Hydroxyl-radical-induced reactions of poly(vinyl methyl ether): a pulse radiolysis, EPR and product study in deoxygenated and oxygenated aqueous solutions

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Hydroxyl radicals were generated radiolytically in N_2O-saturated aqueous solutions in the presence of poly(vinyl methyl ether) (PVME, 6×10^4 Da, 10^{-3}–10^{-2} mol dm^{-3} in monomer units). As measured by pulse radiolysis, they react ($k = 2.2 \times 10^8$ dm^3 mol^{-1} s^{-1}) with PVME by giving rise to mainly α-alkoxyalkyl radicals (~72%) that reduce ($k \approx 2 \times 10^9$ dm^3 mol^{-1} s^{-1}) Fe(CN)$_6$$^{3-}$, IrCl$_6$$^{2-}$ or tetranitromethane. Based on the formaldehyde yield in the presence of the latter two oxidants (~40% of $^{\bullet}$OH), it is concluded that OH radicals undergo H-abstraction at ROCH$_2$–H, R$_3$C–H and R$_2$HC–H with probabilities of ~40, ~32 and ~28%, respectively. The momentary rate constant of the decay of the PVME radicals depends on the number of radicals per polymer chain and drops as they decay. The yield of intermolecular crosslinks, as measured by an increase in the molecular weight, strongly increases with decreasing dose rate, and it is concluded that the majority of crosslinks occur intramolecularly, even at the lowest dose rate used [0.0015 Gy s^{-1}, G(intermolecular crosslinks) = 0.62×10^{-7} mol J^{-1}]. In the presence of dioxygen, the primary PVME radicals are converted into their corresponding peroxyl radicals. They undergo efficient autoxidation via intramolecular H-abstraction [e.g. G(dioxygen uptake) $\approx 110 \times 10^{-7}$ mol J^{-1} at 0.0015 Gy s^{-1}]. Most of the hydroperoxides are unstable, i.e. the high dioxygen-uptake yield is not matched by the organic hydroperoxide yield [G(organic hydroperoxide) $\approx 34 \times 10^{-7}$ mol J^{-1} at 0.0015 Gy s^{-1}]. As a consequence of the instability of some of the organic hydroperoxides, chain scission also strongly depends on dose rate [e.g. G(chain breaks) $\approx 15 \times 10^{-7}$ mol J^{-1} at 0.0015 Gy s^{-1}], and prompt chain breakage due to processes occurring in the bimolecular decay of the peroxyl radicals is minor compared to the former pathway.

Poly(vinyl methyl ether), PVME, is one of the simplest water-soluble polymers (for its synthesis and solution properties see ref. 1). Its aqueous solutions have the unusual property of reverse temperature solubility, i.e. the polymer precipitates at around 34–37 °C. Its interactions with water and the mechanism of the phase transitions are presently the subject of considerable interest.[2–4]

Hydrogels, i.e. water-swollen, covalently crosslinked polymer networks, made of poly(vinyl methyl ether) are also heat-sensitive.[5–8] This property, as well as the fact that the gel collapses at a temperature close to body temperature, has elicited a number of studies on its possible use as a stimulus-sensitive biomaterial, e.g. as a thermosensitive (and/or bioadhesive) drug-delivery system[7,9–11] and even as an artificial muscle.[7,12] Other interesting applications of poly(vinyl methyl ether) hydrogels are recyclable separation systems[5,13,14] and chemomechanical valves.[15]

In general, ionizing radiation is a very efficient tool for the formation of hydrogels.[16] The reaction can be carried out at room temperature, is easy to control and environmentally friendly (no additional chemicals, no waste). Using γ-irradiation, homogeneous products of any desired shape and size can be produced. For biomedical applications, the radiation technique allows one to carry out the formation of the hydrogel in one step as well as its sterilization (e.g. refs. 17 and 18).

In particular, hydrogels of poly(vinyl methyl ether) have already been obtained by this method.[6,8,19–21] For a further development of this promising technique, it seems worthwhile to investigate in some detail the underlying radiation chemistry of poly(vinyl methyl ether) in aqueous solution. First attempts at elucidating these processes have already been undertaken,[20–22] but there are marked discrepancies among the published data.

The aim of the present work is to present a more complete picture by combining kinetic and product studies. To aid our interpretations, the radiation-induced reactions of 2,4-dimethoxypentane, a low-molecular-weight model compound of poly(vinyl methyl ether), were also investigated and are described in the preceding paper.[23]

Experimental

Poly(vinyl methyl ether) (Lutonal M40, BASF) has been purified by dissolving it in water (~50 g dm^{-3}) at room temperature. The temperature of solution was then raised above 37 °C until the polymer precipitated. The liquid fraction was discarded, and after this procedure had been repeated five times the polymer solution was subjected to continuous ultrafiltration (Amicon TCF 10 with a Diaflo YM10 membrane of a nominal 10 kDa cut-off) until the UV absorption $\lambda > 200$ nm of the permeate fell below 0.01. After such a treatment the weight-average molecular weight of PVME was 6×10^4 Da as determined by low-angle laser light-scattering.

Tetranitromethane was washed several times with water to reduce the background level of the nitroform anion. All other chemicals were of analytical grade. Solutions were made-up in Milli-Q-filtered (Millipore) water.

γ-Irradiations were carried out with a panorama ^{60}Co-γ-source (Nuclear Engineering) at dose rates ranging from 0.0015 to 0.15 Gy s^{-1}. Pulse radiolysis experiments were performed with a 2.8 MeV van de Graaff accelerator generating electron pulses of 0.4 μs duration, equipped with optical and conductometric detection systems.[24] Optical measurements were based on thiocyanate dosimetry[25] and conductometric measurements on dimethyl sulfoxide dosimetry.[26]

EPR spectra were recorded on a laboratory-built X-band spectrometer with 100 kHz modulation equipped with an interface (Stelar, Mede, Italy) and a PC. For *in situ* experiments, the aqueous solutions containing poly(vinyl methyl ether) and H$_2$O$_2$ were purged with argon, pumped through the quartz cell of the flow-system and irradiated in the EPR cavity with unfiltered focussed light from an argon plasma light source (GAT, Bremerhaven, Germany).

Formaldehyde was determined by HPLC after derivatization with 2,4-dinitrophenylhydrazine (Nucleosil C18 column, eluent: acetonitrile–water 1:1 v/v, optical detection at $\lambda = 360$ nm).[27] The yield of H$_2$O$_2$ and organic hydroperoxides was determined spectrophotometrically with molybdate-activated iodide.[28] The absorbance of I$_3^-$ resulting from the reaction with H$_2$O$_2$ appears immediately after mixing, while the subsequent slower increase is attributed to the reduction of organic hydroperoxides [*cf.* ref. 29].
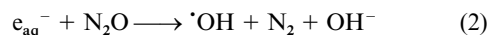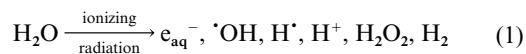
Dioxygen consumption was determined by a dioxygen-sensitive membrane electrode (Wiss. Techn. Werkstätten, Weilheim).

