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Reaction of Organic Sulfur Compounds with Hyperoxide Anion ($O_2^{\cdot-}$). IV.[1)] Evidence for Formation of Peroxysulfur Intermediates: Oxidation of Sulfoxides, Phosphines, and Olefins[2)] with Intermediary Peroxysulfur Species

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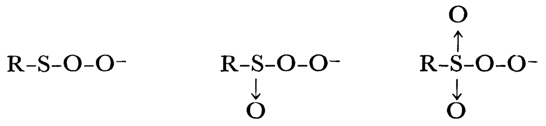
Formations of peroxy-sulfenate(I), -sulfinate(II), and -sulfonate(III) as intermediates have been confirmed by stripping the peroxy oxygen with three kinds of trapping agents such as sulfoxides, phosphines, and olefins, added in the reaction systems of various organic sulfur compounds with hyperoxide anion ($O_2^{\cdot-}$). These sulfoxides, phosphines, and olefins were inert to $O_2^{\cdot-}$ alone while electrophilic olefins, such as α,β-unsaturated ketones reacted readily with $O_2^{\cdot-}$ to afford the carboxylic acid. Sulfoxides, added into the reaction system of disulfide, thiosulfinic *S*-ester, thiosulfonic *S*-ester, or sulfonyl chloride with $O_2^{\cdot-}$, were found to be oxidized to the sulfones with peroxysulfur intermediates formed *in situ* in the system. Phosphines, added into the reaction system of disuflide or sodium thiolate with $O_2^{\cdot-}$ were also oxidized to the phosphine oxides. Not only stilbene and acenaphthylene but also chalcone and its derivatives, placed in the reactions of sulfonyl chloride, sulfinyl chloride and thiosulfonic *S*-ester with $O_2^{\cdot-}$ were found to be oxidized to the corresponding epoxides. These observations suggest clearly that the intermediary peroxysulfur compounds can act as oxidizing agents which oxidize these trapping agents by the nucleophilic oxygenative oxidation. Similar intermediates were postulated and confirmed in the alkaline autoxidations of thiol and disulfide in which added phosphines and sulfoxides were also found to be oxidized to their oxides. The mechanisms of the reactions of these trapping agents with peroxysulfur intermediates are discussed.

The discovery of superoxide dismutase(SOD) by Fridovich and McCord in 1969[3)] has given the considerably vital energies on the investigation of hyperoxide anion radical($O_2^{\cdot-}$), not only in biochemistry but also in organic chemistry.

Since the observation of Valentine and Curtis in which KO_2 can be appreciably dissolved in aprotic solvents, by complexation with crown ethers,[4)] has quickly promoted the use of this reagent for many reactions with simple organic substrates, numerous reports dealing with reactions of various organic substrates with "naked" hyperoxide anion have appeared within only five years. However, nobody has looked into the reaction of organic sulfur compounds with $O_2^{\cdot-}$ till we initiated as a part of our works on the oxygenative oxidation of organic sulfur compounds,[5)] except some sporadic experiments.[6)]

The oxidation with $O_2^{\cdot-}$ may be limited partly due to its relatively weak reactivity. In fact, $O_2^{\cdot-}$ has been called as a moderate reducing agent but a pitifully weak oxidizing agent.[7)] However, its reactivity has been seen in oxidation, reduction, nucleophilic substitutions, and also radical reactions.

We reported recently that several organic sulfur compounds are oxidized with $O_2^{\cdot-}$ generated *in situ* from KO_2 and 18-crown-6 to the corresponding sulfinic and sulfonic acids under mild conditions.[5a,b)] These organic sulfur compounds are either those which have sulfur–sulfur linkage such as disulfide, thiosulfinic *S*-ester, thiosulfonic *S*-ester, or thiolate and sulfinate, all of which are expected to give peroxy-sulfur compounds such as peroxy-sulfenate(I), -sulfinate(II), and -sulfonate (III) as initial intermediates in the reactions with $O_2^{\cdot-}$. In fact, Berger already postulated the intermediary peroxy-sulfenate(I) and -sulfinate(II) in the autoxidation of thiol to the sulfinic and sulfonic acids in strong alkali media.[8)] Since the two reactions give both sulfinic and sulfonic acids and are presumed to involve common intermediates of peroxysulfur species, we have carried out the experiments which would suggest the formation of these peroxysulfur intermediates in the reactions with $O_2^{\cdot-}$, and obtained evidence to support the intermediary formations of these new class of peroxy compounds (I—III) in the reactions of several sulfur compounds with $O_2^{\cdot-}$. Namely, sulfoxides, phosphines, and olefins(which are inert to $O_2^{\cdot-}$ without any one of sulfur substrates) were found to be oxidized to their oxides in the reaction systems of various sulfur compounds with $O_2^{\cdot-}$. Similar results were obtained in the alkaline autoxidations of thiol and disulfide.



$$\text{R-S-O-O}^- \qquad \underset{\text{O}}{\underset{\downarrow}{\text{R-S}}}\text{-O-O}^- \qquad \underset{\text{O}}{\underset{\downarrow}{\overset{\text{O}}{\overset{\uparrow}{\text{R-S}}}}}\text{-O-O}^-$$

Peroxysulfenate I Peroxysulfinate II Peroxysulfonate III

Results and Discussion

All of the sulfur compounds shown below, *i.e.* **1**, **2**, **3**, **4**, and **5** have been found in our earlier study to be oxidized with $O_2^{\cdot-}$ to afford the corresponding sulfinic and sulfonic acids,[5a,b)] while sulfenyl(**6**), sulfinyl(**7**) and sulfonyl(**8**) chlorides have also been found to be oxidized to the corresponding sulfinic and sulfonic acids. When unsymmetrical thiosulfinic and thiosulfonic *S*-esters were treated with KO_2 and 18-crown-6, formation of symmetrical disulfides from only the sulfenyl sulfur side was observed.

Since the peroxysulfur species, formed *in situ* during the reaction of these sulfur compounds with $O_2^{\cdot-}$, are

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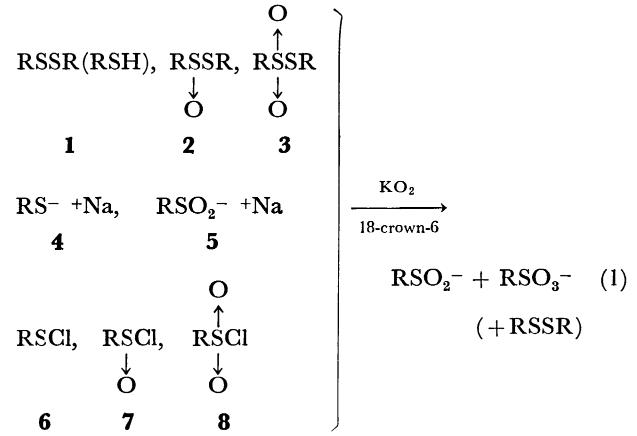
Table 1. Oxidation of sulfoxide

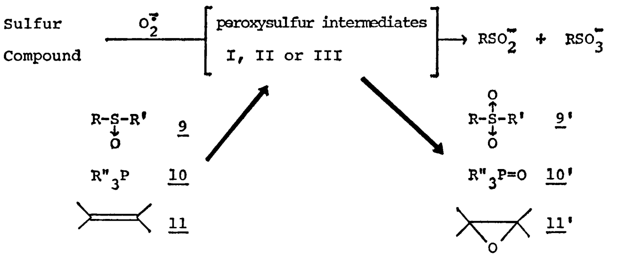
Entry No.	Substrate	Conversion %	Temp °C	Time min	KO_2	Crown	Added sulfoxide	Solvent	Yield of sulfone[a)] %
1	*p*-TolSSTol-*p*	95	22	240	(6)[d)]	(1)[d)]	$p\text{-Tol}\underset{\overset{\downarrow}{\mathrm{O}}}{\mathrm{S}}\text{Me}(2)^{\mathrm{d)}}$	CH_3CN	72[b)]
2	$\text{Ph}\underset{\overset{\downarrow}{\mathrm{O}}}{\mathrm{S}}\text{STol-p}$	*ca.* 100	17	10	(5)	(1)	$\text{Ph}\underset{\overset{\downarrow}{\mathrm{O}}}{\mathrm{S}}\text{Ph}(2)$	Py	17[c)]
3	$\text{PhS}\overset{\overset{\mathrm{O}}{\uparrow}}{\underset{\overset{\downarrow}{\mathrm{O}}}{\mathrm{S}}}\text{Ph}$	89	0	58	(4)	(1)	$\text{Ph}\underset{\overset{\downarrow}{\mathrm{O}}}{\mathrm{S}}\text{Ph}(2)$	Py	3[c)]
4	*p*-TolSNa	*ca.* 100	25	120	(3)	(0.5)	$\text{Me}\underset{\overset{\downarrow}{\mathrm{O}}}{\mathrm{S}}\text{Me}(5)$	CH_3CN	93[b)]
5	$PhSO_2Na$	80	25	150	(1)	(0.5)	$\text{Ph}\underset{\overset{\downarrow}{\mathrm{O}}}{\mathrm{S}}\text{Ph}(1)$	Py	3[c)]
6	$p\text{-Tol}\underset{\overset{\downarrow}{\mathrm{O}}}{\mathrm{S}}\text{Cl}$	*ca.* 100	22	25	(3)	(1/3)	$\text{Me}\underset{\overset{\downarrow}{\mathrm{O}}}{\mathrm{S}}\text{Me}(3)$	CH_3CN	57[b)]
7	$p\text{-Tol}\overset{\overset{\mathrm{O}}{\uparrow}}{\underset{\overset{\downarrow}{\mathrm{O}}}{\mathrm{S}}}\text{Cl}$	*ca.* 95	25	480	(3)	(1/10)	$p\text{-ClC}_6\text{H}_4\underset{\overset{\downarrow}{\mathrm{O}}}{\mathrm{S}}\text{Me}(1/2)$	CH_3CN	46[b)] (23)[e)]

a) Yield of sulfone based on the substrate. b) Yield by NMR. c) Isolated yield. d) Value in parenthesis is molar ratio. e) Yield calculated on the basis of the sulfoxide added.

