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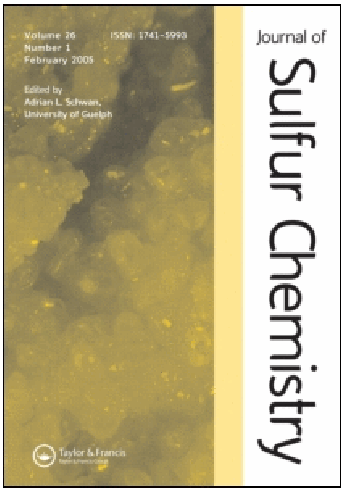

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Photooxidation of Organosulfur Compounds

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PHOTOOXIDATION OF ORGANOSULFUR COMPOUNDS

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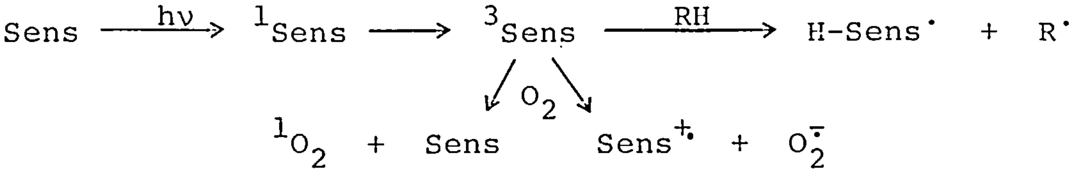
Considerable attention has focused on the oxidation of sulfur compounds in connection with the study of photodynamic action with biological substrates. Irradiation of alkyl sulfides in the presence of a photosensitizer and oxygen gives the corresponding sulfoxides in approximately quantitative yields after consumption of one half mole of oxygen per mole of sulfide. These reactions presumably involve an intermediate such as a peroxy sulfoxide or possibly a cyclic peroxide which is capable of converting another sulfide molecule to the corresponding sulfoxide or rearranging more slowly to the isomeric sulfone. Clean conversions to sulfoxides were observed upon direct photolysis of sulfides in air. In this case an excited charge transfer complex mechanism between oxygen as an electron acceptor and the sulfide as an electron donor has been proposed. A number of biologically important molecules containing disulfide bond are known to be succeptible to photodynamic action. Photosensitized oxygenation of the simplest acyclic disulfides has been reported to give the corresponding thiolsulfinates in good yield. The molecular oxygen reacts with thiones very efficiently to yield the corresponding carbonyl compounds, and singlet oxygen may be involved as the reactive species. Several mechanistic studies of the photooxygenation of vinyl sulfides show oxidative cleavage of the carbon-carbon double bond to take place via the corresponding 1,2-dioxetane intermediate. On the other hand, tri- and tetrasubstituted thioethylenes give products due to oxidative cleavage of the C-S bond. The oxidation of vinyl sulfides possessing an activated double bond and allylic hydrogen atoms affords both 1,2-dioxetane mode products and ene reaction mode products. The dioxetane mode is favored exclusively in protic solvents and slightly favored over the ene mode in aprotic solvents. The photooxidation of vinyl sulfides sensitized by 9,10-dicyanoanthracene has also been studied, and may proceed by electron transfer from the sulfur atom to the sensitizer which again transfers its electron to oxygen to give a superoxide anion radical.

Photosensitized oxygenation of heterocyclic compounds containing sulfur atoms gives products derived from an intermediate endoperoxide. Some sulfur ylides have been oxidized with singlet oxygen to give carbonyl oxide intermediates which can transfer an oxygen atom to an acceptor.

Introduction

Oxygen as a chemical species has undergone two centuries of investigation. One might have imagined that it would have no great new secrets to reveal, but research on molecular oxygen is effecting a revolution in understanding the role of oxygen in physical, chemical, and biological systems with special features in photon and radiation-induced reactions.

The absorption of light in living organisms by endogeneous or exogeneous photosensitizers in the presence of oxygen causes oxidation which leads to many chemical and biological effects known as photodynamic action.[1-9] Recently, chemists have pointed out that in some cases photodynamic action involves either singlet oxygen or superoxide ion.



$$\mathrm{Sens} \xrightarrow{h\nu} {}^{1}\mathrm{Sens} \longrightarrow {}^{3}\mathrm{Sens} \xrightarrow{RH} \text{H-Sens}^{\bullet} + R^{\bullet}$$

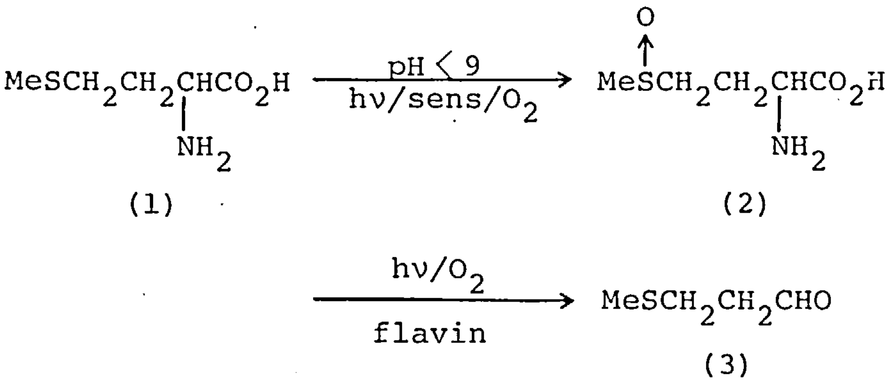
$$^{3}\mathrm{Sens} \xrightarrow{O_2} {}^{1}O_2 + \mathrm{Sens} \quad ; \quad {}^{3}\mathrm{Sens} \xrightarrow{O_2} \mathrm{Sens}^{+\bullet} + O_2^{-\bullet}$$

Singlet oxygen and superoxide ion, as well as hydrogen peroxide are known to be formed in normal biological processes.[10,11]

Recently, considerable attention has focused on the oxidation of sulfur compounds in connection with the study of photodynamic action with biological substrates containing cystine, methionine, or lipoic acid, or other sulfur linkages,[9,12-14] and more recently, for naturally occurring optically active sulfoxides such as sulforaphen ($MeSOCH{=}CHCH_2NCS$, the first known natural product in which the optical activity does not depend on the carbon skeleton)[15], biotin l-sulfoxide[16], and S-methyl-L-cysteine sulfoxide.[17] It is hoped that this survey of the photooxidation of sulfur compounds will stimulate new interest in this family of compounds.

I. Sensitized Photooxidation of Sulfides

Some of the earliest information on photodynamic action involving sulfur compounds was derived from the studies of Weil and coworkers[13] on the dye-sensitized oxygenation of methionine (1) to the corresponding sulfoxide (2)[18], with flavins under some conditions methional (3) is the product. These photooxidations to the sulfoxide have been strongly correlated with the deactivation of several enzymes, for example phosphoglucomutase and chymotrypsin.[14]



$$\underset{(1)}{MeSCH_2CH_2\underset{NH_2}{\underset{|}{C}}HCO_2H} \xrightarrow[h\nu/sens/O_2]{pH < 9} \underset{(2)}{Me\overset{O}{\overset{\uparrow}{S}}CH_2CH_2\underset{NH_2}{\underset{|}{C}}HCO_2H}$$

$$\xrightarrow[flavin]{h\nu/O_2} \underset{(3)}{MeSCH_2CH_2CHO}$$

(1) (2) (3)

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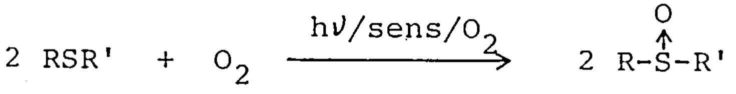
The oxidation of methionine depends on the pH, with one mole of oxygen consumed per mole of methionine at high pH; at pH of 5 or lower, one mole of oxygen oxidizes two methionines.[9]

The stoichiometry is the one reported for the oxidation of simple dialkyl sulfides. Irradiation of dialkyl sulfides in the presence of Rose Bengal and oxygen gives the corresponding sulfoxides in approximately quantitative yields after consumption of one half mole of oxygen per mole of sulfide according to the overall reaction.[19,20]



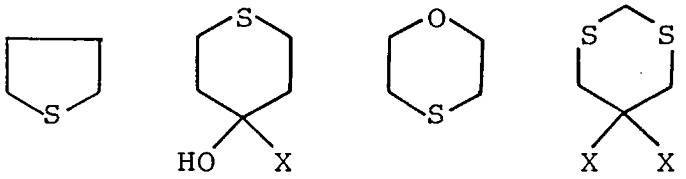
$$2\ RSR' + O_2 \xrightarrow{h\nu/sens/O_2} 2\ R\text{-}\overset{\overset{O}{\uparrow}}{S}\text{-}R'$$

R = R' -Et, $-(CH_2)_2Me_3$, $-CH_2CH_2OH$,

$-CH_2-CH=CH_2$, $-CH_2Ph$, $-CMe_3$

R ≠ R' $EtSC_6H_4$-Me-p, $x-C_6H_4-S-(CH_2)_nCOOH$

x=H, Me, Cl n=1-3



Irradiation of dimethylsulfoxide and diethylsulfoxide in the presence of Rose Bengal and oxygen yields the corresponding sulfones in a rather slow reaction.

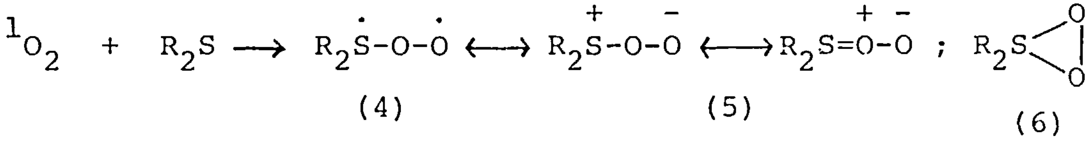
$$2Me\text{-}SO\text{-}Me \xrightarrow{sens./h\nu\ /O_2} 2\ Me\text{--}SO_2\text{-}Me$$

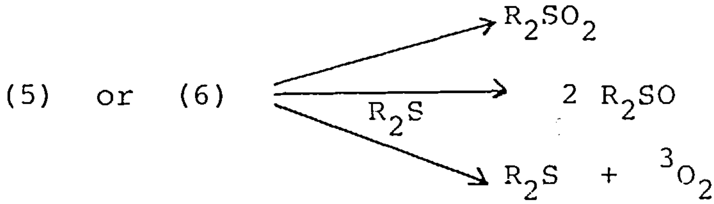
$$2\ Et\text{-}SO\text{-}Et \xrightarrow{sens./\ h\nu\ /O_2} 2\ Et\text{-}SO_2\text{-}Et$$

Transformation into sulfoxides proceeds efficiently in methanol, but very inefficiently in benzene. These reactions presumably involve an intermediate which was formulated by Gollnick as a biradical (4)[21]; however, Foote and Peters recently developed convincing evidence that singlet oxygen is the reactive intermediate which reacts directly with sulfide sulfur to yield a reactive peroxy sulfoxide (5) or possibly a cyclic peroxide (6) which is capable of converting another sulfide molecule into sulfoxide, or rearranging more slowly into sulfone in competition with quenching by

$$\text{Sens} \xrightarrow{h\nu} {}^{1}\text{Sens} \longrightarrow {}^{3}\text{Sens}$$

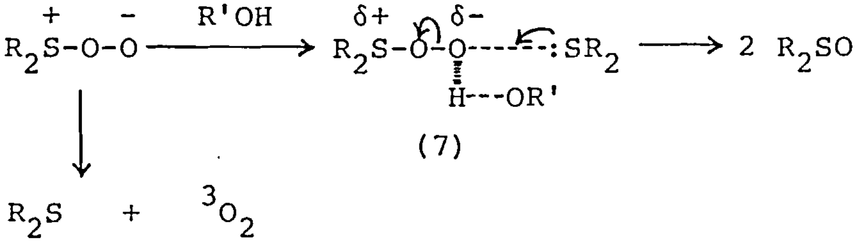
$$^{3}\text{Sens} + {}^{3}O_2 \longrightarrow \text{Sens} + {}^{1}O_2$$


(4) (5) (6)



dissociation into sulfide and triplet oxygen.[22,23]

The remarkable effect of protic solvents is perhaps best explained by the above mentioned peroxy sulfoxide intermediate suffering either nucleophilic attack by a second sulfide molecule to form the sulfoxide if the intermediate is hydrogen bonded [(7)] by solvent, or collapse to ground state oxygen after collision with a second sulfide molecule if no hydroxylic solvent is available for hydrogen bonding.


(7)

The rate of the reaction of diethyl sulfide with singlet oxygen in methanol is $1.71 \times 10^{7}\text{mol}^{-}\text{s}^{-1}$, the total rate of reaction plus quenching is the same as that in benzene ($2.0 \times 10^{7}\text{mol}^{-}\text{s}^{-1}$), although the process is complete reaction in methanol and 95% quenching in benzene[24]. Steric blocking of the sulfide has a considerable effect; the relative rates of reaction of diethyl, diisopropyl, and di-t-butyl sulfides are 1.0 : 0.15 : 0.009; an approximately tenfold decrease in rate occurs for every pair of methyl groups added symmetrically.

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Furthermore, diphenyl sulfide reacts 2800 times slower than diethyl sulfide with singlet oxygen, however, when mixtures of diethyl sulfide and diphenyl sulfide are irradiated, both diphenyl sulfoxide and diethyl sulfoxide are formed in comparable yields.[22]

TABLE I

Rate Constants for Reaction with $^1O_2$ and Oxidation Potentials for Various Sulfides

RSR′	k_s (mol^{-1}s^{-1}) × 10^{-7} [a]	$K_{rel.}$	$E_{p/2}$V (vs SCE)[b]
Et_2S	1.71 ± 0.06[c]	1.00	1.65
PhSMe	0.20 ± 0.01	0.12	1.51
Ph_2S	0.01[c]	0.006	1.65
i-Pr_2S	0.25 ± 0.003	0.15	1.63
t-Bu_2S	0.15[c]	0.009	1.65
p-Cl-C_6H_4SMe	0.083 ± 0.005	0.048	1.60
p-Me-C_6H_4SMe	0.31 ± 0.02	0.18	1.32
p-MeO-C_6H_4SMe	0.53 ± 0.02	(0.31)	1.13

[a] in methanol assuming $K_d = 1.1 \times 10^5 s^{-1}$, Rose Bengal sensitized

[b] Half-peak potential in CH_3CN.

[c] Methylene Blue sensitized.

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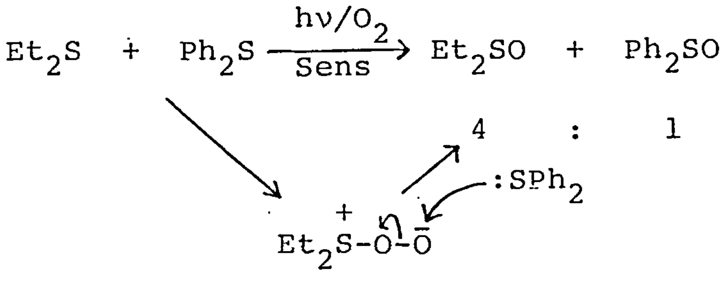

Competitive cooxidation of pairs of p-monosubstituted diphenyl sulfides with singlet oxygen showed a *ρ*-value of −0.94, and with diethyl peroxy sulfoxide a *ρ*-value of −0.61.[25]

Singlet oxygen rate constants have been measured for cyclic sulfides. While the rate constants for the six- and seven-membered ring compounds are about the same as those for comparable acyclic compounds, that of tetrahydrothiophene is a factor of three greater.[26]

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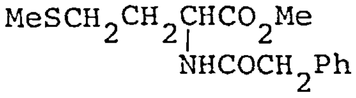
TABLE II

Rate Constants for the Reaction of $^1O_2$ with Cyclic Sulfides.

Sulfide	k_s (mol^{-1}s^{-1}) × 10^{-7}
$(CH_2)_4S$	4.2
$(CH_2)_5S$	1.3
$(CH_2)_6S$	1.3
$O(CH_2CH_2)_2S$	0.15

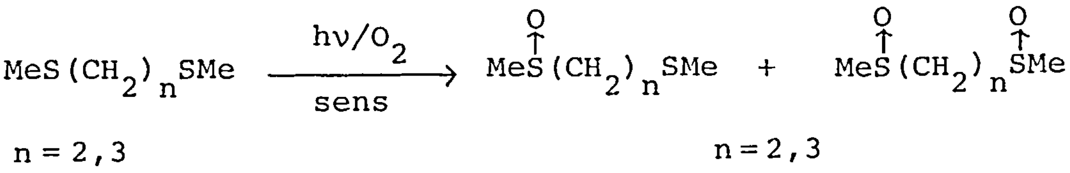
Because of the importance of methionine photooxidation in photodynamic action, k_s was measured for a chloroform soluble methionine derivative (9) to be about the same as that for a sulfide of similar structure, but less than 3×10^7 mol^{-1}s^{-1} in methanol -water[27]; and 5×10^7 mol^{-1}s^{-1} in water[28].



$$MeSCH_2CH_2\underset{NHCOCH_2Ph}{\underset{|}{C}H}CO_2Me$$

(9)

In compounds containing bis-sulfide (10) groupings; 1,2-bismethylthioethane, 1,3-bismethylthiopropane and 1,4-dithiane, the second sulfide moiety can serve as an intramolecular trap for the intermediate formed by addition of singlet oxygen to the first sulfur atom, the product is the disulfoxide along with some monosulfoxide[23]. The fraction of intramolecular reaction is concentration dependent with intramolecular trapping being favored at low concentration.

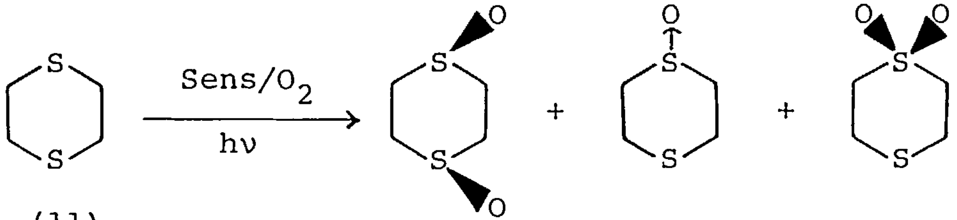


$$MeS(CH_2)_nSMe \xrightarrow[sens]{h\nu/O_2} Me\overset{O}{\overset{\uparrow}{S}}(CH_2)_nSMe + Me\overset{O}{\overset{\uparrow}{S}}(CH_2)_n\overset{O}{\overset{\uparrow}{S}}Me$$

$n = 2,3$ $n = 2,3$

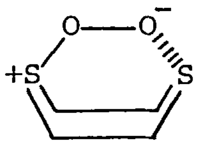
(10)

1,4-Dithiane also undergoes both inter- and intramolecular reactions; however, intramolecular reaction is less efficient than with either of the acyclic bis-sulfides. Intramolecular photooxidation of 1,4-dithiane (11) was observed only in solvents such as benzene and dry acetonitrile in which oxidation is extremely inefficient compared to methanol. No trans disulfoxide was detected in any of the runs.



(11)

The intramolecular modes of quenching and of reaction are inefficient, probably because of conformational unavailability of the sulfide group in the peroxy sulfoxide intermediate which presumably exists in the chair form. Intramolecular quenching or reaction would require a boat conformation (12). This could also explain why intramolecular oxidation is more efficient with the acyclic disulfide (13).



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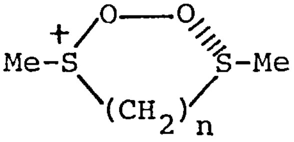
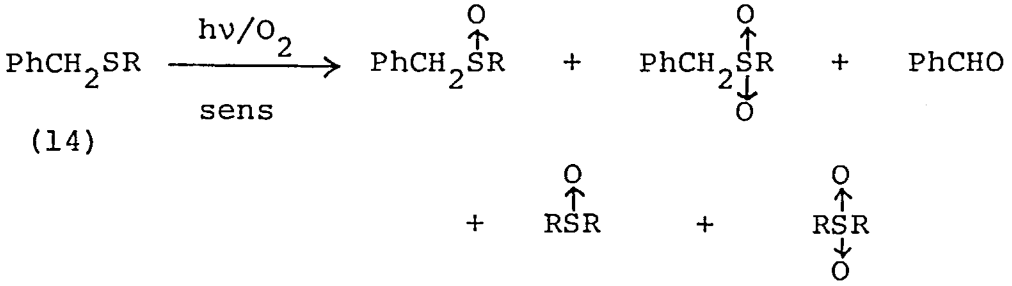


(13)

Favored with n=2

The photooxidation of some sulfides gives unusual products. Alkyl benzyl sulfides (14) are susceptible to,photooxygenation giving alkyl benzyl sulfoxide and some alkyl benzyl sulfone. However, C—S bond cleavage products are obtained as major products.[29]



$$PhCH_2SR \xrightarrow[\text{sens}]{h\nu/O_2} PhCH_2\overset{\overset{O}{\uparrow}}{S}R + PhCH_2\underset{\underset{O}{\downarrow}}{\overset{\overset{O}{\uparrow}}{S}}R + PhCHO + R\overset{\overset{O}{\uparrow}}{S}R + R\underset{\underset{O}{\downarrow}}{\overset{\overset{O}{\uparrow}}{S}}R$$

(14)

TABLE III

Photooxidation of Benzyl Alkyl Sulfides

$PhCH_2S$-R	Yield	Sulfoxide	Sulfone	Frag.
$-CH_2Ph$	76%	36%	19%	45%
—t-Bu	80	35	19	46
$-CH_2Bu$—t	81	25	—	75
$-CH_2CH_2CH=CH_2$	95	28	6	64

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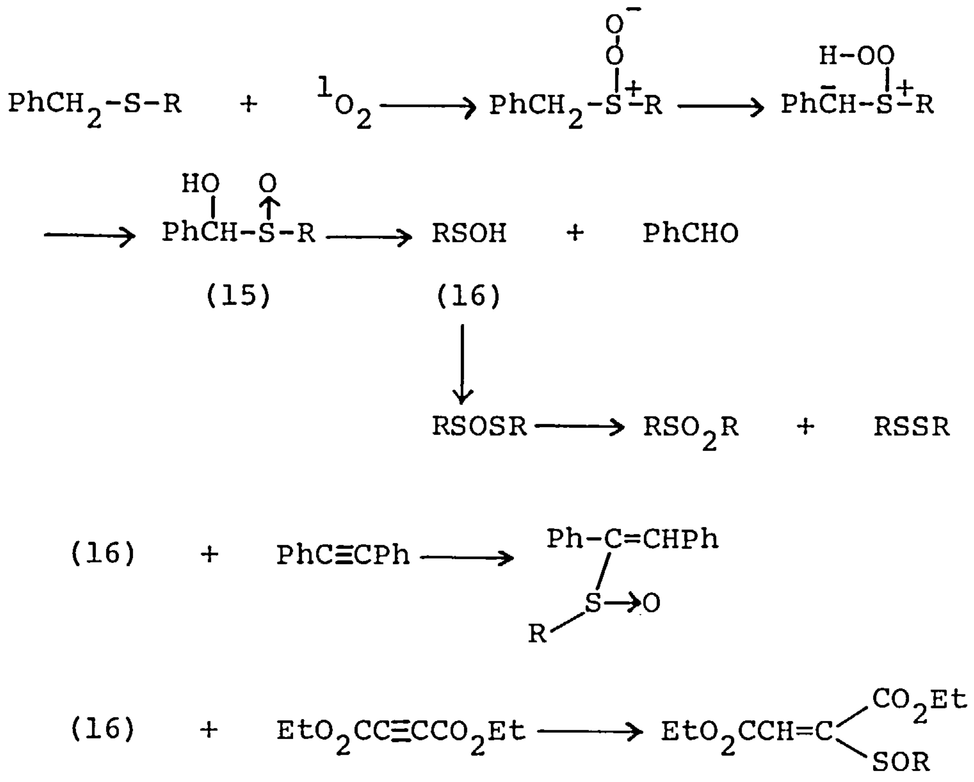
These fragmentation products may result from decomposition of the hydroxy sulfoxide (15) to form benzaldehyde and sulfenic acid (16) which can be trapped with diphenylacetylene or dicarboethoxyacetylene.