The weight-average molecular weight was determined by low-angle laser light-scattering at $\lambda = 633$ nm (Chromatix KMX-6) after having filtered the samples (0.45 μm, Minisart NML, Millipore). The specific refractive index increment (d*n*/d*c*) of PVME in aqueous solutions was determined with a laser differential refractometer (Chromatix KMX-16, $\lambda = 633$ nm, 25 °C). Extrapolation to zero PVME concentration yielded d*n*/d*c* = 0.127 cm^3 g^{-1}. Molar concentrations of PVME solutions are given in terms of its repeating unit (molecular weight = 58 g mol^{-1}).

Results and discussion

Generation and UV-optical properties of PVME radicals

Upon irradiation of dilute, N$_2$O-saturated PVME solutions, OH radicals and H atoms are formed in reactions (1) and (2).

$$H_2O \xrightarrow[\text{radiation}]{\text{ionizing}} e_{aq}^-, \ ^{\bullet}OH, H^{\bullet}, H^+, H_2O_2, H_2 \qquad (1)$$

$$e_{aq}^- + N_2O \longrightarrow \ ^{\bullet}OH + N_2 + OH^- \qquad (2)$$

Under such conditions the radiation-chemical yield of the OH radical is $G = 5.8 \times 10^{-7}$ mol J^{-1}, while the H atoms are formed with $G = 0.6 \times 10^{-7}$ mol J^{-1}.

The OH radicals and H atoms react with PVME by H-abstraction [*e.g.* reactions (3)–(5)]. For the sample used in the present study, the rate constant for the OH radical is 2.2×10^8 dm^3 mol^{-1} s^{-1},[22] while the H atoms react more slowly ($k < 1 \times 10^7$ dm^3 mol^{-1} s^{-1}).[21,22]

Initial absorption spectra of PVME-radicals **1**–**3** are featureless and only show an increased absorbance at shorter wavelengths.[22] Thus, they resemble the spectra of the radicals derived from the model compound 2,4-dimethoxypentane[23] as well as spectra for other ether-derived radicals, *e.g.* diisopropyl ether[30] and 1,3-dioxane.[31] It has been reported that the absorption spectrum of the PVME-derived radicals shows a maximum
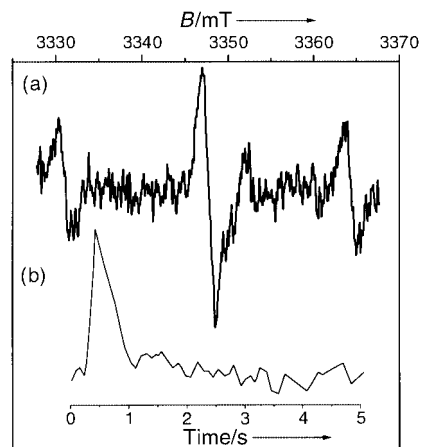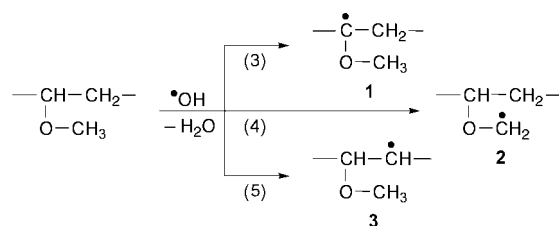
Fig. 1 UV-irradiation of Ar-saturated 0.1 mol dm^{-3} PVME solutions containing 0.1 mol dm^{-3} H$_2$O$_2$, pH ~6.5. (a) Steady-state EPR spectrum (base line subtracted) of PVME-derived radicals generated in a flow system. (b) Decay of the EPR signal.

at 310 nm.[20] We reproduced this result with a non-purified commercial sample, and conclude that low-molecular-weight impurities contained in the commercial material must give rise to the absorption maximum at 310 nm.

Identification of PVME radicals by EPR

For *in-situ* EPR measurements, PVME radicals were generated by UV-irradiation of Ar-saturated 0.1 mol dm^{-3} PVME solutions containing 0.1 mol dm^{-3} H$_2$O$_2$. The photolysis of hydrogen peroxide leads to the formation of OH radicals, which in turn react with the polymer [reactions (3)–(5)]. The steady-state EPR spectrum of the PVME radicals [Fig. 1(a)] is a 1:2:1 triplet that can be attributed to the primary α-alkoxyalkyl radical **2**, the splitting of 1.68 mT being due to two protons at the α-carbon. Radicals **1** and **3** located on the backbone of the polymer are in a relatively rigid environment. Line broadening due to incomplete averaging of dipolar couplings might be the reason for the failure to detect these species in the EPR experiment. The decay of the EPR signal is shown in Fig. 1(b); its half-life was estimated at about 220 ms.

Spin-trapping experiments provide evidence that radicals **1** and **3** are also formed in UV irradiated 1×10^{-2} mol dm^{-3} PVME solutions containing 0.5 mol dm^{-3} H$_2$O$_2$. Upon UV irradiation in the presence of 2-methyl-2-nitrosopropane three distinguishable signals were detected (Fig. 2) and attributed to the spin adducts of radicals **1**–**3**. The signal of spin-trapped radical **1** is a triplet with $a_N = 1.70$ mT with no splitting by H-atoms. The spin adduct of radical **2** gives rise to a triplet of triplets with $a_N = 1.633$ mT and $a_H(2) = 0.99$ mT, while the positions labelled with arrows in Fig. 2 may be due to low amounts of the spin adduct of radical **3** with $a_N = 1.48$ mT and $a_H = 1.41$ mT.

Although the EPR data provide information on the structures of the PVME radicals and their high rate of bimolecular termination, they do not yield quantitative information as to the relative abundance of PVME radicals and the rate constant of their decay cannot be extracted from the EPR measurements. This aspect is dealt with below.
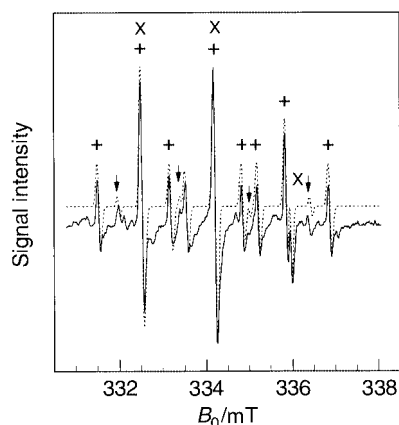
Fig. 2 Experimental (solid line) and simulated (dotted line) EPR spectra of spin adducts generated by UV-irradiation of an Ar-saturated solution containing 0.1 mol dm^{-3} PVME, 0.25 mol dm^{-3} H$_2$O$_2$, and 0.01 mol dm^{-3} MMP at pH 6. A similar spectrum was obtained at pH 3.5. The signals are assigned to spin adducts of radical **1** ($\times$), radical **2** ($+$) and radical **3** ($\downarrow$).