believed to have fairly strong nucleophilic oxidizing abilities, sulfoxides, phosphines, and olefins, which are relatively inert to $\mathrm{O_2^{\cdot-}}$ alone but reactive with rather strong nucleophilic oxidizing agents, were added into the reaction system of one of these sulfur substrates with $\mathrm{O_2^{\cdot-}}$, expecting that these additives would be oxidized to the corresponding oxides. Indeed, while the organic sulfur compounds were all oxidized to the sulfinic and sulfonic acids, added sulfoxides, phosphines, or olefins were also found to be oxidized to the corresponding sulfones, phosphine oxides, or epoxides. The added substrates, *i.e.* **9**, **10**, and **11**, are thus believed to be oxidized by the intermediary peroxysulfur compounds(I—III) formed *in situ* during the reactions of these sulfur compounds with $\mathrm{O_2^{\cdot-}}$.



$$\left.\begin{array}{lll} \underset{\mathbf{1}}{\text{RSSR(RSH),}} & \underset{\mathbf{2}}{\text{R}\underset{\overset{\downarrow}{\mathrm{O}}}{\mathrm{S}}\text{SR,}} & \underset{\mathbf{3}}{\text{R}\overset{\overset{\mathrm{O}}{\uparrow}}{\underset{\overset{\downarrow}{\mathrm{O}}}{\mathrm{S}}}\text{SR}} \\ \underset{\mathbf{4}}{\text{RS}^- \ {}^+\text{Na,}} & \underset{\mathbf{5}}{\text{RSO}_2^- \ {}^+\text{Na}} & \\ \underset{\mathbf{6}}{\text{RSCl,}} & \underset{\mathbf{7}}{\text{R}\underset{\overset{\downarrow}{\mathrm{O}}}{\mathrm{S}}\text{Cl,}} & \underset{\mathbf{8}}{\text{R}\overset{\overset{\mathrm{O}}{\uparrow}}{\underset{\overset{\downarrow}{\mathrm{O}}}{\mathrm{S}}}\text{Cl}} \end{array}\right\} \xrightarrow[\text{18-crown-6}]{\mathrm{KO_2}} \begin{array}{c} \mathrm{RSO_2^-} + \mathrm{RSO_3^-} \\ (+\mathrm{RSSR}) \end{array} \quad (1)$$



Scheme 1.

Oxidation of Sulfoxide. As a typical run, a solution of a selected sulfoxide (**9**, 0.5—6 eq.) and an organic sulfur compound (one of **1**—**8**, 1 eq.) in dry pyridine or acetonitrile was added into a heterogeneous solution of KO_2 (1—6 eq., finely powdered) and dry 18-crown-6 (0.5—1.0 eq.) in the same solvent at a set temperature and the resulting mixture was stirred under argon atmosphere. After extraction or filtration, the corresponding sulfone was obtained in the yield shown in Table 1. In the aqueous layer both sulfinic and sulfonic acids were obtained as reported previously.[5a,b)] Yield of the sulfone obtained thus was determined by isolation by means of column chromatography on silica gel, or by comparison of the integral ratio of the NMR spectrum of the reaction mixture after evaporation of organic solvent. The sulfones were produced in most cases, except methyl phenyl sulfoxide which was not oxidized in the reaction system of benzenesulfenyl chloride with $\mathrm{O_2^{\cdot-}}$ but reduced exothermically to the corresponding sulfide by the sulfenyl chloride in a very short time (≈5 min), like the reduction by sulfinyl chloride.[9)] However, the sulfenyl chloride itself was readily oxidized with $\mathrm{O_2^{\cdot-}}$ to the corresponding sulfinic and sulfonic acids.

TABLE 2. EFFECTS OF SOLVENT, TEMPERATURE, AND SULFOXIDE, AND OTHER EFFECTS

Entry No.	Substrate	Conversion %	Temp °C	Time min	KO_2	Crown	Added sulfoxide	Solvent	Yield of sulfone[a] %
1	PhSSPh	64	25	133	(6)[d]	(1)[d]	$\mathrm{Ph}\underset{\substack{\downarrow\\ \mathrm{O}}}{\mathrm{S}}\mathrm{Ph}(2)$[d]	Py	22[c]
2	*p*-TolSSTol-p	93	21	330	(6)	(1)	$\mathrm{Ph}\underset{\substack{\downarrow\\ \mathrm{O}}}{\mathrm{S}}\mathrm{Ph}(2)$	CH_3CN	57[c]
3	*p*-TolSSTol-*p*	91	21	300	(6)	(1)	$\mathrm{Ph}\underset{\substack{\downarrow\\ \mathrm{O}}}{\mathrm{S}}\mathrm{Ph}(2)$	CH_3CN	56[c]
4	*p*-TolSNa	*ca.* 100	25	270	(3)	(1)	$\mathrm{Ph}\underset{\substack{\downarrow\\ \mathrm{O}}}{\mathrm{S}}\mathrm{Ph}(1)$	Py	4[c]
5	*p*-TolSNa	—	25	120	(5)	(1/2)	$\mathrm{Me}\underset{\substack{\downarrow\\ \mathrm{O}}}{\mathrm{S}}\mathrm{Me}(5)$	CH_3CN	93[b]
6	$\mathrm{Ph}\underset{\substack{\downarrow\\ \mathrm{O}}}{\mathrm{S}}\mathrm{STol}\text{-}p$	*ca.* 100	25	35	(5)	(1)	$\mathrm{Ph}\underset{\substack{\downarrow\\ \mathrm{O}}}{\mathrm{S}}\mathrm{Ph}(2)$	Py	32[c]
7	$p\text{-}\mathrm{Tol}\underset{\substack{\downarrow\\ \mathrm{O}}}{\mathrm{S}}\mathrm{STol}\text{-}p$	*ca.* 100	17	10	(5)	(1)	$\mathrm{Ph}\underset{\substack{\downarrow\\ \mathrm{O}}}{\mathrm{S}}\mathrm{Ph}(3)$	Py	15[c]
8	$\mathrm{Ph}\underset{\substack{\downarrow\\ \mathrm{O}}}{\mathrm{S}}\mathrm{STol}\text{-}p$	*ca.* 100	−25	60	(5)	(1)	$\mathrm{Ph}\underset{\substack{\downarrow\\ \mathrm{O}}}{\mathrm{S}}\mathrm{Ph}(2)$	Py	9[c]
9	$\mathrm{Ph}\underset{\substack{\downarrow\\ \mathrm{O}}}{\mathrm{S}}\mathrm{STol}\text{-}p$	*ca.* 100	−40	90	(5)	(1)	$\mathrm{Ph}\underset{\substack{\downarrow\\ \mathrm{O}}}{\mathrm{S}}\mathrm{Ph}(2)$	Py	4[c]
10	*p*-TolSSTol-*p*	91	21	300	(6)	(1)	$\mathrm{Ph}\underset{\substack{\downarrow\\ \mathrm{O}}}{\mathrm{S}}\mathrm{Ph}(2)$	CH_3CN	54[c]
11	*p*-TolSSTol-*p*	100	20	240	(6)	(1)	$p\text{-}\mathrm{Tol}\underset{\substack{\downarrow\\ \mathrm{O}}}{\mathrm{S}}\mathrm{Ph}(2.3)$	CH_3CN	56[b]
12	*p*-TolSSTol-*p*	95	22	240	(6)	(1)	$p\text{-}\mathrm{Tol}\underset{\substack{\downarrow\\ \mathrm{O}}}{\mathrm{S}}\mathrm{Me}(2)$	CH_3CN	72[b]
13	*p*-TolSSTol-*p*	95	22	264	(6)	(1)	$p\text{-}\mathrm{ClC_6H_4}\underset{\substack{\downarrow\\ \mathrm{O}}}{\mathrm{S}}\mathrm{Me}(2)$	CH_3CN	71[b]
14	*p*-TolSSTol-*p*	95	25	240	(6)	(1)	$\mathrm{Ph}\underset{\substack{\downarrow\\ \mathrm{O}}}{\mathrm{S}}\mathrm{Me}(2)$	CH_3CN	50[b]
15	$p\text{-}\mathrm{Tol}\underset{\substack{\downarrow\\ \mathrm{O}}}{\mathrm{S}}\mathrm{Cl}$	*ca.* 100	20	90	(3)	(1/3)	$p\text{-}\mathrm{ClC_6H_4}\underset{\substack{\downarrow\\ \mathrm{O}}}{\mathrm{S}}\mathrm{Me}(2)$	CH_3CN	17[b]
16	$p\text{-}\mathrm{Tol}\underset{\substack{\downarrow\\ \mathrm{O}}}{\mathrm{S}}\mathrm{Cl}$	*ca.* 100	22	25	(3)	(1/3)	$\mathrm{Me}\underset{\substack{\downarrow\\ \mathrm{O}}}{\mathrm{S}}\mathrm{Me}(3)$	CH_3CN	57[b]
17	*p*-TolSSTol-*p*	97	25	300	(6)	(1)	$p\text{-}\mathrm{Tol}\underset{\substack{\downarrow\\ \mathrm{O}}}{\mathrm{S}}\mathrm{Me}(6)$	CH_3CN	111[b]

Table notes are same as those in Table 1.

