EPR–Spin-trapping Studies of the Heterogeneous Oxidative Curing of some Liquid Polysulfide Polymers: Evidence for the Mediation of Thiyl Radicals, Disulfide Radical-anions and Oxygen-centred Radicals

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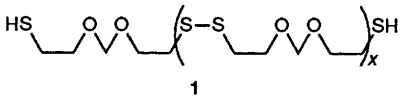
The use of spin-trapping techniques (with DMPO and MNP) in conjunction with EPR and NMR spectroscopic studies has allowed mechanistic details to be obtained about the process whereby thiols (particularly liquid polysulfide polymers) can be linked *via* reaction with inorganic oxidants (especially activated MnO_2). The roles of activation, basic additives, and oxygen are interpreted in terms of the involvement of thiyl radicals which can undergo both dimerization and reaction with thiolate anions, evidently to give disulfide radical-anions as important reaction intermediates.

There is considerable contemporary interest in the free-radical chemistry of sulfur compounds and in the structure and properties of the wide range of sulfur-centred radical intermediates which can be formed during oxidation processes (*e.g.* $RSO^{\bullet}$, $RSO_2^{\bullet}$, $RSO_3^{\bullet}$, $R_2S^{\bullet+}$, $R_2SSR_2^{\bullet+}$ *etc.*).[1] This is particularly true of thiol compounds, whose reactions are important in many atmospheric, biological and radiochemical processes—for example the formation of acid rain[2] and the mechanisms whereby biological thiols 'repair' free-radical-damaged sites in the body.[3]

We have previously employed EPR spectroscopy (in connection with flow methods, spin trapping and kinetic analysis) to explore the properties of thiyl radicals ($RS^{\bullet}$) and sulfur–oxygen radicals (*e.g.* $RSO_2^{\bullet}$) when generated in systems involving RSH and RSSR in the presence of the hydroxyl radical and peroxides, and obtained evidence for dimerization and oxidation (with H_2O_2) of $RS^{\bullet}$, as well as for intramolecular reactions with thiolate (to give species of the type $RSSR^{\bullet-}$).[4] In the research to be described here we have extended our study of thiol-containing molecules to an EPR-based investigation of the mechanism whereby oxidation is brought about by inorganic oxidants. We have focused in particular on the oxidation of some Liquid Polysulfide (LP) polymers† of type **1**, and some model compounds, with MnO_2: these compounds



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are commercially available, high-viscosity liquids which are oxidized, largely *via* the formation of new –SS– links, to high molecular weight polymers, in processes of wide applicability in the manufacture of sealants.[5]

Results and Discussion

Oxidation of a range of liquid polysulfide polymers and model thiols in methylbenzene has been brought about by reactions with several types of 'activated' MnO_2 [including Riedel de Haen types C, FA and G, and that supplied by Aldrich (21,764–6)]. In experiments with degassed solutions in the presence of the spin trap 5,5-dimethyl-1-pyrroline *N*-oxide, DMPO **2**, very strong EPR signals were detected in each case from the appropriate thiyl-radical adducts **3** [see Table and Fig. 1(*a*),

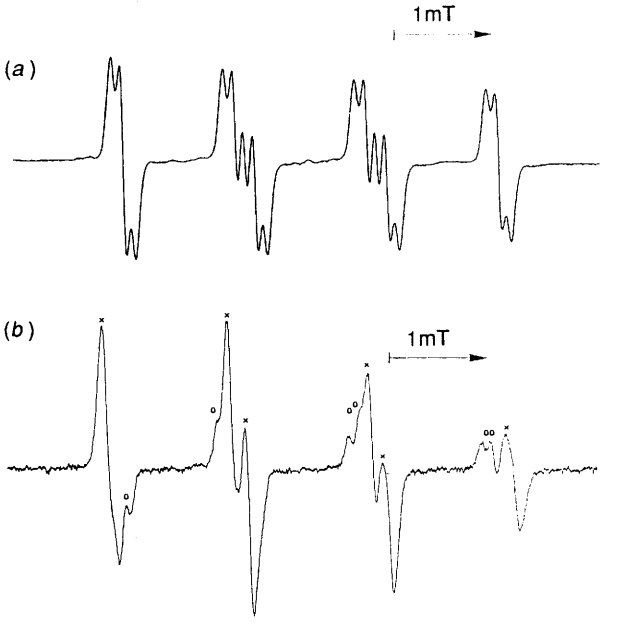
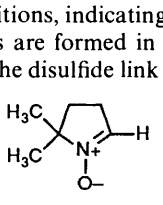


