova, Yu A Chikin, G V Shiryaeva, G P German, G I Mandych, M P Svin'in, V I Troenko, in *Doklady III Vsesoyuz. Soveshch. po Primeneniyu Uskoritelei Zaryazhennykh Chastits v Narodnom Khozyaistve (Iyun', 1979, Leningrad)* [Reports at the Third All-Union Meeting on the Application of Charged Particle Accelerators in the National Economy (June, 1979, Leningrad)] (Leningrad: NIIEFA, 1979) Vol. 2, p. 62
215. V I Al'bertinskii, V I Nikishkin, M P Svin'in, Yu S Studennikov, E D Bundur, A A Karpenko, G I Mandych, R I Sosul'skii, in *Doklady III Vsesoyuz. Soveshch. po Primeneniyu Uskoritelei Zaryazhennykh Chastits v Narodnom Khozyaistve (Iyun', 1979, Leningrad)* [Reports at the Third All-Union Meeting on the Application of Charged Particle Accelerators in the National Economy (June, 1979, Leningrad)] (Leningrad: NIIEFA, 1979) Vol. 2, p. 69
216. A P Meleshevich, in *Radiatsionnaya Khimiya i Tekhnologiya Monomerov i Polimerov* (Radiation Chemistry and Technology of Monomers and Polymers) (Kiev: Naukova Dumka, 1985) p. 14

217. B M Vanyushkin, A A Kolesnikov, A V Usanova, R N Khelevin, V V Korovkin, in *Doklady III Vsesoyuz. Soveshch. po Primeneniyu Uskoritelei Zaryazhennykh Chastits v Narodnom Khozyaistve (Iyun', 1979, Leningrad)* [Reports at the Third All-Union Meeting on the Application of Charged Particle Accelerators in the National Economy (June, 1979, Leningrad)] (Leningrad: NIIEFA, 1979) Vol. 2, p. 79
218. A E Voskoboev, B M Vanyushkin, N A Ostman, A V Isaev, in *Tez. Dokl. VI Vsesoyuz. Soveshch. po Primeneniyu Uskoritelei Zaryazhennykh Chastits v Narodnom Khozyaistve (Oktyabr', 1988, Leningrad)* [Abstracts of Reports at the Sixth All-Union Meeting on the Application of Charged Particle Accelerators in the National Economy (October, 1988, Leningrad)] (Moscow: TsNIIAtom-inform, 1988) p. 100
219. *Vestn. ADS "RadTekh-SSSR"* **1** 55 (1991)
220. E A Samchenko, E V Marchenko, S D Kotov, A M Panasyuk, V I Golovko, in *Vtoraya Vsesoyuz. Konf. po Teoreticheskoi i Prikladnoi Radiatsionnoi Khimii, Oktyabr', 1990, Obninsk (Tez. Dokl.)* [Second All-Union Conference on Theoretical and Applied Radiation Chemistry, October, 1990, Obninsk (Abstracts of Reports)] (Moscow: NIITEKhim, 1990) p. 247
221. V I Kopchenov, V B Shik, A S Kurapov, I N Mysin *Vestn. ADS "RadTekh-Evraziya"* **1(3)** 29 (1992)
222. V Koptchenov, V Shik, V Konev, I Misin, V Gavrilov, V Malik *Radiat. Phys. Chem.* **42** 187 (1993)
223. A S Hoffman *Radiat. Phys. Chem.* **18** 323 (1981)
224. A S Hoffman, in *Industrial Application of Radioisotopes and Radiation Technology* (Vienna: IAEA, 1982) p. 279
225. A S Hoffman, D Cohn, S R Hanson, L A Harker, T A Horbett, B D Ratner, L O Reynolds *Radiat. Phys. Chem.* **22** 267 (1983)
226. S Rösinger, J P Fisher, P Fuhge, in *Industrial Application of Radioisotopes and Radiation Technology* (Vienna: IAEA, 1982) p. 323
227. G Gaussens, in *Industrial Application of Radioisotopes and Radiation Technology* (Vienna: IAEA, 1982) p. 343
228. W Pekala, J Posiak, A Rucinska-Rybus, K Burczak, S Galant, T Czolczynska *Radiat. Phys. Chem.* **27** 275 (1986)
229. S Lora, M Garenza, G Palma, P Caliceti *Radiat. Phys. Chem.* **35** 117 (1990)
230. D Müller-Schulte *Radiat. Phys. Chem.* **42** 891 (1993)
231. N A Vengerova, A P Rudman, B S El'tsefon, N S Snegireva, V P Shilokhvost, L K Tsivinskaya, R I Kaluzhnaya, L P Sidorova, T I Reshetilova, V Ya Kabanov, A B Zezin *Vysokomol. Soedin., Ser. A* **25** 1245 (1983)
232. A Rucinska, J Rosiak, W Pekala *Radiat. Phys. Chem.* **24** 495 (1984)
233. K Otsunaga, M T Razzak, R L Castanares, Y Tabata, F Ohashi, A Takeuchi *Radiat. Phys. Chem.* **25** 537 (1985)
234. A Chapiro, D Domurado, M Foex-Millequant, A-M Endrychowska-Bonamour *Radiat. Phys. Chem.* **18** 1203 (1981)
235. B Jansen, G Ellinghorst *Radiat. Phys. Chem.* **18** 1195 (1981)
236. B Jansen, G Ellinghorst, L W Storz *Radiat. Phys. Chem.* **25** 529 (1985)
237. S Fujioka, K Fujikawa, N Ueno, A Okamoto *Radiat. Phys. Chem.* **18** 865 (1981)
238. Y Ikada, M Suzuki, M Taniguchi, H Iwata, W Taki, H Miyake, Y Yonekawa, H Handa *Radiat. Phys. Chem.* **18** 1207 (1981)
239. Li Yu Ming, Yang Yue Qi, Chen Jie, Ma Zu Teh *Radiat. Phys. Chem.* **35** 122 (1990)
240. Hou-Ching Yang, J Silverman *Radiat. Phys. Chem.* **25** 375 (1985)
241. Hou-Ching Yang, J Silverman *Radiat. Phys. Chem.* **31** 721 (1988)
242. C Gopinathan, T P Balan, in *Proceedings of the Conference on Radiation Curing, RadTech Asia '91 (April, 1991, Osaka)* (Osaka: Organizing Committee, 1991) p. 600
243. J Roziak, in *Radiation Effects on Polymers (ACS Symp. Ser. 475)* (Eds R C Clough, S W Shalaby) (Washington, DC: American Chemical Society, 1991) p. 271