Oxidation of radicals 1 and 2 by Fe(CN)$_6$$^{3-}$, IrCl$_6$$^{2-}$ and tetranitromethane

Among the three radicals which are formed upon $^{\bullet}$OH attack [reactions (3)–(5)] radicals **1** and **2** carry an alkoxyl group in the α-position and thus are strongly reducing, *i.e.* they react rapidly with oxidants. Their one-electron oxidation leads to carbocations [*e.g.* **4**, reaction (6)] which react rapidly with water giving rise to hemiacetals [*e.g.* **5**, reaction (7)]. These are unstable and, for example, **5** releases formaldehyde [reaction (8)].

In a pulse radiolysis experiment, the oxidation by Fe(CN)$_6$$^{3-}$ has been studied by following the bleaching of Fe(CN)$_6$$^{3-}$ at $\lambda = 420$ nm as a function of the Fe(CN)$_6$$^{3-}$ concentration. There was only one kinetic component in the bleaching process ($k = 1.9 \times 10^9$ dm^3 mol^{-1} s^{-1}), and the total bleaching of Fe(CN)$_6$$^{3-}$ corresponds to 75% of the initial yield of $^{\bullet}$OH + H$^{\bullet}$. Thus, radicals **1** and **2** react at a very similar rate. At the low rate of the reaction of H$^{\bullet}$ with the polymer and its high reaction rate with Fe(CN)$_6$$^{3-}$ ($k = 6.3 \times 10^9$ dm^3 mol^{-1} s^{-1})[32] practically all H$^{\bullet}$ radicals (>90%) are scavenged by Fe(CN)$_6$$^{3-}$. Based on this correction, we calculate that $^{\bullet}$OH radicals produce ~72% reducing radicals **1** and **2** and thus ~28% radicals **3**.

The same result was obtained upon γ-radiolysis. This indicates that an H-transfer reaction, that would convert radicals **3** into radicals **1** and/or **2** does not occur under these conditions. Such an H-transfer was, in fact, observed in the free radical chemistry of low molecular alcohols[33] as well as in poly(vinyl alcohol),[34] where the rate constants for this reaction are in the order of 500 s^{-1}.

A similar phenomenon, as in PVME, *i.e.* the absence of a reasonably fast H-transfer, has also been observed with its low-molecular-weight model, 2,4-dimethoxypentane.[23] In H-transfer reactions, six-membered transition states are favour-

able, but five-membered transition states are not, *i.e.* in the latter case such reactions may be substantially retarded by steric effects. These seem to play a substantial role in PVME (and apparently also in the model system). In PVME, the polymer segments within the coil are packed much more tightly than in other polymers as evidenced by comparatively smaller coil dimensions at a similar molecular weight (Janik, unpublished results). This suggests that there are structure-building hydrophobic interactions, which could also result in a high activation barrier for a configuration change necessary for the H-transfer.

In experiments carried out with other oxidants, namely tetranitromethane and IrCl$_6$$^{2-}$, the total yield of α-alkoxyalkyl radicals was confirmed, by optical measurements of nitroform anion formation and IrCl$_6$$^{2-}$ bleaching, to be ~75% of the initial yield of $^{\bullet}$OH + H$^{\bullet}$, again, irrespective of whether these experiments were carried out using pulse radiolysis or γ-radiolysis.

The oxidation of radicals **1** and **2** by tetranitromethane was also studied by pulse radiolysis with optical and conductometric detection. The use of the latter technique allowed us to monitor the release of protons. The rate of the reaction of tetranitromethane with **1** and **2** is ~2 × 10^9 dm^3 mol^{-1} s^{-1}, as has also been observed for other α-alkoxyl radicals.[35] First a short-lived adduct may be formed [*e.g.* **6**, reaction (9)] which subsequently hydrolyses [reaction (10)] yielding the carbocation and nitroform anion which has been detected by its strong absorption at 350 nm. The carbocation is also very short-lived and a proton is released [*cf.* reaction (7)] which leads to the observed conductivity increase.

Decomposition of hemiacetal **5** leads to the formation of formaldehyde [reaction (8)] (an analogous reaction was observed for the model compound, ref. 23). The formaldehyde yield in the presence of the oxidants tetranitromethane or IrCl$_6$$^{2-}$, which is also a measure of the yield of radicals **2**, is $G = 2.4 \times 10^{-7}$ mol J^{-1}, *i.e.* ~40% of initial yield of $^{\bullet}$OH [using Fe(CN)$_6$$^{3-}$ only gives G(CH$_2$O) = 1.3 × 10^{-7} mol J^{-1}; much lower G(CH$_2$O) values have also been observed for the radicals derived from 2,4-dimethoxypentane and dimethyl ether,[23] *i.e.* side reactions must occur with this oxidant]. Having established the yield of radical **2** to be ~40% and the sum of **1** + **2** to be ~72%, the yield of radical **1** is calculated to be ~32%, and the remaining ~28% is attributed to radical **3**. Based on the number of hydrogen atoms available for abstraction (random H-abstraction) one calculates 17% **1**, 50% **2** and 33% **3**. Thus there seems to be some preference for the formation of the tertiary radical **1**. On the other hand, the formation of the primary radical **2**, although stabilized by an alkoxyl group, seems not much favoured over that of the secondary radical **3**. A substantial preference for abstraction of the tertiary hydrogen has also been noted in our model compound 2,4-dimethoxypentane (35 *vs.* 12.5% for random attack)[23] or diisopropyl ether (78 *vs.* 14% for random attack).[30]