Sulfoxides were shown to be rather inert to $\mathrm{O}_2^{\overline{\cdot}}$ by Valentine and Curtis who revealed that KO_2 is nicely soluble in DMSO by complexation with perhydrodibenzo-18-crown-6.[4] Effects of solvent, temperature, and added sulfoxide were then investigated. The oxidation of sulfoxides during the reaction of organic sulfur compounds with KO_2 and the crown ether has been found to be affected by both solvent and temperature (entries 1—5, Table 2). Sulfoxides were oxidized in better yields in acetonitrile than in pyridine. Decomposition of $RS(O)_xOO^-$ (x=0—2: I—III) is presumably facilitated in pyridine, while acetonitrile may interact with the peroxysulfur species which might live longer in acetonitrile than in pyridine and hence would be a better nucleophilic oxidizing agent for sulfoxide. However, acetonitrile was found to react with disulfide in the presence of $\mathrm{O}_2^{\overline{\cdot}}$, forming bis(arylthio)acetonitrile in the yield of 25—50%.[5b] A radical process shown below (Eqs. 2—4) seems to be responsible for the formation of bis(arylthio)-

acetonitrile, and details of the reaction are under investigation.

$$O_2^{\overline{\cdot}} + CH_3CN \longrightarrow HO_2^- + \cdot CH_2CN \qquad (2)$$

$$ArSSAr + \cdot CH_2CN \longrightarrow ArSCH_2CN \qquad (3)$$

$$ArSCH_2CN \xrightarrow{O_2^{\overline{\cdot}}} \xrightarrow{ArSSAr} (ArS)_2CHCN \qquad (4)$$

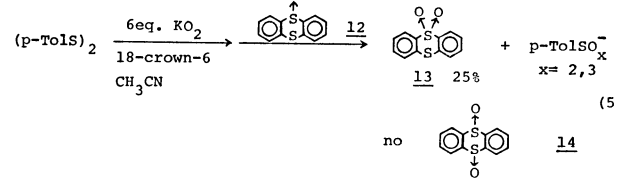
The yield of diphenyl sulfone from the added sulfoxide into the reaction system of **2** with $O_2^{\overline{\cdot}}$ increased as the temperature of the reaction was raised (entries 6—9). Change of sulfoxide did not affect much the yield of the corresponding sulfone in the reaction of di-*p*-toly disulfide with $O_2^{\overline{\cdot}}$ (entries 10—14). However, in the reaction of *p*-toluenesulfinyl chloride with $O_2^{\overline{\cdot}}$, dimethyl sulfone was obtained in a much better yield than methyl *p*-chlorophenyl sulfone (entries 15 and 16). An analogous result was observed in the oxidation of sodium *p*-toluenethiolate(entries 4 and 5), though the conditions of the above two reactions are somewhat different.

Meanwhile, since the yield of the sulfone was calculated based on the amount of the starting organic sulfur compound used, the yield of sulfone more than 100% (111%, entry 17) is not surprizing, as the amount of the added sulfoxide was six equivalent to the organic sulfur compound used. This may mean that more than an equimolar amount of peroxysulfur intermediate(s) is produced from the organic sulfur compound during the reaction. Thus, the yield of the sulfone clearly increased as the amount of the added sulfoxide to the reaction system increased.

Sulfoxide, having *p*-nitrophenyl group, such as *p*-nitrophenyl phenyl and methyl *p*-nitrophenyl sulfoxides, were not oxidized to the sulfones but presumably reacted with $O_2^{\overline{\cdot}}$. The reaction mixture turned to reddish brown and no product, even the starting material, was obtained from the organic layer.

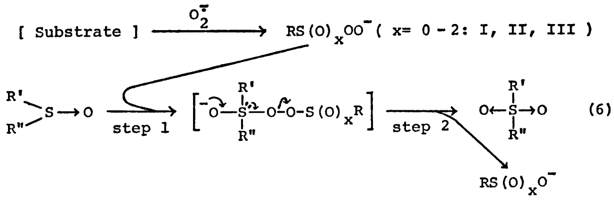
Common sulfides such as diethyl, methyl phenyl, and diphenyl sulfides were found not to be oxidized at all under the conditions, as in the reaction with $O_2^{\overline{\cdot}}$ which was reported to be unreactive toward sulfides.[10)]

In order to reconfirm the facile reaction of sulfoxides and no reactivity of sulfides in these oxidation systems, thianthrene 9-oxide (**12**) was used as the trapping agent, and found to be oxidized to thianthrene 9,9-dioxide(**13**), but not to the 9,10-dioxide(**14**) in the reaction of di-*p*-tolyl disulfide with $O_2^{\overline{\cdot}}$ in CH_3CN at 25 °C for 4 h (Eq. 5). This result clearly indicates that the peroxysulfur intermediates formed during the reaction oxidize trivalent sulfinyl function but not divalent sulfenyl function.



Although oxygenation of sulfide is well-known to be initiated by the electrophilic attack of oxidant on the sulfide, oxygenation of the sulfoxide involves either the initial electrophilic attack of the electrophilic oxidant,[11a)] or the nucleophilic attack of nucleophilic oxidant.[11b,c)] In general, the anions of peroxy acid and hydroperoxide which are well-known to be powerful α-nucleophiles,[12)] have been shown to oxidize sulfoxide through the nucleophilic attack on the trivalent sulfur.[11b,13)] Therefore, peroxysulfur intermediates, being α-nucleophiles, would oxidize similarly the sulfoxide by nucleophilic oxidation.[11c)]

The yield of the sulfone alone cannot give any difinite information on the effect of substituent in these oxidations of various sulfoxides with the peroxysulfur intermediates (Table 2). Modena *et al.* showed that the electron-withdrawing substituent on sulfoxide accelerates the rate of the oxidation of sulfoxide but could not obtain any clear-cut relationship on the effect of the substituent,[11b)] since decomposition of the sulfurane intermediate is also a slow reaction and could become the rate-determining step of the overall reaction. The two successive reaction steps, *i.e.* the nucleophilic attack of acyloxy anion on sulfur atom and the collapse of the sulfurane intermediate, demand the entirely opposite electronic environments. The oxidation of sulfoxide with the peroxysulfur intermediates is considered to proceed similarly. As shown in Eq. 6, sulfoxide would be attacked by one



of the peroxysulfur intermediates generated *in situ*, forming incipiently the sulfurane intermediate which collapses to sulfone and $RS(O)_xO^-$ in the subsequent step.

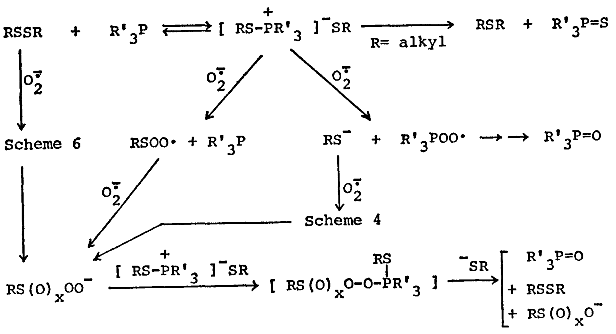
An alternative mechanism which involves radical species of peroxysulfur intermediates in the oxidation of sulfoxide to the sulfone may be postulated. However, this seems to be quite unlikely because of the lack of nucleophilicity of the radical species, as was suggested earlier in the oxidation of dimethyl sulfoxide with *t*-butyl hydroperoxide.[14)]