Fig. 1(*a*) EPR spectrum of the radical adduct **3**, recorded during the reaction of LP3 (**1**, $x = 5$) with MnO_2 (type FA) in the presence of the spin-trap **2** in deoxygenated solution in methylbenzene at room temperature. (**1**, 0.05 mol dm^{-3}; MnO_2, 20 g dm^{-3}; **2**, 0.025 mol dm^3). (*b*) EPR spectra of the adducts **3** (○) and **4** (×) recorded during the oxidation of LP3 with MnO_2 (type FA) in the presence of the spin-trap **2** and 1,3-diphenylguanidine (DPG) in methylbenzene at room temperature, under partially deoxygenated conditions. (**1**, 0.05 mol dm^{-3}; **2**, 0.025 mol dm^{-3}; MnO_2, 20 g dm^{-3}; DPG 0.05 mol dm^{-3})

which gives details of the typical conditions and concentrations employed]. The signals built up rapidly (in seconds) and decayed relatively slowly over a period ranging from minutes (type C and Aldrich) to several hours (types FA and G). Some simple model thiols behaved similarly (see Table). No signals were obtained when a range of disulfides was oxidized under similar conditions, indicating that, as might be anticipated, the thiyl radicals are formed in the oxidation of the thiol groups rather than the disulfide link in **1**.[6]



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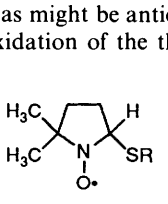

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† LP[R] is the registered trademark of Morton International Ltd.

Table 1 EPR parameters for spin-adducts of DMPO and MNP detected in thiol oxidation reactions[a]

	DMPO				MNP		
Radical trapped	a(N)	a(β-H)	a(other)	g	a(N)	a(β-H)	g
RS•							
Thiyl from **1**, $x = 5$	1.34	1.14	0.11[b]	2.0064	1.85	—	2.0072
BuS•	1.35	1.11	0.10[b]	2.0064	1.82	—	2.0072
$HS(CH_2)_2O(CH_2)_2S$•	1.34	1.14	0.11[b]	2.0064	1.85	—	2.0072
HO•	1.45	1.27	—	2.0061	—	—	—
H•	—	—	—	—	1.31	1.13	2.0065

[a] For conditions of generation see text. Solutions are in methylbenzene. Splittings in mT (±0.01); g ± 0.0001. [b] ∂-H splittings (triplet) from $-SCH_2$ protons on alkyl thiyl group.