Previously, data have been reported where the yield of radicals **1** plus **2** has been determined at only 26% by following their oxidation by thionine.[20,21] However, repeating this experiment with our purified sample led to a yield of about 70%, in good agreement with the value obtained with the other
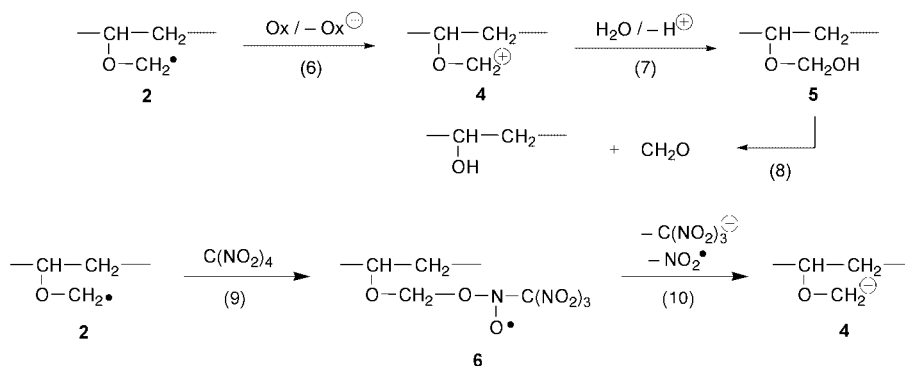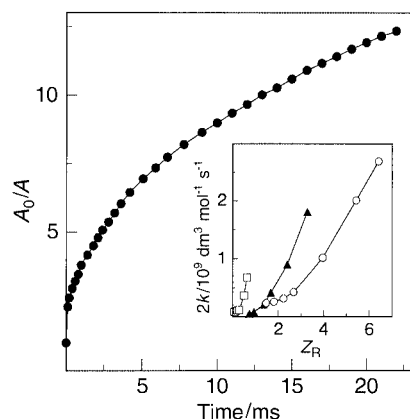
Fig. 3 Pulse radiolysis of PVME (1×10^{-3} mol dm^{-3}) in N$_2$O saturated aqueous solution. The ratio of the absorbance at 290 nm directly after pulse (A_0) to the absorbance (A) observed at a given time after the pulse. Inset: momentary second-order rate constants as a function of concentration of radicals per macromolecule Z_R. Polymer concentration: 2×10^{-3} mol dm^{-3} (○), 1×10^{-2} mol dm^{-3} (▲) and 1×10^{-1} mol dm^{-3} (□).

oxidants. Here, the error might have arisen from the high scavenging capacity of low-molecular-weight contaminations (*cf.* also spectral differences). We therefore believe that the values reported previously[20,21] are on the low side.

We also have to correct our own preliminary data, where the yield of radicals **1** plus **2** was estimated to be ~54%.[22] There were probably two sources for errors that may have contributed to this underestimate; a different (and probably less efficient) purification technique, and dosimetry problems due to a relatively poor stability over time of the electron beam parameters when the ELU-6 linear accelerator (a machine different to that used in the present study) was operated in the untypical low-dose mode.

Decay of the PVME radicals

The radicals derived from the PVME model compound 2,4-dimethoxypentane decay with an overall bimolecular rate constant of $2k = 1 \times 10^9$ dm^3 mol^{-1} s^{-1}.[23] In contrast, the bimolecular decay of PVME radicals cannot be described by simple second-order kinetics (*cf.* also ref. 20). Similar effects have been described for a number of other polymers and their low-molecular-weight models.[36–40]

When the reciprocal of the radical concentration ([R˙]) is plotted *vs.* the time, a straight line is obtained if simple second-order kinetics are followed. For PVME, however, such a plot is strongly curved (Fig. 3), and the observed momentary second-order rate constant decreases with time.

Bimolecular rate constants calculated from the slopes of curves of the type shown in Fig. 3 (main graph) are shown in the inset as a function of the average number of radicals present on each polymer chain (Z_R). The three data sets represent different irradiation conditions (dose per pulse and polymer concentration), *i.e.* three different *initial* average numbers of radicals per chain Z_{R0}. The polymer concentrations in our experiments are lower than the critical hydrodynamic concentration (for our sample ~0.5 mol dm^{-3} at 25 °C as estimated by viscometry and multi-angle laser light-scattering); *i.e.* the polymer coils do not overlap.

For understanding why the momentary termination rate constant decreases in the course of the reaction, one has to recall that in pulse radiolysis many radicals are formed within each macromolecule. This implies that, at least in the first stages, recombination is mainly *intra*molecular. Radicals at a polymer chain cannot move freely and independently, as in homogeneous, diffusion-controlled reactions. Instead, a distribution of distances and possibly of activation energy exists, which

implies different reactivities. Moreover, in the course of termination new C–C bonds are formed between the segments. This decreases segment mobility, and slows down the rate of the subsequent termination event. Two more sources of deviation from the homogeneous kinetics may be mentioned. The initial spatial distribution of the radicals within the macromolecule is not random, but rather reflects the fact that ˙OH radicals are formed in spurs. Those radicals formed in a close vicinity are expected to recombine fast. At a later stage, when the average Z_R is close to one, many macromolecules bear only one radical. These radicals have to terminate *inter*molecularly, *i.e.* the termination mechanism now changes. In addition to segmental diffusions, *inter*molecular termination requires the diffusion of macromolecules as a whole, and therefore is slower than the *intra*molecular termination.

When the three data sets in the inset of Fig. 3 are compared, it becomes evident that the momentary rate constant of termination depends not only on the momentary number of radicals per chain Z_R, but also on the *initial* number of radicals per chain, Z_{R0}. In fact, when we compare data for equal Z_R but different Z_{R0}, we compare recombination at different stages. A sample which starts with a low Z_{R0} is at a relatively early stage, *i.e.* it has only some radical pairs for recombination and no or only a few internal crosslinks. On the other hand, a sample which starts with a high Z_{R0} is, at the same Z_R, at a later stage, with no more fast-reacting pairs and a higher number of internal crosslinks. As a consequence of this, the momentary termination rate constant, if compared for two samples of the same Z_R, is lower for the sample of higher Z_{R0}.

Crosslinking of PVME chains

Under dioxygen-free conditions, the resulting molecular weight depends on the ratio of the rate constants of radical recombination and chain scission. Unimolecular chain scission resulting from β-fragmentation of polymer radicals is typically a slow process [*e.g.* for poly(acrylic acid) $k = 0.025$ s^{-1},[39] for poly(methacrylic acid)[41,42] $k = 1.8$ s^{-1}] and only plays a role when the competing recombination reactions are slow as well. This is especially the case with radicals derived from polyelectrolytes such as poly(acrylic acid) and poly(methacrylic acid), where, due to the repulsive electrostatic forces between the charged chains, the termination rate constants are <100 dm^3 mol^{-1} s^{-1}.[39,41–43] With the exception of polysaccharides,[44] for the irradiation of uncharged polymers, where the termination rate constants are typically in the order of 10^7–10^9 dm^3 mol^{-1} s^{-1}, no decrease in the molecular weight of the polymer has been reported.

When termination dominates over scission, the extent of the increase in average molecular weight depends on two more factors: the proportion of recombination and disproportionation and the ratio of inter- and intramolecular recombination.