Oxidation of Phosphines. Both triphenyl- and tributylphosphines were also selected as trapping agents. Although these phosphines are known to be oxidized readily to the phosphine oxides with molecular oxygen,[15)] both phosphines were quite inert under the present oxidation conditions in pyridine in dry argon atmosphere. The reaction procedure is identical to that in "*Oxidation of Sulfoxide.*" However, when the phosphines are used as trapping agents no oxygenated sulfur compounds could be used as the substrate for the oxidation with $O_2^{\overline{\cdot}}$, since the oxygenated sulfur compounds (**2**, **3** *etc.*) are known to be reduced readily with phosphines.[16)] In fact, thiosulfinic *S*-ester was very readily reduced to the disulfide with triphenylphosphine in pyridine even at −25 °C. This reduction of thiosulfinic *S*-ester with triphenylphosphine is considered to compete with the reaction of thiosulfinic *S*-ester with $O_2^{\overline{\cdot}}$. Therefore,

TABLE 3. OXIDATION OF PHOSPHINES

Entry No.	Substrate	Conversion %	Temp °C	Time min	KO_2	Crown	Added phosphine	Solvent	Yield of product[a)] %
1	PhSSPh	60	25	66	(6)	(1)	Ph_3P(1)	Py	Ph_3P=O 17
2	PhSSPh	81	23	300	(6)	(1)	Ph_3P(2)	Py	Ph_3P=O 21
3	PhSSPh	49	21	60	(6)	(1)	Bu_3P(2)	Py	Bu_3P=O Quant.
4	PhSSPh	95	25	240	(6)	(1)	Ph_3P=S(1)	Py	Ph_3P=O 0
5	MeSSMe	—	25	90	(6)	(1)	Ph_3P(1)	Py	Ph_3P=O 6 Ph_3P=S 13
6	BuSSBu	31	25	56	(6)	(1)	Ph_3P(1)	Py	Ph_3P=O 30 Ph_3P=S Trace
7	$PhCH_2SSCH_2Ph$	95	25	30	(6)	(1)	Ph_3P(1)	Py	Ph_3P=O 11 Ph_3P=S 31
8	*p*-TolSNa	*ca.* 100	20	300	(3)	(1/2)	Bu_3P(1)	Py	Bu_3P=O 5
9	*p*-TolSNa	*ca.* 100	25	1380	(5)	(1/2)	Ph_3P(2)	CH_3CN	Ph_3P=O 37

a) Yields were determined by GC.



Scheme 2.

the disulfide and sodium thiolate were chosen as the substrates in the reaction with $O_2^{\cdot-}$ in the presence of the phosphine to yield the phosphine oxide (Table 3). Yields of the phosphine oxides were determined directly by GC in order to avoid the autoxidation of phosphines. When tributylphosphine was added as a trapping agent of the peroxysulfur intermediate in the oxidation of disulfide with $O_2^{\cdot-}$, a vigorous exothermic reaction took place and the phosphine oxide was formed quantitatively within an hour, during which the conversion of the disulfide to the acids was still incomplete as shown in Table 3 (entry 3). In the oxidation of alkyl disulfide such as dibenzyl disulfide, triphenylphosphine was not only oxidized to the phosphine oxide but also converted to the phosphine sulfide. The phosphine sulfide thus formed along with the phosphine oxide was found to be quite inert to $O_2^{\cdot-}$ and recovered completely when it was added into the reaction system of disulfide with $O_2^{\cdot-}$ (entry 4). Therefore, formation of the phosphine oxide is not derived from the phosphine sulfide which is a simple by-product formed by the nucleophilic attack of the phosphine to the disulfide. Here again, triphenylphosphine was oxidized in a better yield in acetonitrile than in pyridine (entries 8 and 9), suggesting the reaction to proceed *via* an ionic pathway.

Phosphines are known to react with alkyl disulfide in an equilibrium reaction and generally yield the phosphine sulfide and monosulfide.[17)] In the reaction of alkyl disulfide with $O_2^{\cdot-}$ in the presence of the phosphine the initial step is also considered to be the formation of alkylthiophosphonium ion which undergoes the Albuzov type reaction to yield the phosphine sulfide, by the nucleophilic attack of thiolate anion (counter anion of the phosphonium salt) on the carbon atom attached to the sulfur atom (Scheme 2). Due to the lack of nucleophilic attack of arenethiolate anion on aromatic carbon, diaryl disulfide did not give any phosphine sulfide (Table 3). Meanwhile, the formation of the phosphine oxide would be rationalized by Scheme 2. While $O_2^{\cdot-}$ can attack directly the disuflide as shown by Scheme 6, $O_2^{\cdot-}$ can attack competitively both sulfur and phosphorous atoms of the phosphonium ion. Although direct attack of $O_2^{\cdot-}$ on phosphorus atom may finally afford phosphine oxide, peroxysulfur species formed during the reaction, being good nucleophiles, may also attack the phosphorus atom of the phosphonium ion to afford an incipient phosphorane intermediate which upon nucleophilic attack of thiolate anion on the sulfur atom can give the phosphine oxide, as shown in Scheme 2. The rapid oxidation of tributylphosphine, therefore, may be due to the shift of the equilibrium between disulfide and the phosphine to right side to form the phosphonium ion which then would preferentially be attacked by $O_2^{\cdot-}$ on the phosphorus atom, to afford tributylphosphine oxide quantitatively before all the disulfide was oxidized to the acids.

Triphenylphosphine was not oxidized quantitatively in the reaction of sodium thiolate with $O_2^{\cdot-}$. The oxidation of triphenylphosphine in the reaction of sodium thiolate with $O_2^{\cdot-}$ seems to be different from that in the reaction of disulfide with $O_2^{\cdot-}$. The initial step is very likely the one electron transfer from thiolate anion to $O_2^{\cdot-}$ in view of the reducing nature of $O_2^{\cdot-}$.[18)] Then, the peroxysulfur free radical formed *in situ* may oxidize directly the phosphine as reported in the autoxidation of trialkylphosphines.[15)] Another possibility for the oxidation of the phosphine involves the initial reaction of thiyl radical with the phosphine to form arylthiophosphoryl radical, which can react with either $O_2^{\cdot-}$ or $RS(O)_xOO\cdot$ to give a phosphorane

TABLE 4. CHEMICAL SHIFTS OF EPOXIDES (δ, $CDCl_3$, TMS, 27 °C)

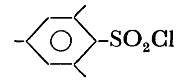
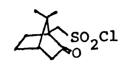
	Expoxide	Chemical shift	Lit	Ref.
1	*trans*-Stilbene oxide	3.83	3.88	20
2	*trans*-Chalcone oxide	4.08 4.30 (J=1.7 Hz)	4.06 4.27 (J=1.7 Hz)	21
3	*trans*-4-Bromochalcone oxide	4.03 4.25 (J=1.6 Hz)	3.99 4.19	22
4	*trans*-4-Methoxychalcone oxide	4.02 4·25 (J=1.8 Hz)	3.97 4.23	22
5	Acenaphthylene oxide	4.75	4.56	23

TABLE 5. EPOXIDATION OF OLEFIN (AT 20 °C)[a)]

Entry No.	Substrate	Olefin	Time/h	Solvent	Yield/mol%	
					Epoxide[b)]	Recovery[b)]
1	TsCl	**15**, X=Br	15.5	CH_3CN	85 (66)[c)]	Trace (5)[c)]
2	TsCl	**15**, X=H	15	CH_3CN	85	8
3	TsCl	**15**, X=OMe	3	CH_3CN	60 (45)[d)]	Trace
4	*p*-TolSOCl	**15**, X=H	22.5	Benzene	60	35
5	**18**[f)]	**15**, X=H	20.5	CH_3CN	26	58
6	PhCOCl	**15**, X=H	9	CH_3CN	41	49
7	TsCl	**16**	24	Benzene	40 (39)[c)]	55
8	PhCOCl	**16**[e)]	10	Benzene	30 (20)[c)]	20 (15)[c)]
9	TsCl	**17**	10	CH_3CN	— (30)[d)]	— (70)[d)]

a) Molar ratio: olefin:sub.:KO_2:crown=10:5:30:1. b) Yield by HPLC. c) Isolated yield. d) Yield by NMR. e) Molar ratio of PhCOCl/Olefin(**16**)=5/2. f) *p*-$ClC_6H_4S(O)_2SC_6H_4CH_3$-*p*(**18**).