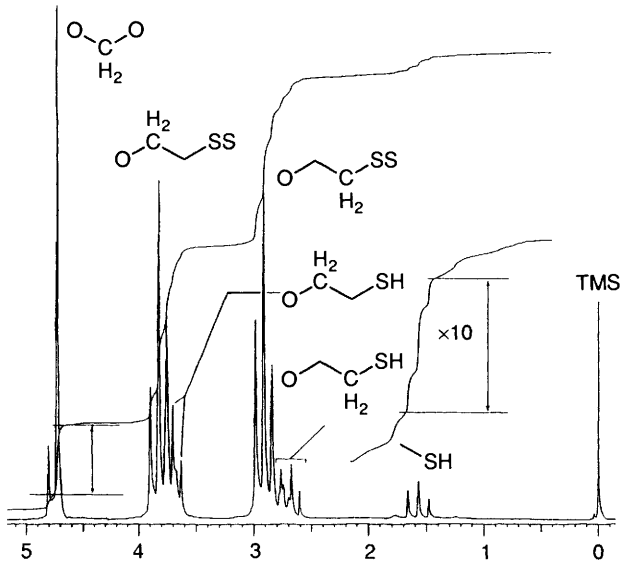


Fig. 2 90 MHz ^{1}NMR spectrum of **1**, $x = 5$ in $CDCl_3$

^{1}H NMR spectra recorded during the oxidation of LP3 polymer [(**1**; $x = 5$), M. wt. *ca.* 1000] with MnO_2 (of different types, as above) in benzene, under generally comparable conditions, simply showed the disappearance of the resonance associated with the thiol hydrogen (δ *ca.* 1.59) as well as those from the neighbouring methylene protons at δ 2.72 and 3.70 (see Fig. 2); the reaction was typically complete in *ca.* 20 min for the type C and Aldrich samples, but took several hours for types FA and G.* The EPR and NMR observations taken together strongly suggest that the reaction involves oxidation of the thiol to the appropriate thiyl radical with subsequent dimerization to give the disulfide [reactions (1) and (2)]. As expected on this basis, addition of the spin trap PBN (α-phenyl-*N*-*tert*-butylnitrone†) retarded the formation of product, as judged by the reduction of the rate of polymerization (as indicated by the retardation of the dramatic increase in viscosity which accompanies the reaction).

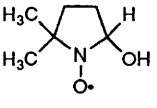
$$RSH \xrightarrow{MnO_2} RS^{\bullet} \quad (1)$$

$$2RS^{\bullet} \longrightarrow RSSR \quad (2)$$

* The corresponding reaction when repeated in a plasticizer rather than a mobile solvent leads to oxidative curing of the polymer.
† *N*-Benzylidene-*tert*-butylamine *N*-oxide.

Evidence that a more complex reaction pathway may also be appropriate derives from experiments in which the roles of oxygen and other additives were explored. For example, in spin-trapping experiments in which oxygen was not initially removed from the reactions involving the two most active oxidants (Type C and Aldrich) we observed not only that the signals from **3** had a shorter lifetime but also that oxygen was steadily removed from the system. Thus EPR signals from **3** were initially broadened, with a loss of detailed hyperfine splitting (evidently on account of the presence of O_2); a steady sharpening of the signals is taken to indicate the subsequent removal of oxygen. Corresponding ^{1}H NMR studies for all the MnO_2 samples showed that the reaction to give polymer proceeds faster in the presence of oxygen, though the product was unchanged (in particular there was no evidence of the formation of sulfur–oxygen links). Broadly similar results were obtained with PbO_2.

In a separate set of experiments we explored the effect of addition of base to the oxidation reactions.‡ For example, in spin-trapping experiments with LP3, DMPO and MnO_2 (FA) in the presence of oxygen, the addition of 1,3-diphenylguanidine (DPG) led to the formation of the thiyl adduct **3** and to the appearance of the spectrum attributed to the *hydroxyl*-radical adduct of the trap **4** [see Fig. 1(*b*) and Table].[7] In similar



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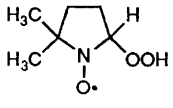

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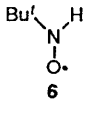
experiments with Et_3N and 1,1,3,3-tetramethylguanidine (TMG) the corresponding extra radical trapped [with a(N) 1.37 mT a(H) 1.04 mT] is believed to be the adduct of HO_2• **5** (or possibly a peroxyl radical RO_2•: see ref. 8).

Related experiments with the two most active forms of MnO_2 (types C and Aldrich) in the presence of the spin trap 2-methyl-2-nitrosopropane (Me_3CNO; MNP) and in the presence or absence of oxygen gave signals from the *hydrogen*-atom adduct of the trap, **6**, and the corresponding thiyl-adduct **7**, even in the absence of base (see Table 1). The adduct Bu^tNHO• was not



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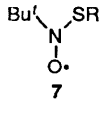

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‡ DPG and TMG are employed commercially as basic additives to accelerate curing. We believe that it is particularly significant that, of the most reactive MnO_2 samples used here, the pH value of an aqueous solution in contact with the solid is typically 10–11 (for a suspension containing 10 g of MnO_2 in 190 cm^3 of H_2O).