244. J M Rosiak, J Olejniszak *Radiat. Phys. Chem.* **42** 903 (1993)
245. D Darwis, N Hilmy, L Hardiningsih, T Erlinda *Radiat. Phys. Chem.* **42** 907 (1993)
246. N Hilmy, D Darwis, L Hardiningsih *Radiat. Phys. Chem.* **42** 911 (1993)
247. I Kaetsu *Radiat. Phys. Chem.* **18** 343 (1981)
248. I Kaetsu *Radiat. Phys. Chem.* **25** 517 (1985)
249. M Kobayashi, I Kaetsu, in *Industrial Application of Radioisotopes and Radiation Technology* (Vienna: IAEA, 1982) p. 353
250. I Kaetsu, M Kumakura, T Fujimura, M Yoshida, M Asano, N Kasai, M Tamada *Radiat. Phys. Chem.* **27** 245 (1986)
251. W Gombotz, A Hoffman, G Schmer, S Uenoyama *Radiat. Phys. Chem.* **25** 549 (1985)
252. A S Hoffman, W R Gombotz, S Uenoyama, L C Dong, G Schmer *Radiat. Phys. Chem.* **27** 265 (1986)
253. M Carenza *Radiat. Phys. Chem.* **39** 485 (1992)
254. M Carenza, S Lora, P Caliceti, O Schiavon, F M Veroneze *Radiat. Phys. Chem.* **42** 897 (1993)
255. Jie Chen, Yueqi Yang, Pingbo Qian, Zueteh Ma, Weibin Wu, Peizhi Sung, Xingguo Wang, Jinghui Li *Radiat. Phys. Chem.* **42** 915 (1993)
256. Zhai Maolin, Ha Hongfei, Wu Jilan *Radiat. Phys. Chem.* **42** 919 (1993)
257. Xie Huaijiang, Song Juzhong, Peng Tao *Radiat. Phys. Chem.* **42** 931 (1993)
258. J L Garnett, S V Jankewicz, R Levot, D F Sangster *Radiat. Phys. Chem.* **25** 509 (1985)
259. Liang Chang Dong, A S Hoffman *Radiat. Phys. Chem.* **28** 177 (1986)
260. M Alves da Silva, M H Gil, J Guiomar, E Lapa, E Machado, M Moreira, J T Guthrie, S Kotov *Radiat. Phys. Chem.* **36** 589 (1990)
261. A S Hoffman, in *Radiation Technology for Immobilization of Bioactive Materials* (Vienna: IAEA, 1988) p. 25
262. I Kaetsu, M Kumakura *Radiat. Phys. Chem.* **30** 653 (1987)
263. F M Veroneze, G Ceriotti, G Keller, S Lora, M Carenza *Radiat. Phys. Chem.* **35** 88 (1990)
264. K D Pismannik, V D Orekhov, B L Tsetlin *Zh. Vses. Khim. O-va im. D I Mendeleeva* **26** 401(1981)
265. W K Walsh, W Oraby, J Rucker, T Guion, A Hildebrando, A Marati *Radiat. Phys. Chem.* **18** 253 (1981)
266. V Stannett, W K Walsh, E Buttencourt, R Liepins, J R Surles *J. Appl. Polym. Symp.* **31** 201 (1977)
267. W K Walsh, E Bittencourt *Radiat. Phys. Chem.* **9** 289 (1977)
268. J Silverman *Radiat. Phys. Chem.* **14** 17 (1979)
269. A Chapiro *Radiat. Phys. Chem.* **22** 7 (1983)
270. K D Pismannik, V D Orekhov, O G Pustovoit, V Ya Romanov, B M Vanyushkin, A E Voskoboev, N G Kon'kov, M P Svin'in, M T Fedotov, A Kheger, Kh Pessler, G Vil'de, in *Doklady III Vsesoyuz. Soveshch. po Primeneniyu Uskoritelei Zaryazhennykh Chastits v Narodnom Khozyaistve (Iyun', 1979, Leningrad)* [Reports at the Third All-Union Meeting on the Application of Charged Particle Accelerators in the National Economy (June, 1979, Leningrad)] (Leningrad: NIIEFA, 1979) Vol. 2, p. 54
271. B L Tsetlin, I Yu Babkin, V Ya Kabanov, A N Ponomarev *Khim. Vys. Energ.* **19** 303 (1985)
272. M Raetzsch, H Paessler, A Heger *Radiat. Phys. Chem.* **25** 649 (1985)
273. J W Leonhardt *Radiat. Phys. Chem.* **35** 649 (1990)
274. D Mitra, S P Ramnani, P K Bhattacharyya, in *TSRP-94. Trombay Symposium on Radiation and Photochemistry, Preprints of Contributed Papers (January, 1994, BARC)* (Trombay, India: Organizing Committee BARC, 1994) Vol. 2, p. 145
275. C Guimon *Radiat. Phys. Chem.* **14** 841 (1979)
276. I Ishigaki, T Sugo, K Senoo, T Takayama, S Machi, J Okamoto, T Okada *Radiat. Phys. Chem.* **18** 899 (1981)
277. N D Rozenblyum, L V Chepel', L L Kocherginskaya, D M Margolin, L G Zhitkova, L A Vasil'ev, V D Terekhov, Kh A Stasyuk *Khim.Vys. Energ.* **8** 339 (1974)
278. N D Rozenblyum, L L Kocherginskaya, L G Zhitkova, I V Smirnova, G I Larchenko, E V Martens, D M Margolin, V D Terekhov, L A Vasil'ev *Plast. Massy* (9) 20 (1975)
279. Huang Qitao *Radiat. Phys. Chem.* **42** 23 (1993)
280. H Omichi, K Yoshida, K Suzuki, K Araki *Radiat. Phys. Chem.* **11** 327 (1978)
281. A K Pikaev, L V Shemenkova, V F Timofeeva, P Ya Glazunov *Radiat. Phys. Chem.* **35** 132 (1990)
282. J Okamoto, T Sugo, K Fujiwara, H Sekiguchi *Radiat. Phys. Chem.* **35** 113 (1990)

283. F Yoshii, T Sugo, T Sasaki, K Makuuchi, I Ishigaki *Radiat. Phys. Chem.* **42** 65 (1993)
284. V Bilgin, J T Guthrie *Radiat. Phys. Chem.* **36** 581 (1990)
285. S Kiatkamjornwong, J Chvajarernpun, C Nakason *Radiat. Phys. Chem.* **42** 47 (1993)
286. I M Rangwalla, S V Nablo *Radiat. Phys. Chem.* **42** 41 (1993)
287. V Ya Kabanov, L P Sidorova, R E Aliev, V N Kudryavtsev, L L Zatikyan, L N Grushevskaya *Khim. Vys. Energ.* **31** 579 (1988)