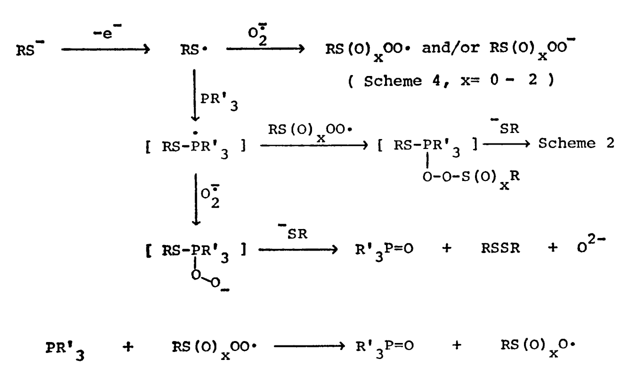
TABLE 6. EFFECTS OF SOLVENT, CROWN ETHER, AND SUBSTRATE (AT 20 °C)[a)]

Entry No.	Substrate	Olefin	Crown	Time/h	Solvent	Yield/%	
						Epoxide[b)]	Recovery[b)]
1	TsCl	**15**, X=H	(1)	15	CH_3CN	85	8
2	TsCl	**15**, X=H	(1)	20[f)]	CH_2Cl_2	65	25
3	TsCl	**15**, X=H	(1)	17	Benzene	39	52
4	TsCl	**15**, X=Br	(1)	15.5	CH_3CN	85 (66)[c)]	Trace (5)[c)]
5	TsCl	**15**, X=Br	(1)	21	Benzene	35 (25)[c)]	50 (48)[c)]
6	TsCl	**16**	(1)	24	Benzene	40 (39)[c)]	55
7	TsCl	**16**[g)]	(1)	3	CH_3CN	Complex mixture	
8	PhCOCl	**16**	(1)	10	Benzene	30 (20)[c)]	20 (15)[c)]
9	PhCOCl	**16**	(1)	1	CH_3CN	10	20
10	TsCl	**15**, X=H	(0)	22	CH_3CN	75	10
11	TsCl	**15**, X=OMe	(0)	13	Benzene	Trace	95
12		**15**, X=OMe	(1)	11[f)]	CH_3CN	— (75)[d)]	— (25)[d)]
13	Cl_3CSO_2Cl	**15**, X=H	(1)	15.5[f)]	CH_3CN	40	55
14		**15**, X=H	(1)	104	CH_3CN	50 (41)[c,e)]	35

a) Molar ratio: sub.:olefin:KO_2:crown=10:5:30:1. b) Yiled by HPLC. c) Isolated yield. d) Yield by NMR. e) (+)-*d*-Camphor-10-sulfonyl chloride: $[\alpha]_D^{25}$ +20.9°. f) Reaction at 18 °C. g) Molar ratio of TsCl/Olefin=5/2.

intermediate which then reacts according to Scheme 2(Scheme 2′).

Oxidation of Olefin. Several olefins were found to be readily oxidized to the corresponding epoxides in appreciable yields when these olefins were added into the reaction system of any one of the organic sulfur compounds (**3**, **7**, and **8**) with $O_2^{\overline{\cdot}}$. Since the epoxide formed was sensitive to alkaline media, the reaction mixture was immediately filtrated to remove alkali and the yields of the epoxides were obtained by measuring the NMR spectra of the mixtures, and the epoxides were isolated through column chromatography on silica gel using benzene–hexane mixture as an eluent. In NMR spectra of the epoxides, signals of methine protons of the usual three membered oxyrane ring appear at high fields (Table 4). Olefins used are the following three compounds, *i.e.* chalcone derivatives(**15**), stilbene(**16**), and acenaphthylene(**17**). Both **16** and **17** were quite inert to $O_2^{\overline{\cdot}}$ while **15** and its derivatives were found to react with $O_2^{\overline{\cdot}}$ as described later. Most epoxides obtained in the reactions were *trans* since the olefins used were also *trans*. However,



Scheme 2′.

the epoxide obtained from acenaphthylene was apparently *cis* but not *trans*, indicating that all the epoxidations in these systems were found to take place in *cis* fashion. Results obtained are listed in Tables 5 and 6, though the yields are not optimized.

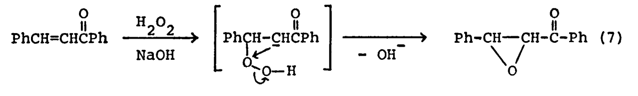
The epoxidation proceeds very little when disulfide (**1**) and thiosulfinic *S*-ester (**2**) were used. Sodium thiolate(**4**) and sulfenyl chloride(**6**), both of which can be oxidized with $O_2^{\cdot-}$, were effective for the epoxidation of none of these olefins, giving complicated reaction mixtures with no epoxide.

Other olefins such as cyclohexene and cinnamonitrile were not oxidized and recovered nearly quantitatively under the conditions, while dibenzoylethylene was very readily oxidized (<1 h) by $O_2^{\cdot-}$ with and without the sulfur compounds to give benzoylformic acid in a good yield as reported previously.[19]

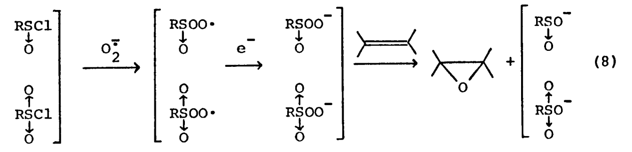
Recently the epoxidation of stilbene, in the reaction system of benzoyl chloride with $O_2^{\cdot-}$, was observed by Hirobe *et al.*[24] We also confirmed the epoxidation of stilbene in the same system (entry 8, Table 5; entries 8 and 9, Table 6). By-products in these reactions are carboxylic acids formed by direct oxidation of olefin and the epoxide with $O_2^{\cdot-}$.

Solvent, crown ether, and substrate also affected the epoxidation (Table 6). Inspection of data in Table 6 reveals that such a polar solvent as acetonitrile is better than dichloromethane or benzene in the epoxidation of chalcones, and the yield of the epoxide increased as the polarity of the solvent increased. However, acetonitrile was not a good solvent in the epoxidation of stilbene since other polar products including benzaldehyde were formed by the cleavage of C–C bond. This was confirmed in both cases using tosyl and benzoyl chlorides. Without crown ether, the yield of the epoxide was rather little in benzene but remained nearly the same in acetonitrile as shown in Table 6 (entries 10 and 11). Even the sterically hindered mesitylene and (+)-*d*-camphor-10-sulfonyl chlorides were also found to be effective in the epoxidation of olefins, however, the yields of the epoxides were relatively low and the rate of the reaction seemed to be slower than that with tosyl chloride. Chalcone epoxide, obtained by the oxidation of chalcone added in the reaction system of (+)-*d*-camphor-10-sulfonyl chloride ($[\alpha]_D^{25}+20.9°$) with $O_2^{\cdot-}$, did not show any optical activity, presumably because the optically active center is so far away from the reaction center.

The yield of stilbene oxide was lower than that of the epoxide from chalcone and its derivatives. Epoxidation of chalcone is known to be initiated by nucleophilic attack of an oxidant such as hydrogen peroxide anion as shown below (Eq. 7).[25] Even stilbene is known to undergo the Michael type addition by the attack of a strong nucleophile in some cases.[26]

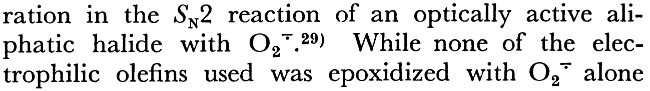


Chalcone, added in the reaction system of disulfide (**1**) with $O_2^{\cdot-}$ in acetonitrile, was not oxidized much, however, upon heating the reaction mixture in the absence of air at 50 °C chalcone decomposed to the corresponding carboxylic acids by the cleavage of C–C bond, as was reported by Rosenthal and Frimer.[27] Chalcone was oxidized in argon atmosphere much more readily without organosulfur compounds than in the presence, revealing that the rate of the reaction of chalcone with $O_2^{\cdot-}$ is appreciably slower than that of the reaction of organic sulfur compound with $O_2^{\cdot-}$. Since the reactions of both sulfinyl and sulfonyl chlorides with $O_2^{\cdot-}$ are considerably faster than that of chalcone with $O_2^{\cdot-}$, the epoxidation is considered to proceed *via* the initial nucleophilic substitution of the chlorides with $O_2^{\cdot-}$ and subsequent one electron transfer to afford the peroxysulfinate(II) and peroxysulfonate (III) which then oxidize olefin to the epoxide as shown in Eq. 8.



Nucleophilicity of $O_2^{\cdot-}$ has been nicely demonstrated in the reactions of various organic compounds with $O_2^{\cdot-}$,[28] and also in the complete inversion of configuration in the S_N2 reaction of an optically active aliphatic halide with $O_2^{\cdot-}$.[29] While none of the electrophilic olefins used was epoxidized with $O_2^{\cdot-}$ alone in our experiment, some cyclic α,β-unsaturated ketones were shown to be epoxidized with $O_2^{\cdot-}$ though in considerably low yields.[30]

Recently, Grieco and his-coworkers found that common nucleophilic olefins are nicely oxidized to the epoxides with benzeneperoxyseleninic acid which is generated *in situ* from benzeneseleninic acid and hydrogen peroxide,[31] apparently suggesting the formation of analogous intermediary peroxyselenium compound (Eq. 9).



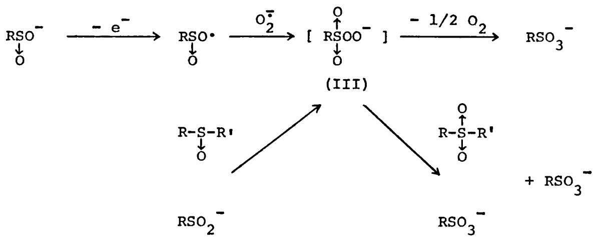
Oxidation Mechanisms of Several Sulfur Compounds with $O_2^{\cdot-}$. We have shown previously that several sulfur compounds (**1**—**8**) are oxidized to the corresponding sulfinic and sulfonic acids,[5a,b] and have suggested that the oxidation proceeds *via* formation of peroxysulfur intermediates (I, II, and III). Now let us consider the mechanisms of oxidations of several these sulfur compounds with $O_2^{-\cdot}$ to the sulfinic and sulfonic acids.