The data on the model compound, 2,4-dimethoxypentane, indicate that β-fragmentation reactions must be of little importance and that recombination and disproportionation occur with equal probability.[23] Thus, one may expect that chain scission is also negligible in the case of PVME. Assuming a similar ratio of recombination to disproportionation would thus set the total (intra- plus intermolecular) crosslinking yield close to 1.5×10^{-7} mol J^{-1}.

The increase in weight-average molecular weight of PVME upon γ-irradiation in N$_2$O-saturated solutions is shown in Fig. 4.

Based on eqn. (11),[45,46] where M_{w0}, M_w (in g mol^{-1}) are the

$$[\text{Intermolecular crosslinks}] = 0.5\,(M_{w0}^{-1} - M_w^{-1})\,c_{PVME} \quad (11)$$

weight-average molecular weights before and after irradiation and c_{PVME} is the polymer concentration (in g dm^{-3}), the concentration of intermolecular crosslinks was calculated.
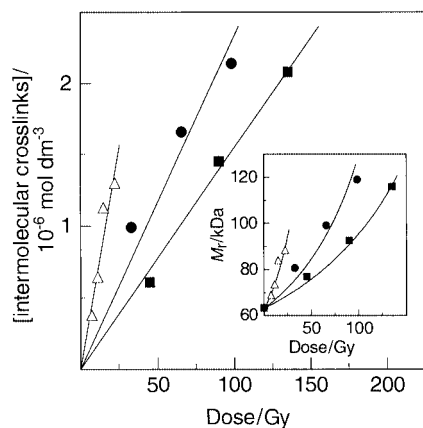
Fig. 4 γ-Radiolysis of PVME (1×10^{-2} mol dm^{-3}) in N$_2$O-saturated aqueous solutions. Concentration of intermolecular crosslinks (main graph) and weight-average molecular weight (inset) as a function of dose. Dose rates: 0.15 Gy s^{-1} (■), 0.013 Gy s^{-1} (●) and 0.0015 Gy s^{-1} (△).

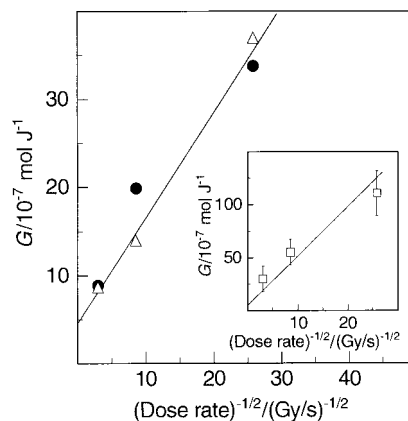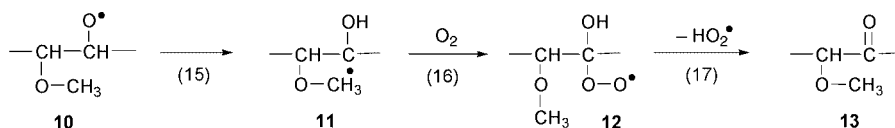**Fig. 5** γ-Radiolysis of PVME (1×10^{-2} M) in N$_2$O–O$_2$-saturated aqueous solutions at various dose rates. G-values of organic hydroperoxides (●), formaldehyde (△) and dioxygen uptake (□, inset), as a function of inverse square root of the dose rate.

The linear plots of the concentration of intermolecular crosslinks *vs.* the dose allowed us to calculate G(intermolecular crosslinks) for three different dose rates, 0.150, 0.013 and 0.0015 Gy s^{-1}, at 0.15×10^{-7}, 0.23×10^{-7} and 0.62×10^{-7} mol J^{-1}, respectively.

The observed yields of *inter*molecular crosslinks are significantly lower than the expected total yield of crosslinking. This fact, along with the observed dependence of G(intermolecular crosslinks) on the dose rate, indicates the importance of *intra*molecular recombination under our experimental conditions. This process does not change the average molecular weight of the polymer but leads to changes in coil dimensions and flexibility (*cf.* refs. 40,47). As expected, the lower dose rate favours an intermolecular recombination due to a lower probability for the presence of two or more radical sites on a single polymer chain in the steady state.

The existence of hydrophobic sites on the PVME chain that tend to associate in the inner part of the polymer coil leads to a kind of ordered structure, less flexible than expected for a random coil, *i.e.*, as mentioned above, to a very compact conformation of the PVME coils. This effect must slow down segmental diffusion and should lead to reduced mobility of a radical located inside such a structure, nearly preventing this radical from intermolecular recombination. It seems probable that some of these single radicals trapped inside the coils undergo termination when, during further irradiation, another radical is formed within the same coil. This mechanism would enhance the yield of intramolecular crosslinking at the expense of intermolecular crosslinking.

Oxygenated conditions

In the presence of dioxygen, radicals **1–3** are rapidly converted into the corresponding peroxyl radicals **7–9** [reactions (12)–(14)]. As in the model system 2,4-dimethoxypentane,[23] these reactions cannot be followed by pulse radiolysis because of the similarity of the absorption spectra of the parent radicals and their corresponding peroxyl radicals.

Based on the data reported for other water-soluble polymers,[48] one can assume that the rate constant of dioxygen addition to PVME-derived radicals is in the order of $(0.5–1) \times 10^{9}$ dm^3 mol^{-1} s^{-1}.
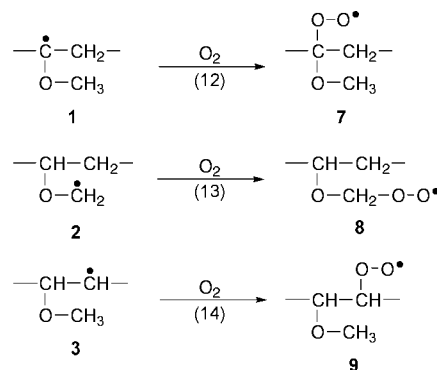
Peroxyl radicals decay *via* a short-lived tetraoxy compound (for a review on peroxyl radical reactions in water see ref. 49). The present system does not allow us to investigate the ensuing reactions, but the review[49] and the study on the PVME model systems[23] give some indications as to the expected products.

The decay of the PVME peroxyl radicals is slower than that of the carbon-centred precursor radicals and also does not follow the second-order kinetics. The main reason is the same as discussed above in the absence of dioxygen. As in the case of 2,4-dimethoxypentane, there is now also some contribution of HO$_2$$^{•}$/O$_2$$^{•-}$ to the observed absorption that further complicates the evaluation of the kinetics of the decay of the PVME peroxyl radicals.