288. K Hayakawa, K Kawase, H Yamakita *Radiat. Phys. Chem.* **22** 929 (1983)
289. A E Witt, P D Henise, L W Griest *Radiat. Phys. Chem.* **18** 67 (1981)
290. T Czvikovszky *Radiat. Phys. Chem.* **25** 439 (1985)
291. M Khan, K M Idriss Ali, J L Garnett *Radiat. Phys. Chem.* **42** 167 (1993)
292. A E Witt *Radiat. Phys. Chem.* **9** 271 (1977)
293. F Z Raichuk *Vestn. ADS "RadTekh-SSSR"* **1** 24 (1991)
294. T Czvikovszky, in *Industrial Application of Radioisotopes and Radiation Technology* (Vienna: IAEA, 1982) p. 128
295. S Sundardi, M Ridman, G Ismininingsih, M Utama *Radiat. Phys. Chem.* **18** 1275 (1981)
296. C Singson, C Carmona *Radiat. Phys. Chem.* **18** 1291 (1981)
297. Ying-Kai Fu *Radiat. Phys. Chem.* **31** 293 (1988)
298. L H L Chia, F Y C Boey, S H Feoh *Radiat. Phys. Chem.* **32** 671 (1988)
299. K Y Chan, M G S Yap, L H L Chia, K G Neoh *Radiat. Phys. Chem.* **33** 197 (1989)
300. K Y Chan, M G S Yap, L H L Chia, K G Neoh *Radiat. Phys. Chem.* **33** 205 (1989)
301. U-P Wang *Radiat. Phys. Chem.* **14** 317 (1979)
302. G N P'yankov, in *Radiatsionnaya Khimiya i Tekhnologiya Monomerov i Polimerov* (Radiation Chemistry and Technology of Monomers and Polymers) (Kiev: Naukova Dumka, 1985) p. 37
303. I Yu Babkin, K N Knyazev, B A Kovalev, A G Kovaleva *Vestn. ADS "RadTekh-Evraziya"* **3/4 (5/6)** 104 (1992)
304. R Ramiere, in *Industrial Application of Radioisotopes and Radiation Technology* (Vienna: IAEA, 1982) p. 255
305. O Güven *Radiat. Phys. Chem.* **22** 877 (1983)
306. E A Knizhnik, A D Onisko, in *Radiatsionnaya Khimiya i Tekhnologiya Monomerov i Polimerov* (Radiation Chemistry and Technology of Monomers and Polymers) (Kiev: Naukova Dumka, 1985) p. 239
307. T Giumann, T S Kowalski, A Menger *Radiat. Phys. Chem.* **32** 275 (1988)
308. R Schaudy *Radiat. Phys. Chem.* **35** 71 (1990)
309. A Egan, J Mardian, E King, A Millington, M Nevin, C Butler, J Barker, D Fletcher *Radiat. Phys. Chem.* 1995 (in the press)
310. Qian Mengping, Yu Ye, Chen Baokang, Xu Zhili *Radiat. Phys. Chem.* **42** 193 (1993)
311. F Sundardi, A Zubir, I Marliyanti *Radiat. Phys. Chem.* **18** 1109 (1981)
312. V T Stannett, in *Emulsion Polymerization* (Ed. I Piirma) (New York: Academic Press, 1982) p. 415
313. Zhang Zhicheng, Zhang Manwei *Radiat. Phys. Chem.* **42** 175 (1993)
314. I Kaetsu, K Yoshida, H Okubo, F Yoshii, K Hayashi *Radiat. Phys. Chem.* **14** 737 (1979)
315. I Kaetsu, M Kumakura, F Yoshii, K Yoshida, S Nishiyama, O Abe, H Tanaka, S Nakamura *Radiat. Phys. Chem.* **25** 879 (1985)
316. B G Ershov, E P Petryaev *Khim. Vys. Energ.* **19** 483 (1985)
317. J Leonhardt, G Arnold, M Baer, H Langguth, M Gey, S Hübert *Radiat. Phys. Chem.* **25** 899 (1985)
318. A S Klimentov *Vestn. ADS "RadTekh-Evraziya"* **1** 68 (1993)
319. I Yu Babkin, S P Solov'ev *Radiat. Phys. Chem.* **18** 371 (1981)
320. K Lunkwitz, H J Brink, D Handte, A Ferse *Radiat. Phys. Chem.* **33** 523 (1989)
321. G A Blokh, V N Kalinichenko, A Ya Vakser, N P Sulyaeva, V M Tarasenko, in *Radiatsionnaya Khimiya i Tekhnologiya Monomerov i Polimerov* (Radiation Chemistry and Technology of Monomers and Polymers) (Kiev: Naukova Dumka, 1985) p. 187
322. A P Meleshevich, V V Mikhailova, V F Drozdovskii, D R Razgon, A S Kutsenko, O Ch Turonok, L F Kulish *Vestn. ADS "RadTekhEvraziya"* **3/4 (5/6)** 91 (1992)
323. V V Mikhailova, V F Drozdovskii, D R Razgon, A P Meleshevich, A S Kutsenko, O Ch Turonok, V S Zhikharev *Vestn. ADS "RadTekhEvraziya"* **3/4 (5/6)** 99 (1992)
324. Wang Binglin, Xu Ziyan, Zeng Xingmiao, Ma Shiming, Zhang Yuxi, Sun Daoming *Radiat. Phys. Chem.* **42** 215 (1993)
325. B M Vanyushkin, A E Voskoboev, G G Garifzyanov, V V Korneeva, E L Matukhin, D S Nusinovich, G M Khapkovskii, in *Tez. Dokl. VI Vsesoyuz. Soveshch. po Primeneniyu Uskoritelei Zaryazhennykh Chastits v Narodnom Khozyaistve (Oktyabr', 1988, Leningrad)* [Abstracts of Reports at the Sixth All-Union Meeting on the Application of Charged Particle Accelerators in the National Economy (October, 1988, Leningrad] (Moscow: TsNIIAtominform, 1988) p. 103
326. W Brenner, B Bugy, C Rogers *Radiat. Phys. Chem.* **9** 389 (1977)
327. K Kojima, S Miyake, I Uda *Radiat. Phys. Chem.* **22** 901 (1983)
328. M Kumakura, I Kaetsu *Radiat. Phys. Chem.* **23** 523 (1984)
329. T Kume, H H Mutaat, M R Awang, H Ito, S Hashimoto, in *Proceedings of the International Conference on the Evolution in Beam Applications (November, 1991, Takasaki, Japan)* (Tokyo: JAERI, 1992) p. 497
330. M R Awang, H H Mutaat, R M Deres, T Kume, in *Proceedings of the International Conference on the Evolution in Beam Applications (November, 1991, Takasaki, Japan)* (Tokyo: JAERI, 1992) p. 501