Oxidation of Sodium Sulfinate with $O_2^{-\cdot}$. Anhydrous sodium arenesulfinate can be oxidized with an equimolar amount of $O_2^{-\cdot}$ to afford mainly the sulfonic acid in pyridine at 25 °C for 2.5 h (Eq. 10).[5b] The

$$\begin{array}{llll} \mathrm{RSO_2Na} & \xrightarrow[\substack{\text{18-crown-6}\\ \text{pyridine}\\ 25\,^\circ\text{C, 2.5 h}}]{\text{eq. KO}_2} \mathrm{RSO_3^-} & (+\mathrm{RSO_2^-}:\text{recovery}) & (10) \\ \mathrm{R=Ph} & \qquad\qquad \approx 80\% & \approx 17\% & \\ p\text{-Tol} & & & \end{array}$$

initial step of the reaction would be the electron transfer. The resulting sulfonyl radical is known to be an excellent initiator in the polymerization of vinyl monomers or in the autoxidation of sulfinic acid.[32] Peroxysulfonyl radical, $RS(O)_2OO\cdot$, was also postulated in the photolysis of sulfur dioxide[33] in air and also in the autoxidation of sulfinic acid.[32,34] Thus, the oxidation of arenesulfinate with $O_2^{-\cdot}$ is considered to be initiated by one electron transfer and proceed *via* subsequent coupling of the resulted arenesulfonyl radical with $O_2^{-\cdot}$. The peroxyarenesulfonate(III) formed thus would slowly decompose to the sulfonic acid and molecular oxygen, or oxidize the present sulfinate or added sulfoxide to the sulfonate or the sulfone (Scheme 3).

The one electron transfer process from $O_2^{-\cdot}$ or to $O_2^{-\cdot}$ has been shown to be in operation in several reactions of $O_2^{-\cdot}$.[18] In view of the redox potentials of O_2—$O_2^{-\cdot}$ and $O_2^{-\cdot}$—H_2O_2 at neutral pH being −0.33 and +0.94 V, respectively, this radical anion is considered to act as a reductant in the presence of an electron acceptor and as an oxidant in the presence of an electron donor.[19] In fact, during a series of these experiments, evolution of molecular oxygen was observed by gas-mass spectrometry at the peak height of oxygen (*m*/*e* 32) along with that of argon (*m*/*e* 40) used, when the reaction was carried out in argon gas. This observation also seems to support the one electron transfer from $O_2^{-\cdot}$.

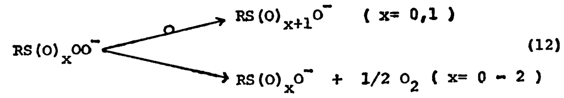


Scheme 3.

Oxidation of Sodium Thiolate with $O_2^{-\cdot}$. Sodium arenethiolate was also found to be oxidized to afford the corresponding sulfinic and sulfonic acids with a small amount of disuflide (Eq. 11).[5b] A similar one

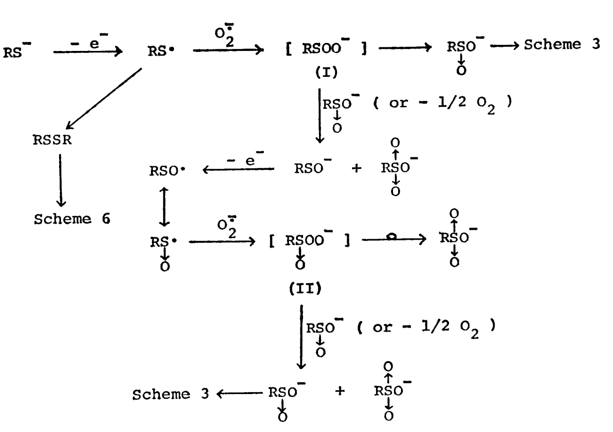
$$\begin{array}{lllll} \mathrm{RS^{-+}Na} & \xrightarrow[\substack{\text{18-crown-6, r.t.}\\ \text{pyridine, 4 h}}]{\text{3eq. KO}_2} \mathrm{RSO_2^-} & + \mathrm{RSO_3^-} & + \mathrm{RSSR} & (11) \\ & \qquad\qquad \approx 10\% & \approx 86\% & \text{trace} & \end{array}$$

electron transfer process is important in this oxidation. Recently, Degrand and Lund suggested that radical recombination of thiyl radical and $O_2^{-\cdot}$ gives sulfinate *via* the rearrangement of the peroxysulfenate(I) in the electrochemical synthesis of sulfinic acid from alkyl disulfide and molecular oxygen.[35] As shown in Scheme 4, the thiyl radical thus formed would either dimerize to the disulfide or react with $O_2^{-\cdot}$ to form the incipient peroxysulfenate(I). Recombination of two thiyl radicals has been reported to be very fast ($k=10^9$—10^{10} $M^{-1}\,s^{-1}$).[36] In the reaction of arenethiolate with $O_2^{-\cdot}$ all the intermediates (I—III) can thus be produced and would oxidize the added sulfoxides or the phosphines to the sulfones or the phosphine oxides. Rearrangement of the intermediates(I and II) to the sulfinate and the sulfonate are also conceivable while the degradation of all the intermediates may give both molecular oxygen and the acids (Eq. 12). Peroxysulfur intermediates may also



$$\mathrm{RS(O)_xOO^-} \begin{cases} \xrightarrow{} \mathrm{RS(O)_{x+1}O^-} & (x=0,1) \\ \xrightarrow{} \mathrm{RS(O)_xO^-} + 1/2\ \mathrm{O_2} & (x=0-2) \end{cases} \qquad (12)$$

oxidize arenesulfinate directly to the sulfonate since the added trivalent sulfoxide is readily oxidized and the sulfinate is also another trivalent sulfur compound. Formation of a small amount of disulfide should be due to the recombination of the thiyl radicals. A small amount of diaryl disulfide was also obtained in the alkaline autooxidation of arenethiol, in which thiyl radical and $O_2^{-\cdot}$ were considered to be formed *via* one electron transfer.[36b] This oxidation of thiolate with $O_2^{-\cdot}$ required a little longer reaction time than that of sulfinate, in keeping with the suggested mechanism.



Scheme 4.

Oxidation of Sulfenyl, Sulfinyl, and Sulfonyl Chlorides with $O_2^{-\cdot}$. The reactions of arene-sulfenyl, -sulfinyl, and -sulfonyl chlorides with $O_2^{-\cdot}$ are considered to be initiated by nucleophilic substitution of the chlorides

$$\left.\begin{array}{c} \mathrm{RSCl} \\[4pt] \mathrm{RSCl} \\ \downarrow \\ \mathrm{O} \\[4pt] \mathrm{O} \\ \uparrow \\ \mathrm{RSCl} \\ \downarrow \\ \mathrm{O} \end{array}\right\} \xrightarrow{O_2^{-\cdot}} \left\{\begin{array}{ccc} \mathrm{RSOO\cdot} & & \mathrm{RSOO^-} \\[4pt] \mathrm{RSOO\cdot} & \xrightarrow{e^-} & \mathrm{RSOO^-} \\ \downarrow & & \downarrow \\ \mathrm{O} & & \mathrm{O} \\[4pt] \mathrm{O} & & \mathrm{O} \\ \uparrow & & \uparrow \\ \mathrm{RSOO\cdot} & & \mathrm{RSOO^-} \\ \downarrow & & \downarrow \\ \mathrm{O} & & \mathrm{O} \end{array}\right\} \longrightarrow$$

$$\mathrm{RSO_2^-} + \mathrm{RSO_3^-} \qquad (13)$$

with $O_2^{\cdot-}$. Therefore, these three systems should be the best systems to give three peroxysulfur intermediates cleanly (Eq. 13). These three radicals, RSOO·, RS(O)OO·, and $RS(O)_2OO$·, thus formed readily undergo one electron transfer from $O_2^{\cdot-}$ to form the corresponding peroxysulfur anions, which oxidize sulfoxides and olefins, added into the reaction system. The reaction of a sulfonyl chloride with NaO_2 without crown ether have already been reported to afford the corresponding sulfonate in refluxing benzene.[6a)]

Oxidation of Thiol and Disulfide with $O_2^{\cdot-}$. Thiols react very readily with $O_2^{\cdot-}$ at first to afford the disuflides, which are then oxidized with $O_2^{\cdot-}$ to the corresponding sulfinic and sulfonic acids (Eq. 14). The

$$RSH \xrightarrow{O_2^{\cdot-}} RSSR \xrightarrow[\substack{\text{18-crown-6, r.t.}\\ \text{pyridine or}\\ \text{acetonitrile}}]{6\text{ eq. KO}_2} RSO_2^- + RSO_3^- \qquad (14)$$

$$RSH + O_2^{\cdot-} \longrightarrow RS\cdot + HOO^-(RS^- + HOO\cdot)$$
$$2RS\cdot \longrightarrow RSSR$$
$$HOO^- \longrightarrow 1/2O_2 + HO^-$$

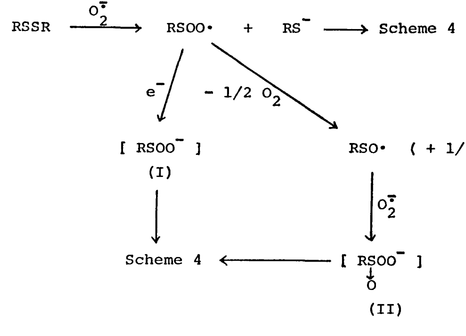
Scheme 5.

initial step of the reaction is the formation of the hydroperoxide anion and the thiyl radical which rapidly coupled to give the disulfide, while hydroperoxide anion may decompose slowly to molecular oxygen and hydroxide anion (Scheme 5).