One of the reaction pathways following the decay of the short-lived tetraoxy compounds leads to the formation of oxyl radicals such as **10**. When these radicals have H-atoms at the α-position, they undergo a rapid 1,2-H shift [*e.g.* reaction (15)].[50–52] The resulting α-hydroxyalkyl radicals add dioxygen and form α-hydroxyalkyl peroxyl radicals that decompose releasing HO$_2$$^{•}$/O$_2$$^{•-}$ [*e.g.* reactions (16)–(17), *cf.* ref. 53].

Under pulse radiolysis conditions, the yield of HO$_2$$^{•}$/O$_2$$^{•-}$ is ~2.6×10^{-7} mol J^{-1} as determined by using tetranitromethane as a scavenger.[54] This relatively high yield of O$_2$$^{•-}$ is even higher under the conditions of γ-radiolysis [G(O$_2$$^{•-}$) = 3.2×10^{-7} mol J^{-1}].

Dioxygen uptake

Dioxygen uptake in γ-irradiated N$_2$O–O$_2$-saturated 1×10^{-2} mol dm^{-3} PVME solutions has been measured at different dose rates (inset in Fig. 5).

In the absence of chain reactions, dioxygen uptake should be in the range of $(3–6) \times 10^{-7}$ mol J^{-1}.[55] However in the present system, dioxygen uptake is considerably higher at all the dose rates studied. With decreasing dose rate the dioxygen uptake increases, as was also observed in the case of the model compound 2,4-dimethoxypentane[23] and to some extent with ethers[53] containing only one ether function.[30] This strong dose rate effect indicates that bimolecular decay of PVME-derived peroxyl radicals competes with a first order process. The main route of such chain autoxidations are H-abstraction reactions of peroxyl radicals, which in the present system can proceed *via* a favourable six-membered transition state [*e.g.* reactions (18)–(20)].
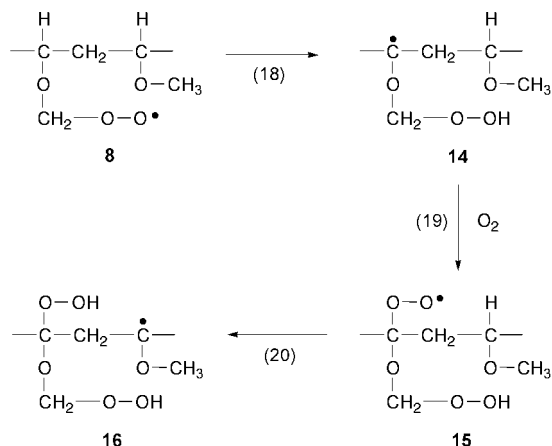
In the model system 2,4-dimethoxypentane, O_2-uptake is 19×10^{-7} mol J^{-1} at the same dose rate whereas in PVME a value of 110×10^{-7} mol J^{-1} is found. In the model system, the H-transfer is mainly *intra*molecular, but the chain length is limited because the molecule is very small and only has two ether functions. In PVME this chain can propagate *intra*molecularly much more efficiently as is indicated by reactions (18)–(20). The slowness of the bimolecular termination of the PVME peroxyl radicals further favours the chain autoxidation.

High G(dioxygen uptake) values are also reported for poly(ethylene oxide),[55] but even for the lowest dose rate used (0.04 Gy s^{-1}) dioxygen uptake in poly(ethylene oxide) was only $\sim 20 \times 10^{-7}$ mol J^{-1}, *i.e.* not as high as in PVME. In the latter, the tertiary hydrogen which is much more easily abstracted than the secondary ones in poly(ethylene oxide) may be the main reason for this difference.

As a consequence of the autoxidation, organic hydroperoxides are formed [*cf.* reactions (18)–(20)]. Similar to dioxygen uptake, an almost linear dependence of the yield of organic hydroperoxides on the inverse square root of the dose rate is observed (Fig. 5). A comparison of organic hydroperoxide yields with those of dioxygen uptake shows that *stable* organic hydroperoxides make up only a part of the hydroperoxides expected from the H-abstraction reactions. Thus, some of the hydroperoxides may have decayed prior to analysis.

As in the model 2,4-dimethoxypentane system,[23] the γ-radiolysis of PVME in the presence of dioxygen affords formaldehyde in surprisingly high yield, and its dose rate dependence (Fig. 5) suggests that it must be formed in the course of the chain autoxidation process. A possible source of formaldehyde may be a hydroperoxide located at the methoxy group [*e.g.* reaction (21)]. It is not clear, whether it is released from the polymer during or shortly after irradiation or results from an acid-catalysed decomposition of hydroperoxides during derivatization of formaldehyde in its assay.
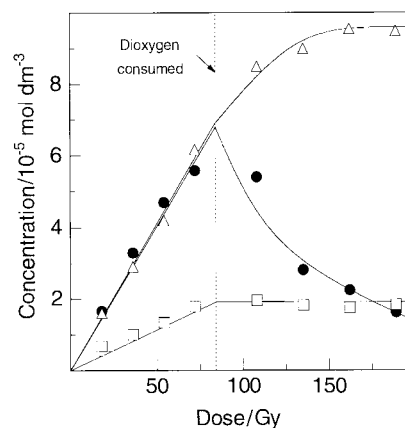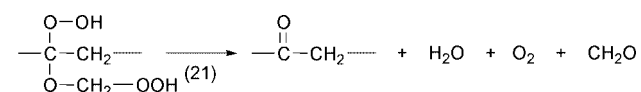

Fig. 6 γ-Radiolysis of PVME (1×10^{-2} mol dm^{-3}) in N_2O–O_2-saturated aqueous solutions at a dose rate of 0.110 Gy s^{-1}. Changes of product concentrations as a function of dose: CH_2O (△), organic hydroperoxides (●) and H_2O_2 (□).

Fig. 6 shows the change in the yields of organic hydroperoxides, hydrogen peroxide and formaldehyde as a function of dose.

Knowing the yield of dioxygen uptake at this dose rate (29×10^{-7} mol J^{-1}) allows us to calculate the dose at which dioxygen is fully consumed (~83 Gy, dotted line in Fig. 6). Upon further irradiation, there is no further formation of H_2O_2, the concentration of organic hydroperoxides decreases dramatically, while the concentration of formaldehyde continues to increase. The decrease in the concentration of hydroperoxides can be attributed to an H-abstraction by the radicals formed during further (anoxic) irradiation [reaction (22)].

$$R^{\bullet} + ROOH \longrightarrow RH + ROO^{\bullet} \qquad (22)$$

H-abstraction reactions from hydroperoxides are rather slow in an aqueous environment (*cf.* ref. 56 and references cited therein), but the hydrophobic properties of PVME may favour this reaction and account for the rapid decay of the hydroperoxides shown in Fig. 6. Surprisingly, during their decay formaldehyde is formed in a rather large yield. Mechanistic details of this reaction are not yet understood.