331. T Kume, S Matsuhashi, S Hashimoto, M R Awang, H Hamdani, H Saitoh *Radiat. Phys. Chem.* **42** 727 (1993)
332. R M Brinston *Radiat. Phys. Chem.* **35** 390 (1993)
333. J N Aaronson, S V Nablo *Radiat. Phys. Chem.* **31** 711 (1988)
334. D A Cleghorn, S V Nablo *Radiat. Phys. Chem.* **35** 382 (1990)
335. V L Auslender, V A Polyakov, A G Golnik, D A Kaushansky, I V Skoromnov *Radiat. Phys. Chem.* **42** 563 (1993)
336. *Beta-Gamma* (3/4) 11 (1990)
337. V N Ponomarev, T I Noskova *Vestn. ADS "RadTekh-Evraziya"* **1 (5)** 18 (1993)
338. V G Khrushchev, E P Pavlov, V V Generalova *Vestn. ADS "RadTekh-Evraziya"* **1 (5)** 13 (1993)
339. N G S Gopal, K M Patel, G Sharma, H L Bhalla, P A Wills, N Hilmy *Radiat. Phys. Chem.* **32** 619 (1988)
340. G O Phillips, in *Technical and Economic Comparison of Irradiation and Conventional Methods* (Vienna: IAEA, 1988) p. 69
341. G O Phillips *IAEA Bull.* **36** (1) 19 (1994)
342. J F Swinwood, B K Wilson *Radiat. Phys. Chem.* **35** 369 (1990)
343. *Beta-Gamma* (3/4) 3 (1990)
344. B D Reid, B K Wilson *Radiat. Phys. Chem.* **42** 595 (1993)
345. V Handlos *Radiat. Phys. Chem.* **18** 175 (1981)
346. *Process Control Guides for Gamma Radiation Sterilization of Medical Devices* (Arlington, VA: Association for the Advancement of Medical Instrumentation, 1984)
347. A K Pikaev, P Ya Glazunov, Yu S Pavlov *Radiat. Phys. Chem.* **42** 887 (1993)
348. H Landfield *Radiat. Phys. Chem.* **15** 39 (1980)
349. W E Skiens *Radiat. Phys. Chem.* **15** 47 (1980)
350. J L Williams, T S Dunn *Radiat. Phys. Chem.* **15** 59 (1980)
351. T S Dunn, E E Williams, J L Williams *Radiat. Phys. Chem.* **19** 287 (1982)
352. H Wilski *Radiat. Phys. Chem.* **35** 186 (1990)
353. G P Jakobs *Radiat. Phys. Chem.* **26** 133 (1985)
354. V V Bochkarev, V T Kharlamov, A K Pikaev, L P Shubnyakova, Z M Potapova, E P Pavlov, in *Radiation Sterilization of Medical Products 1974* (Vienna: IAEA, 1975) p. 365
355. A K Pikaev, L I Kartasheva, Z M Potapova, V T Kharlamov *Radiat. Phys. Chem.* **12** 1 (1978)
356. V V Bochkarev, V T Kharlamov, A K Pikaev, V V Sedov, E P Pavlov, Z M Potapova, L P Shubnyakova, E G Tushov *Med. Radiolog.* (12) 17 (1975)
357. V L Tal'roze, V I Trofimov *Khim. Vys. Energ.* **17** 233 (1983)
358. L P Shubnyakova, V T Kharlamov, A K Pikaev *Khim. Vys. Energ.* **10** 49 (1976)
359. K Kishore, P N Moorthy, K N Rao *Radiat. Eff.* **29** 165 (1979)
360. V V Bochkarev, V T Kharlamov, A K Pikaev, Z M Potapova, E P Pavlov, E G Tushov, L P Shubnyakova *Khim.-Farm. Zh.* **14** (10) 82 (1980)
361. V I Trofimov *Vestn. ADS "RadTekh-Evraziya"* **1 (5)** 43 (1993)
362. V L Talrose, V I Trofimov *Radiat. Phys. Chem.* 1995 (in the press)

363. K H Morganstern, in *Sterilization by Ionizing Radiation* (Eds E R L Gaughran, A J Goudie, R F Morrissey) (Montreal: Multiscience, 1977) Vol. 2, p. 371
364. K H Morganstern *Radiat. Phys. Chem.* **35** 520 (1990)
365. A K Pikaev *Current Status of Radiation Treatment of Water and Waste Water. Report at IAEA Consultants' Meeting on Irradiation Treatment of Water, Waste Water and Sewage Sludges (December, 1994, Vienna)*
366. A K Pikaev, V N Shubin *Radiat. Phys. Chem.* **24** 77 (1984)
367. S A Brusentseva, P I Dolin, V E Kazarinov, V N Shubin, in *Rol' Khimii v Okhrane Okruzhayushchei Sredy* (The Role of Chemistry in the Protection of the Environment) (Kiev: Naukova Dumka, 1983) p. 217
368. A V Ponomarev, I E Makarov, A V Bludenko, A K Pikaev *Radiat. Phys. Chem.*1995 (in the press)
369. C N Kurucz, T D Waite, W J Cooper, M J Nickelsen, in *Advances in Nuclear Technology* Vol. 22 (Eds J Levin, M Becker) (New York: Plenum, 1991) p. 1
370. E H Bryan, R I Dick, J F Swinwood, P Kruger, D A Carlson, G Hare, T Waite *Radiation Energy Treatment of Water, Waste Water and Sludge. A State-of-the-Art Report by the Task Committee on Radiation Energy Treatment, Air and Radiation Management Committee, Environmental Engineering Division, American Society of Civil Engineers* (New York: American Society of Civil Engineers, 1992)
371. A K Pikaev *Khim. Vys. Energ.* **28** 5 (1994)
372. N Getoff, W Lutz *Radiat. Phys. Chem.* **25** 21 (1985)
373. N Getoff, S Solar *Radiat. Phys. Chem.* **31** 121 (1988)
374. N Getoff *Radiat. Phys. Chem.* **35** 432 (1990)
375. P Gehringer, E Proksch, H Eschweiler, W Szinovatz *Radiat. Phys. Chem.* **35** 456 (1990)
376. P Gehringer, H Eschweiler, W Szinovatz, H Fiedler, R Steiner, G Sonneck *Radiat. Phys. Chem.* **42** 711 (1993)
377. P Gehringer, H Eschweiler, H Fiedler *Radiat. Phys. Chem.* 1995 (in the press)