The reaction of disulfide with $O_2^{\cdot-}$ undoubtedly involves nucleophilic attack of $O_2^{\cdot-}$ on S–S bond. Aromatic disulfide reacts faster than aliphatic disulfide, in keeping with the mechanism involvling the initial nucleophilic attack of $O_2^{\cdot-}$ on disulfide bond. Solvent effect may also support this process.[5b)]

The peroxysulfenyl radical formed at the initial stage would undergo one electron transfer or collapse to form I or sulfinyl radical and molecular oxygen, as shown in Scheme 6. The peroxysulfur intermediates can oxidize the added sulfoxides or phosphines to the oxides.

Recently, Hirobe *et al.* reported[24)] that two symmetrical disulfides, upon reacting with electrochemically generated $O_2^{\cdot-}$, gave three disulfides involving a new unsymmetrical disulfide in a theoretical ratio of the equilibrium mixture (1:2:1), without any oxidized product. This is quite reasonable if a very small amount of $O_2^{\cdot-}$ (only 1/60 amount of our case) was used. The reaction is considered to generate the thiyl radical either through the initial one electron transfer from $O_2^{\cdot-}$ to the disulfide or direct S_N2 type displacement of the disulfide with $O_2^{\cdot-}$. The thiyl radical thus formed would scramble the disuflides through S_N2 process rapidly, eventually resulting in the formation of the equilibrium mixture of disulfides.[37)] However, when the amount of $O_2^{\cdot-}$ is abundant the initial step should be the nucleophilic reaction of $O_2^{\cdot-}$ on S–S linkage in view of the solvent effect[5b)] and the following order of the reactivities, *i.e.* thiosulfinic *S*-ester>thiosulfonic *S*-ester>disulfide.[5b)]

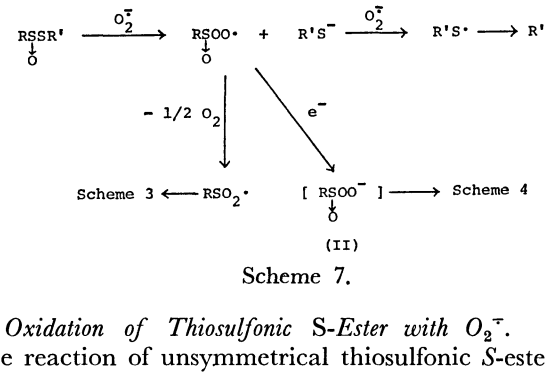


Scheme 6.

Oxidation of Thiosulfinic S-*Ester with $O_2^{\cdot-}$.* Thiosulfinic *S*-ester was found to react with $O_2^{\cdot-}$ more easily than any other sulfur compounds used.[5b)] The reaction proceeded readily even at −40 °C within an hour, and not only sulfinic and sulfonic acids but also symmetrical disulfide were obtained (Eq. 15).[5)]

$$R\underset{\substack{\downarrow\\ O}}{S}SR' \xrightarrow[\substack{\text{18-crown-6}\\ \text{pyridine, }-40\,^\circ\text{C}\\ \text{within 1 h}}]{5\text{ eq. KO}_2} \underset{\text{trace}}{RSO_2^-} + \underset{\approx 48\%}{RSO_3^-} + \underset{\approx 50\%}{R'SSR'} \qquad (15)$$

The symmetrical disulfide was formed in ≈50% yield only from the sulfenyl side and the two acids only from the sulfinyl side, revealing that the nucleophilic attack of $O_2^{\cdot-}$ occurs only on the sulfinyl sulfur of the unsymmetrical thiosulfinic *S*-ester. The predominant formation of the sulfonic acid may indicate that the main reaction path after the attack of $O_2^{\cdot-}$ is the rearrangement of peroxysulfinate(II) to the sulfonate. Therefore, peroxysulfinate(II) would be unstable enough to rearrange to the sulfonate under these conditions, and hence it would not be a good oxidizing agent of sulfoxide, thus yield of the sulfone being rather small (Table 2). Only when the temperature was elevated, the yield of the sulfone gradually increased (Table 2).



Scheme 7.

Oxidation of Thiosulfonic S-*Ester with $O_2^{\cdot-}$.* In the reaction of unsymmetrical thiosulfonic *S*-ester with $O_2^{\cdot-}$, however, two sulfinic and two sulfonic acids were obtained from both sulfur sides along with a small amount of symmetrical disulfide (*ca.* 25%) from the sulfenyl sulfur side (Eq. 16),[5b)] revealing clearly that

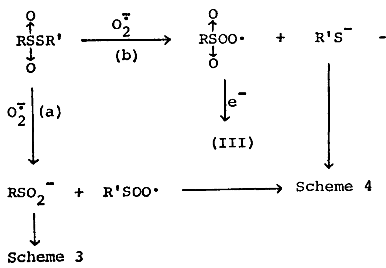
$$R\overset{\substack{O\\ \uparrow}}{\underset{\substack{\downarrow\\ O}}{S}}SR' \xrightarrow[\substack{\text{18-crown-6}\\ \text{pyridine, 0 }^\circ\text{C}\\ \approx 30\text{ min}}]{4\text{ eq. KO}_2} \left[\begin{matrix} RSO_2^- \\ R'SO_2^- \end{matrix}\right. + \left[\begin{matrix} RSO_3^- \\ R'SO_3^- \end{matrix}\right. + R'SSR' \qquad (16)$$

the nucleophilic attack of $O_2^{\cdot-}$ occurs at both sulfenyl (a) and sulfonyl (b) sulfur atoms of the thiosulfonic *S*-ester (Scheme 8). The thiolate anion formed in the initial step must be converted to the disulfide by

Table 7. Change of product distribution[a)]

Entry No.	Substrate	Temp/°C	Time/min	Solvent	Additive	Yield/%	Yield/%		
							RSO_2^-	RSO_3^-	RSSR
1	PhSSPh	23	300	Pyridine	—	—	9	68	—
2	PhSSPh	23	300	Pyridine	Ph_3P	26[b)]	29	67	—
3	*p*-TolSSTol-*p*	22	300	CH_3CN	—	—	6	88	—
4	*p*-TolSSTol-*p*	22	300	CH_3CN	$\mathrm{Ph}\underset{\underset{\mathrm{O}}{\downarrow}}{\mathrm{S}}\mathrm{Ph}$	62[c)]	31	61	—
5	*p*-TolS(O)STol-*p*	18	10	Pyridine	—	—	14	37	50
6	*p*-TolS(O)STol-*p*	17	10	Pyridine	$\mathrm{Ph}\underset{\underset{\mathrm{O}}{\downarrow}}{\mathrm{S}}\mathrm{Ph}$	17[c)]	24	26	50

a) Molar ratio of substrate:KO_2:crown ether:additive = 1:6:1:2 or 1:5:1:2 for disulfide or thiolsulfinate. b) Yield by GC. c) Isolated yield.



Scheme 8.

rapid recombination of the thiyl radicals after one electron transfer. At *ca.* 0 °C, the sulfinate would not be oxidized any further. The low yield of the sulfone formation from added sulfoxide should be also due to the low reaction temperature.

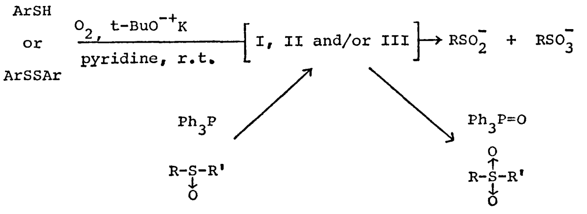
Both this reaction and that of thiosulfinic *S*-ester clearly involve the initial nucleophilic attack of $O_2^{\cdot-}$ at sulfur atoms of S–S linkage and gave partially the disulfide. A similar nucleophilic substitution(S_N2) on sulfur atom of S–S linkage has been observed in the alkaline hydrolyses of both compounds.[37)]††

Addition of the sulfoxide or the phosphine as a trapping agent into the reaction systems of disulfide and thiosulfinic *S*-ester with $O_2^{\cdot-}$ changed distribution of the products (Table 7). Amount of the sulfinate increased appreciably while that of sulfonate decreased only a little by the additives, very likely due to the two competitive reactions, *i.e.* the reactions of peroxysulfinate(II) with sulfoxides or phosphines to the sulfones or the phosphine oxides and the rearrangement of II to the sulfonate.