Scission of PVME

In irradiated dioxygen-containing polymer solutions the rapid addition of dioxygen prevents the formation of crosslinks (*cf.* also the absence of dimers in the case of our low-molecular-weight model, 2,4-dimethoxypentane[23]). For polymer peroxyl radicals, the possibility of forming relatively stable crosslinks is limited to the recombination of two oxyl radicals. However, their lifetime is too short to reach a sufficient steady-state concentration to become important. In agreement with this, a dominance of chain scission is observed with all polymers studied under such conditions.[37]

The inset in Fig. 7 shows a decrease in the weight-average molecular weight of PVME upon γ-irradiation in N_2O–O_2 saturated solution, as a function of dose, for three different dose rates.

Assuming the absence of competing intermolecular cross-linking reactions (see above), the yields of chain breaks were determined on the basis of eqn. (23),[45,46] where M_{w0} and M_w

$$[\text{Chain breaks}] = 2(M_w^{-1} - M_{w0}^{-1})\, c_{PVME} \qquad (23)$$

are the weight average molecular weights (in g mol^{-1}) before and after irradiation and c_{PVME} is the PVME concentration in g dm^{-3}.

As can be seen from Fig. 7, the yield of chain breaks increases linearly with increasing dose. This is generally
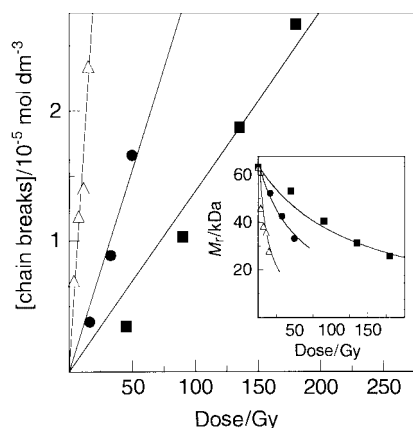
Fig. 7 γ-Radiolysis of PVME (1×10^{-2} mol dm^{-3}) in N$_2$O–O$_2$-saturated aqueous solutions. Formation of chain breaks and decrease in molecular weight (inset) as a function of dose at 0.15 (■), 0.014 (●) and 0.0015 Gy s^{-1} (△).
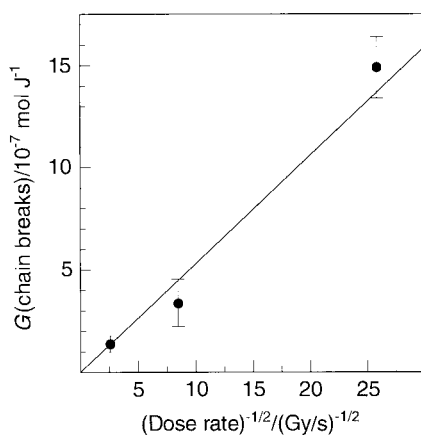

Fig. 8 γ-Radiolysis of PVME (1×10^{-2} mol dm^{-3}) in N$_2$O–O$_2$-saturated aqueous solutions. G(chain breaks) as a function of the (dose rate)$^{-\frac{1}{2}}$.

assumed to be caused by the β-fragmentation of an oxyl radical formed in the decay of peroxyl radicals (*cf.* ref. 57). In the present system, it is however observed that the yield of strand breaks strongly depends on the dose rate. A plot of G(strand breaks) *vs.* (dose rate)$^{-1/2}$ yields a straight line (Fig. 8), with close to zero intercept.

Thus, the present system shows very unusual behaviour, *i.e.* chain scission occurs largely in the course of the chain reaction, *e.g.* by the (thermal and/or proton-catalyzed) decomposition of a rather short-lived hydroperoxide ($t_{\frac{1}{2}} < 20$ min, the time required for the determination of the molecular weight is 30–60 min), *i.e.* a mechanism involving oxyl radical cannot be fully excluded, since such intermediates are created in the thermal breakdown of hydroperoxides.

Conclusions

Due to its compactness in aqueous solutions, PVME has properties that enable reactions to occur that may also be undergone by other polymers, but to a lesser extent. For example, there is now evidence that intramolecular crosslinking can be of much greater importance than intermolecular crosslinking even at very low radical steady-state concentrations. Thus conditions can be chosen easily that favour *e.g.* nanogel formation. This raises the question as to whether compaction of other water-soluble polymers, *e.g.*, by the addition of salt or by lowering the temperature, could be beneficial if nanogel formation is desired.

In the presence of dioxygen, chain scission strongly depends on the dose rate in the case of PVME, but detailed studies on

other polymers have not yet been carried out. Certainly, the question of whether such dose rate effects on chain scission and the potential involvement of hydroperoxides also play a role with other polymers or whether it is a curiosity restricted to PVME will have to be addressed. In the case of poly(acrylic acid), however, the decay of intermediate hydroperoxides is already fairly well understood,[48] and the elucidated process does not lead to chain scission.