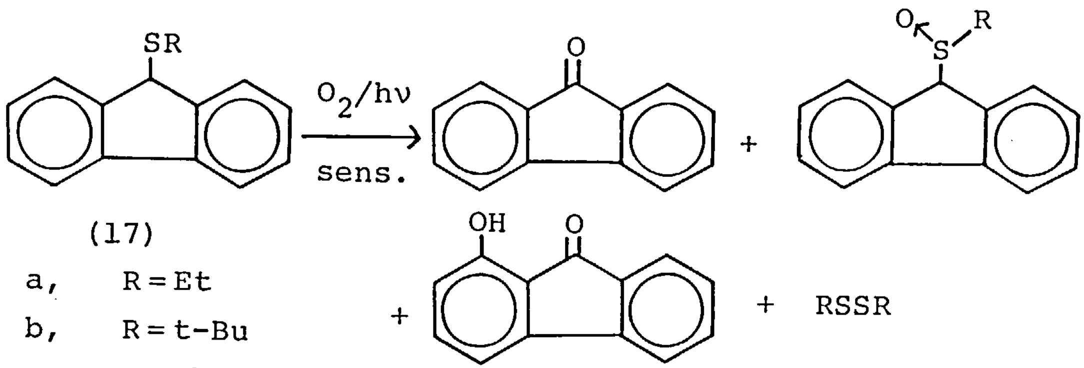


(15) (16)

(16)

(16)

Photosensitized oxygenation of 9-fluorenyl alkyl sulfides (17) in dry benzene or dichloromethane gives the corresponding sulfoxides and fluorenone, but also 1-hydroxy-9-fluorenone in comparable yield[30]



(17)

a, R = Et

b, R = t-Bu

c, R = Ph

(18)

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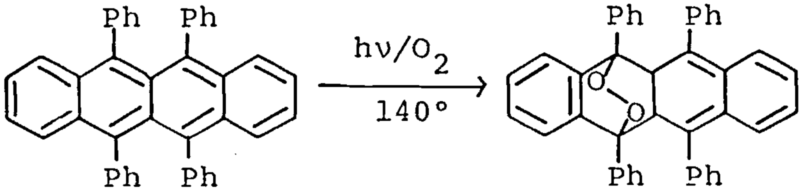
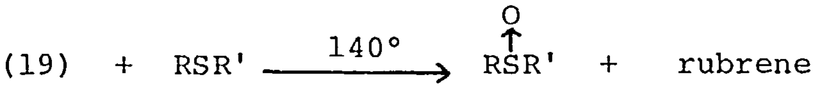
On the other hand, when rubrene peroxide (19), a source of singlet oxygen at 140°, is heated with an aliphatic sulfide, the red color of rubrene rapidly emerges and the reaction forming aliphatic sulfoxide appears to be complete in a short time. Under the same conditions, the rubrene peroxide was heated with deuterated allyl phenyl sulfide (20), and the isomerization to (21) was greatly accelerated.[31]



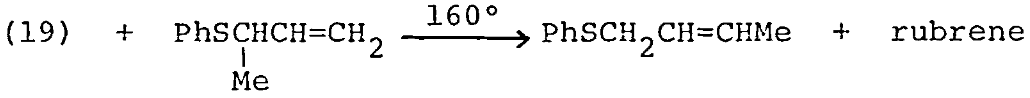
(19)

$$(19) \xrightarrow{140^\circ} \text{rubrene} + {}^1O_2$$



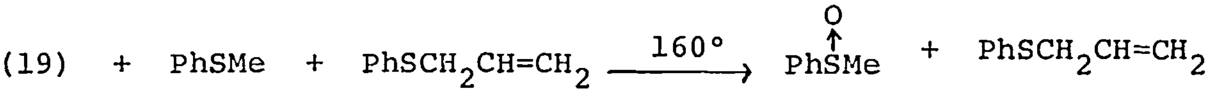
$$(19) + RSR' \xrightarrow{140^\circ} R\overset{O}{\overset{\uparrow}{S}}R' + \text{rubrene}$$

$$(19) + \underset{(20)}{PhSCH_2CH{=}CD_2} \xrightarrow{160^\circ} \underset{(21)}{PhSCD_2CH{=}CH_2} + \text{rubrene}$$



$$(19) + PhS\underset{\displaystyle Me}{\underset{|}{C}}HCH{=}CH_2 \xrightarrow{160^\circ} PhSCH_2CH{=}CHMe + \text{rubrene}$$

The unusual behavior of singlet oxygen towards allyl phenyl sulfide is confirmed in studies of the oxidation of thioanisole to its sulfoxide by endoperoxide sources of singlet oxygen. The yield of methyl phenyl sulfoxide (9%) realized in the absence of allyl phenyl sulfide is nearly doubled (17%) in the presence of the allyl sulfide, but no allyl phenyl sulfoxide could be detected.



$$(19) + PhSMe + PhSCH_2CH{=}CH_2 \xrightarrow{160^\circ} Ph\overset{O}{\overset{\uparrow}{S}}Me + PhSCH_2CH{=}CH_2$$

The simplest explanation of the role of singlet oxygen in bringing about an acceleration of the thia-allylic rearrangement must encompass some common features in the catalytic action of all these reagents. Since there are no products formed from direct covalent bonding of singlet oxygen to either the S or C centers of the substrate, it must be assumed that its resistance against quenching must be the result of a reversible donor-acceptor complex (22) which is considerably more stable than that formed with thioanisol. The following scheme is presented as a rationalization of the facts discussed above.

Thia-allylic Catalysis by Singlet Oxygen[a]

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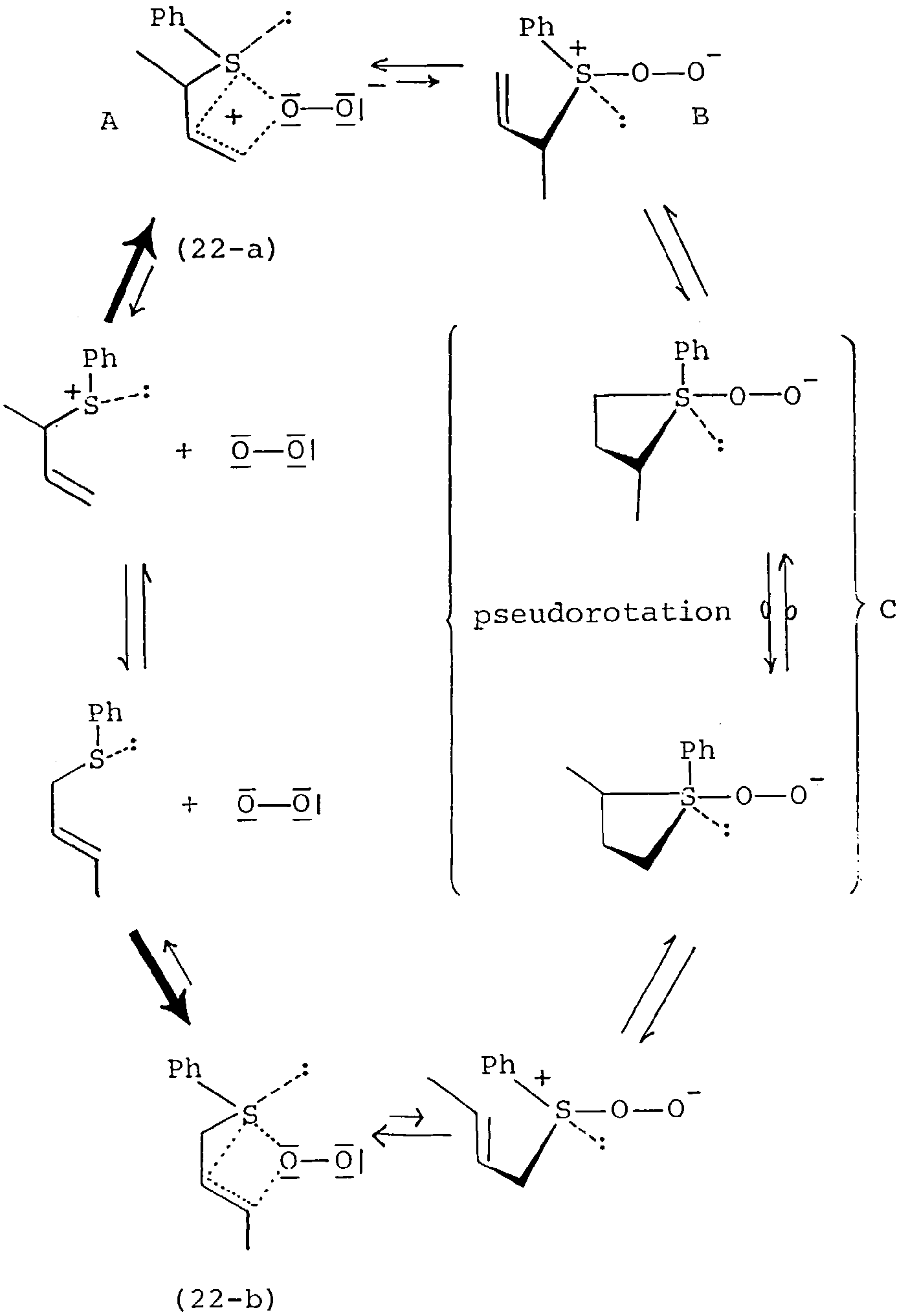

[a]A, donor-acceptor complex stabilizing $^1O_2$; B, rearrangement of complex with octet expansion and TBP formation; C, TBP with weak axial bond in the persulfide.

II. Interactive Intermediates Involving Sulfur and Oxygen

The assumption of a possible transitional intermediate such as a peroxy sulfoxide in the reaction between singlet oxygen and divalent sulfur led to the idea that a related species might be stable enough to allow direct observation or isolation.

This idea was vindicated in the work of Martin[32] who succeeded with the oxidative introduction of the hexafluorocumyloxy ligand (OR_f) to the sulfur of diphenyl sulfide to give the sulfurane (23), a ketal analog derived from a sulfoxide, a crystalline material stable indefinitively at room temperature. The sulfurane (23) is very sensitive to moisture and reacts very rapidly at −78°C with hydrogen peroxide in the presence of dimethyl sulfide to give 52% dimethyl sulfoxide. The reaction of dimethyl sulfide with hydrogen peroxide is slow under these conditions in the absence of the sulfurane. In the absence of dimethyl sulfide, the reaction of the sulfurane with hydrogen peroxide at −78° gives diphenyl sulfone (80%), diphenyl sulfoxide (15%), and a trace of diphenyl sulfide. The rearrangement of (24) to sulfone is shown by the above product data to be comprehensive with loss of oxygen to give sulfide or, in the presence of dimethyl sulfide, with the pictured reductive scavenging reaction.

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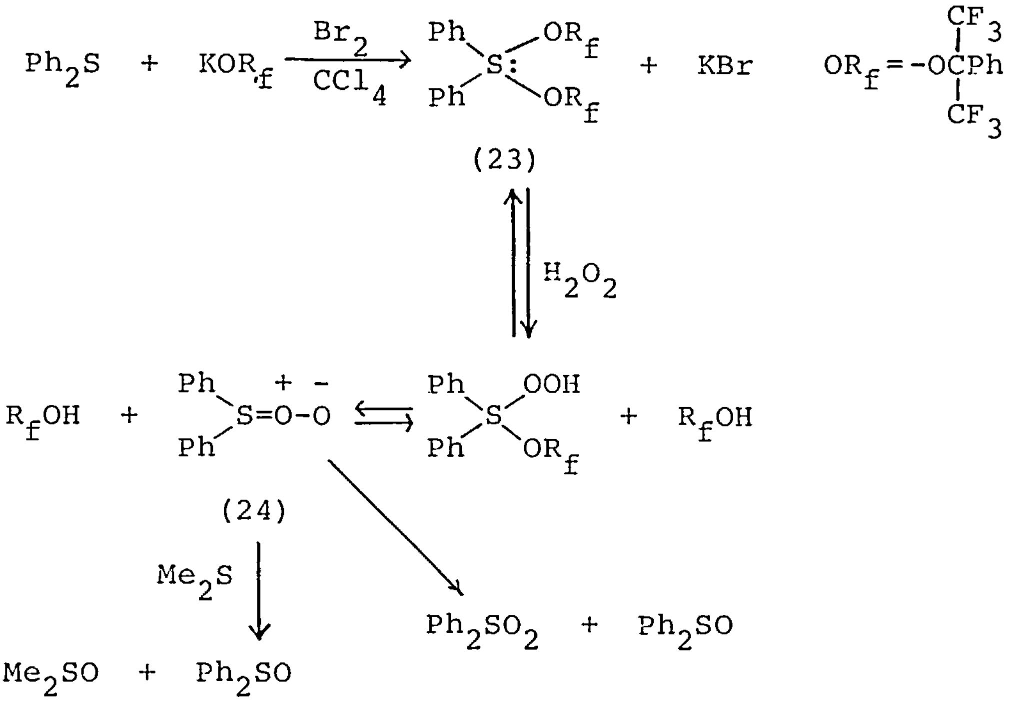
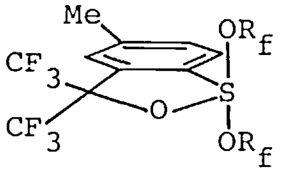


The analogous reaction of trialkoxysulfurane (25) with hydrogen peroxide gives a related scavengeable intermediate formulated as (26) or (27).



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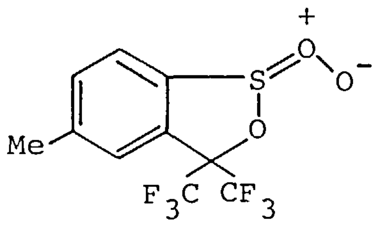

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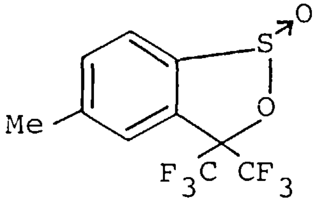

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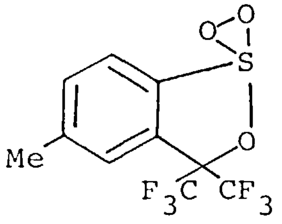

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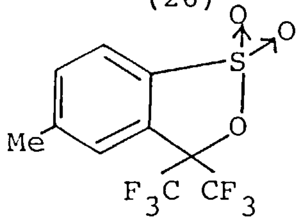

(28)

The reaction of (25) with hydrogen peroxide at −78°C in dichloromethane gives a sultone (28) in quantitative yield. In the presence of excess dimethyl sulfide the transient intermediate is diverted quantitatively to give the sultine (29) instead of the sultone, and 90% of dimethyl sulfoxide is formed.

Competitive kinetic studies of the oxidation with (24) of mixtures of symmetrically disubstituted diphenyl sulfides at −78°C showed the oxidant to an electrophile taking part in a reaction with a *p*-value of −0.43 while the corresponding reaction with (26) or (27) gave a *p*-value of −0.86.

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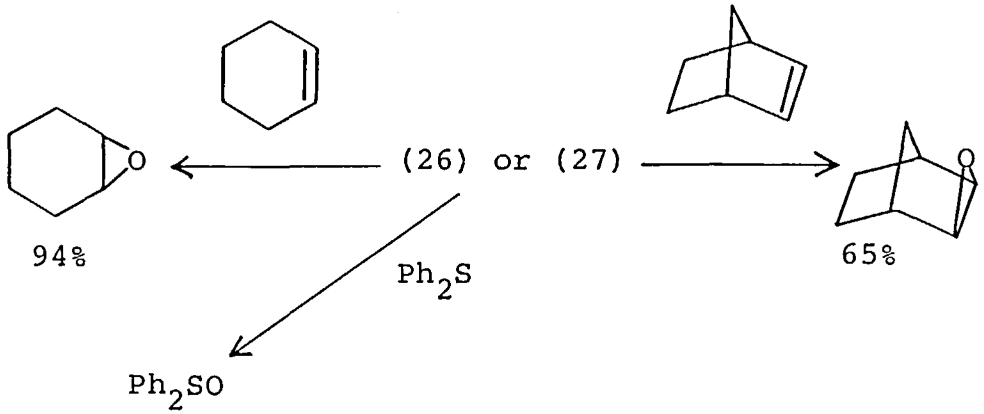

When peroxy sulfoxide (24) is generated in the presence of cyclohexene, no reaction with olefin is observed. However, peroxy sulfoxide (26) or (27) is trapped by added olefin. When norbornene is treated with excess oxidizing agent at −78°C and then warmed to room temperature, exo-norbornene oxide is obtained in 65% yield. Similarly, cyclohexene is converted into the epoxide in 94% yield.

An oxenoid system mechanism, which could resemble those of biological epoxidations, is suggested for this epoxidation reaction.[34] Edward has also reported

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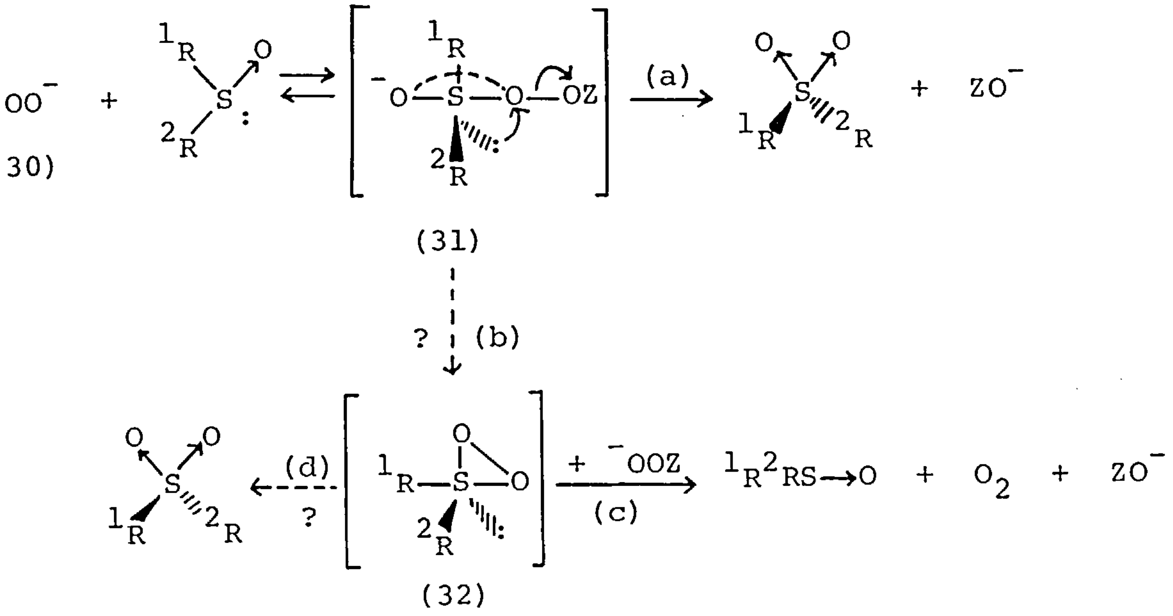
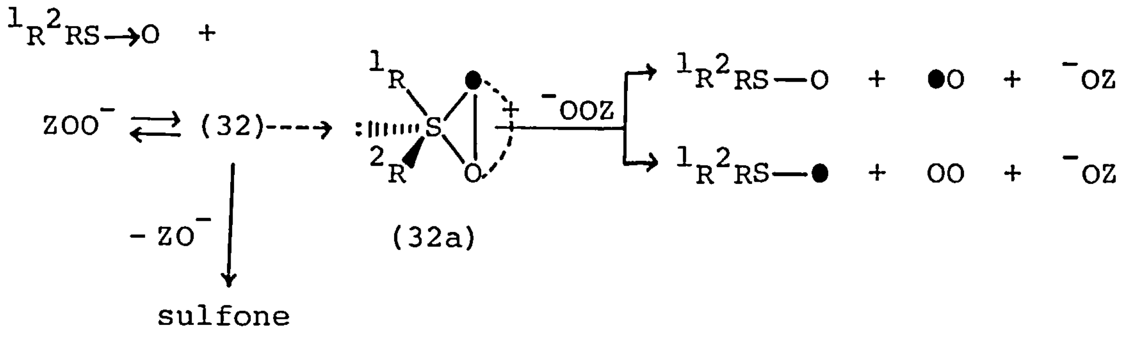
a method of producing this peroxy sulfoxide intermediate[35]. One instance of possible formation of such an intermediate is seen in a side branch of the reaction of caroate (30) with sulfoxides (which produces sulfones in high yield).



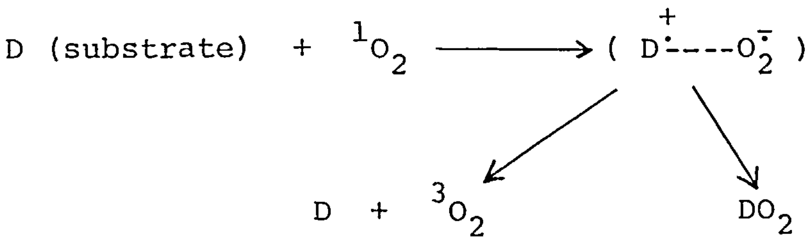
Dioxirane formation in peroxide reactions



(with $^{18}O = \bullet$; $Z = {}^{-}OSO_2{-}$)

This encouraged these authors to carry out an exploratory labeling experiment. Using ^{18}O labeled p-Tol-SO-Ph (7.4 ± 0.3%)[36], the labeled sulfoxide was allowed to react with unlabeled caroate and the small amount of sulfoxide recovered analyzed for its ^{18}O contents. The sulfoxide now contained 6.6 ± 0.5% ^{18}O label indicating that only a small, if any, loss of label had occurred. Since the recovered sulfoxide showed practically no loss of label, it can be assumed that a fraction of the overall reaction between sulfoxide and caroate can actually be diverted along a pathway involving dioxathiirane formation.

Some photosensitized oxygenations have been suggested to involve interaction of singlet oxygen with electron rich donors, such as amines, phenol, some metal complexes, sulfide, iodide, azide, and superoxide ion etc., to give a charge-transfer complex (or perhaps even complete electron transfer in some cases) which can either transfer the electron back, giving ground state oxygen, or combine to give product (DO_2).[37]



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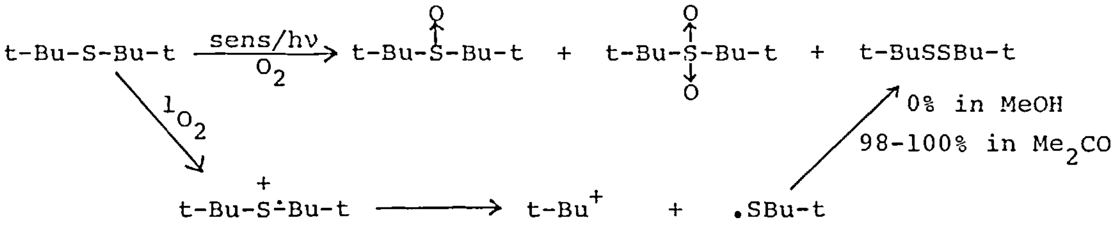
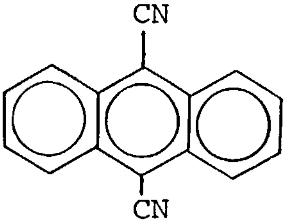
Evidence for the involvement of ion radicals in photooxidation comes from the observation of cleavage of certain sulfides with formation of unoxidized disulfides. Unlike the benzyl alkyl sulfides, di-t-butyl sulfide gives, on oxidation with several photosensitizers, in addition to the corresponding sulfoxide and sulfone, amounts of di-t-butyl disulfide varying from traces with Rose Bengal or methylene blue in methanol to 97%.and 100% in acetone with Rose Bengal dissolved or bound to polymer beads, respectively. The yield of the disulfide may be a measure of the relative rates with which the cation radical dissociates to the t-butyl cation and the t-butyl thiyl radical in the various media.[38]



The other products of the photooxidations are mixtures of di-t-butyl sulfoxide and di-t-butyl sulfone, these mixtures becoming steadily richer in sulfone as the reaction progress. No disulfide was produced with sensitizer in the absence of oxygen. Oxygen plays an essential part in generating the cation radicals, even though direct attack of singlet oxygen on the sulfide is not a part of the process.