378. L I Kartasheva, T P Zhestkova, V N Chulkov, A K Pikaev *Khim. Vys. Energ.* 1995 (in the press)
379. D Wessel, J W Leonhardt, E Beise *Radiat. Phys. Chem.* **25** 57 (1985)
380. K Vacek, F Pastuszek, M Sedlacek *Radiat. Phys. Chem.* **28** 573 (1986)
381. G G Eichholz, C G Jones, H E Haynes *Radiat. Phys. Chem.* **32** 139 (1988)
382. F Pastuszek, K Vacek, V Vondruska *Radiat. Phys. Chem.* **42** 699 (1993)
383. M R Cleland, R A Fernald, S R Maloof *Radiat. Phys. Chem.* **24** 179 (1984)
384. T Miyata, M Kondoh, T Minemura, H Arai, M Hosono, A Nakao, Y Seike, O Tokunaga, S Machi *Radiat. Phys. Chem.* **35** 440 (1990)
385. Te Sawai, M Sekiguchi, T Shimokawa, Ta Sawai *Radiat. Phys. Chem.* **42** 723 (1993)
386. C N Kurucz, T D Waite, W J Cooper *Radiat. Phys. Chem.* **45** 299 (1995)
387. E Lyu, I E Makarov, Yu I Kuryatnikov, R V Mazanko, R V Dzhagatspanyan, A K Pikaev *Radiat. Phys. Chem.* **22** 503 (1983)
388. E Lyu, I E Makarov, A K Pikaev *Khim. Vys. Energ.* **17** 50 (1983)
389. S P Buslaeva, B M Vanyushkin, A V Gogolev, S A Kabakchi, Yu A Panin, A V Putilov, L B Upadyshev *Khim. Promst.* (6) 47 (1991)
390. H D Sivinski, in *Radiation for a Clean Environment* (Vienna: IAEA, 1975) p. 151
391. E A Podzorova, A I Kasperovich *Khim. Vys. Energ.* **24** 99 (1990)
392. M Takehisa, A Sakumoto, in *Industrial Application of Radioisotopes and Radiation Technology* (Vienna: IAEA, 1982) p. 217
393. A Sakumoto, T Miyata *Radiat. Phys. Chem.* **24** 99 (1984)
394. W C Hay, in *Radiation for a Clean Environment* (Vienna: IAEA, 1975) p. 433
395. S A Brusentseva, V N Shubin, G K Nikonorova, D M Zorin, A A Sosnovskaya, E P Petryaev, E I Vlasova, I P Edimicheva, N N Subbotina *Radiat. Phys. Chem.* **28** 569 (1986)
396. D I Danilin, V N Shubin *Khim. Vys. Energ.* **26** 40 (1992)
397. T Lessel, in *The Sewage Sludge Plant in Geiselbullach. Report at Joint Meeting of the American Society of Civil Engineers' Task Committee on Radiation Treatment of Water, Waste Water and Sludges and the IAEA Coordination Research Group, Arlington, VA (USA) 1990* p. 1
398. M Takehisa, H Arai, M Arai, T Miyata, A Sakumoto, S Hashimoto, K Nishimura, H Watanabe, W Kawakami, I Kuriyama *Radiat. Phys. Chem.* **25** 63 (1985)
399. S A Kabakchi, E A Demenkova, A R Bekker *Khim. Vys. Energ.* **25** 15 (1991)
400. A V Gogolev, S A Kabakchi, A K Pikaev *Khim. Vys. Energ.* **25** 531 (1991)
401. A M Dmitriev, V M Kalinin, V S Vetrov *Radiatsionnaya Obrabotka Stochnykh Vod Zhivotnovodcheskikh Kompleksov* (Radiation Treatment of Waste Water from Stock Farms) (Minsk: Urozhai, 1981)
402. V N Shubin *Khim. Vys. Energ.* **17** 349 (1983)
403. V L Auslender, R A Salimov, G A Spiridonov *Vestn. ADS "RadTekh-SSSR"* **1** (4) (1991)
404. B M Vanyushkin, Yu A Panin, S P Buslaeva *Vestn. ADS "Radtekh-SSSR"* **2** 1 (1991)
405. M M Nesterov, V L Varentsov, B M Vanyushkin, S P Buslaeva, G A Spiridonov, in *Tez. Dokl. VII Soveshch. po Primeneniyu Uskoritelei Zaryazhennykh Chastits v Narodnom Khozyaistve (Iyun', 1992, St. Petersburg)* Abstracts of Reports at the Seventh Meeting on the Application of Charged Particle Accelerators in the National Economy (July, 1992, St.Petersburg) (Moscow: TsNIIAtominform, 1992) p. 69
406. T Lessel, H Moetsch, E Hennig, A Suess, A Rosopulo, G Schurmann, in *Radiation for a Clean Environment* (Vienna: IAEA, 1975) p. 447
407. T Lessel, in *Radiation Processing of Sewage Sludge by Gamma Radiation, Electron Beam Radiation and Other Alternative Methods (Review of the Status of the Technology). Report at IAEA Consultants' Meeting on Irradiation Treatment of Water, Waste Water and Sewage Sludge (December, 1994, Vienna)* p. 1
408. J S Sivinski, S B Ahlstrom *Radiat. Phys. Chem.* **24** 17 (1984)
409. S B Ahlstrom *Radiat. Phys. Chem.* **31** 131 (1988)
410. K Krishnamurthy, A D Naik, S S Patel, M K Sinha, D S Lavale, M R Shah, in *New Developments and Trends in Radiation Chemistry and Technology* (Vienna: IAEA, 1989) p. 281
411. J G Trump, E W Merrill, K A Wright *Radiat. Phys. Chem.* **24** 55 (1984)
412. S Hashimoto, K Nishimura, S Machi *Radiat. Phys. Chem.* **31** 109 (1989)
413. S Hashimoto, in *Proceedings of the International Conference on the Evolution in Beam Applications (November, 1991, Takasaki, Japan)* (Tokyo: JAERI, 1992) p. 466
414. N A Vysotskaya, in *Rol' Khimii v Okhrane Okruzhayushchei Sredy* (The Role of Chemistry in the Protection of the Environment) (Kiev: Naukova Dumka, 1983) p. 230