Acknowledgements

References

1 P. Molyneux, *Water-Soluble Synthetic Polymers. Properties and Applications*, CRC Press, Boca Raton, 1987.
2 H. Maeda, *J. Polym. Sci. B*, 1994, **32**, 91.
3 H. Schafer-Soenen, R. Moerkerke, H. Berghmans, R. Koningsveld, K. Dusek and K. Solc, *Macromolecules*, 1997, **30**, 410.
4 F. Meeussen, Y. Bauwens, R. Moerkerke, E. Nies and H. Berghmans, *Polymer*, 2000, **41**, 3737.
5 O. Hirasa, S. Ito, A. Yamauchi, S. Fujishige and H. Ochijo, in *Polymer Gels*, ed. D. De Rossi, Plenum Press, New York, 1991, p. 247.
6 B. G. Kabra, M. K. Akhtar and S. H. Gehrke, *Polymer*, 1992, **33**, 990.
7 K. Dusek (Ed.), *Responsive Gels: Volume Transitions*, Springer, Berlin, 1993.
8 R. Moerkerke, F. Meeussen, R. Koningsveld and H. Berghmans, *Macromolecules*, 1998, **31**, 2223.
9 N. A. Peppas and J. J. Sahlin, *Biomaterials*, 1996, **17**, 1553.
10 M. C. Bonferoni, S. Rossi, F. Ferrari and C. Caramella, *Pharm. Dev. Technol.*, 1999, **4**, 45.
11 A. D. Woolfson, D. F. McCafferty and G. P. Moss, *Int. J. Pharm.*, 1998, **169**, 83.
12 R. Kishi, H. Ichijo and O. Hirasa, *J. Intell. Mater. Syst. Struct.*, 1993, **4**, 533.
13 H. Ichijo, R. Kishi, O. Hirasa and Y. Takiguchi, *Polym. Gels Networks*, 1994, **2**, 315.
14 M. Hiraide and A. Morishima, *Anal. Sci.*, 1997, **13**, 829.
15 H. Ichijo, O. Hirasa, R. Kishi, M. Oowada, E. Kokufuta and S. Ohno, *Radiat. Phys. Chem.*, 1995, 185.
16 J. M. Rosiak and P. Ulanski, *Radiat. Phys. Chem.*, 1999, **55**, 139.
17 J. M. Rosiak, in *Radiation Effects on Polymers*, ed. R. C. Clough and S. W. Shalaby, American Chemical Society, Washington, 1991, p. 271.
18 J. M. Rosiak, *J. Controlled Release*, 1994, **31**, 9.
19 X. D. Liu, R. M. Briber and B. J. Bauer, *J. Polym. Sci. B: Polym. Phys.*, 1994, **32**, 811.
20 S. Sabharval, H. Mohan, Y. K. Bhardwaj and A. B. Majali, *J. Chem. Soc., Faraday Trans.*, 1996, **92**, 4401.
21 S. Sabharval, H. Mohan, Y. K. Bhardwaj and A. B. Majali, *Radiat. Phys. Chem.*, 1999, **54**, 643.
22 I. Janik, P. Ulanski and J. M. Rosiak, *Nucl. Instrum. Methods Phys. Res., Sect. B*, 1999, **151**, 318.
23 I. Janik, P. Ulanski, J. M. Rosiak and C. von Sonntag, *J. Chem. Soc., Perkin Trans. 2*, 2000, preceding paper (DOI: 10.1039/b004776g).
24 C. von Sonntag and H.-P. Schuchmann, *Methods Enzymol.*, 1994, **233**, 3.
25 G. V. Buxton and C. R. Stuart, *J. Chem. Soc., Faraday Trans.*, 1995, **91**, 279.
26 D. Veltwisch, E. Janata and K.-D. Asmus, *J. Chem. Soc., Perkin Trans. 2*, 1980, 146.
27 F. Lipari and S. J. Swarin, *J. Chromatogr.*, 1982, **247**, 297.
28 A. O. Allen, C. J. Hochanadel, J. A. Ghormley and T. W. Davis, *J. Phys. Chem.*, 1952, **56**, 575.
29 P. Dowideit and C. von Sonntag, *Environ. Sci. Technol.*, 1998, **32**, 1112.
30 M. N. Schuchmann and C. von Sonntag, *Z. Naturforsch., Teil B*, 1987, **42**, 495.
31 C. Nese, M. N. Schuchmann, S. Steenken and C. von Sonntag, *J. Chem. Soc., Perkin Trans. 2*, 1995, 1037.

32 G. V. Buxton, C. L. Greenstock, W. P. Helman and A. B. Ross, *J. Phys. Chem. Ref. Data*, 1988, **17**, 513.

33 H.-P. Schuchmann and C. von Sonntag, *Radiat. Phys. Chem.*, 1988, **32**, 149.

34 C. von Sonntag, E. Bothe, P. Ulanski and A. Adhikary, *Radiat. Phys. Chem.*, 1999, **55**, 599.

35 J. Eibenberger, D. Schulte-Frohlinde and S. Steenken, *J. Phys. Chem.*, 1980, **84**, 704.

36 I. A. Raap and U. Gröllmann, *Macromol. Chem.*, 1983, **184**, 123.

37 P. Ulanski, E. Bothe, J. M. Rosiak and C. von Sonntag, *Makromol. Chem.*, 1994, **195**, 1443.

38 P. Ulanski, Zainuddin and J. M. Rosiak, *Radiat. Phys. Chem.*, 1995, **46**, 917.

39 P. Ulanski, E. Bothe, K. Hildenbrand, J. M. Rosiak and C. von Sonntag, *J. Chem. Soc., Perkin Trans. 2*, 1996, 13.

40 P. Ulanski, I. Janik and J. M. Rosiak, *Radiat. Phys. Chem.*, 1998, **52**, 289.

41 P. Ulanski, E. Bothe and C. von Sonntag, *Nucl. Instrum. Methods Phys. Res., Sect. B*, 1999, **151**, 350.

42 P. Ulanski, E. Bothe, K. Hildenbrand and C. von Sonntag, *Chem. Eur. J.*, 2000, in the press.

43 P. Ulanski, E. Bothe, K. Hildenbrand, C. von Sonntag and J. M. Rosiak, *Nukleonika*, 1997, **42**, 425.

44 B. G. Ershov, *Russ. Chem. Rev.*, 1998, **67**, 315.

45 A. Charlesby, *Atomic Radiation and Polymers*, Pergamon Press, Oxford, 1960.

46 W. Schnabel, *Polymer Degradation. Principles and Practical Applications*, Hanser, München, 1981.

47 P. Ulanski and J. M. Rosiak, *Nucl. Instrum. Methods Phys. Res., Sect. B*, 1999, **151**, 356.

48 P. Ulanski, E. Bothe, K. Hildenbrand, J. M. Rosiak and C. von Sonntag, *J. Chem. Soc., Perkin Trans. 2*, 1996, 23.

49 C. von Sonntag and H.-P. Schuchmann, in *Peroxyl Radicals*, ed. Z. B. Alfassi, Wiley, Chichester, 1997, p. 173.

50 V. M. Berdnikov, N. M. Bazhin, V. K. Fedorov and O. V. Polyakov, *Kinet. Catal.* (*Engl. Transl.*), 1972, **13**, 986.

51 B. C. Gilbert, R. G. G. Holmes, H. A. H. Laue and R. O. C. Norman, *J. Chem. Soc., Perkin Trans. 2*, 1976, 1047.

52 H.-P. Schuchmann and C. von Sonntag, *J. Photochem.*, 1981, **16**, 289.

53 M. N. Schuchmann and C. von Sonntag, *J. Phys. Chem.*, 1982, **86**, 1995.

54 K.-D. Asmus, A. Henglein, M. Ebert and J. P. Keene, *Ber. Bunsenges. Phys. Chem.*, 1964, **68**, 657.

55 M. Isildar, M. N. Schuchmann, D. Schulte-Frohlinde and C. von Sonntag, *Int. J. Radiat. Biol.*, 1982, **41**, 525.

56 P. Ulanski, G. Merényi, J. Lind, R. Wagner and C. von Sonntag, *J. Chem. Soc., Perkin Trans. 2*, 1999, 673.

57 U. Gröllmann and W. Schnabel, *Makromol. Chem.*, 1980, **181**, 1215.