Another sensitizer which might be expected to generate a radical anion on excitation in the presence of an electron donor is 9,10-dicyanoanthracene (33).[39] Foote and coworkers found this compound to be a sensitizer for oxygenation without any evidence of singlet oxygen being involved, yet its action in producing diphenyl sulfoxide from diphenyl sulfide suggests that the oxidation intermediate might be a peroxy sulfoxide or similar intermediate (24).



$$\xrightarrow{h\nu} DCA^{*} \xrightarrow{Ph_2S} DCA^{\overline{\cdot}} + Ph_2S^{\overset{+}{\cdot}}$$

(DCA) (33)

$$DCA^{\overline{\cdot}} + {}^{3}O_2 \longrightarrow DCA + O_2^{\overline{\cdot}}$$

$$\begin{tikzcd}
Ph_2S^{\overset{+}{\cdot}} + O_2^{\overline{\cdot}} \arrow[r] & Ph_2\overset{+}{S}\text{-}OO^{-} \arrow[dl] \\
Ph_2SO &
\end{tikzcd}$$

(24)

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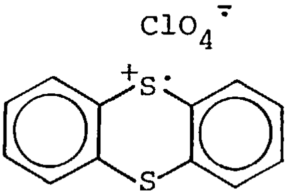
It was found that diphenyl sulfide was three times as reactive as diethyl sulfide, whereas diphenyl sulfide is 2800 times less reactive than diethyl sulfide toward singlet oxygen (in methanol).

Cation radicals are strongly implicated in the series of catalysts discovered by Barton and coworkers[40] which, some photochemically and some thermally, produce peroxides from ergosteryl acetate and other dienes in methylene chloride at −78°C. These catalysts, including Lewis acids, carbonium ions, or ammonium ion radicals, are in remarkable contrast to those just mentioned in that they have not been observed to produce any oxidation products.

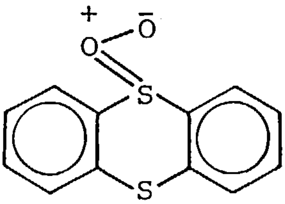
Evidence of oxidation through direct coupling of cation radical and superoxide ion was seen in the reaction of thianthrene cation radical perchlorate (35) and potassium superoxide ion. The results indicate that, at least from a stoichiometric view point, both the annihilation reaction and the direct coupling reaction occur.[41]

$$\begin{tikzcd}
 & DO_2 \\
D^{+\cdot} + O_2^{\overline{\cdot}} \arrow[ur] \arrow[dr] & \\
 & D + {}^{1}O_2
\end{tikzcd}$$



(D$^{+\cdot}$)

(35)



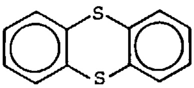
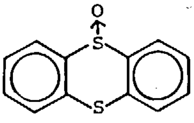
(DO$_2$)

(36)

The annihilation gives thianthrene and oxygen in comparable yields. In the presence of diphenyl sulfide, thianthrene 5-oxide formation is apparently suppressed, and the yield of thianthrene is concomitantly increased. Furthermore, the yields of thianthrene 5-oxide (37) and diphenyl sulfoxide are approximately equal.

TABLE IV

Reaction of Thianthrene Cation Radical Perchlorate (35) with KO_2 and Na_2O_2[a]

		Products Yields (%)[b)]			
Entry	System		 (37)	Ph_2SO	O_2
I	H_2O	46	54		
II	KO_2	43	47		55
III	KO_2 + excessPh_2S	80	15	17	50
IV	Na_2O_2	59	34		23
V	Na_2O_2 + excessPh_2S	75	14	21	0

[a] The reaction was carried out with 1-2 mmol of thianthrene cation radical perchlorate (35), 4 mmol of KO_2 or Na_2, and 20 mmol or Ph_2S in MeCN. [b] Average of to w experiments.

These results were explained in terms of complete interception of the peroxy sulfoxide (36) intermediate by diphenyl sulfide. This intermediate was also produced by the reaction of peroxide ion, O_2^{2-}, with (35), but yields of (37) and oxygen definitely decreased.

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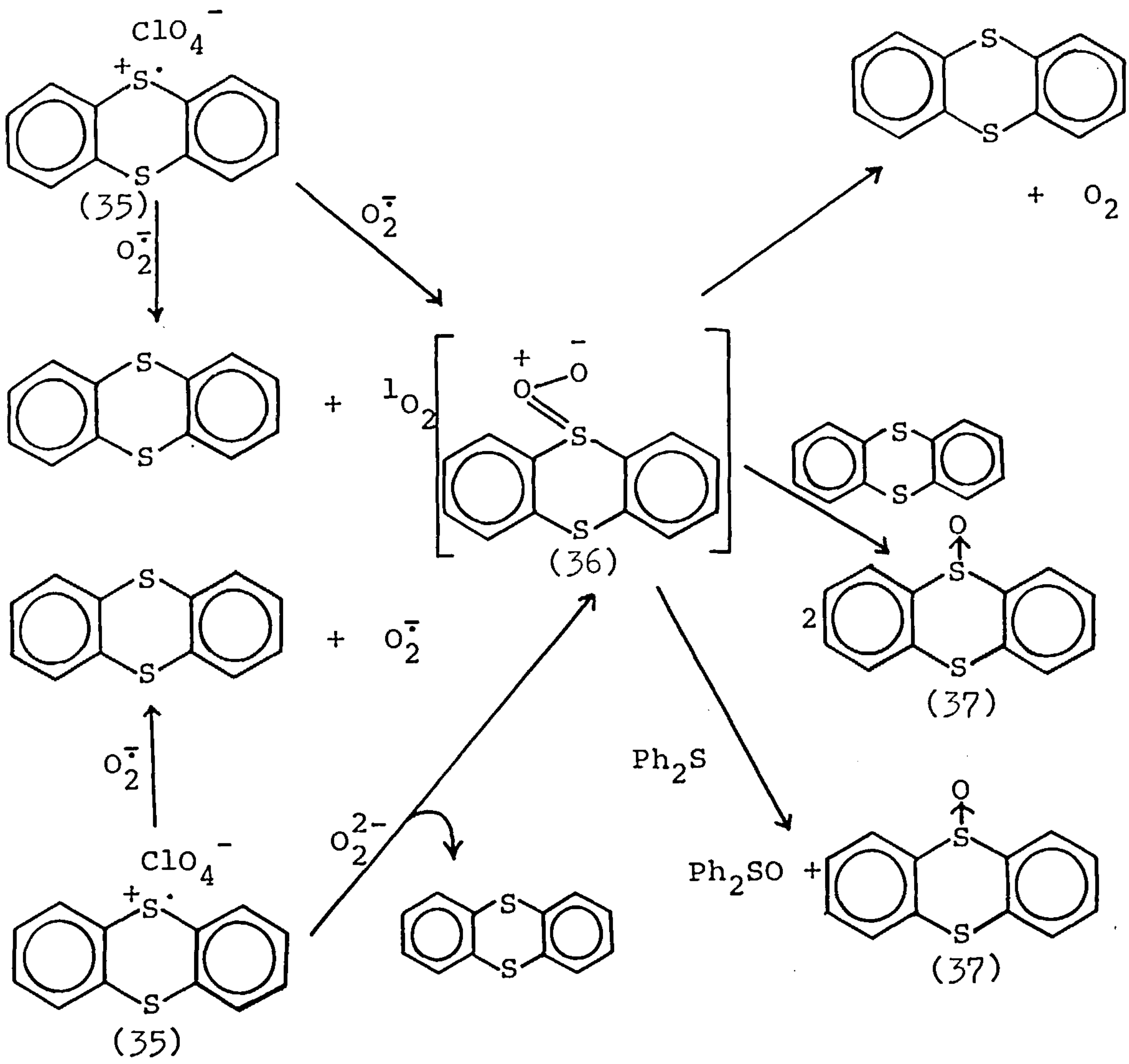

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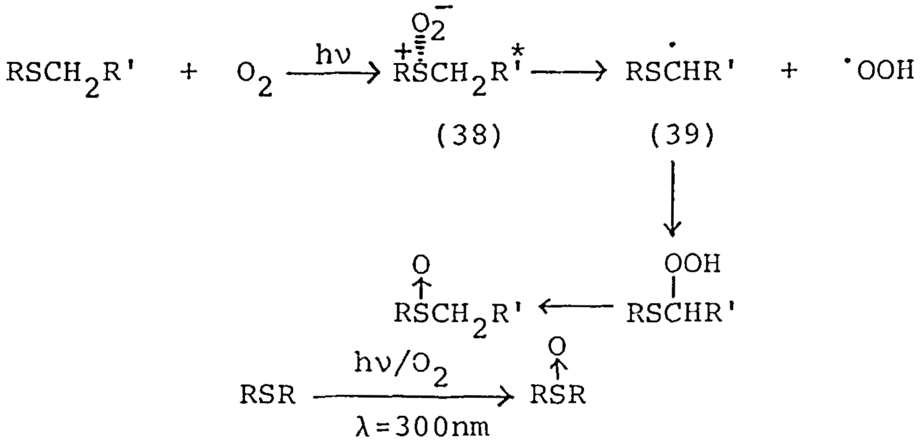
III. Direct Photooxidation of Sulfides

The direct photooxidations of aliphatic sulfides in hydrocarbon solution and in the solid state have been reported. Clean conversions to sulfoxides are observed upon irradiation of solid crystalline samples of sulfides in air. Similarly, by irradiation of hexane solutions of sulfides the corresponding sulfoxides are obtained quantitatively.[42] Di-t-butyl sulfide is not oxidized. Since an intense absorption appears on saturating liquid di-n-butyl sulfide and liquid t-butyl sulfide (l_{max} = 300nm) with oxygen, or charge transfer complex mechanism between oxygen as an electron acceptor and sulfide as an electron donor has been proposed. In this case excited charge transfer complex chemistry leads to an α-alkyl-alkylthio radical

(39) capable of combining with a hydroperoxide radical. Peroxy sulfoxides (38) have been suggested as common intermediates in thermal autooxidation.



$$\mathrm{RSCH_2R' + O_2 \xrightarrow{h\nu} R\overset{O_2^{-}}{\overset{+}{S}}CH_2R'^{*} \longrightarrow RS\dot{C}HR' + {}^{\bullet}OOH}$$

(38) (39)

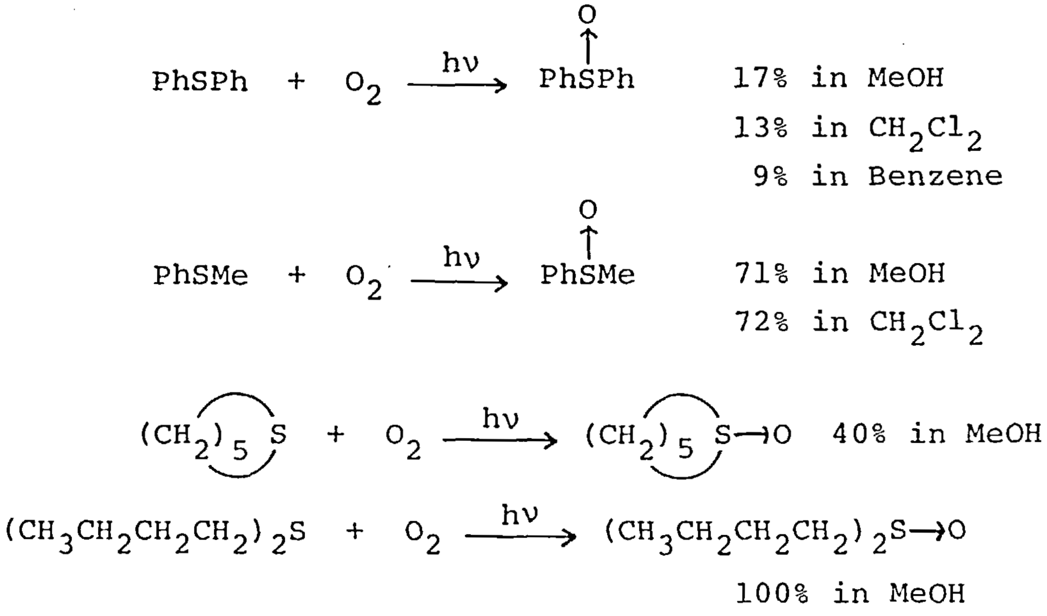
$$\mathrm{RS\overset{OOH}{\overset{|}{C}}HR' \longrightarrow R\overset{O}{\overset{\uparrow}{S}}CH_2R'}$$

$$\mathrm{RSR \xrightarrow[\lambda=300nm]{h\nu/O_2} R\overset{O}{\overset{\uparrow}{S}}R}$$

R= n-Bu, $-C_{12}H_{25}$, $-C_{14}H_{29}$, $-CH_2CO_2C_{12}H_{25}$

$-CH_2CH_2CO_2C_{12}H_{25}$, t-Bu

On the other hand, direct oxygenation of diphenyl sulfide has been reported to give diphenyl sulfoxide. No α-hydrogen is required in the oxidation. The excited complex has been proposed to play an important role in these reactions.[43]



$$\mathrm{PhSPh + O_2 \xrightarrow{h\nu} Ph\overset{O}{\overset{\uparrow}{S}}Ph}$$

17% in MeOH
13% in CH_2Cl_2
9% in Benzene

$$\mathrm{PhSMe + O_2 \xrightarrow{h\nu} Ph\overset{O}{\overset{\uparrow}{S}}Me}$$

71% in MeOH
72% in CH_2Cl_2

$$\mathrm{(CH_2)_5S + O_2 \xrightarrow{h\nu} (CH_2)_5S \rightarrow O}$$

40% in MeOH

$$\mathrm{(CH_3CH_2CH_2CH_2)_2S + O_2 \xrightarrow{h\nu} (CH_3CH_2CH_2CH_2)_2S \rightarrow O}$$

100% in MeOH

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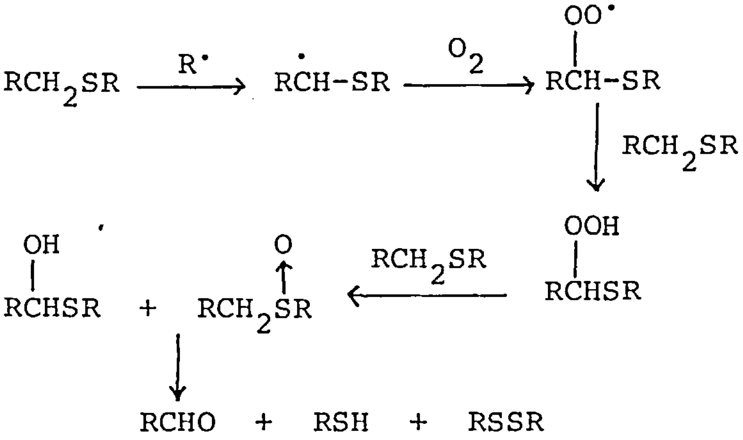
The free-radical nature of these oxidations has also been demonstrated by their reponse to common free-radical catalysts and inhibitors.

Irradiation with near ultraviolet light promotes oxidation even of benzyl sulfides which are otherwise inert.

Azobisisobutyronitrile acts similarly and in addition induces the oxidation of saturated alkyl sulfides. Significantly diphenyl sulfide, which has no C—H bond adjacent to the sulfur atom, remains unaffected.[44] A remarkable anomaly is that t-butyl and cyclohexyl hydroperoxides and benzoyl peroxide are inactive as catalysts. In the presence of azobisisobutyronitrile, n-butyl methyl sulfide, crotyl methyl sulfide and cyclohexyl methyl sulfide absorb oxygen to give the corresponding sulfoxide, water, and compounds resulting from scission of the weaker C—S bond; crotyl methyl sulfide, for example, gives the sulfoxide, water, dimethyl disulfide, and crotonaldehyde. The reaction features described in outline can be rationalized by the following mechanistic scheme.



IV. Sensitized Photooxidation of Disulfides

A number of biologically important molecules containing disulfide bonds are known to be susceptible to photodynamic action. Weil, Gordon and Buchert[45] originally reported that cystine is photooxidized in aqueous medium in the presence of methylene blue. More recently, however, Weil reported that cystine reacts only sluggishly in photosensitized oxidation.[46] The possibility of photodynamic action in biological substrates containing the cystine residue is now examined with regard to photosensitized oxidation.

3,3-Dithiodipropionic acid (40), 3,3-dithiodipropionic bisdiethylamide (41), and cystamine are all photooxidized in the presence of methylene blue. For cystamine and 3,3-dithiodipropionic acid the oxidation is essentially completely quenched in the presence of an oxygen quencher.[47] While the products of the photosensitized oxidations reported here have not been isolated, it is presumed on the basis of work with simple disulfides, that they are the corresponding thiolsulfinates.

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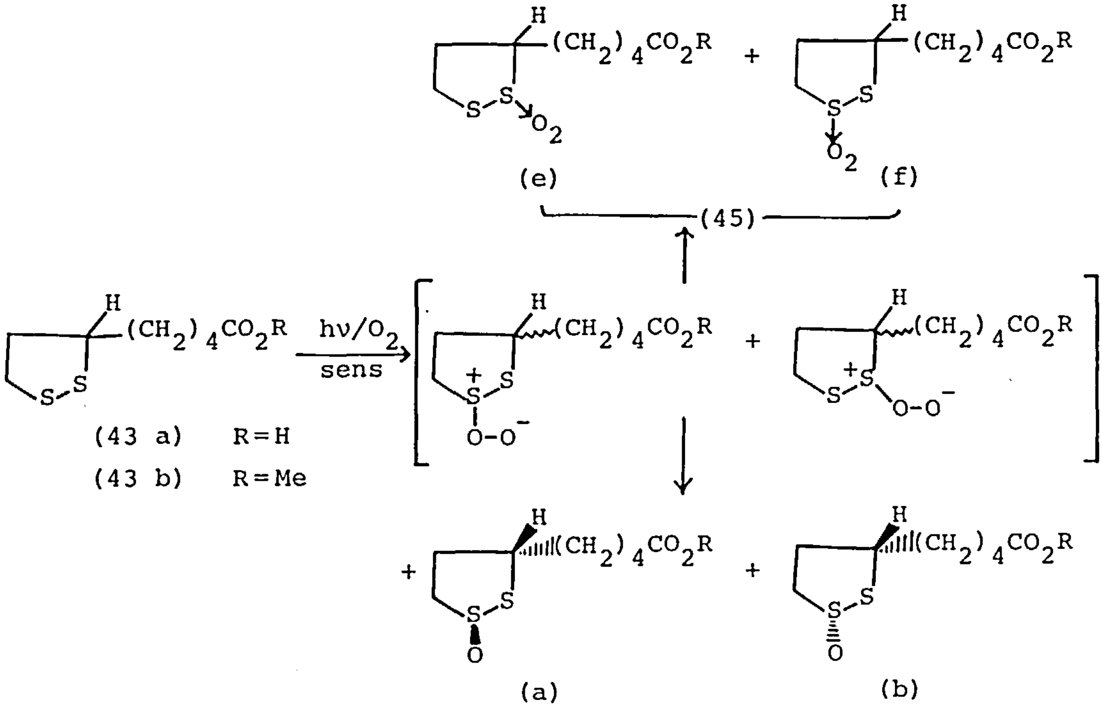
TABLE V

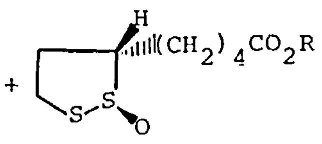
Oxygen Absorption in the Photooxidation of Disulfides

RSSR R	Time (min.)	Temp. (°C)	Oxygen Absorbed mole %
$(CH_2)_2COOH$ (40)	300	30–35	0.238
$(CH_2)_2COOH$	304	24–27	0.05
$CH_2CHCOOH$ $NH_2\cdot HCl$	370	27–29	0.00
$(CH_2)_2CONEt_2$ (41)	306	0	0.22
$(CH_2)_2CONEt_2$	367	0	1.04
$(CH_2)_2NH_2$ (42)	120	0	0.075

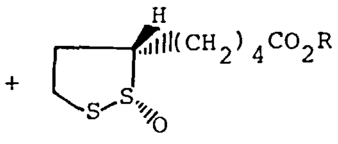
In the case of cystine hydrochloride in aqueous solvent, little or no oxidation is observed, consistent with the more recent observations of Weil.[48]

Interest in the oxidation of α-lipoic acid and derivatives (43), which has been known as a growth factor for many bacteria and protozoa, began with the parent compound.[49,50] The product was called β-lipoic acid (protogen-B) (44) and it was not known whether it was a naturally occurring substance or whether it was produced by oxidation of α-lipoic acid during the work-up. Likewise it was not possible to determine which sulfur atom has been oxidized.





(c)



(d)

(a) ~ (d) ··· (44)

Structure (44 a,b) has generally been favored for β-lipoic acid oxide since the specific rotation of the thiolsulfinate prepared from (+) lipoic acid is almost identical with those of the parent compounds. An nmr chemical shift reagent Eu $(fod)_3-d_{27}$ has been used to show that the products include four thiolsulfinates (44) in all cases plus two thiosulfonates. A number of chemical oxidations of (43b) using a number of reagents which had been used for the oxidation of (43a) showed similar results.[51]

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TABLE VI

Results of Oxidation of Methyl α-lipoate

Methyl- α-lipoate	Sulfinate				Total Yield	Sulfonate		Total Yield
	a	b	c	d	(44)	e	f	(45)
Sens/O_2 in $CHCl_3$	9	48	28	16	64%	59	41	25.7%
in MeOH	14	29	25	32	75.4	54	46	15.4
$(NH_4)_2S_2O_8$ 90% EtOH	15	30	25	30	21			trace
t-BuOOH in MeOH	10	35	20	35	69			trace
CH_3CO_3H in Et_2O	4	37	26	33	42	10	90	N.D.
in MeOH	11	29	26	34	52			
$(PhO)_3PO_3$ in CH_2Cl_2	12	33	23	32	26			

Barltrop, Hayes, and Calvin[52] studied the kinetics of the oxidation of 1,2-dithiolanes and α-lipoic acid, and demonstrated second-order kinetics of the oxidation of 1,2-dithiolanes with ammonium persulfate.

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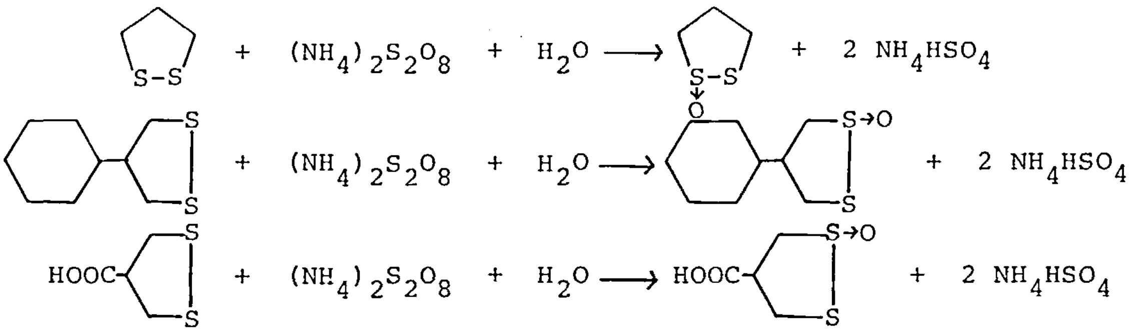
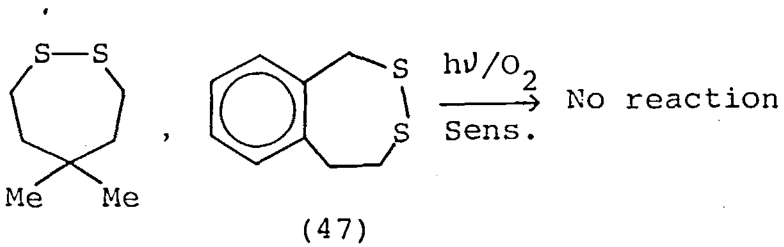
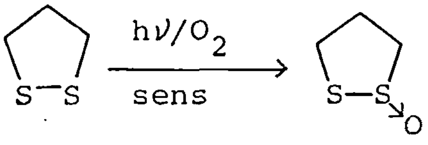


Calvin and coworkers also concluded that five-membered cyclic disulfides are more readily oxidized than open-chain disulfides. Similarly, Bergson also confirmed these results with regard to α-lipoic acid and showed that 2,3-dithiaspiro-4,5-decane and 1,2-dithiolane-4-carboxylic acid are oxidized to the corresponding cyclic thiolsulfinates with ammonium persulfate in ethanol/water solution.[53]

Among cyclic disulfides, (46) and (47) were found to be inert to photosensitized oxidation,[54] while 1,2-dithiolane (48) gives the corresponding cyclic thiolsulfinate (49).