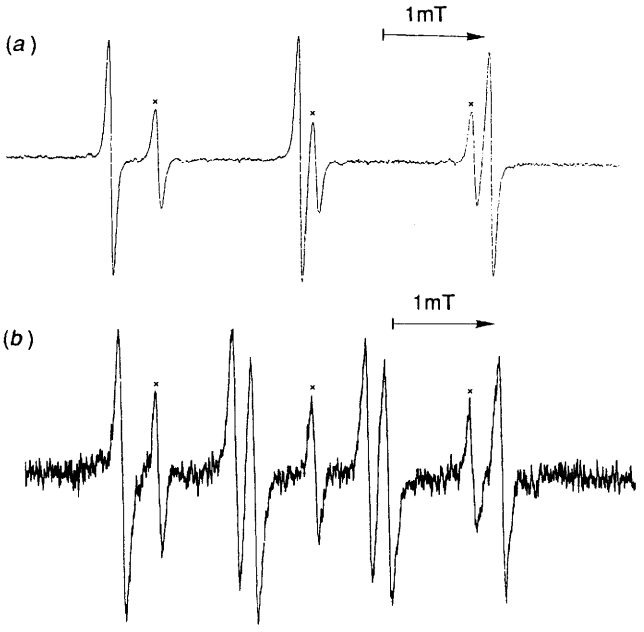


Fig. 3(*a*) EPR spectrum of the radical adduct **7** obtained in the reaction of **1**, $x = 5$ with MnO_2 (type FA) in the presence of spin-trap MNP. (**1**, 0.05 mol dm^{-3}; MNP 0.025 mol dm^{-3}; MnO_2, 20 g dm^{-3}). Signals from $Bu^t_2NO^\bullet$ are marked ×. (*b*) EPR spectrum of the adduct **6** formed from the reaction of **1**, $x = 5$ with MnO_2(FA) in the presence of MNP and TMG in deoxygenated methylbenzene at room temperature. (**1**, 0.05 mol dm^{-3}; MnO_2, 20 g dm^{-3}; TMG, 0.05 mol dm^{-3} MNP, 0.025 mol dm^{-3}). Signals from $Bu^t_2NO^\bullet$ are indicated.

observed in the absence of base with the less reactive types of MnO_2, but when base was added the signals quickly appeared (see Fig. 3).

Our EPR experiments provide convincing evidence that, under appropriate conditions, a more complex mechanism is needed to account for the increased rate of production of disulfide from thiols in oxidation with MnO_2. We propose that under basic conditions thiyl radicals react readily with thiolate anions (for which intra- and inter-molecular analogues exist[4,9]) to give disulfide radical-anions which react with oxygen (and an added nitroso spin-trap) by electron transfer (see Scheme 1). Activation of oxygen, initially to $O_2^{\bullet-}$ and $HO_2^\bullet$, which may itself be trapped,* may ultimately lead to H_2O_2, which itself

$$RSH \xrightarrow{MnO_2} RS^\bullet \quad (1)$$

$$2RS^\bullet \longrightarrow RSSR \quad (2)$$

$$RSH \xrightarrow{base} RS^- \quad (3)$$

$$RS^- + RS^\bullet \longrightarrow RSSR^{\bullet-} \quad (4)$$
(8)

$$RSSR^{\bullet-} + O_2 \longrightarrow RSSR + O_2^{\bullet-}(HO_2^\bullet) \quad (5)$$

$$RSSR^{\bullet-} + {}^\bullet O_2H \xrightarrow{H^+} RSSR + H_2O_2 \quad (6)$$

$$RSSR^{\bullet-} + H_2O_2 \longrightarrow RSSR + HO^\bullet + HO^- \quad (7)$$

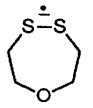
$$RSSR^{\bullet-} + Bu^tNO \longrightarrow RSSR + Bu^tNO^{\bullet-} \xrightarrow{H^+} Bu^tNHO^\bullet \quad (8)$$
(6)

Scheme 1

* Trapping of $O_2^{\bullet-}$ and/or $HO_2^\bullet$ can account for the observation of the corresponding $HO^\bullet$ adduct (*cf.* ref. 10).

could be decomposed to $^\bullet OH$ following electron-transfer [reaction (7)]; this mechanism would account for the removal of oxygen detected in some experiments as well as providing a chain mechanism for further thiol oxidation (*via* $HO^\bullet$ and/or $HO_2^\bullet$).