415. E P Petryaev, A A Sosnovskaya, N N Subbotina, V S Vetrov, G M Vasilevskii, M F Denisenko, in *Vtoraya Vsesoyuz. Konf. po Teoreticheskoi i Prikladnoi Radiatsionnoi Khimii, Oktyabr', 1990, Obninsk (Tez. Dokl.)* [The Second All-Union Conference on Theoretical and Applied Radiation Chemistry, October, 1990, Obninsk (Abstracts of Reports)] (Moscow: NIITEKhim, 1990) p. 217
416. J F Swinwood, B K Wilson *Radiat. Phys. Chem.* **35** 461 (1990)
417. J F Swinwood, F M Frazer *Radiat. Phys. Chem.* **42** 683 (1993)
418. A G Chmielewski, Z Zimek, T Bryl Sandalewska, L Kalisz, M Kazmierczuk *Radiat. Phys. Chem.* 1995 (in the press)
419. K Kawamura, S Aoki, W Kawakami, S Hashimoto, S Machi, in *Radiation for a Clean Environment* (Vienna: IAEA, 1975) p. 621
420. S Machi, O Tokunaga, K Nishimura, S Hasimoto, W Kawakami, M Washino, K Kawamura, S Aoki, K Adachi *Radiat. Phys. Chem.* **9** 371 (1977)
421. K Kawamura, V H Shui, in *Industrial Application of Radioisotopes and Radiation Technology* (Vienna: IAEA, 1982) p. 197
422. K Kawamura, T Katayama, K Kawamura *Radiat. Phys. Chem.* **18** 389 (1981)
423. K Kawamura, V H Shui *Radiat. Phys. Chem.* **24** 145 (1984)

424. O Tokunaga, H Arai, S Hashimoto, in *Proceedings of the International Conference on the Evolution in Beam Applications (November, 1991, Takasaki, Japan)* (Tokyo: JAERI, 1992) p. 417
425. N Frank, S Hirano, K Kawamura *Radiat. Phys. Chem.* **31** 57 (1988)
426. *Beta-Gamma* (1) 42 (1990)
427. S Jordan *Radiat. Phys. Chem.* **31** 21 (1988)
428. A G Chmielewski, E Iller, Z Zimek, J Licki, in *Proceedings of the International Conference on the Evolution in Beam Applications (November, 1991, Takasaki, Japan)* (Tokyo: JAERI, 1992) p. 440
429. A G Chmielewski, E Iller, Z Zimek, J Licki *Radiat. Phys. Chem.* **40** 321 (1992)
430. A P Voronin, N Z Lyakhov, R A Salimov, G A Spiridonov *Zh. Vses. Khim. O-va im. D I Mendeleeva* **35** (1) 72 (1990)
431. V Nagibin *Radiat. Phys. Chem.* **40** 307 (1992)
432. T Doi, S Suda, A Morichige, O Tokunaga, Y Aoki, S Sato, M Komiya, N Hashimoto, M Nakajima, in *Proceedings of the International Conference on the Evolution in Beam Applications (November, 1991, Takasaki, Japan)* (Tokyo: JAERI, 1992) p. 482
433. T Doi, Y Osada, A Morishige, O Tokunaga, T Miyata, K Hirota, M Nakajima, M Komiya, S Baba *Radiat. Phys. Chem.* **42** 679 (1993)
434. H Namba, O Tokunaga, T Tanaka, Y Ogura, S Aoki, R Suzuki, in *Proceedings of the International Conference on the Evolution in Beam Applications (November, 1991, Takasaki, Japan)* (Tokyo: JAERI, 1992) p. 476
435. H Namba, O Tokunaga, T Tanaka, Y Ogura, S Aoki, R Suzuki *Radiat. Phys. Chem.* **42** 669 (1993)
436. N W Frank, V Markovic *IAEA Bull.* **36** (1) 7 (1994)
437. J C Person, D O Ham *Radiat. Phys. Chem.* **31** 1 (1988)
438. S Jordan *Radiat. Phys. Chem.* **35** 409 (1990)
439. O Tokunaga, H Namba, in *New Development and Trends in Radiation Chemistry and Technology* (Vienna: IAEA, 1989) p. 265
440. H-R Paur, S Jordan *Radiat. Phys. Chem.* **31** 9 (1988)
441. H-R Paur, G Albrecht, W Baumann, H Matzing, Th Wascher, R Mehnert, L Prager, A Sobotka *Radiat. Phys. Chem.* 1995 (in the press)
442. A N Ermakov, N P Tarasova, L T Bugaenko *Khim. Vys. Energ.* **25** 493 (1991)
443. I V Vasil'eva, S S Denisov, K I Finkel'shtein *Vestn. ADS "RadTekh-Evraziya"* **1** (3) 58 (1992)
444. A G Chmielewski, E Iller, B Tyminski, Z Zimek, in *The First International Conference on Advanced Oxidation Technologies for Water and Air Remediation. Abstracts of Reports (June, 1994, London, Ontario, Canada)* [London, Ontario (Canada): Organizing Committee, 1994] p. 352
445. A G Chmielewski, E Iller, Z Zimek, M Romanowski, K Koperski *Radiat. Phys. Chem.* 1995 (in the press)
446. A G Chmielewski, B Tyminski, J Licki, E Iller, Z Zimek, A Dobrowolski *Radiat. Phys. Chem.* **42** 663 (1993)
447. H-R Paur, W Baumann, H Matzing, W Lindner *Radiat. Phys. Chem.* 1995 (in the press)
448. J W Leonhardt *Radiat. Phys. Chem.* **24** 167 (1984)
449. J Bös, in *Electron Beam Processing of Combustion Flue Gases* (Vienna: IAEA, 1987) p. 85
450. Z Zimek, A G Chmielewski, S Bulka, G W Lysov, N W Frank *Radiat. Phys. Chem.* 1995 (in the press)
451. N Frank, K Kawamura, G Miller *Radiat. Phys. Chem.* **25** 35 (1985)
452. *Beta-Gamma* (3/4) 3 (1990)
453. J F Swinwood, T D Waite, P Kruger, S M Rao *IAEA Bull.* **36** (1) 11 (1994)
454. V A Rudoi, E A Podzorova, V A Gol'din *Vestn. ADS "RadTekh-Evraziya"* **1** (5) 79 (1993)
455. H Arai, M Hosono, G Zhu, M Miyata, in *Proceedings of the International Conference on the Evolution in Beam Applications (November,1991, Takasaki, Japan)* (Tokyo: JAERI, 1992) p. 492