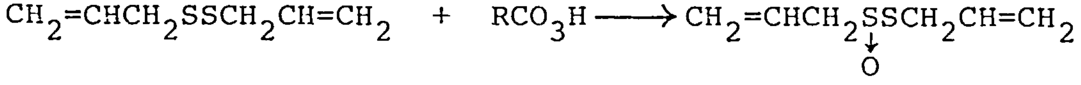
(46) (47)



(48) (49)

The product thiolsulfinates are interesting themselves, since a large number of dialkyl thiosulfinates have antibiotic activity. The isolation of allicin from Allium sativum, the common garlic, in 1944 and the elucidation of its—$\underset{\downarrow}{\underset{O}{S}}$S— containing structure opened the door to thiolsulfinate chemistry.

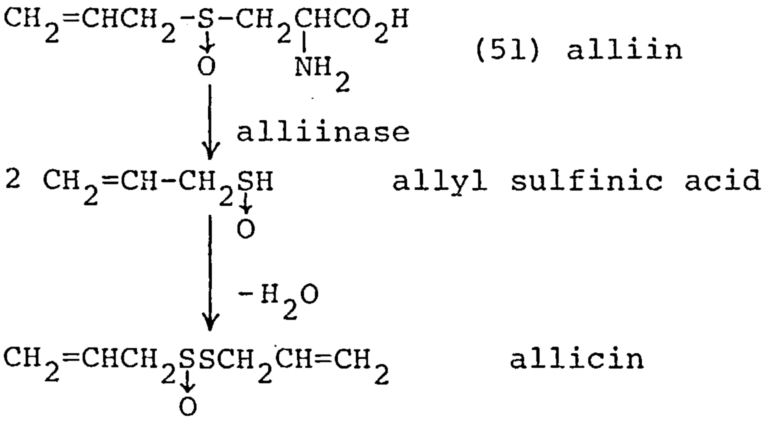
On the basis of chemical observations, Cavallito, Buck, and Suter[55] then proposed a diallyl thiolsulfinate structure (50) for allicin, which was derived by oxidation of allyl disulfide to allicin.



$$CH_2{=}CHCH_2SSCH_2CH{=}CH_2 + RCO_3H \longrightarrow CH_2{=}CHCH_2\underset{\underset{O}{\downarrow}}{S}SCH_2CH{=}CH_2$$

(50)

At the same time the antibacterial activity of allicin was ascribed to the $\text{—}\underset{\underset{O}{\downarrow}}{S}S\text{—}$ grouping and it was believed to involve the inhibition of growth by reaction with essential thiol groups in bacterial cells. The formation of allicin from alliin (51) is catalyzed by the enzyme alliinase. The following reaction sequence has been proposed for the conversion.[56]



$$CH_2{=}CHCH_2\text{-}\underset{\underset{O}{\downarrow}}{S}\text{-}CH_2\underset{\underset{NH_2}{|}}{C}HCO_2H \quad \text{(51) alliin}$$

$$\Big\downarrow \text{alliinase}$$

$$2\ CH_2{=}CH\text{-}CH_2\underset{\underset{O}{\downarrow}}{S}H \quad \text{allyl sulfinic acid}$$

$$\Big\downarrow -H_2O$$

$$CH_2{=}CHCH_2\underset{\underset{O}{\downarrow}}{S}SCH_2CH{=}CH_2 \quad \text{allicin}$$

On the other hand, in fact, very little work on photosensitized oxygenation of simple acyclic disulfides has been reported. The attempted photosensitized oxygenation of dialkyl disulfides was found to give the corresponding thiolsulfinates in good yields,[57] while diphenyl disulfide is inert to these reaction conditions.

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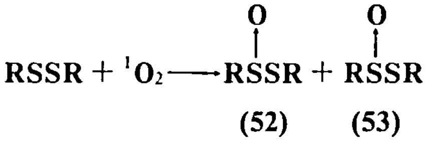
TABLE VII

Photooxygenation of Dialkyl Disulfides



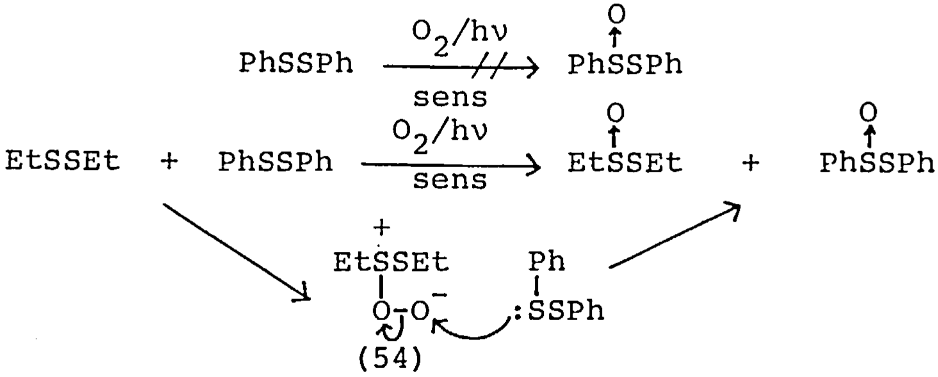
$$RSSR + {}^1O_2 \longrightarrow R\overset{O}{\overset{\uparrow}{S}}SR + R\overset{O}{\overset{\uparrow}{S}}SR$$

(52) (53)

R	Time (min.)	O_2 absorption	(52)	(53)
t-Bu	215	0.55	75%	0%
Ph	53	0	0	0
Me	135	0.56	60	13
Me	60	0.4	69	8
Et	205	0.51	48.7	trace
i-Pr	352	0.45	73	—
t-Bu[a]	270	0.04	2.3	0

[a] in the presence of 3 moles excess of DABCO

In the case of dimethyl disulfide the thiolsulfinate disproportionates to thiolsulfonate and disulfide. A trace of thiolsulfonate were also evident in the diethyl disulfide case. Since diphenyl disulfide is inert to the conditions of photosensitized oxygenation, it is oxidized in the presence of diethyl disulfide, presumably by the zwitterion (54) produced from the diethyl disulfide.



The observation that dialkyl disulfides are photooxidized to the corresponding thiolsulfinates suggested that photodynamic action in biological substrates containing the cystine residue could occur by a similar mechanism. The very slow photooxidation of cystine in the presence of methylene blue may be due to the singlet oxygen quenching effect of the free amino group.[58]

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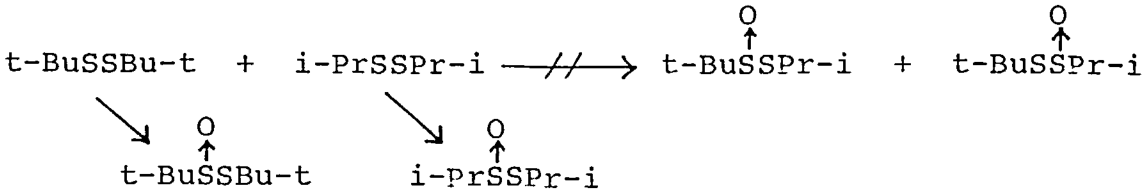
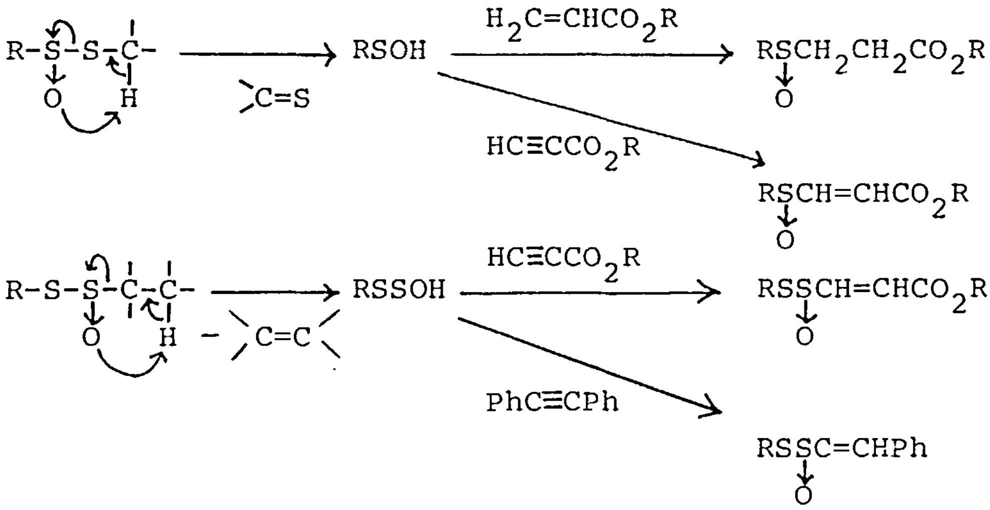
When mixtures of di-t-butyl disulfide and di-i-propyl disulfide were used in the reaction, no mixed thiolsulfinate, i.e., no t-butyl-i-propyl thiolsulfinate, was found. No cleavage of the disulfide bond seems to be involved.



An interesting thermolysis of alkyl thiolsulfinates reminescent of the t-butyl sulfoxide decomposition, reported by Colclough[59] and Shelton[60] was recently published by Block.[61]

Under relatively mild conditions (96°C, 16–18 hrs), mixtures of thiolsulfinate and various alkenes or alkynes produce sulfinic acid adducts in good yields (33–90%). The additional reactions obey Markonikov's rule, and, with alkynes, produce cis-unsaturated sulfoxides not readily available by other methods.[62] Block postulates[63] the following mechanism: The slow steps are followed by rapid thiolsulfinate-sulfenic acid exchange involving a hydrogen bonded complex. The sulfenic acid is trapped by the alkene or alkyne, present in excess, thus producing a sulfoxide.



Mixing of two different thiolsulfinates results in a complete scrambling of the sulfenyl and sulfinyl groups. An alternative mode of thiolsulfinate decomposition was demonstrated by mass spectroscopic studies and trapping experiments using alkynes.

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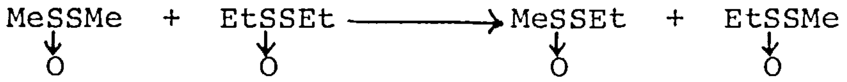
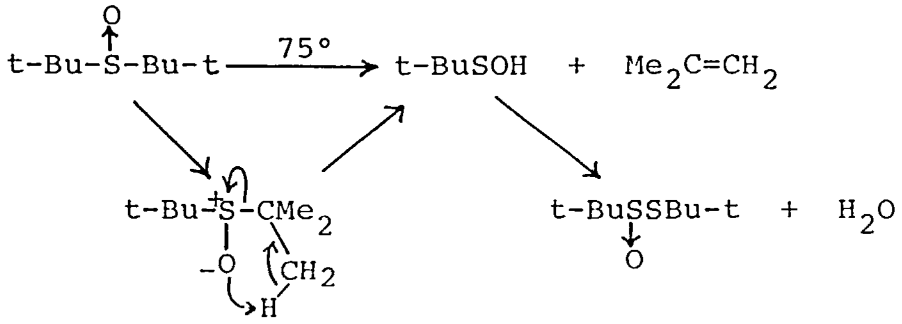


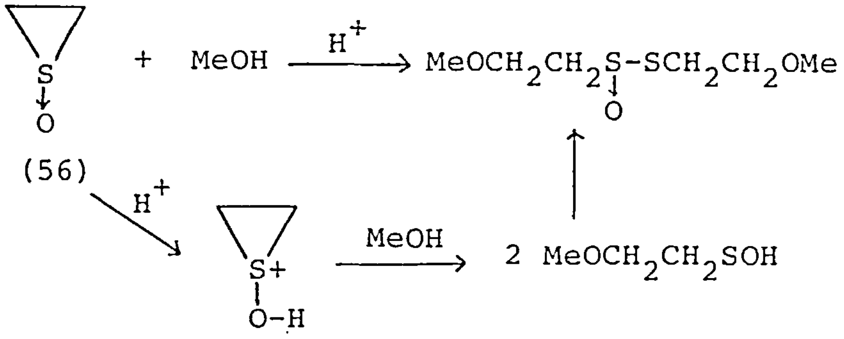
$$\mathrm{Me\underset{\substack{\downarrow\\ O}}{S}SMe} + \mathrm{Et\underset{\substack{\downarrow\\ O}}{S}SEt} \longrightarrow \mathrm{Me\underset{\substack{\downarrow\\ O}}{S}SEt} + \mathrm{Et\underset{\substack{\downarrow\\ O}}{S}SMe}$$

Di-t-butyl sulfoxide yielded alkene, water, and thiolsulfinate at 75°C, the latter compounds were formed from an intermediate sulfenic acid, partly via a cyclic transition state (55) as postulated below.[59,60]



(55)

Kondo, Negishi and Ojima obtained thiosulfinates via acid catalyzed ring opening of episulfides. Ethylene episulfoxide (56) in methanol in the presence of one drop of concentrated sulfuric acid affords β-methoxyethyl-β-methoxyethanethiosulfinate in 97% yield.



Stereochemical investigation of this reaction with cis- and trans-isomers of 2-butene and stilbene episulfoxides led to the conclusion that the nucleophile is introduced stereospecifically with inversion of configuration at the point of attack.[64]

Evidence is accumulating that singlet oxygen and superoxide ion are interconvertible.[65] Interesting oxidations of disulfides with superoxide ion are reported to give both sulfinic and sulfonic acids, di-t-butyl disulfide not oxidized at all, revealing that the initial step is the nucleophilic attack of superoxide ion at the sulfur atom which is suppressed substantially by bulky substituents such as t-butyl group.[66]

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TABLE VIII

Reactions of Disulfides with Superoxide Ion

$$RSSR \xrightarrow[\text{crown ether} \atop \text{pyridine}]{\text{eq. } KO_2 \ 25°C} RSO_2^- + RSO_3^-$$

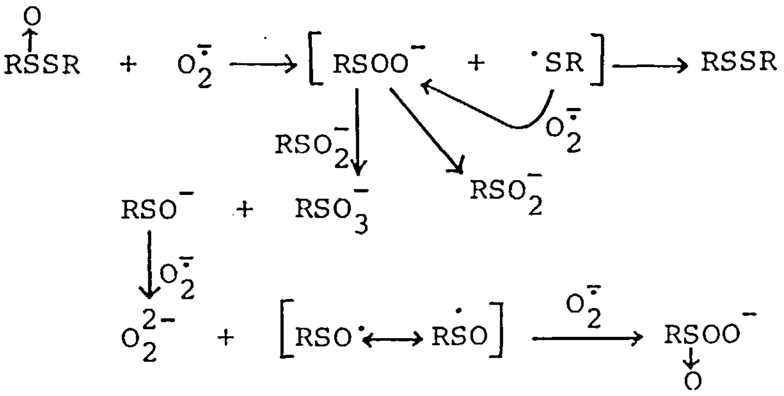
R	React. time (min.)	RSO_2^-	RSO_3^-	recov.
Me	3.0	0%	57%	—
t-Bu	24.0	0	0	100%
Ph	6.0	trace	81	trace
p-Tol.	1.0	24	64	12
p-Cl-C_6H_4	0.5	46	53	trace

Thiolsulfinate are also very readily oxidized to sulfonic and sulfinic acids, even at temperatures where disulfides are quite inert. The results clearly reveal the initial nucleophilic attack of superoxide ion to be at the sulfinyl sulfur atom of the thiolsulfinate.

TABLE IX

Reactions of Thiolsulfinates with Superoxide Ion

$R-\overset{\overset{O}{\uparrow}}{S}SR' + 5 \text{ eq. } KO_2 \xrightarrow{0° \sim -40°C}$		RSO_2^- +	RSO_3^- +	$R'SSR'$
R=p-Tol,	R_1=Ph	6%	41%	34%
Ph,	p-Tol	trace	48	16
Ph,	Ph	trace	48	35



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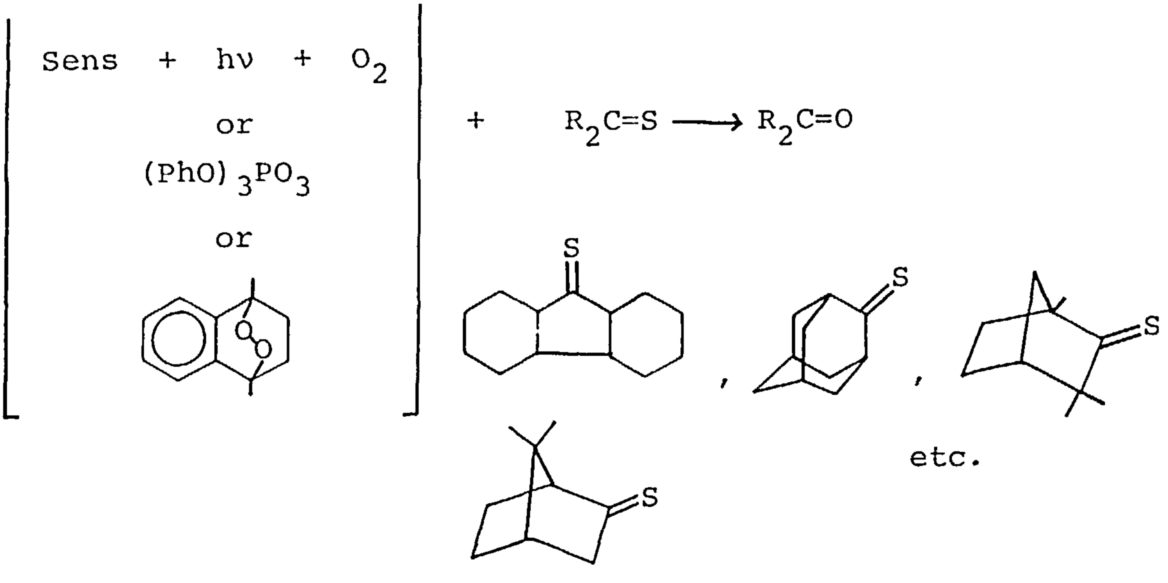
V Photosensitized Oxidation of Thiocarbonyl Compounds.

Although the oxidation of the carbon-sulfur double bond by air has been known for long time, it has recently been found that molecular oxygen reacts with thiones very efficiently to yield the corresponding carbonyl compounds.[67] Furthermore, the reactive species involved in the air oxidation of thiones in the presence of light has been characterized as singlet molecular oxygen.[68] These oxidation reactions, unlike reactions of singlet oxygen with olefins[69], are not chemiluminscent.



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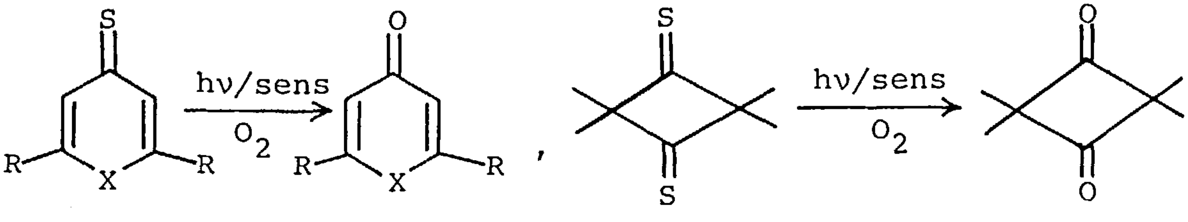
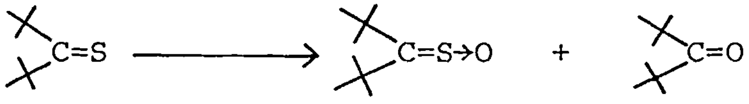
Methylene blue sensitized photooxidations of 4H-pyran-4-thiones (57) and 4H-thiopyran-4-thiones (58) give the corresponding ketones.[71] While the oxidation of 2,6-diphenyl-4H-pyran-4-thione is quenched by a triplet quencher, the methylene blue sensitized oxygenation in chloroform gives 60% yield of the corresponding ketone.[72]



(57) X=O

(58) X=S R=H, Me, Ph

Di-t-butyl thioketone (59) has been oxidized to give di-t-butyl ketone (48%) and 21% of di-t-butyl sulfine.[74] These data are comparable to those of the reaction with phosphine ozonide and of the ozone reaction, where, however, preferential formation of the sulfine is observed.



(59)

a)	sens/O_2/hν	36%	54%
b)	Ph_3PO_3	36.6	23
c)	O_3	74.3	25.7

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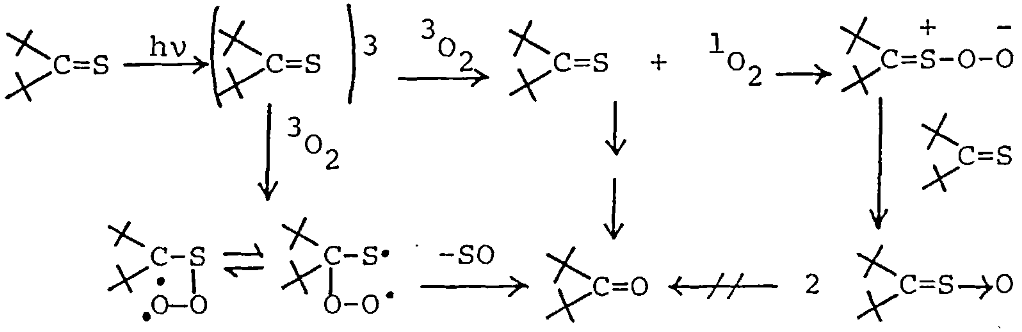
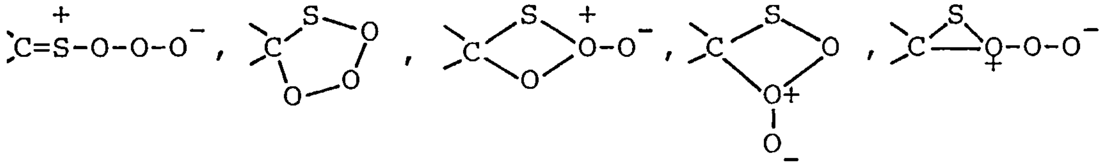
This oxidation may involve two different routes; either via a singlet oxygen process or a short-lived biradical path. In this case di-t-butyl sulfine is perfectly stable toward irradiation and attack of singlet oxygen in contrast to some oxidations of sulfines by singlet oxygen to the corresponding ketones.[75]



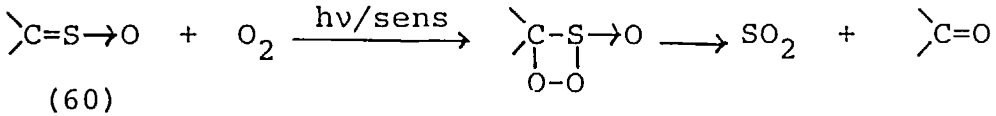
The partial formation of sulfine is only observed with sterically hindered thioketones; unhindered thioketones, such as thiobenzophenone[76] give only rise to the corresponding ketones. A reaction of thiones with ozone has been reported by Senning,[77] and five intermediary structures are in principle possible.[78]

$$Ph_2C{=}S \;+\; O_3 \longrightarrow Ph_2C{=}O \;+\; SO_2$$

100% yield



The conversion of the sulfine system (60) into the carbonyl group takes place smoothly by the reaction with singlet oxygen.[75] Steric effects probably play the most important role during the oxygenation of mesityl phenyl thiosulfine since this sulfine reacts much slower than phenyl phenyl thiosulfine.