Thus, the reactions of these organosulfur compounds each having S–S linkage with $O_2^{\cdot-}$ are another S_N2 processes, like the nucleophilic substitution of alkyl halide or tosylate with $O_2^{\cdot-}$.[39)] This S_N2 mechanism with $O_2^{\cdot-}$ is in good accordance with the order of the reactivities of the three disulfidic species (**2**>**3**>**1**).[5)] This order is identical to that of the reactivities of the three in the alkaline hydrolyses.[38)]

Among a few trapping agents used, dimethyl sulfoxide was found to be the best reagent. Phosphines were not the good trapping agents since they reacted easily with several substrates. Olefins are relatively less reactive while the epoxides formed are usually so reactive that the epoxide itself reacted with various species present in the reaction system.

Since the alkaline autoxidation of thiols and disulfides gives sulfinate and sulfonate, and is expected to involve the peroxysulfur intermediates,[8,40)] a mixture of the sulfoxide or the phosphine (2 mmol), thiol or disulfide (1 mmol) and potassium *t*-butoxide (2 mmol) was treated in pyridine (5 ml) under pure oxygen atmosphere at room temperature for 0.5—11 h. Indeed, the sulfone (≈10.6%) or the phosphine oxide (≈20.2%) was obtained besides the autoxidation products of sulfinic and sulfonic acids[41)] (Scheme 9). Both sulfoxides and phosphines were inert under the conditions without any one of these sulfur compounds. Thus, the mechanism for the autoxidation suggested by Berger[8)] is considered to be identical to that of the reactions of disulfides and other related sulfur compounds with $O_2^{\cdot-}$, involving the common peroxysulfur intermediates (I, II, and/or III).



Scheme 9.

Among these peroxysulfur intermediates the peroxysulfenate(I) seems to collapse most readily. The oxidation of sulfoxide with I—III seems to be faster than that of olefin (Tables 1, 2, 5, and 6). The peroxysulfinate(II) is more stable and fairly reactive while only the peroxysulfonate(III) is stable enough to be characterized and hence be utilized for the oxidation of sulfoxide and olefin.

Experimental

General. All the reactions with $O_2^{\cdot-}$ were carried

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†† These two reactions can be also conceivable but the second reaction (B) should be minor since amount of $O_2^{\cdot-}$ is considerably large at the initial stage in the reactions of both **2** and **3**.

$$\text{R-S(O)}_x\text{-S-R}' \xrightarrow{O_2^{\cdot-}} \text{R-S(O)}_x\text{OO}\cdot + \text{R}'\text{-S}^- \qquad \text{(A)}$$

$$\text{R-S(O)}_x\text{-S-R}' + \text{R}'\text{-S}^- \longrightarrow \text{RS(O)}_x^- + \text{R}'\text{SSR}' \qquad \text{(B)}$$

out under dry argon atmosphere.

Melting points were taken on a Yanaco instrument. NMR spectra were recorded on a Hitachi Perkin-Elmer R-20 spectrometer. Gas and liquid chromatographic analyses were carried out with Shimadzu GC-6A and Yanaco L-1030 instruments, respectively. Specific rotations were calculated from the values of optical rotations which were measured by a JASCO DIP-140 polarimeter using a 5 cm quartz cell.

Materials. KO_2 was obtained from Ventron Products. 18-Crown-6 was from Wako Pure Chemical Ind. and used after drying *in vacuo* by heating at 60—70 °C. All the solvents used except for CH_2Cl_2 were purified by distillation and dried with drying agent, as shown in the preceding paper.[5b] Purification of CH_2Cl_2 was performed at first by drying with $CaCl_2$ and then distillation after filtration. Distilled CH_2Cl_2 was stored in dark under N_2 in the presence of $CaCl_2$.

Preparation and purification of all the disulfides, thiosulfinic *S*-esters, thiosulfonic *S*-esters, sodium thiolates, and sodium sulfinates as substrates are reported in our previous paper.[5b]

Extra pure reagent grade triphenyl- and tributylphosphines, *trans*-stilbene and trichloromethanesulfonyl chloride from Wako Pure Chemical Ind. were directly used without any treatment. Tosyl and mesitylene-sulfonyl chlorides from Wako were used after recrystallization from hexane. Benzoyl chloride was purified by distillation and dehydration with $CaCl_2$, and DMSO was purified by distillation and stored under dry nitrogen gas. Diphenyl sulfoxide and acenaphthylene from Tokyo Kasei Kogyo were also used after recrystallyzation. Three chalcone derivatives were all from Aldrich Chemical Company and directly used for the reaction.

Sulfoxides, *i.e. p*-chlorophenyl methyl, methyl *p*-tolyl, and methyl phenyl sulfoxides, were prepared by oxidations of the corresponding sulfides with H_2O_2 in AcOH.[42] All the sulfoxides were determined by measuring the absorption peaks at the region of 1040—1060 cm^{-1} in their IR spectra. Thianthrene 9-oxide was prepared by a known method.[43] Benzenesulfenyl chloride was prepared by the reaction of benzenethiol with gaseous chlorine according to a known method.[44] The crude product was purified by distillation (bp 75—79 °C/3.0 Torr (1 Torr=133.322 Pa)). *p*-Toluenesulfinyl chloride was also prepared by the reaction of *p*-toluenethiol with gaseous chlorine in the presence of acetic anhydride.[44] The crude product was purified by distillation (bp 110 °C/2.5 Torr).

*(+)-*d*-Camphor-10-sulfonyl chloride* was prepared by treating (+)-*d*-camphor-10-sulfonic acid (from Wako) with PCl_5. To the sulfonic acid (0.5 mol) dissolved in $CHCl_3$ (150 ml) was added slowly solid PCl_5 (0.7—0.9 mol). After slow evolution of HCl gas, the mixture was heated at refluxing temperature for *ca.* 1 h. The resulting clean colorless mixture was washed more than three times with water. Organic layer was dried with $MgSO_4$ and the solvent was evaporated to afford the sulfonyl chloride which was purified by recrystallization from hexane. Yield 72%. IR (KBr, cm^{-1}, S=O) 1365 and 1168. $[\alpha]^{25}_{D}+20.9°$ (c=4.3, $CHCl_3$) (lit,[45] $[\alpha]^{25}_{D}+28.8°$ (C=4.2, $CHCl_3$).

Oxygen Trapping Reaction. The amount of KO_2 in the reaction of each substrate was not kept constant and hence is shown in each Table, which also shows reaction time, molar ratio of additives, and solvent used.

Oxidation of Additives Added in The Reaction System with $O_2^{-\cdot}$. The following is a typical run for the "*Oxidation of Sulfoxide.*" A solution of diphenyl sulfoxide (2 mmol) and di-*p*-tolyl disulfide (1 mmol) in dry acetonitrile (5 ml) was added with a syringe into a heterogeneous solution of KO_2 (6 mmol, finely powdered in advance and stored under nitrogen) and dry 18-crown-6 (1 mmol, dried *in vacuo* at 60—70 °C) in the same solvent in a two-necked flask under dry argon atmosphere at 21 °C. The resulting heterogeneous mixture was stirred at the same temperature for 6 h, during which the substrate generally disappears nearly completely. After the consumption of the substrate the reaction mixture was quenched by pouring into excess cold water containing crushed ice. Extraction with $CHCl_3$, drying with $MgSO_4$ and evaporation of $CHCl_3$ gave an oily residue. The residue, containing oxidized sulfone, unreacted sulfoxide, and crown ether, was subjected to column chromatography through silica gel using an eluent of a mixed solvent of hexane:EtOAc:$CHCl_3$=4:1:1. Yield of sulfone was 54% based on the starting disulfide.

When a sulfoxide bearing methyl group was used the yield of the sulfone was directly determined by integration ratio of the NMR spectrum of the crude mixture. The sulfones formed were identified by comparing the melting points or chemical shifts in NMR spectra with those of authentic samples.

Oxidation of phosphines in the reaction system was carried out according to the same procedure as mentioned for sulfoxide. The yield of the phosphine oxide was measured by injecting the reaction mixture directly into GC since the phosphine was actually oxidized in the usual work-up. The phosphine oxide was not produced at all, even if the reaction mixture was injected directly into GC instrument. The phosphine oxides obtained were found to be identical to the authentic samples by comparing the retention times in GC.

Epoxidation of olefin in the reaction system was also carried out similarly. However, the work-up was different, *i.e.* the reaction mixture, after stirring till the disappearance of most of substrate, was stirred further for a few hours. The resulting heterogeneous reaction mixture was filtered and the residue was washed with a large amount of CH_2Cl_2 (≈40 ml). The combined organic layer was subjected to the assay after evaporation of organic solvent. Yield of the epoxide in the residue was sometimes determined by isolation by column chromatography through silica gel using benzene (or benzene–hexane) as an eluent. However, the amount of the epoxide was determined usually by HPLC. In some cases, the yield of the epoxide was directly estimated by measuring the NMR spectrum of the residual mixture. Epoxides thus obtained were identified by comparing the chemical shifts of the methine protons with those of the authentic samples as shown in Table 4.

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