456. K A Gray, R J Hilarides, in *The First International Conference on Advanced Oxidation Technologies for Water and Air Remediation. Abstracts of Reports(June, 1994, London, Ontario, Canada)* [London, Ontario (Canada): Organizing Committee, 1994] p. 139
457. S M Matthews, A J Boegel, J A Loftis, R A Caufield, B J Mincher, D H Meikrantz, R J Murphy *Radiat. Phys. Chem.* **42** 689 (1993)
458. S M Matthews, A J Boegel, D W Camp, R A Caulfield, J O Cunningham, P F Daley, J J Greci, M C Jovanovic, J A Loftis, P D Soran, F T Wang, T Mill, M Su, C C D Yao, in *Proceedings of The First Interntional Conference on Advanced Oxidation Technologies for Water and Air Remediation (June, 1994, London, Ontario, Canada)* [London, Ontario (Canada): Organizing Committee, 1994] p. 143
459. P Loaharanu *IAEA Bull.* **36** (1) 30 (1994)
460. M Furuta, T Katayama, N Ito, A Mizohata, H Toratina, A Takeda *Radiat. Phys. Chem.* **35** 349 (1990)
461. C A Wakeford, R Blackburn, A J Swallow *Radiat. Phys. Chem.* **38** 29 (1991)
462. D J S Findlay, T V Parsons, M R Sene *Radiat. Phys. Chem.* **42** 417 (1993)
463. M Takehisa *Radiat. Phys. Chem.* **18** 159 (1981)
464. J Farkas *Radiat. Phys. Chem.* **35** 248 (1990)
465. G A Zakladnoi, A I Men'shenin, E S Pertsovsky, R A Salimov, V G Cherepkov, B F Bogolyubov, I S Stanev *Radiat. Phys. Chem.* **34** 991 (1989)
466. C L Gallien, J Paquin, C Ferradini, T Sadat *Radiat. Phys. Chem.* **25** 81 (1985)
467. T Sadat, M Vassenaix *Radiat. Phys. Chem.* **36** 661 (1990)
468. M Ahmed *Radiat. Phys. Chem.* **42** 245 (1993)
469. F Fraser *Radiat. Phys. Chem.* **42** 429 (1993)
470. D D Derr, R E Engel *Radiat. Phys. Chem.* **42** 289 (1993)
471. W Migdal, L Walis, A G Chmielewski *Radiat. Phys. Chem.* **42** 567 (1993)
472. P Loaharanu *IAEA Bull.* **32** (2) 44 (1990)
473. H J van der Linde, R A Basson *Radiat. Phys. Chem.* **31** 257 (1988)
474. H Delincee, D A E Ehlerman *Radiat. Phys. Chem.* **34** 877 (1988)
475. K W Boegl *Radiat. Phys. Chem.* **35** 301 (1990)
476. H Delincee *Radiat. Phys. Chem.* **42** 351 (1993)
477. W Meier, R Buergin, D Froelich *Radiat. Phys. Chem.* **35** 332 (1990)
478. K M Morehouse, Y Ku *Radiat. Phys. Chem.* **42** 359 (1993)
479. M H Stevenson, A V J Crone, J T G Hamilton, C H McMurray *Radiat. Phys. Chem.* **42** 363 (1993)
480. H Delincee *Radiat. Phys. Chem.* 1995 (in the press)
481. Qi Shengchu, Wu Jilan, Yuan Rongyao *Radiat. Phys. Chem.* **35** 329 (1990)
482. M Grootveld, P Jain *Radiat. Phys. Chem.* **34** 925 (1989)
483. J Farkas, A Koncz, M M Sharif *Radiat. Phys. Chem.* **35** 324 (1990)
484. M M Sharif, J Farkas *Radiat. Phys. Chem.* **42** 383 (1993)
485. A J Swallow *Radiat. Phys. Chem.* **35** 311 (1990)
486. E M Stewart, M H Stevenson, R Gray, C H McMurray *Radiat. Phys. Chem.* **42** 367 (1993)
487. S P Solov'ev, I I Kuz'min *Zh. Vses. Khim. O-va im. D I Mendeleeva* **18** 308 (1973)
488. N G Kolin, S P Solov'ev, A A Stuk *Vestn. ADS "RadTekh-Evraziya"* **1/8** 12 (1994)
489. A Pavlenco, V Tokarevsky, Yu Struk, P Kurilo, P Baransky, G Gaydar *Radiat. Phys. Chem.* **31** 333 (1988)
490. W J Bowden *Radiat. Phys. Chem.* **18** 357 (1981)
491. R A Pethrick *Radiat. Phys. Chem.* **37** 331 (1991)
492. Y Tabata, S Tagawa, M Washio, N Hayashi *Radiat. Phys. Chem.* **25** 305 (1985)
493. T Ueno, H Shiraishi, K Naraoka, in *Proceedings of the Conference on Radiation Curing, Asia (CRCA'88), October, 1988, Tokyo* (Tokyo: Organizing Committee, 1988) p. 56
494. P G Fuochi, A Martelli, E Combia, F Fasce, M Pasqualetti, M Portesine, M Zambelli, B Passerini *Radiat. Phys. Chem.* **35** 493 (1990)
495. F Frisina, N Tavolo, E Combia, R Mosca, P Chirco, P G Fuochi *Radiat. Phys. Chem.* **35** 500 (1990)
496. G Arcoria, A Patti, P G Fuochi *Radiat. Phys. Chem.* **42** 1015 (1993)
497. Wang Zhongyang, Chen Zhuliang, Liu Yajing, Zhang Yuehong, Chen Zhlin, Shi Jianqing, Fu Jianxin, Yin Nanyong *Radiat. Phys. Chem.* **42** 1035 (1993)
498. Qian Simin, Lan Liqiao, Wang Weiguo, Gu Hongchun *Radiat. Phys. Chem.* **42** 1043 (1993)
499. Z Prazil, Z Schweiner, M Pesek *Radiat. Phys. Chem.* **35** 509 (1990)
500. E A Abramyan, A E Ligachev *Radiat. Phys. Chem.* **31** 829 (1988)
501. I N Meshkov *Radiat. Phys. Chem.* **35** 483 (1990)

502. V V Boldyrev, A P Voronin, N Z Lyakhov, B K Kanimov *Zh. Vses. Khim. O-va im. D I Mendeleeva* **35** 540 (1990)
503. R G Arshakuni, S I Suminov *Vestn. ADS "RadTekh-Evraziya"* **3/4 (5/6)** 8 (1992)
504. O S Gribkov, A P Voronin, V L Auslender *Radiat. Phys. Chem.* 1995 (in the press)
505. R G Arshakuni, Yu A Panin, V E Snigirev, B M Vanyushkin, K A Kostanyan *Vestn. ADS "RadTekh-Evraziya"* **3/4 (5/6)** 20 (1992)