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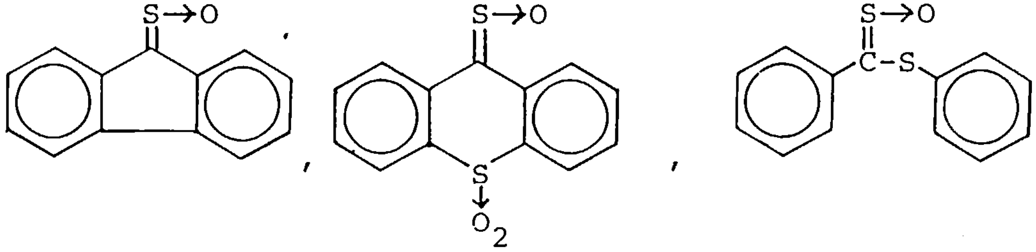
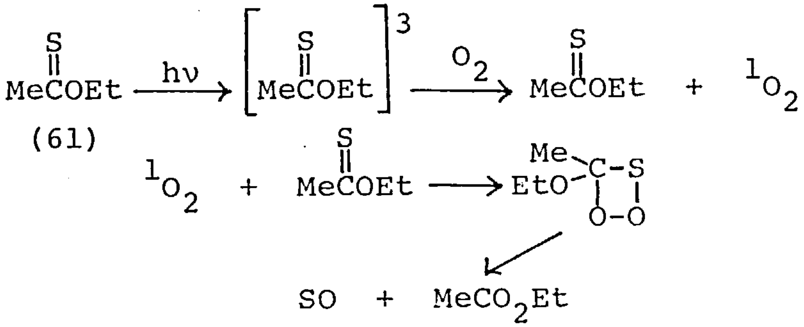


Photochemical replacement of sulfur by oxygen in thioester (61) are also reported in the presence of oxygen. These reactions may appear to proceed by formation of singlet oxygen.[79]



(61)

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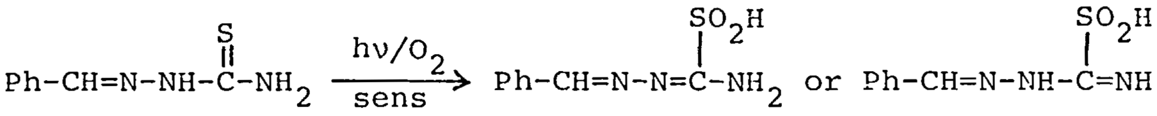
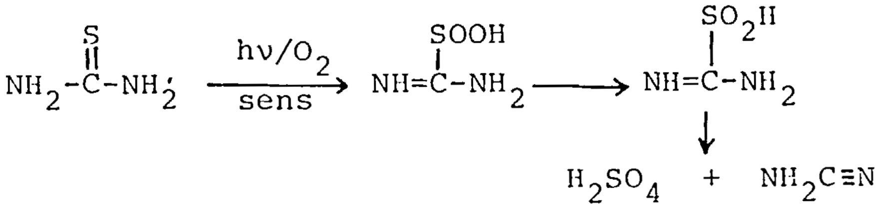
Thiosemicarbazones such as benzaldehyde thiosemicarbazone (62) as well as thiourea give rise to sulfinic acids when subjected to photosensitized oxygenation.[80] It has been suggested that by analogy to olefin oxidation the primary products may be a hydroperoxidic intermediate which instantaneously rearranges to the corresponding sulfinic acid.



$$\text{Ph-CH=N-NH-}\overset{S}{\overset{\parallel}{C}}\text{-NH}_2 \xrightarrow[\text{sens}]{h\nu/O_2} \text{Ph-CH=N-N=}\overset{SO_2H}{\overset{|}{C}}\text{-NH}_2 \text{ or } \text{Ph-CH=N-NH-}\overset{SO_2H}{\overset{|}{C}}\text{=NH}$$

(62)

Aminoiminomethanesulfinic acid precipitates when the reaction is carried out in ethanol, but is soluble in pyridine and therefore oxidized to cyanamide and sulfuric acid in a second reaction. The Warbug-Schocken actinometer consisting of thiourea in pyridine with ethylchlorophyll as a sensitizer is reported to have a quantum yield of oxygen uptake of nearly unity if red, yellow, or blue light is applied.[81]



$$\text{NH}_2\text{-}\overset{S}{\overset{\parallel}{C}}\text{-NH}_2 \xrightarrow[\text{sens}]{h\nu/O_2} \text{NH=}\overset{SOOH}{\overset{|}{C}}\text{-NH}_2 \longrightarrow \text{NH=}\overset{SO_2H}{\overset{|}{C}}\text{-NH}_2 \downarrow H_2SO_4 + NH_2C{\equiv}N$$

Also allylthiourea consumes up to two moles of oxygen under the same reaction conditions. The reaction product decomposes at least partly into SO_2 and other compounds suggesting that N-allyl-aminoiminomethanesulfinic acid may be the first oxygenation product. However, sulfuric acid could not be isolated.[82]

VI Photosensitized Oxygenation of Sulfur Activated Olefins

VI-1 Addition of Singlet Oxygen

The macrolide antibiotics constitute an important group of natural products and have attracted ever-increasing attention in the last few years. Recently, various interesting procedures for the preparation of medium- and large-ring lactones, including several natural products have been reported and their importance has been well recognized.[83] Mahajan recently described the synthesis of the medium and macrocyclic ketothiolactones (64) through photosensitized oxygenation of the bicyclic thioenol ethers (63),[84] while Miyake and Tomoeda have described the formation of thiomacrolides (65) through photooxygenation.[85]

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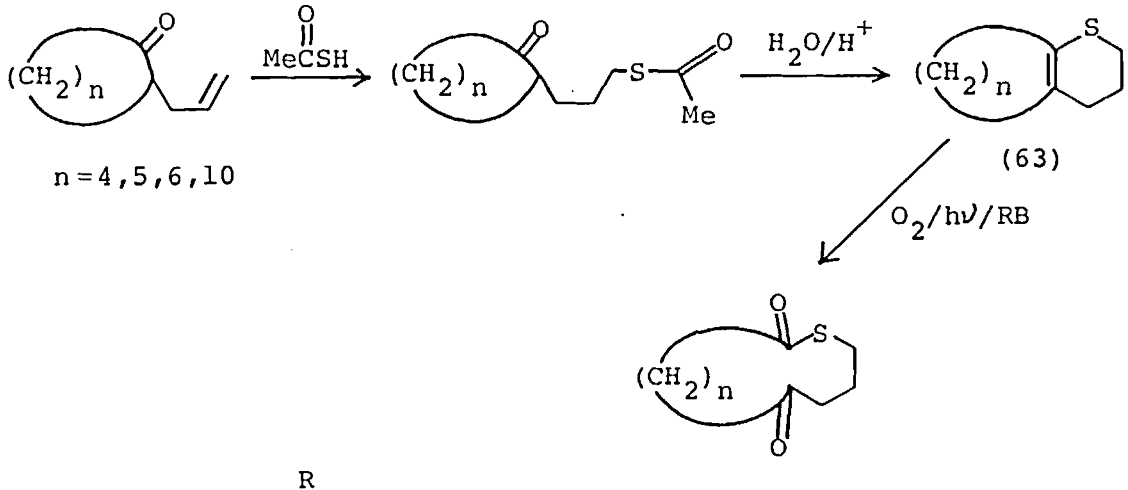
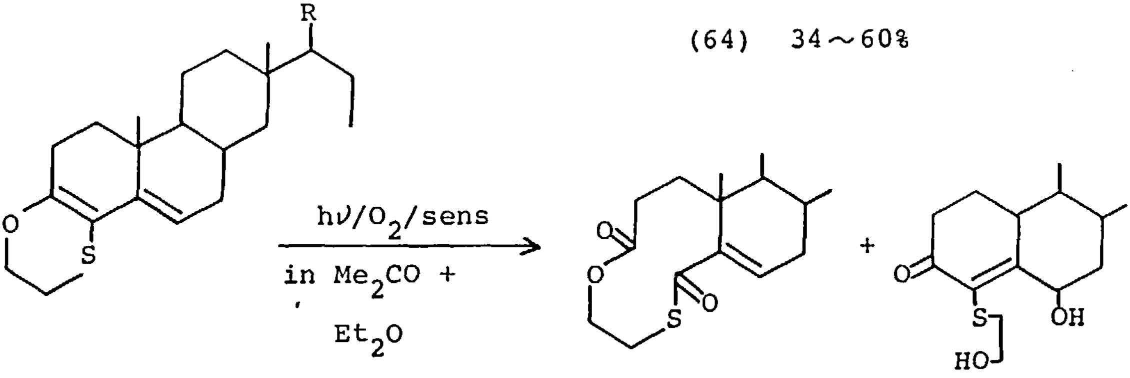


(63)

(64) 34~60%

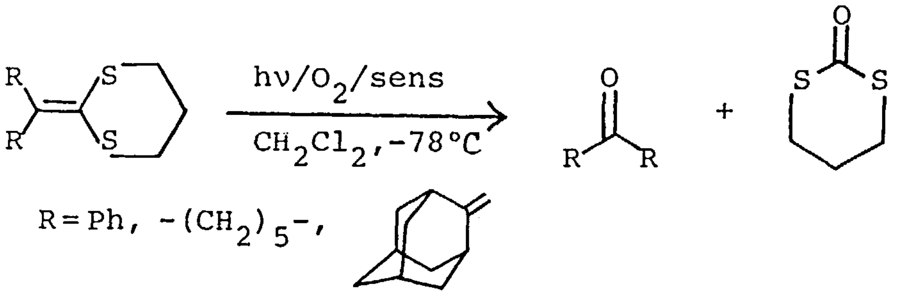


(65) 37%

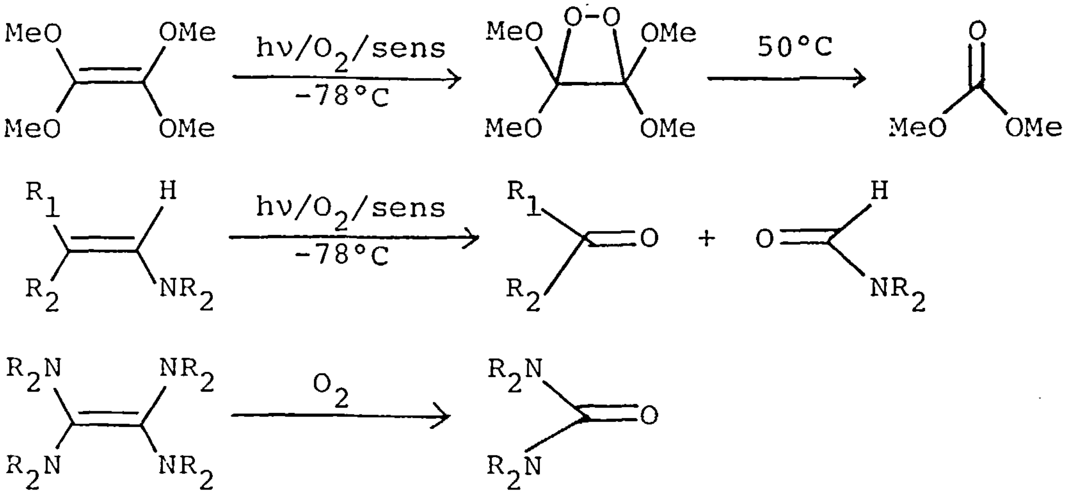
trace

The original mechanistic studies of the photooxygenation of thioethylene were performed by Adam and Liu,[86] and Ando et al.[87] Adam observed that singlet oxygen cleaves 1,2-dithioethylenes to the carbonyl products expected from a 1,2-cycloaddition.

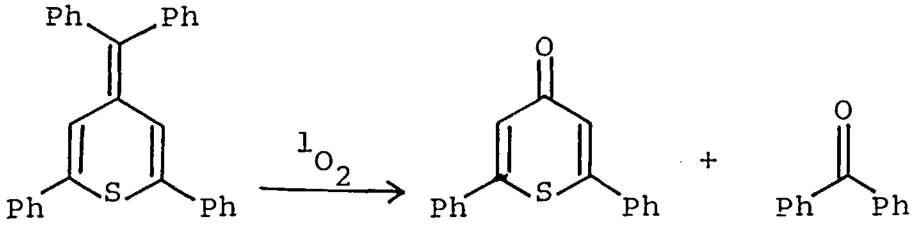
Several examples were reported in the literature involving oxidative cleavage of carbon-carbon bonds where the intermediate 1,2-dioxetanes have been isolated or characterized spectroscopically.



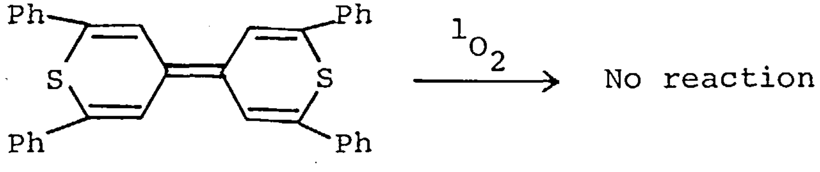
It is relevant to note that tetramethoxyethylene reacts with singlet but not triplet oxygen to yield a dioxetane, tetrakisdimethylaminoethylene reacts spontaneously in air (with chemiluminescence) forming tetramethylurea as the major product.[88,89,90]



The reaction of singlet oxygen with vinylogs of thioethylenes has also been reported. Schönberg and Ardenne found that 2,6-diphenyl-4-diphenylmethylene-4H-thiopyran (66) undergoes cleavage of the exocyclic double bond upon photooxygenation.[91] A later publication by Ishibe et al. appears to indicate that the related olefin (67) is stable to singlet oxygen, but this may be an unintentional implication.[92]



(66)



(67)

In contrast to 1,1-dithioethylenes, the photooxygenation of tetrathioethylenes (68) gives rise to dithiooxalates and disulfides.[87,93] This reaction does not involve triplet

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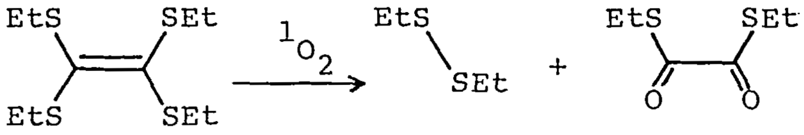
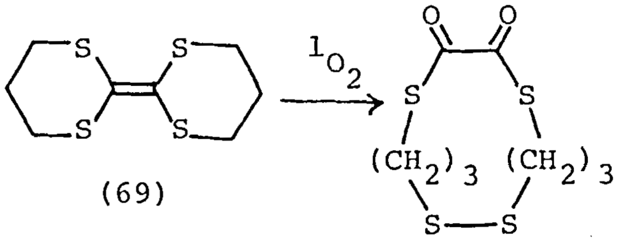
oxygen. Oxidation of 2-(1,3-dithia-2-cyclohexylidenyl)-1,3-dithiane (69) affords 1,2,5,9-tetrathiadodecane-7,8-dione (70) as the sole product.

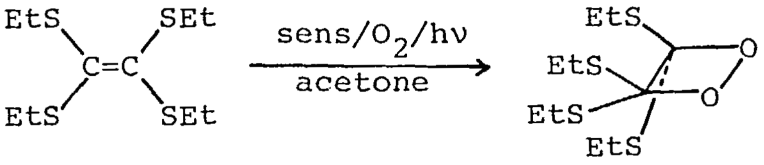


(68)

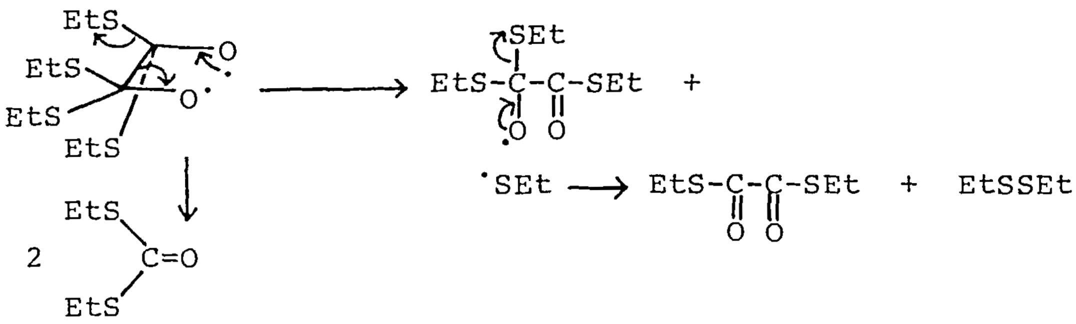


(69)

(70)



(71)



These unusual products are suggested to arise by radical fragmentation of dioxetane (71), dominated by the weakes C—S bond compared to the C—C bond. In this case light emission that might be expected from the dioxetane could not be observed, although the complex nature of the cleavage could account for this. Other alkenyl sulfides, mono-, bis-, tris-, and tetrakissulfides are oxidized to mixtures of products attributable to competitive C—C and C—S bond cleavage in intermediate dioxetanes.

Tris-(ethylthio)-ethylene (72) in acetone is oxidized in the presence of a sensitizer with consumption of oxygen (55% reaction at completion) to give ethyl thioglyoxalate (19%) and diethyl disulfide (32%) together with some dithiooxalate (3%) and dithiocarbonate (1%). However, no corresponding sulfoxides and sulfones are formed in acetone as solvent.

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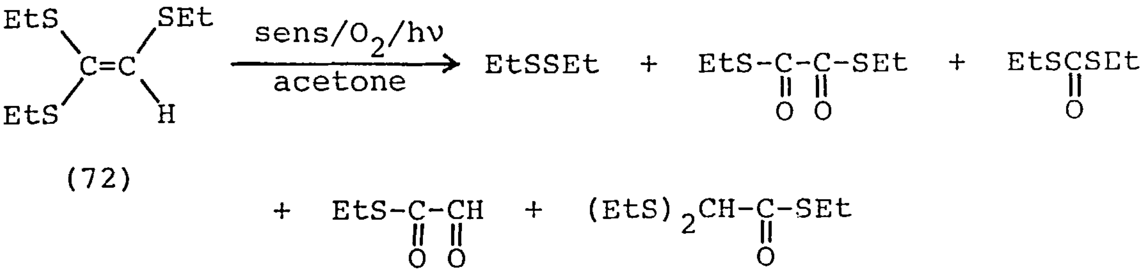
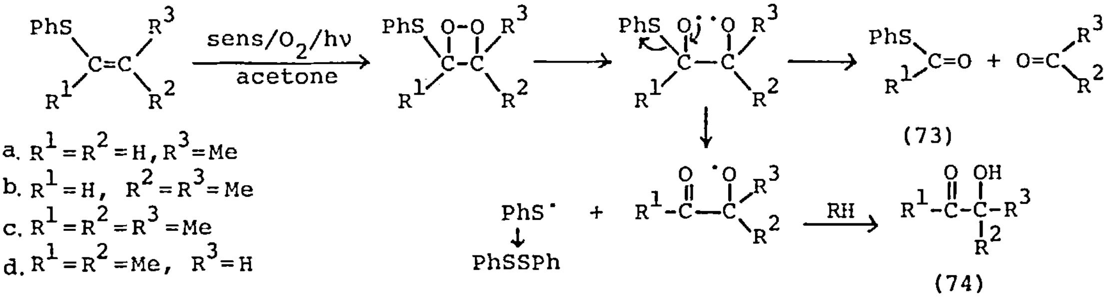


(72)

For comparison, methyl substituted phenylthioethylenes were photooxidized under identical conditions. In acetone each phenylthioethylene gives rise to two products, the phenyl thiolester analogous to (73) and diphenyl disulfide in moderate yields, with another minor product (74) formed by C—S bond cleavage. In less substituted ethylenes, the cleavage of the C—S bond occurs efficiently, and in tetrasubstituted thioethylenes cleavage of the C—C bond takes place to the same extent as cleavage of the C—S bond (Table 10).[94]



a. $R^1 = R^2 = H, R^3 = Me$
b. $R^1 = H, R^2 = R^3 = Me$
c. $R^1 = R^2 = R^3 = Me$
d. $R^1 = R^2 = Me, R^3 = H$

(73)

(74)

TABLE X
Ratio of C—C and C—S bond Cleavage in the Photooxygenation of Phenylthioethylenes

	Ethylene	Product ratio (C—C/C—S bond cleavage) In acetone	In methanol
a	PhSCH=CHMe	0.22	0.05
b	PhSCH=CMe$_2$	0.41	0.22
c	PhSC(Me)=CMe$_2$	1.20	1.05
d	PhSC(Me)=CHMe	1.08	0.48

When the photooxygenations were conducted in methanol solution, products resulting from solvent attack of the intermediate 1,2-dioxetane or epiperoxide were also obtained in significant amounts together with diphenyl disulfide and C—C and C—S bonds cleavage products.

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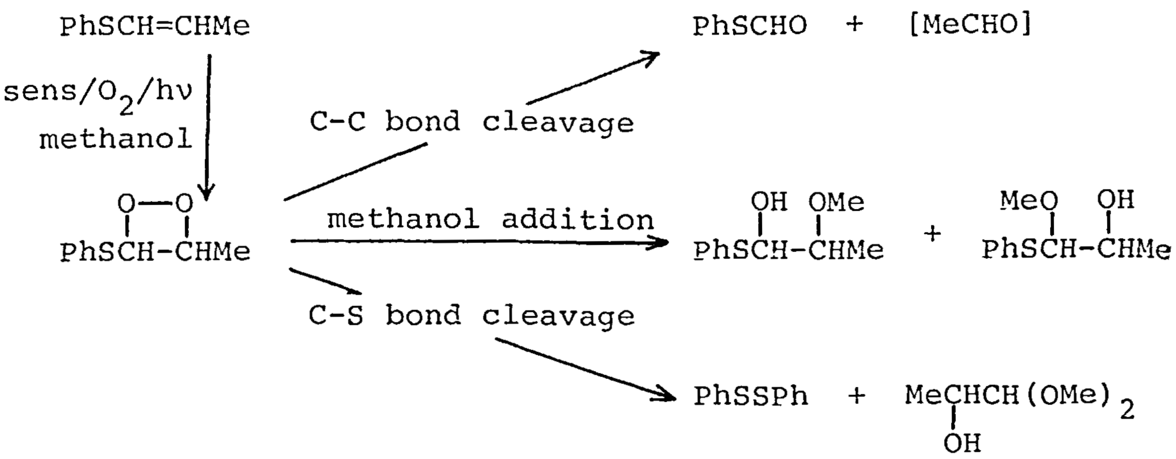
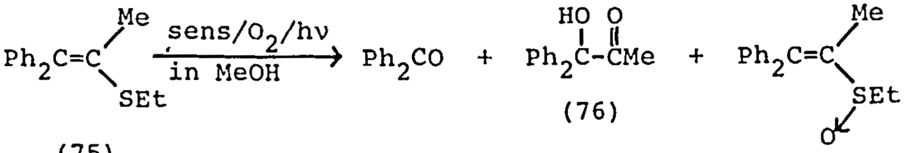
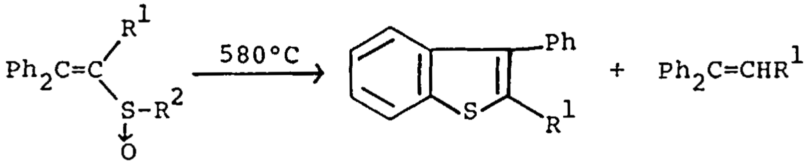


Some thioethylenes are oxidized to sulfoxides when the reaction is carried out in methanol. The thioethylene (75) is oxidized to give benzophenone (38%), hydroxy ketone (76) (6%), and the vinyl sulfoxide (77) (44%), but in benzene only traces of sulfoxide are formed. The sulfoxide (77) is thermally decomposed to give benzothiophene (78) which probably arises from a styrylthiyl radical (79) formed via the corresponding sulfenic acid.[95]

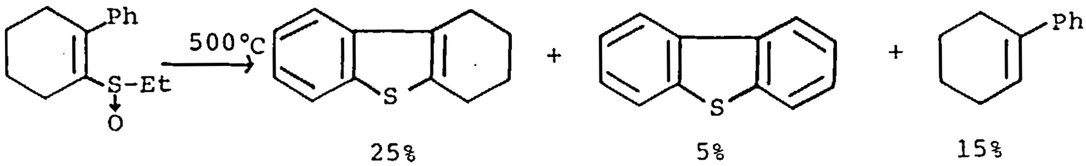


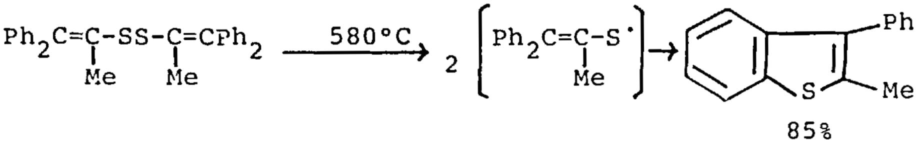
(75) (76) (77)



(78)