Reaction of $RSSR^{\bullet-}$ **8** with MNP is expected to give rise to $Bu^tNO^{\bullet-}$ and thus to **6** [reaction (8)]. As further evidence of this last step we generated the cyclic radical-anion **9** by reaction of $Bu^tO^\bullet$ (generated photolytically from Bu^tOOBu^t) with the thiol $HSCH_2CH_2OCH_2CH_2SH$ in the presence of base, to give thiol and anion in comparable amounts (under conditions recently established by Lunazzi and coworkers[9] as a suitable means to generate disulfide radical-anions for EPR study). The spectrum of **9** has a(4H) 0.64 mT, g 2.0130. As expected, addition of



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Bu^tNO brought about the replacement of the EPR spectrum of **9** by that from $Bu^tNHO^\bullet$ **6**.

Conclusions

Our EPR observations allow us to present a convincing rationale for the occurrence of oxidative dimerization in the heterogeneous oxidation of thiols by MnO_2; evidence is clearly obtained first for the generation of thiyl radicals. Further, observations of the separate effects of oxygen and base suggest that an overall reaction scheme must allow for rapid reaction of first-formed $RS^\bullet$ with the appropriate thiolate anions, and that the resulting radical-anion is converted into product disulfide *via* electron transfer. A full understanding of the reaction mechanism will require more detailed kinetic information (*e.g.* the rate constant of self-reaction of $RS^\bullet$, as well as its reaction with RS^- and O_2) and further experiments on the proposed one-electron transfer reactions of $RSSR^{\bullet-}$ with oxygen and, possibly H_2O_2. The role of $HO^\bullet$ and/or $HO_2^\bullet$ in thiol oxidation and the behaviour of other metal oxides, remains to be explored.

Experimental

EPR spectra were measured on a Bruker ESP 300 Spectrometer equipped with X-band klystron and 100 kHz modulation. Splitting constants were determined (to within ±0.01 mT) and g values (to within ±0.0001) by comparison with parameters for di-*tert*-butyl nitroxide [a(N) 1.57 mT, g 2.0063, in methylbenzene].[11] Substrates were mixed under both aerated and deoxygenated conditions (the latter *via* degassing with a freeze–pump–thaw method) prior to transfer to the spectrometer. ^1H NMR spectra were recorded in $CDCl_3$, with TMS as internal standard, on JEOL FX-90Q and Bruker WP80-SY spectrometers.

All compounds were obtained from either Morton International Ltd. or Aldrich, and used as supplied.

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References

1 B. C. Gilbert, in *Sulphur-Centred Reactive Intermediates in Chemistry and Biology*, ed. K. D. Asmus and C. Chatgilialoglu, Plenum, New York, 1990.

2 G. S. Tyndall and A. R. Ravishankara, *Int. J. Chem. Kinet.*, 1991, **23**, 483.
3 B. Halliwell and J. M. C. Gutteridge, *Free Radicals in Biology and Medicine*, 2nd edn. Oxford University Press, 1990.
4 B. C. Gilbert, H. A. H. Laue, R. O. C. Norman and R. C. Sealy, *J. Chem. Soc., Perkin Trans. 2*, 1975, 892.
5 E. R. Bertozzi, *Rubber Chem. Technol.*, 1968, **41**, 114; N. D. Ghatge, S. P. Vernakar and S. V. Lonikar, *Rubber Chem. Technol.*, 1981, **54**, 197.
6 T. J. Wallace, *J. Org. Chem.*, 1966, **31**, 1217.
7 B. Kalyanaraman, C. Mottley and R. P. Mason, *J. Biochem. Biophys. Methods*, 1984, **9**, 27.
8 G. R. Buettner and R. P. Mason, *Methods Enzymol.*, 1990, **186**, 127; C. F. Chignell and K. Reszka, 3rd Int. Symp. on Spin-Trapping, Kyoto, Japan, 1991, 253.
9 M. A. Cremonini, L. Lunazzi and G. Placucci, *J. Chem. Soc., Perkin Trans. 2*, 1992, 451. See also J. E. Packer, in *The Chemistry of the Thiol Group, Part 2*, ed. S. Patai, Wiley, London 1974, 481–517.
10 E. Finkelstein, E. M. Rosen and E. J. Rauckman, *Mol. Pharmacol.*, 1982, **21**, 262.
11 J. A. Howard and J. C. Tait, *Can. J. Chem.*, 1978, **56**, 176.

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