506. I G Abramson, R M Kapralova, Yu V Nikiforov, A F Vaisman *Vestn. ADS "RadTekh-Evraziya"* **3/4 (5/6)** 29 (1992)
507. G N Flerov *Vest. Akad. Nauk SSSR* (4) 35 (1984)
508. P Yu Apel', A N Kravets, L I Kuznetsov, A Yu Didyk *Khim. Vys. Energ.* **23** 327 (1989)
509. P Yu Apel' *Khim. Vys. Energ.* **25** 132 (1991)
510. D E Harmer, D S Beale, C T Pumpelly, B W Wilkinson, in *Industrial Uses of Large Radiation Sources* Vol. 2 (Vienna: IAEA, 1963) p. 205
511. A Danno, in *Actions Chimiques et Biologiques des Radiations* Vol. 13 (Ed. M Haissinsky) (Paris: Masson, 1969) Part 4
512. V B Osipov, R V Dzhagatspanyan, A S Shtan', V M Simonov, S V Mamikonyan, L D Solodikhina, D P Bodrov, S V Golubkov, I G Lyaskin *At. Energ.* **25** 271 (1968)
513. A A Beer, P A Zagorets, V F Inozemtsev, L S Maiorov, V I Slavyanov, G A Artushov, I F Sprygaev, V A Novozhilov *At. Energ.* **29** 461 (1970)
514. M Baer, K Friese, J Reinhardt, in *Industrial Application of Radioisotopes and Radiation Technology* (Vienna: IAEA, 1982) p. 126
515. A Negron-Mendoza, G Albarran *Radiat. Phys. Chem.* **35** 469 (1990)
516. A Negron-Mendoza, G Albarran *Radiat. Phys. Chem.* **42** 973 (1993)
517. V V Shapovalov, V A Poluektov *Khim. Vys. Energ.* **29** 27 (1995)
518. B Ya Adigamov, V V Lunin, I I Miroshnichenko, Ju I Solovetsky *Radiat. Phys. Chem.* **35** 473 (1990)
519. Yu I Solovetskii *Vestn. ADS "RadTekh-Evraziya"* **3/4 (5/6)** 53 (1992)
520. R G Arshakuni, B M Vanyushkin, Yu A Panin *Vestn. ADS "RadTekh-Evraziya"* **3/4 (5/6)** 48 (1992)
521. A N Ermakov, B M Zhitomirskii, V N Popov *Vestn. ADS "RadTekh-Evraziya"* **3/4 (5/6)** 75 (1992)
522. A Danno *Chem. Econ. Eng. Rev.* **6** (6) 7 (1974)
523. V F Krasnoshtanov, V D Rusanov, in *Atomno-Vodorodnaya Energetika* (Atomic-Hydrogen Energetics) (Moscow: Energoatomizdat, 1984) No 6, p. 237
524. V V Gerasimov *Korroziya Reaktornykh Materialov* (Corrosion of Reactor Materials) (Moscow: Atomizdat, 1980)
525. A K Pikaev, V P Shilov, V I Spitsyn *Radioliz Vodnykh Rastvorov Lantanidov i Aktinidov* (Radiolysis of Aqueous Solutions of Lanthanides and Actinides) (Moscow: Nauka, 1983)
526. M V Vladimirova *Radiatsionnaya Khimiya Aktinidov* (Radiation Chemistry of Actinides) (Moscow: Energoatomizdat, 1983)
527. L A Kul'skii, E V Strakhov, A M Voloshinova, V A Bliznyukova *Voda v Atomnoi Energetike* (Water in Atomic Energetics) (Kiev: Naukova Dumka, 1983)
528. Yu F Balandin, I V Gorynin, Yu I Zvezdin, V G Markov *Konstruktsionnye Materialy AES* (Construction Materials for Nuclear Power Stations) (Moscow: Energoatomizdat, 1984)
529. A K Pikaev, S A Kabakchi, G F Egorov *Radiat. Phys. Chem.* **31** 789 (1988)
530. B G Burns, in *Radiation Research* Vol. 2 (Eds E M Fielden, J F Fowler, J H Hendry, D Scott) (London: Taylor & Francis, 1988) p. 193
531. K Sehested, H Christensen, in *Radiation Research* Vol. 2 (Eds E M Fielden, J F Fowler, J H Hendry, D Scott) (London: Taylor & Francis, 1988) p. 199
532. K Ishigure, in *Radiation Research* Vol. 2 (Eds E M Fielden, J F Fowler, J H Hendry, D Scott) (London: Taylor & Francis, 1988) p. 205
533. G V Buxton, D W Cartmell, R M Sellers, in *Radiation Research* Vol. 2 (Eds E M Fielden, J F Fowler, J H Hendry, D Scott) (London: Taylor & Francis, 1988) p. 212
534. W L McLaughlin, in *High Dose Dosimetry for Radiation Processing* (Vienna: IAEA, 1991) p. 3
535. A K Pikaev, L I Kartasheva, V N Chulkov, V V Generalova, M N Gurskij, in *High Dose Dosimetry for Radiation Processing* (Vienna: IAEA, 1991) p. 147
536. A Kovacs, L Wojnarovits, N B El-Assy, H Y Afeefy, M Al-Sheikhly, W L McLaughlin *Radiat. Phys. Chem.* 1995 (in the press)
537. Z K Kriminskaya, A K Pikaev *Khim. Vys. Energ.* 1995 (in the press)
538. V V Generalova, M N Gurskii, A K Pikaev *Radiat. Phys. Chem.* **31** 449 (1988)
539. K C Humphreys, A D Kantz *Radiat. Phys. Chem.* **9** 737 (1977)
540. F Abdel Rahim, A Miller, W L McLaughlin *Radiat. Phys. Chem.* **25** 767 (1985)
541. D S Spencer, V P Thalacker, J N Chasman, S Siegel *Radiat. Phys. Chem.* **25** 755 (1985)
542. T Prusik, M Montesalvo, T Wallace *Radiat. Phys. Chem.* **31** 441 (1988)
543. K Ueno *Radiat. Phys. Chem.* **31** 467 (1988)
544. W L McLaughlin, W-Z Ba, W J Chappas *Radiat. Phys. Chem.* **31** 481 (1988)
545. W L McLaughlin *Radiat. Phys. Chem.* **35** 693 (1990)
546. A Miller, A Kovacs *Radiat. Phys. Chem.* **35** 774 (1990)
547. Zhang Limin, Gu Jiqing, Xu Peiling, Bai Yihua, Ye Dongsheng, Wu Bin *Radiat. Phys. Chem.* **42** 765 (1993)
548. T Sato, T Takahashi, T Saito, M Takehisa, A Miller *Radiat. Phys. Chem.* **42** 789 (1993)