R^1=H, R^2=Et
R^1=Me, R^2=Et
R^1=Me, R^2=Pr





85%

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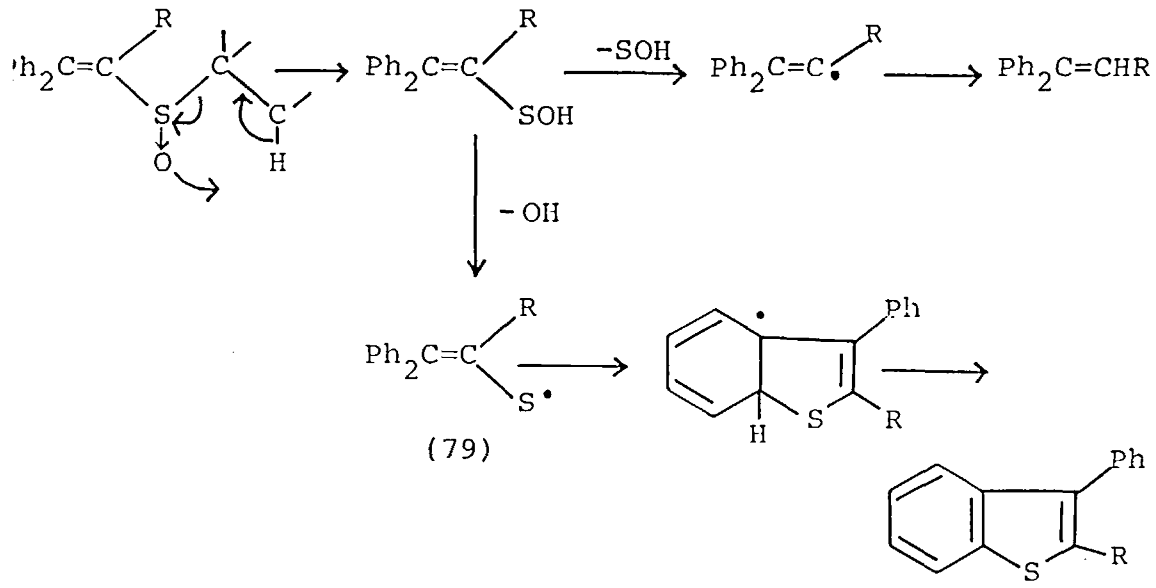

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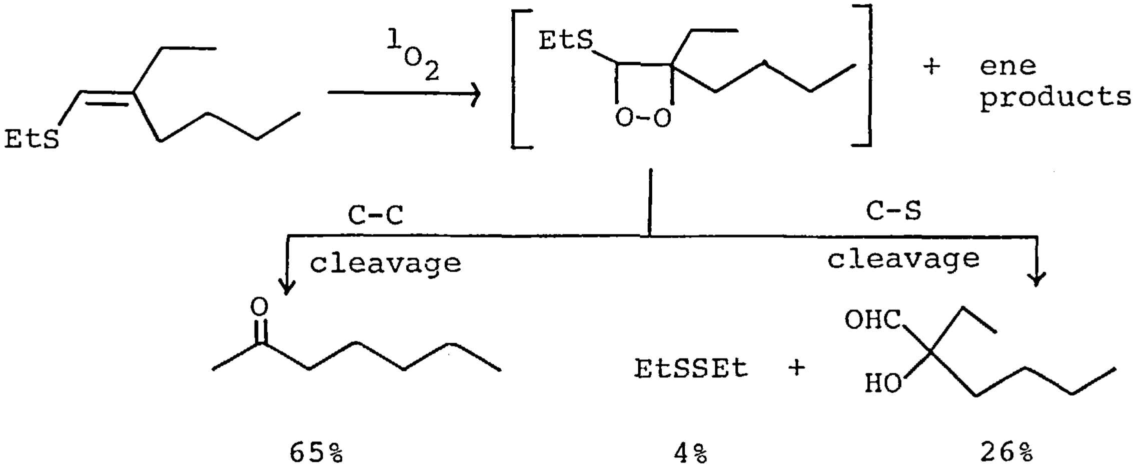
While the aforementioned cleavage of a dioxetane to two carbonyl fragments predominates for alkyl, aryl, and oxy-substituted dioxetanes, those substituted with sulfur or nitrogen groups[96a,b] show a different mode of fragmentation i.e. fission of the C—S or C—N bond subsequent to O—O bond homolysis as well as C—C bond fission. The expulsion of the heteroatomic substituent leads to the formation of a hydroxy ketone. In these cases, it should be noted that the decomposition of dioxetanes is also catalyzed by traces of metals,[97] silical gel,[98] electron donors[99,100] such as sulfides and phosphines, and Lewis acids such as boron trifluoride.[101]



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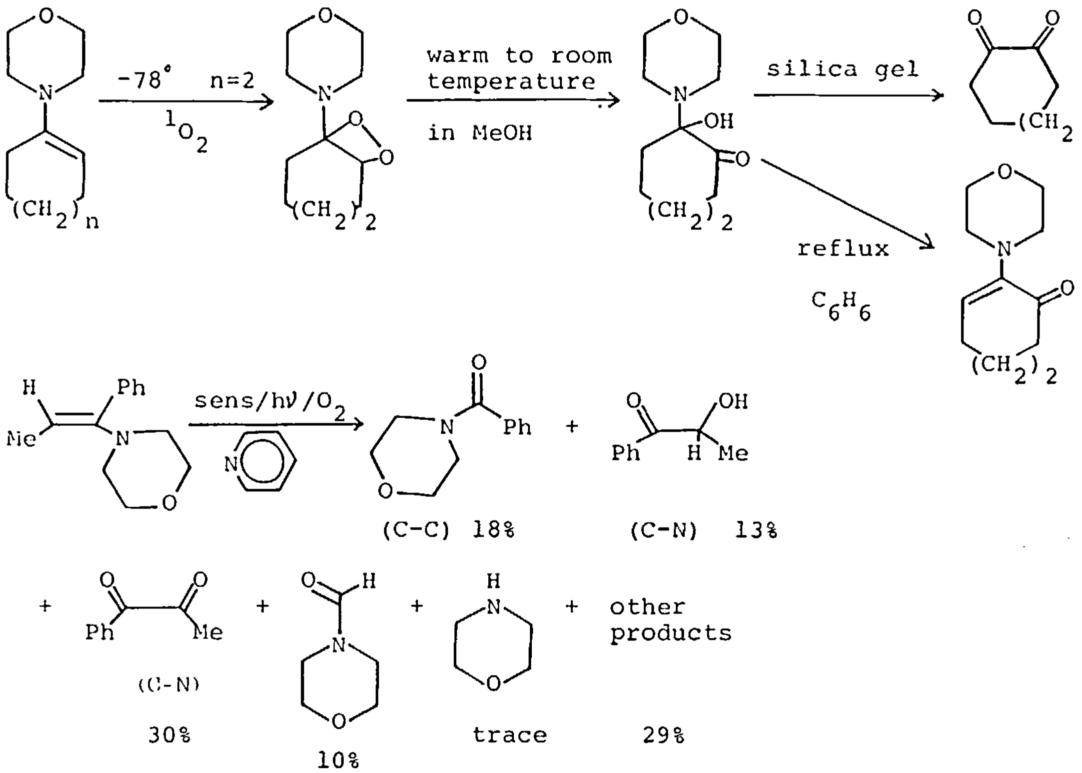
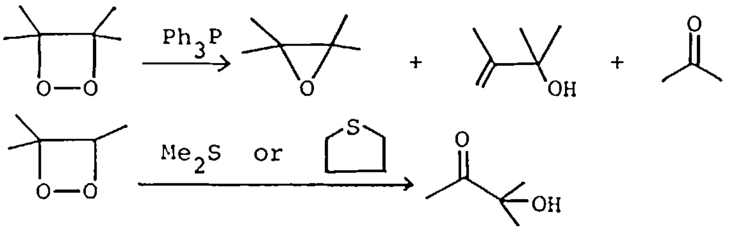
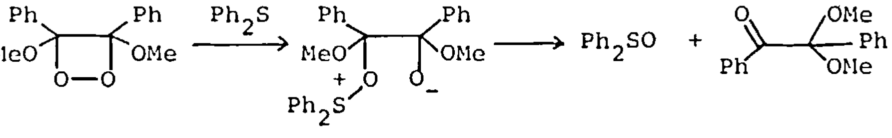
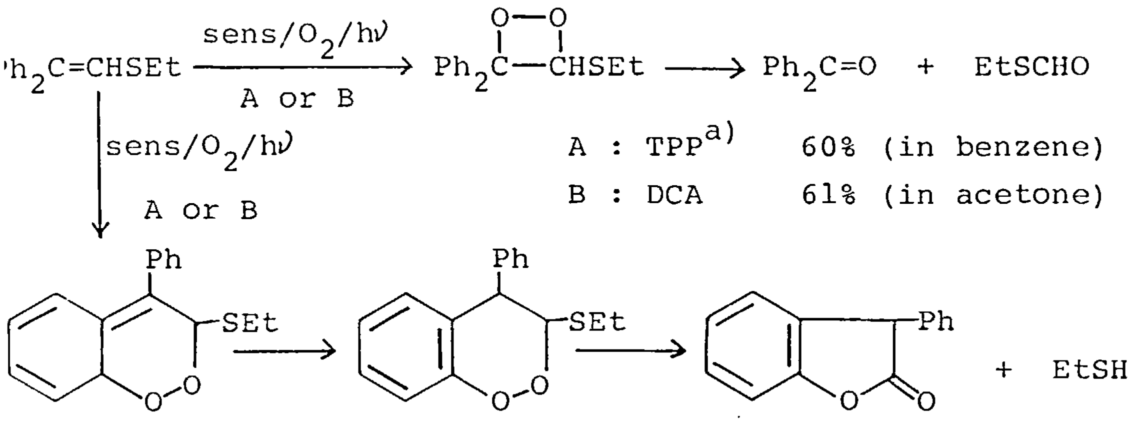






The photooxidation of vinyl sulfides sensitized by 9,10-dicyanoanthracene (DCA) has also been studied and was found to give products derived from the decomposition of the corresponding dioxetanes.[102] This oxidation is not inhibited by the singlet oxygen quencher β-carotene. The oxidation may proceed by electron transfer from the sulfur atom to excited DCA which again transfers its electron to oxygen to give a superoxide anion radical.

As judged by comparison of the product distribution in the oxidation of vinyl sulfides by both dye and DCA sensitized oxygenation and by quenching techniques, both oxidations proceed probably via the same intermediate.



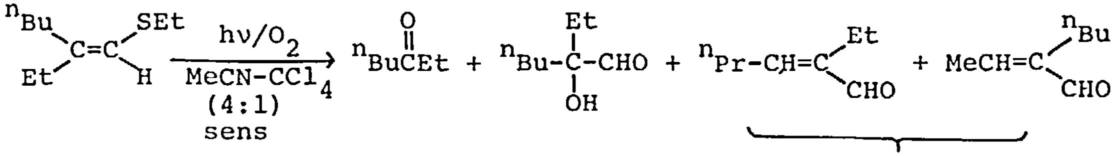
A : TPP$^{a)}$ 60% (in benzene)

B : DCA 61% (in acetone)

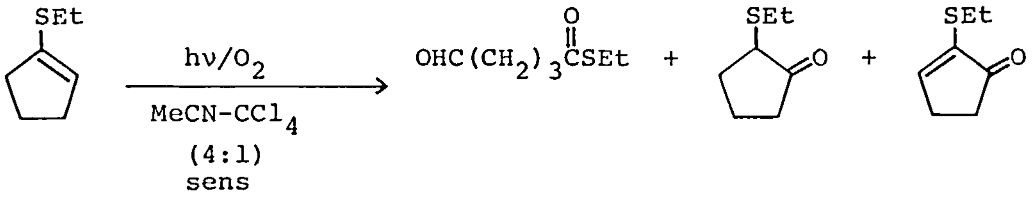
TPP 40%

DCA 39%

a) Tetraphenylporphine



Rose Bengal	70 (%)	14 (%)	16 (%)
DCA with β-carotene	61	14	25



Rose Bengal	98 (%)	0 (%)	2 (%)
DCA with	85[a]	8	7
β-carotene	92[b]	0	8

[a] Irradiation for 3 h. [b] Irradiation for 7 h.

Apparent differences in the product distribution are smaller than the probable error of the analysis, although the choice of solvent and the duration of the photolysis may have some effect. 1,1-Diphenyl-2-methylthioethylene gives the same

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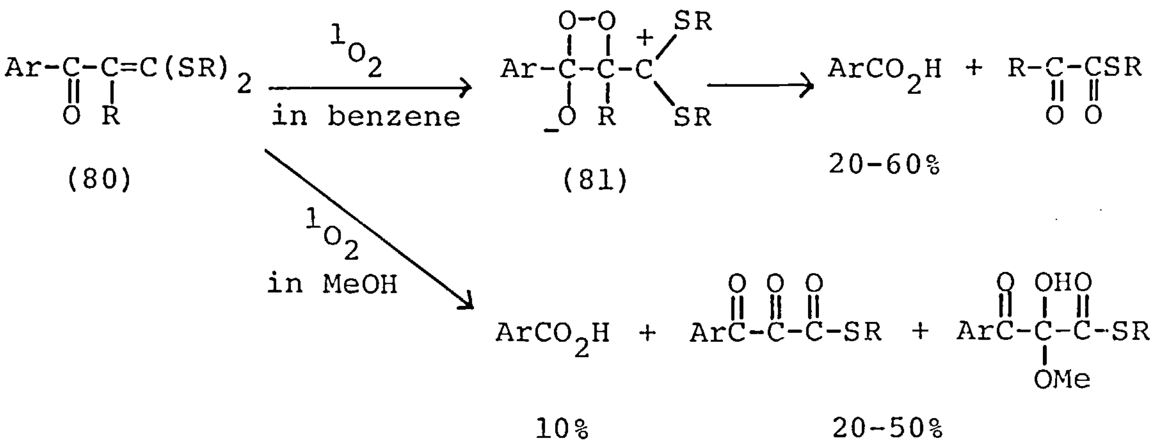
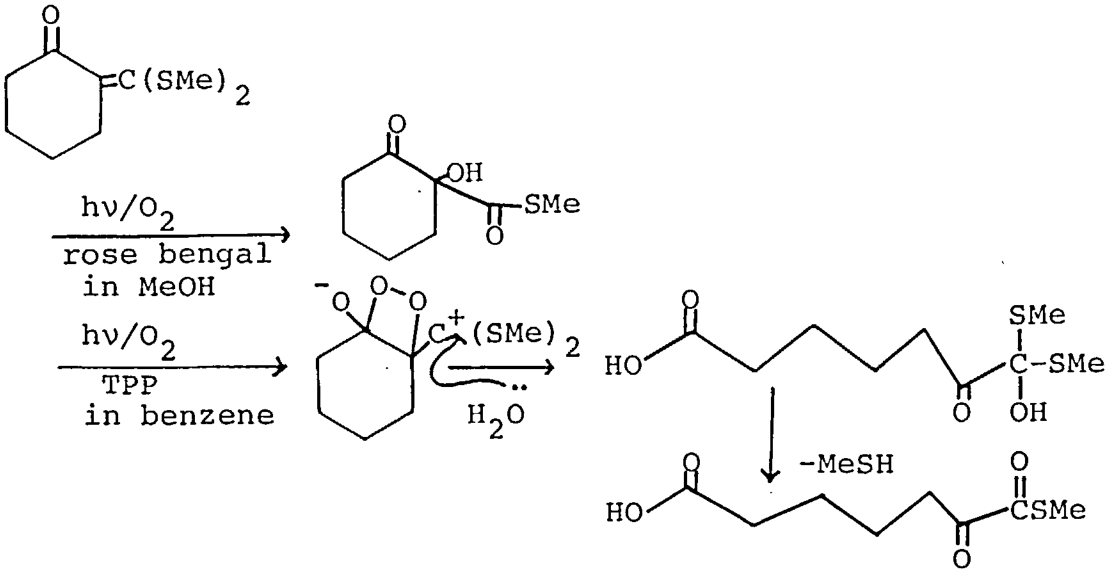
product ratio in each case: a Diels-Alder product, 3-phenylbenzofuran-2-one, and a dioxetane cleavage product, benzophenone. The reaction of singlet oxygen with vinyl sulfides was also extended to α-keto ketone mercaptals (80). In benzene solution, these mercaptals are oxidized to give mainly keto thioesters with concomitant novel acid formation. This result suggests that the dioxetanyl intermediate (81) may be formed with singlet oxygen and then decompose by addition of water.[103] Alternatively, the dioxetane may be formed via an electron-transfer pathway involving superoxide ion, not the singlet oxygen pathway.



The successful cleavage of the C—C σ-bond is undoubtedly due to the stabilization of the carbonium ion by the thioketal group. Otherwise, the usual dioxetane type intermediates formed by addition of singlet oxygen to the double bond would be predominant in methanol and C—S bond cleavage would be found in preference to C—C bond cleavage of the dioxetane intermediate.



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Vinyl sulfides also readily absorb oxygen from the atmosphere and undergo conversion to acid derivatives with migration of the mercapto group. Thus, 1-ethoxy-1-(p-tolylmercapto)-ethylene (82) readily absorbs oxygen to give as the major product ethyl p-tolyl-thio-thioacetate (83).[104]

$$\underset{(82)}{CH_2{=}C(OEt)_2SC_6H_4Me\text{-}p} + \frac{1}{2}O_2 \longrightarrow \underset{(83)}{p\text{-}MeC_6H_4SCH_2COOEt}$$

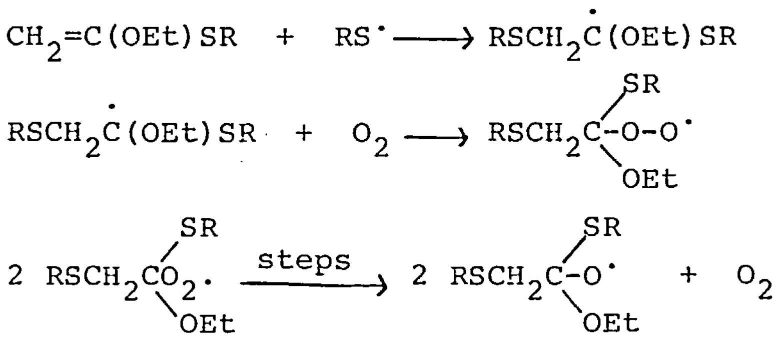
$$CH_2{=}C(SC_6H_4Me\text{-}p)_2 + \frac{1}{2}O_2 \longrightarrow p\text{-}MeC_6H_4SCH_2COSC_6H_4Me\text{-}p$$

TABLE XI

Oxidative Rearrangements of Vinyl Sulfides

Vinylic sulfide	Major product	Yield,%
$CH_2{=}C(OEt)SC_6H_5$	$C_6H_5SCH_2COOEt$	54
$CH{=}C(OEt)SC_6H_4Me\text{-}p$	$p\text{-}MeC_6H_4SCH_2COOEt$	47
$CH_2{=}C(OEt)SC_4H_9\text{-}t$	$t\text{-}C_4H_9SCH_2COOEt$	53
$MeCH{=}C(OEt)SC_6H_5$	$C_6H_5SCH(Me)COOEt$	51
$CH_2{=}C(SC_6H_4Me\text{-}p)_2$	$p\text{-}MeC_6H_4SCH_2CO\cdot(SC_6H_4Me\text{-}p)$	31
$CH_2{=}C(SPr\text{-}i)_2$	$i\text{-}PrSCH_2CO(SPr\text{-}i)$	38
$CH_2{=}CHSC_6H_4Me\text{-}p$	$p\text{-}MeC_6H_4SCH_2CHO$	33
$p\text{-}MeC_6H_4SCH{=}CHSC_6H_4Me\text{-}p$	No reaction	
$CCl_2{=}C(SC_6H_4Me\text{-}p)_2$	No reaction	
$p\text{-}MeC_6H_4SCH{=}C(SC_6H_4Me\text{-}p)_2$	No reaction	

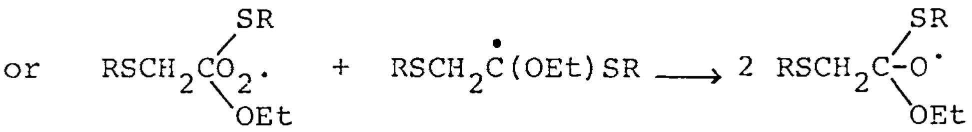
The mechanism may be analogous to that proposed by Walling for the oxidative rearrangement of tetrachloroethylene. Accordingly, a thiol present in small quantities would be expected to catalyze the rearrangement.



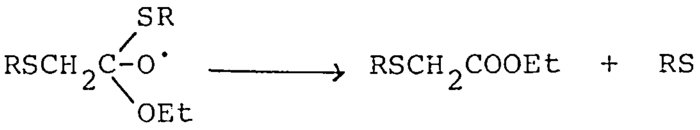
$$CH_2{=}C(OEt)SR + RS^{\bullet} \longrightarrow RSCH_2\dot{C}(OEt)SR$$

$$RSCH_2\dot{C}(OEt)SR + O_2 \longrightarrow RSCH_2\overset{SR}{\underset{OEt}{C}}\text{-}O\text{-}O^{\bullet}$$

$$2\ RSCH_2\overset{SR}{\underset{OEt}{C}}O_2\cdot \xrightarrow{\text{steps}} 2\ RSCH_2\overset{SR}{\underset{OEt}{C}}\text{-}O^{\bullet} + O_2$$

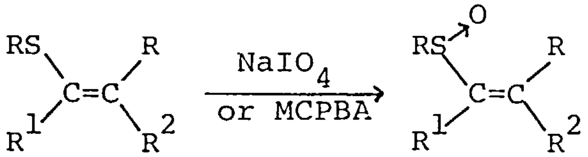


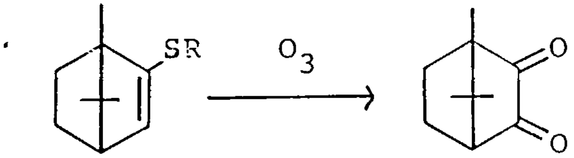
$$\text{or}\quad RSCH_2C(SR)(OEt)O_2\cdot + RSCH_2\dot{C}(OEt)SR \longrightarrow 2\ RSCH_2C(SR)(OEt)O^\cdot$$

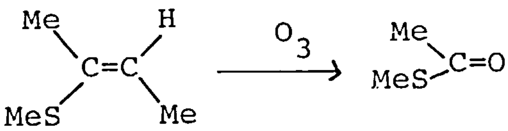


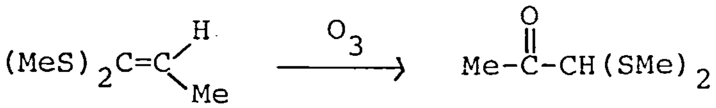
$$RSCH_2C(SR)(OEt)O^\cdot \longrightarrow RSCH_2COOEt + RS$$

Ozonization of vinylic sulfides proceeds with preferential attacks at the unsaturated linkage, not at the sulfur atom.[105]









$$(MeS)_2C=C(H)Me \xrightarrow{O_3} Me-C(=O)-CH(SMe)_2$$

VI-2 Solvent Effects on the Reaction

1-Ethylthio-2-ethyl-1-hexene (84) has an activated double bond and allylic hydrogen atoms and is therefore able to undergo both 1,2-cycloaddition and the ene reaction with singlet oxygen.[106] Photooxygenation of (84) in acetone gives ethyl butyl ketone, (49%), 2-ethyl-2-hydroxyhexanal, and 2-butyl-2-butenal (19%), the latter via the ene

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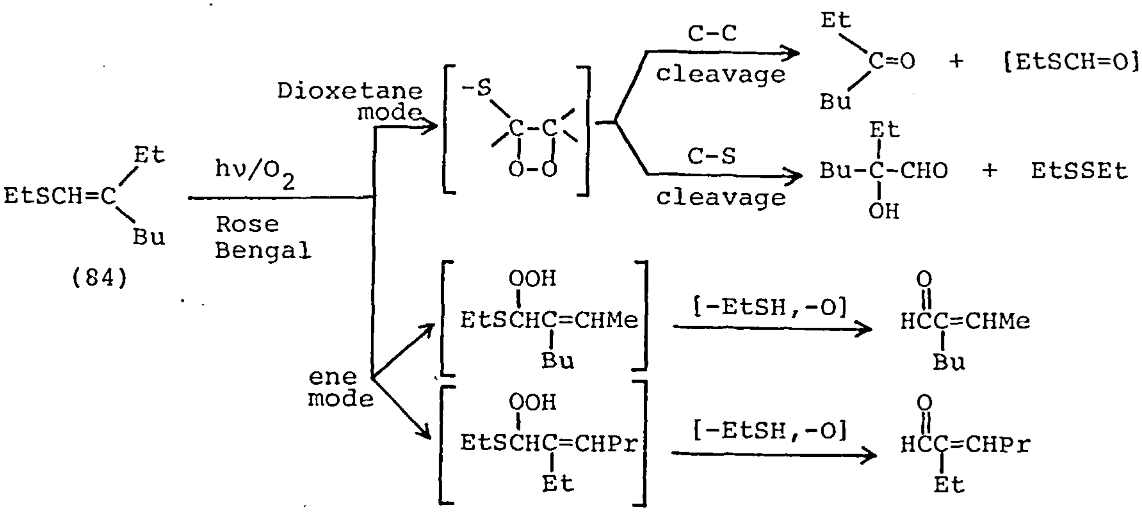
mode. The relative ratio of the two modes has been considered as a measure of the relative rates of two competing processes.



The data may imply that the dioxetane mode is favored exclusively in protic solvents and is slightly favored over the ene mode in aprotic solvents.

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TABLE XII

Solvent Dependence of the Dioxetane and Ene Reaction Modes for 1-Ethylthio-2-ethyl-1-hexene (20°C)

Solvent	Relative yields, % Dioxetane mode	Ene mode
MeOH	100	0
EtOH	100	0
i-PrOH	100	0
CH_3CN	83	17
C_6H_6	82	18
CH_2Cl_2	79	21
Me_2CO	78	22
C_6H_{12}	76	24
CCl_4	64	36

TABLE XIII

Temperature Effect on the Photooxidation of 1-Ethylthio-2-ethyl-1-hexene in Acetone

Temp. °C	Relative yields, % Dioxetane mode	Ene mode
56	55	45
20	78	22
−78	100	0

However, when the reaction was carried out in acetone under reflux conditions, the vinyl sulfide (84) led to equal amounts of products of the ene and dioxetane modes. On the other hand, at low temperature only the products from the dioxetane mode are obtained in acetone. The surprising temperature dependence of these oxidations indicates that the ene mode has probably a transition state of higher potential energy than the dioxetane mode.

It is also found that the yield of dioxetane mode products from alkyl vinyl sulfides is greater than from aryl vinyl sulfides. In such cases, the electron density on the sulfur atom might be important.

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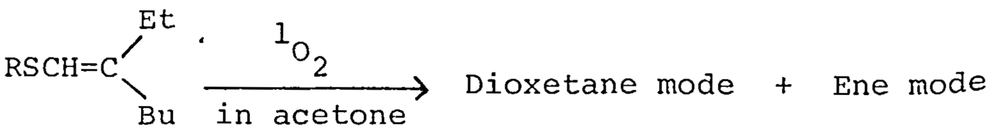
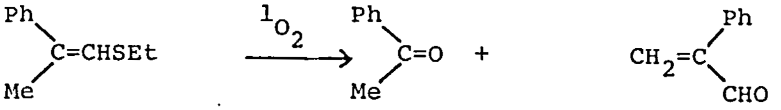


R=t-Bu	85%	15%
=Et	78	22
=Ph	35	65

TABLE XIV

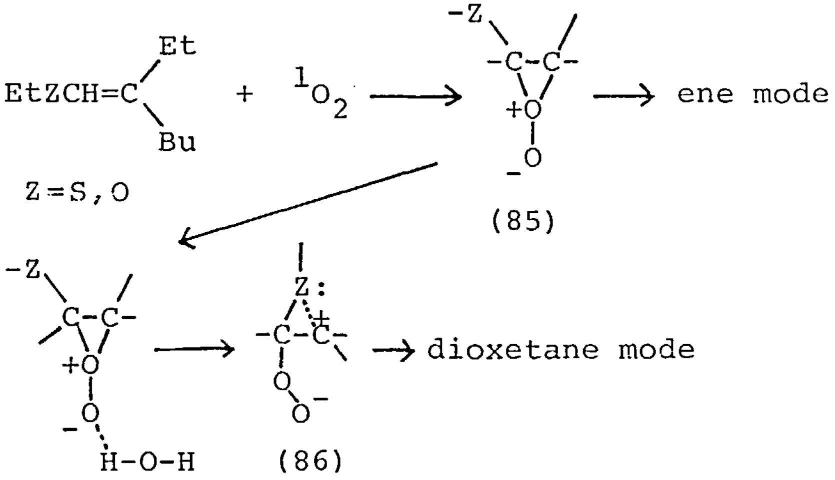


(87)

	(dioxetane mode)	(ene mode)
MeOH	95(%)	5(%)
EtOH	95	7
MeCN	27	73
$CHCl_3$	21	79
MeCOMe	18	82
CH_2Cl_2 (20°)	21	79
(−79°)	88	12

More dramatic solvent and temperature effects were observed in the singlet oxygen reaction with α-methyl-β-ethylthiostyrene (87).[107]

The data may be best explained in terms of the intermediacy of the perepoxide (85) which reacts along two pathways, the ene mode reaction by intermolecular proton transfer and the dioxetane mode reaction via the zwitterion (86).



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A protic solvent can decrease the negative charge density on oxygen by hydrogen bonding, thus promoting nucleophilic attack by neighboring sulfur or oxygen. The explanation of the behavior of the sulfides may be found in neighboring group participation of the sulfide group, in which sulfur vastly excels oxygen, and which stabilizes the polar zwitterion intermediate leading to dioxetane formation.

There are two additional lines of evidence which may support this mechanism.

a) The effects of adding a protic reagent in varying concentration.

b) The effects of changing the RS group.

The photosensitized oxygenation of (87) has been investigated in various mixed solvents with regard to its dependence on added protic reagents. The oxygenation in 65 ml of dichloromethane with 2.5 mmol methanol gave 24% dioxetane mode products and 76% ene mode products. The amount of dioxetane mode products is slightly increased in comparison with the run without alcohol. Furthermore, reaction is 65 ml of dichloromethane with 12.5 mmol methanol gave 47% dioxetane mode products and 53% ene mode products. The products of the two modes are now formed in nearly equal proportion. As the amount of added methanol is increased, the ratio of dioxetane products to ene mode products increases.

The ratio of dioxetane to ene mode products is also a function of the added protic species. The effect of ethanol on the ratio is not so large as that of methanol, but ethanol makes the dioxetane mode less favorable. The reaction in 65 ml of dichloromethane with 25 mmol-butanol gives 23% dioxetane and 77% ene products, which is very similar to the situation in neat dichloromethane. The relative yields of the dioxetane and the ene mode increase in the order t-BuOH, i-PrOH, EtOH, MeOH.

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TABLE XV

Relative Yield of Dioxetane and Ene Modes Products as a Function of Alcohol Concentration in Oxidation of (87)

MeOH in 65 ml CH_2Cl_2	Dioxetane Mode	Ene mode
0.0	21(%)	79(%)
2.5	24	76
6.3	36	64
12.5	47	53
25.0	63	37
50.0	79	21
75.0	90	10
in MeOH	95	5

TABLE XVI

Solvent Dependence for Product Ratio in the Reaction of (87) with Singlet Oxygen

ROH[a]	Dioxetane mode	Ene mode
MeOH	63(%)	37(%)
EtOH	52	48
i-PrOH	31	69
t-BuOH	23	77
CF_3CH_2OH	87	13

[a]) 25mmol ROH in 65 ml of CH_2Cl_2

Thus, the ratio dioxetane ene is closely related to the pK_a of the added alcohol when the concentration of the alcohol is kept constant. In dichloromethane with trifluoroethanol, the ratio of dioxetane to ene mode products is very high, similar to that in neat methanol.

The photooxygenation of 2,3-dihydrothiopyran (88) and its 5-methyl analog (89) gives mainly the C—C bond cleavage product (90) in aprotic solvents, while the sulfoxide is found in protic solvents.[107] These data are comparable with those of dihydropyran (91) which is known to give dioxetane and ene product depending on the solvent.[108]

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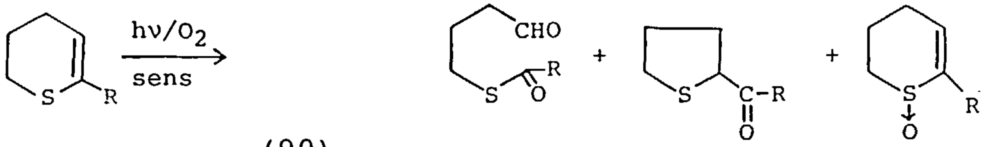
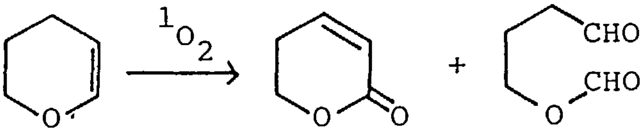
TABLE XVII



(90)

(88) R=H	Acetone[1]	88	12	0
	Benzene[2]	90	10	0
	MeOH[1]	34	2	59
	non sens	0	0	0
(89) R=Me	Acetone[1]	94	6	trace
	Benzene[2]	97	3	0
	MeOH[1]	47	13	40

[1]Rose Bengal sensitizer, [2]Tetraphenylporphine as sensitizer were used



(91) (92) (93)

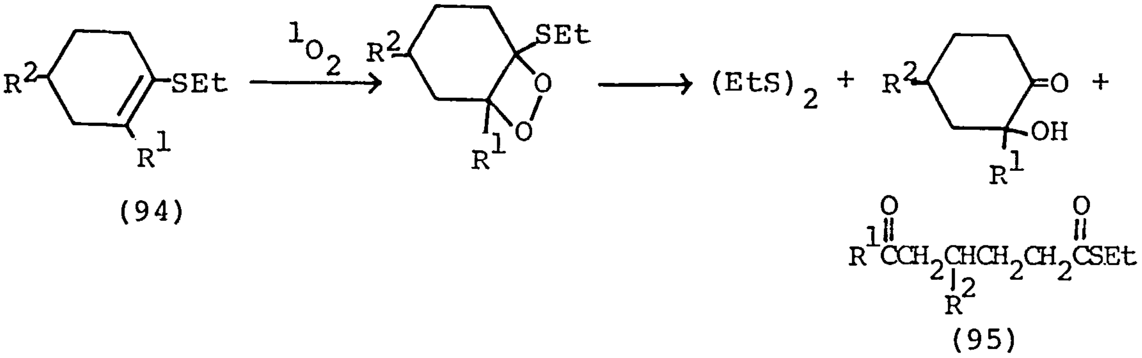
TABLE XVIII

Solvent Effect on the Product Distribution from Dihydropyran

Solvent	Product ratio (93)/(92)
Benzene	0.094
Acetone	0.80
CH_2Cl_2	2.67
CH_3CN	5.51

VI-3 Conformational Effects on the Decomposition of Dioxetanes

As mentioned before, the reaction of various vinyl sulfides with singlet oxygen gave C—S and C—C bond cleavage products derived from intermediate sulfur substituted dioxetanes. The ratio of C—S to C—C cleavage is affected by the conformation of the substrate during the decomposition of the dioxetane. Photosensitized oxygenation of 1-ethylthiocyclohexene (94a) gives the C—C cleavage product, the ω-formylthioester, as the major product. When an alkyl or aryl substituent is introduced in the 2-position, the C—C cleavage increases relative to the C—S cleavage.[109]



(94)

(95)

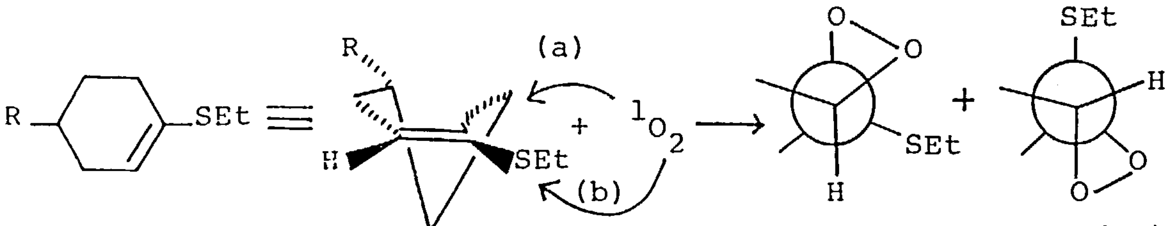
TABLE XIX

Relative Yields[a] of C—S and C—C Cleavage Products (%) in the Reactions of Singlet Oxygen with 2-Substituted 1-Ethylthiocyclohexenes

	R^1	R^2	Methanol		Acetone	
			C–S	C–C	C–S	C–C
(94 a);	H	H	16	84	8	92
(94 b);	Me	H	3	97	2	98
(94 c)	Pr^i	Me	1	99	1	99
(94 d);	Ph	H	5	95	1	99
(94 e);	Bu^t	H	44	56	1	99

[a] Total yield 65–85%.

However, when 1-ethylthio-4-t-butylcyclohexene (94e) in methanol was photo-oxidized, diethyl disulfide (18%), 2-hydroxy-4-t-butylcyclohexanone (24%), and ω-formylthioester (31%) were produced. The ratio of C—S to C—C cleavage of (94e) is influenced by the t-butyl group remote from the 1,2-dioxetane site.



(96)

(97)

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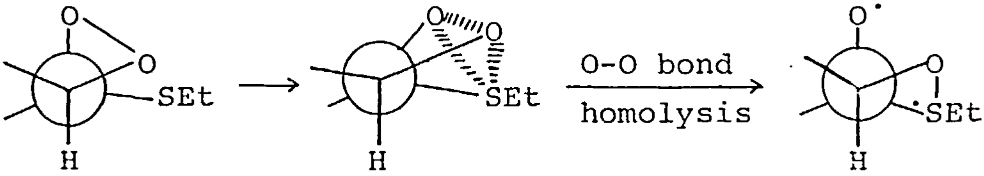
These results can be explained by the conformational requirements of the dioxetane. When singlet oxygen adds to the vinyl sulfide, there are two possible conformations of the resulting dioxetane, i.e. (96) and (97). In (94a), these conformations (96) and (97) are interconvertible and the rate of this interconversion is faster than any dioxetane decomposition which may arise from the more stable conformation (97). However, in the case of (94e) such an interconversion is impossible, and therefore the decomposition of the dioxetane from (94e) proceeds independently from both conformations (96) and (97).



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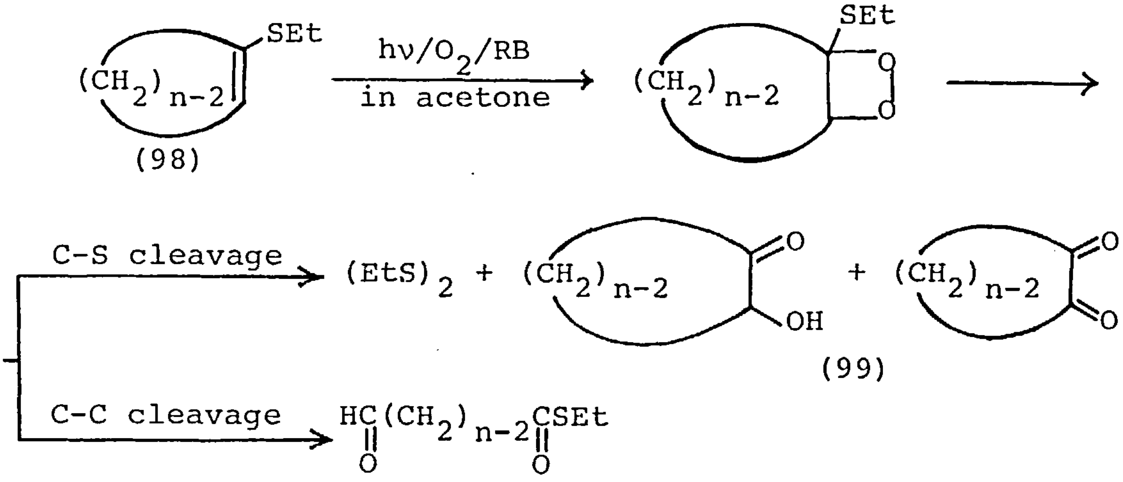
It can be predicted that decomposition from conformation (96) gives the C—S cleavage product and from conformation (97) the C—C cleavage product. In conformation (96) the oxygen and sulfur atoms are nearer to each other, and neighboring group participation by sulfur may lead to homolytic cleavage of the oxygen-oxygen bond.

The reactions of a series of cyclic vinyl sulfides with singlet oxygen have also been studied. The photosensitized oxygenation of (98, n = 6) gives C—C and C—S cleavage products in the ratio of 92:8. On the other hand, the photooxygenation of 1-ethylthiocyclooctane (98, n = 8) gives C—C and C—S cleavage products in the ratio of 5:95. In the photooxygenation of the substrates containing six-and twelve-membered rings, which correspond to the most stable cycloakanes, the C—C cleavage products are obtained almost quantitatively.[110]



(98)

(99)

(100)

TABLE XX

Relative Yield of C—S and C—C Cleavage Products in the Reaction of 1-Ethylthiocycloalkenes with Singlet Oxygen (at 20°).

(98) n	Relative Yield (%) C—S cleavage (99)	 C—C cleavage (100)
5	43	57
6	8	92
7	57	43
8	95	5
10	45	55
12	5	95
a	20	80

a) Compound (84)

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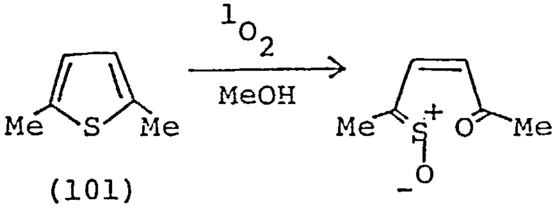
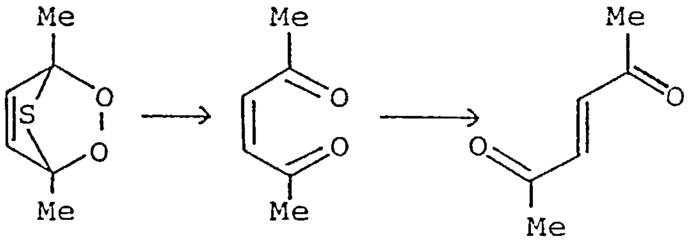
The observed influence of the ring size on the competition between C—C and C—S bond cleavage is quite similar to that on the relative rates of solvolysis of cycloalkyl halides, and of thermolysis of 1-cyanocycloalkenes[111] in which the carbon atom of the reaction center is rehybridized from sp^3 to sp^2 in the course of the reaction, as is the case with the present C—S cleavage in the dioxetane decomposition.

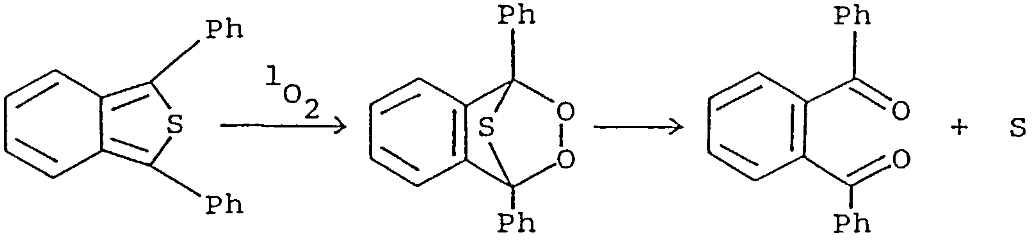
VII. Oxidation of Heterocyclic Systems

VII-1 Photosensitized Oxidation of Thiophenes

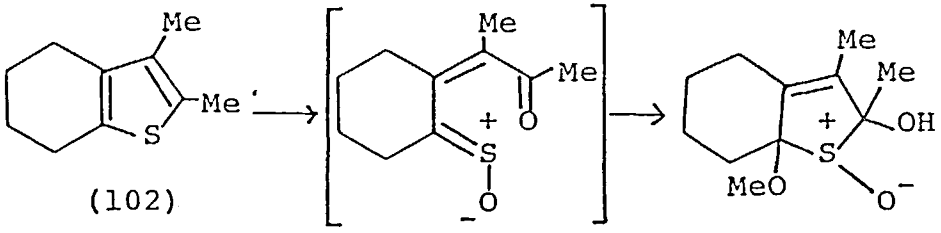
Thiophene and its derivatives are unreactive in dye sensitized photooxygenations. When, however, thiophenes are substituted by alkyl groups, they do undergo attack by singlet oxygen.[112] 2,5-Dimethylthiophene (101) is readily oxidized to sulfine in methanol, and to the trans-diketone in chloroform. The formation of the diketone may take place via an intermediate endoperoxide which loses sulfur and undergoes cis to trans isomerization under the reaction conditions.[112,113]







In the singlet oxygen oxidation of 2,3-dimethyl-4,5,6,7-tetrahedrothianaphthlene (102), the sulfoxide was obtained, presumably by addition of methanol to the sulfine intermediate,[112 b),114]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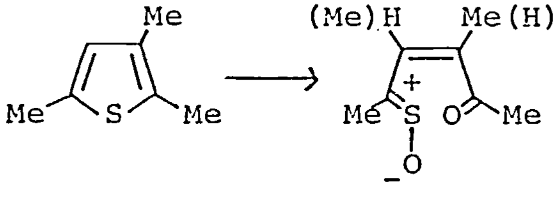
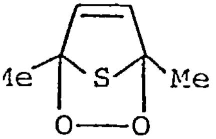


Various types of peroxide intermediates may be considered as precursors of the sulfine, including the endoperoxide (103) the peroxysulfoxide (104), the switterionic peroxide (105) or the dioxetane (106). The evidence available so far does not distinguish between these possibilities.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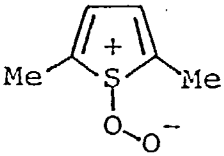
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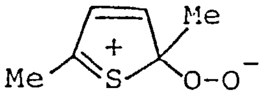
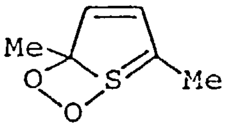

(105)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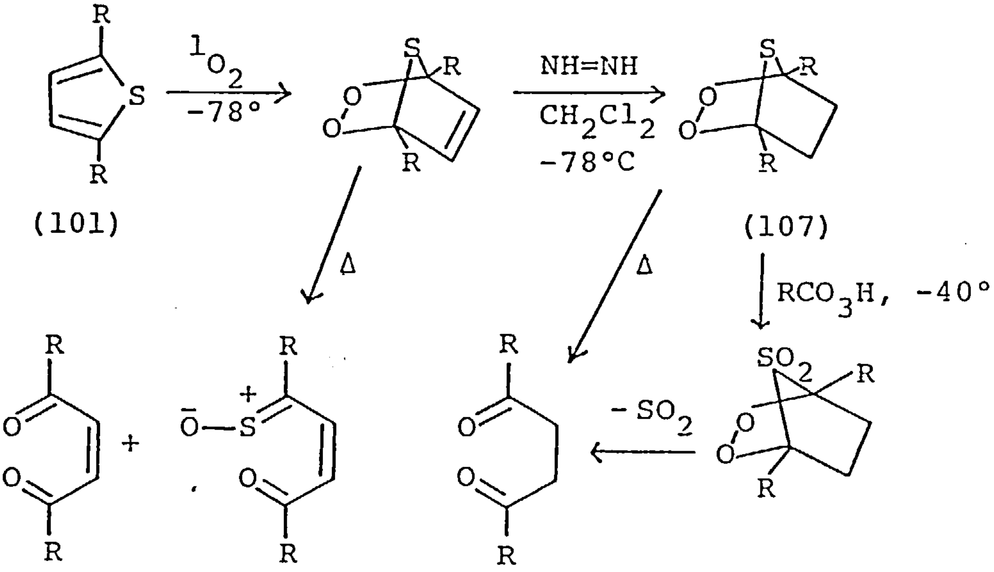
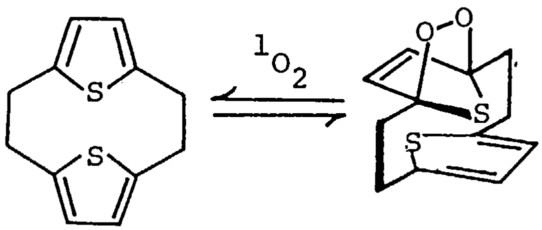
However, if the endoperoxide is really a reaction intermediate in the photosensitized oxygenation of thiophene, then it should be possible to reductively trap it with diazene. Indeed, the endoperoxide formed in the photosensitized oxygenation of 2,5-dimethylthiophene (101) in CH_2Cl_2 at −78° with tetraphenylporphine as sensitizer was subjected by Adam to diazene reduction and gave a 46% overall yield of thioozonide (107).[115] This compound is thermally unstable and rapidly decomposes at room temperature to 2,5-hexadione.



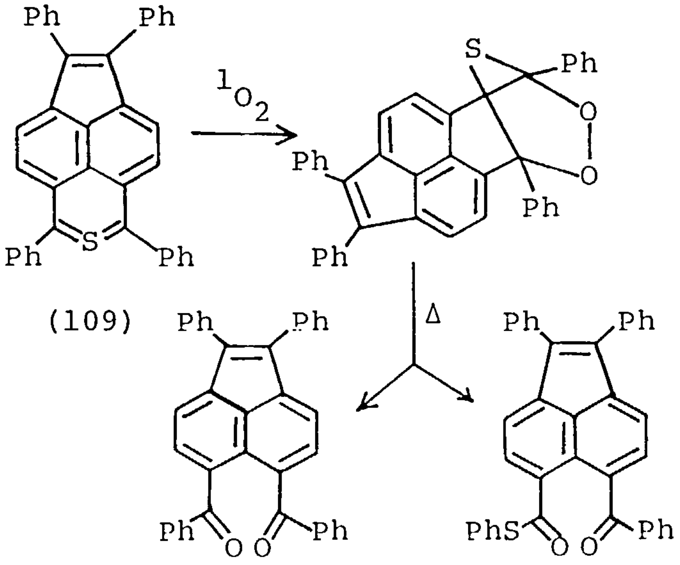
Photooxidation of [2,2](2,5)thiophenophane (108) in chloroformmethanol consumes two molecules of oxygen per thiophenophane molecule, but no products have thus far been identified. If the oxidation is stopped after the consumption of only one equivalent of oxygen and the reaction worked up at ambient temperature, the starting material is recovered quantitatively.[114]



(108)

These observations are in accord with the formation of a thermally unstable, 2,5-endoperoxide which reversibly releases oxygen.

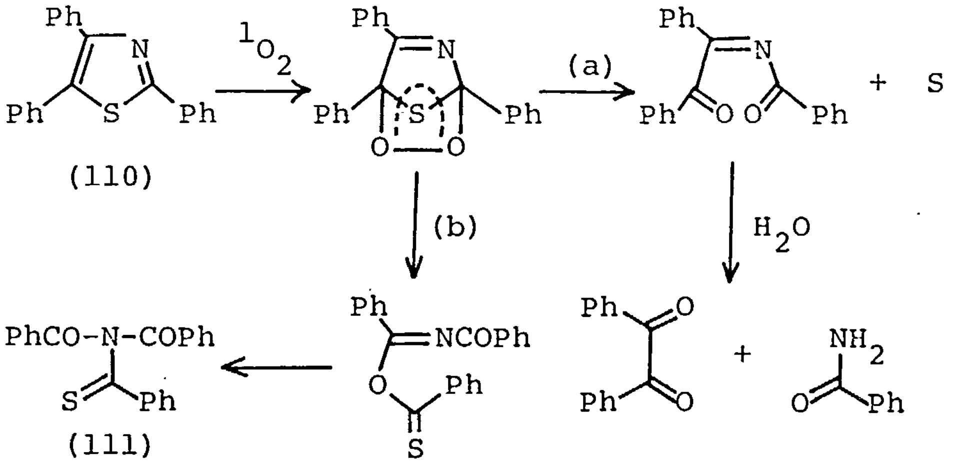
In an interesting reaction related to the singlet oxygen reaction of thiophene, a thioozonide was isolated from the dye sensitized oxidation of 1,3,6,7-tetraphenylacenaphto[5,6-cd]thiopyran (109). The ozonide readily decomposed to diketone and thioester.[115]



(109)

VII-2 Photosensitized Oxidation of Thiazoles.

Thiazoles react with singlet oxygen in a manner similar to the oxidation of thiophenes. Photosensitized oxygenation of 2,4,5-triphenylthiazole (110) in methanol gives benzil and benzamide (path a) while in chloroform the, N,N-diacyl thioamide (111) can be isolated.[117] The latter reaction appears to proceed via an endoperoxide rearrangement involving a Baeyer-Villiger process which produces an intermediate thioimino anhydride. When the thiazole is fused to a six-membered ring the oxidation takes a similar course.[118]



(110)

(111)

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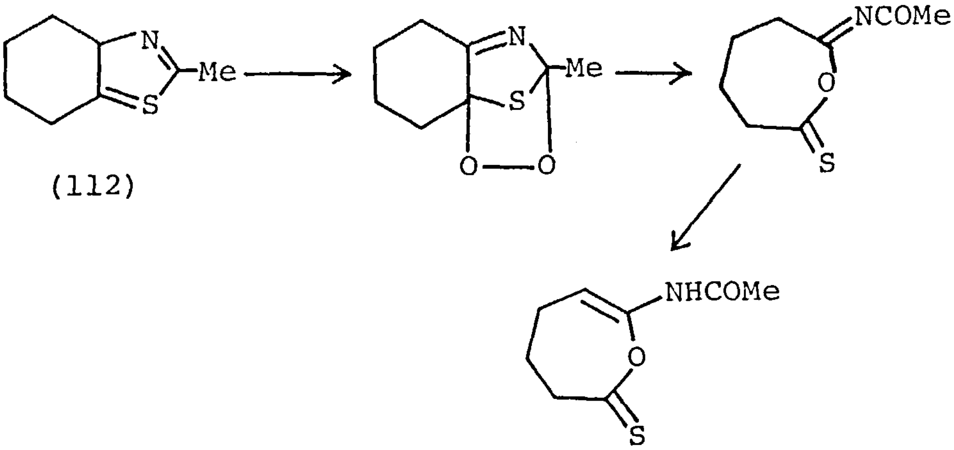
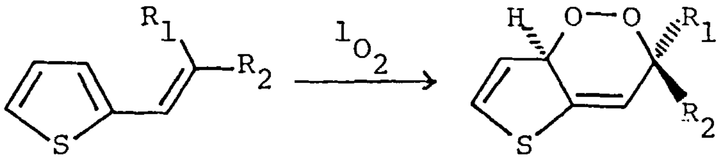


(112)

VIII. Photooxygenation of Various Sulfur Compounds

In the course of their study of Diels-Alder type photooxygenations, Matsumoto and co-workers reported that 1,4-adducts (114) are formed from singlet oxygen and 2-vinylthiophenes (113), the reaction occurring more readily with the heteroaromatic nucleus than with the benzenoid one.[119]



(113) (114)

$R_1 = R_2 = Me$

$R_1 = R_2 = H$

$R_1 = H;\ R_2 = Me$

$R_1 = H;\ R_2 = Ph$

$R_1 = H;\ R_2 = 1\text{-naphthyl}$

Photooxygenation of o-methylthiostyrene (115) in benzene at room temperature leads to four products, a sulfoxide, a hydroperoxide, a benzofuran, and an unusual peroxide derived from the benzene ring.[120] A similar type of peroxide was first described by Foote. 1,1-Diphenyl-2-methoxyethylene (116) undergoes 1,4-addition of singlet oxygen to give an endoperoxide.[121]

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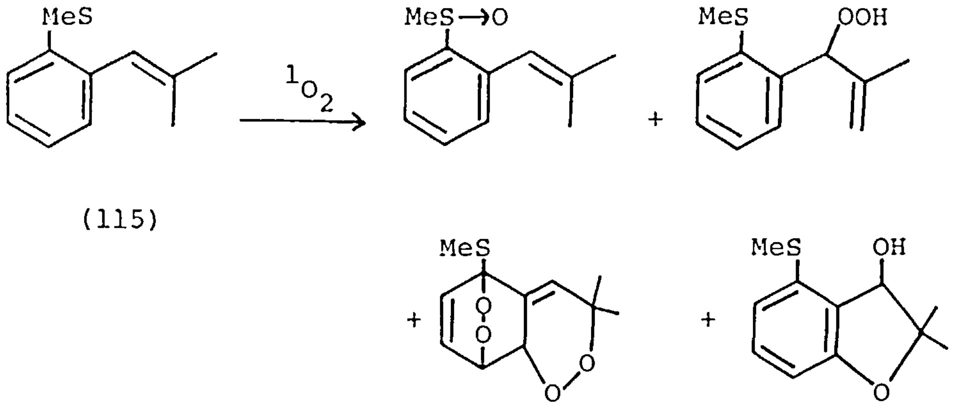
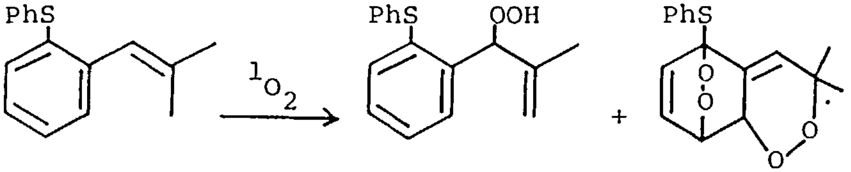
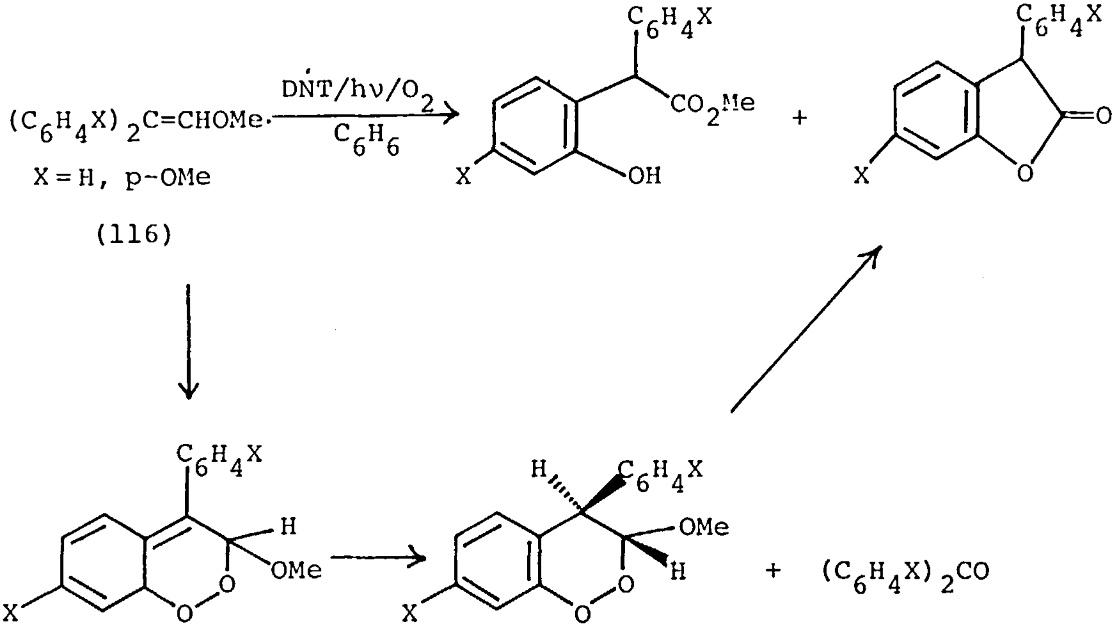


(115)





(116)

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Cyclopropanes are relatively unreactive towards singlet oxygen. However, Rynbrandt and Dutton observed that upon prolonged photooxygenation, aminocyclopropyl sulfide (117) is converted to acyclic carbonyl compounds. Peroxide (118) was proposed as intermediate.[122]

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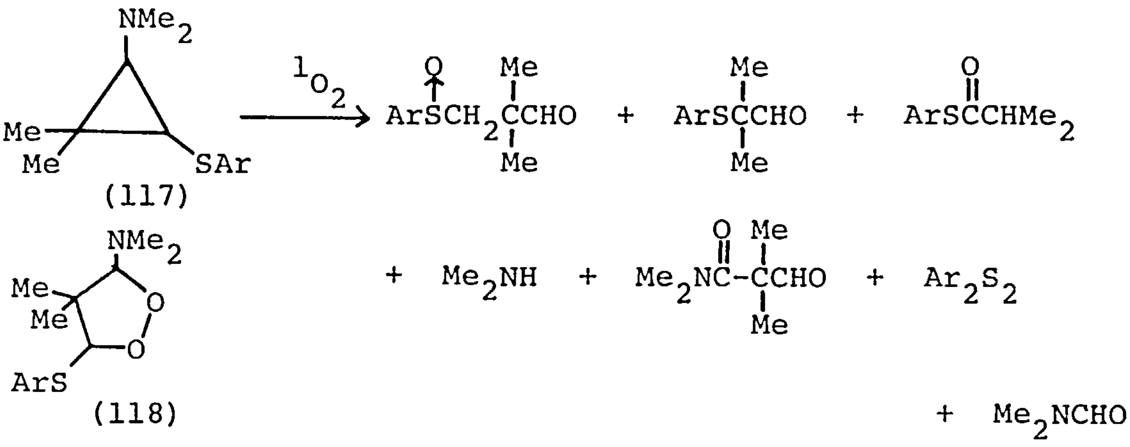
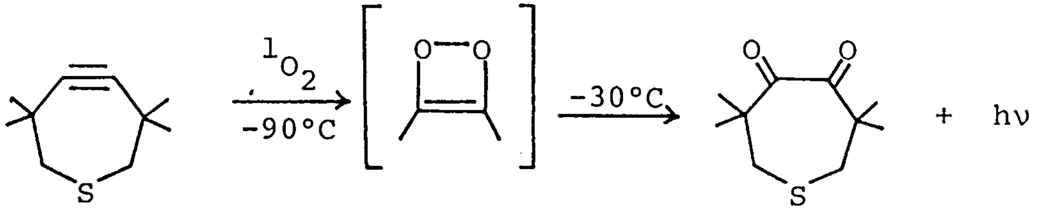


(117)

(118)

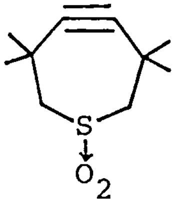
The strained acetylene (119) reacts with singlet oxygen at −90°C to yield an intermediate which is stable at that temperature, but forms (121) on warming to −30°C, with chemiluminescence similar to the fluorescence of (121).[123] The structure of the intermediate is formulated as a dioxetene (120). The acetylenes (122) and (123) show similar behavior in their reactions with singlet oxygen.



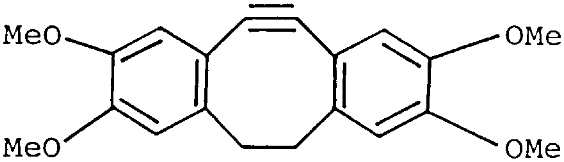
(119)

(120)

(121)

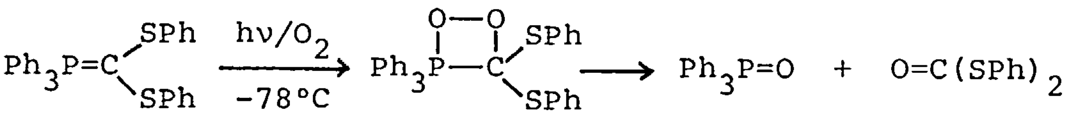


(122)



(123)

Ylides are relatively reactive towards singlet oxygen. Adam and Liu have described the photooxygenation of the phosphonium ylide (124) which gives triphenylphosphine oxide and diphenyl dithiocarbonate (125) in 90 and 98% yield, respectively. The reaction is rapid and does not require a sensitizer.[86,124]



(124)

(125)

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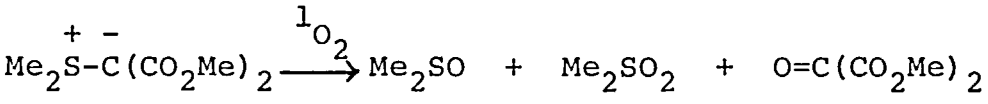
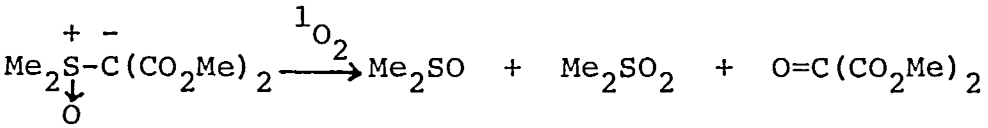
Carbonyl stabilized sulfur and pyridinium ylides have also been studied. Dimethylsulfonium (126), dimethyloxosulfonium (127), and pyridinium biscarbomethoxymethylides (128) have been photooxidized to give dimethyl sulfoxide, dimethyl sulfone and dimethylmesoxalate (129) starting from (126) and (127), and pyridine and (129) starting from (128). Control experiments indicate that these ylides do not react with ground-state oxygen.[125]



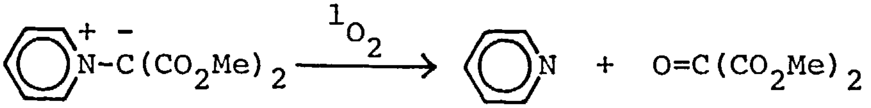
$$Me_2\overset{+}{S}-\overset{-}{C}(CO_2Me)_2 \xrightarrow{^1O_2} Me_2SO + Me_2SO_2 + O{=}C(CO_2Me)_2$$

(126) (129)



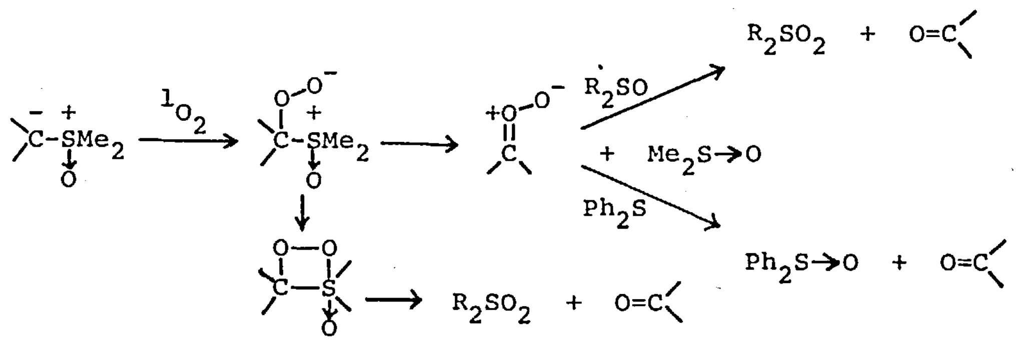
$$Me_2\underset{\downarrow\atop O}{\overset{+}{S}}-\overset{-}{C}(CO_2Me)_2 \xrightarrow{^1O_2} Me_2SO + Me_2SO_2 + O{=}C(CO_2Me)_2$$

(127).



(128)

The elimination of dimethyl sulfoxide and pyridine from the ylides (127) and (128), and the low yield of dimethyl sulfone from (127) suggest that the reaction does not involve only the 1,2-dioxetane intermediate, but also the corresponding carbonyl oxide. Indeed, the photosensitized oxygenation of (128) with singlet oxygen in dimethyl sulfoxide gives dimethyl sulfone. Furthermore, the photooxygenation of the ylides in the presence of diphenyl sulfide gives diphenyl sulfoxide as an oxygen transfer product. Diphenyl sulfide is quite unreactive towards singlet oxygen.



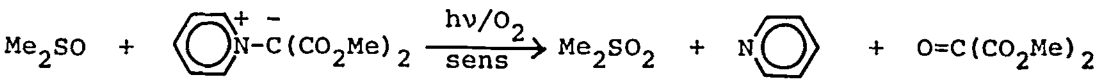


TABLE XXI

Yields of Dephenyl Sulfoxide on Photooxygenation of Ylides (126)–(128) in the Presence of Diphenyl Sulfide*

Ylide	Ph_2SO	Me_2SO	Me_2SO_2	$O{=}C(CO_2Me)_2$	
(126)	53%	67%	18%	63%	
(127)	39	78	10	33	
(128)	45			34	72%

*ca. 0.5 mmol of ylide with ca. 2.0 mmol of diphenyl sulfide was photooxygenated with MB for 2 h in 30 ml of chloroform.

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In the photosensitized oxygenation of dimethyl oxosulfonium phenylphenacylides (130), benzoic acid, derived probably from the decomposition of a 1,2-dioxetane-like intermediate (131), was obtained.[126] This type of intermediate has been proposed in the autooxidation of enolate anions and found to afford the cleavage product, the corresponding carboxylic acid. The cleavage of the C—S bond by elimination of dimethyl sulfoxide is observed as the main reaction process. Dimethyl sulfone is also produced by either the decomposition of the 1,2-dioxetane-like intermediate (132), or by oxygen atom transfer from the carbonyl oxide (133) to dimethyl sulfoxide. The corresponding reaction in methanol affords methyl benzoate. Control experiments showed that methyl benzoate was not formed from benzoic acid under the reaction conditions. Probably, it was produced by attacks of methanol on the intermediate (131).

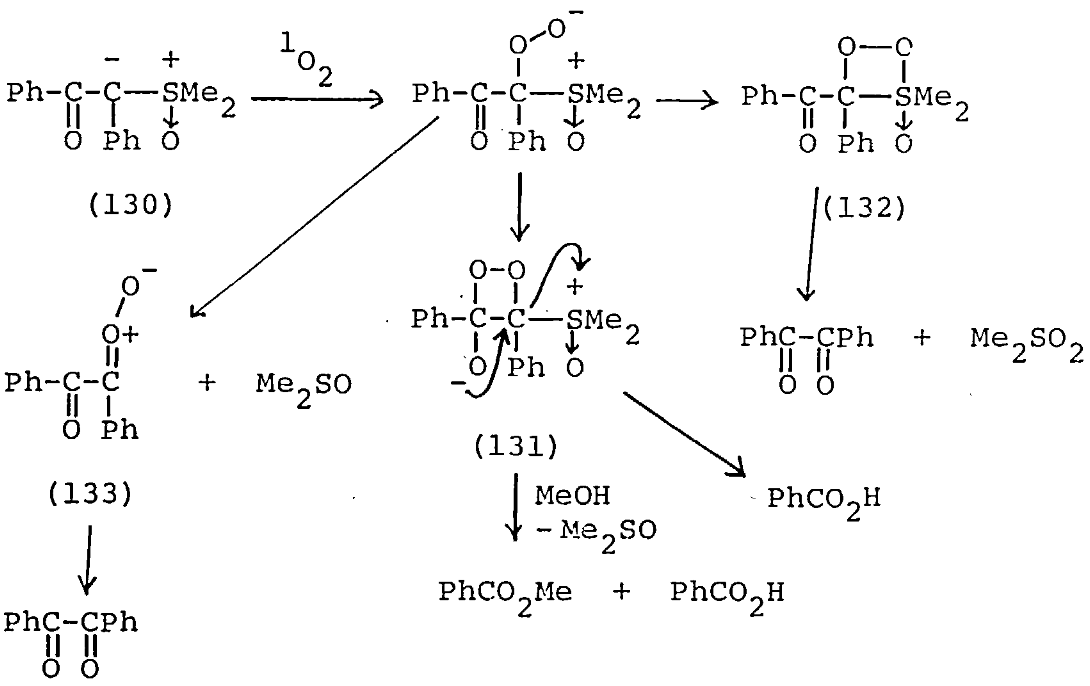
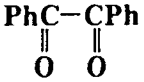


TABLE XXII

Products from the Photooxygenation of (130) in Various Solvents*

Solvent	Sens.	Me_2SO	Me_2SO_2	PhCOOH	 $\mathrm{PhC(=O)-C(=O)Ph}$	$PhCO_2Me$
C_6H_6	TPP	54%	31%	24%	86%	
$CHCl_3$	MB	63	26	45	64	
MeOH	MB	67	3	74	6	45%

*Irradiation time: 40 min.

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