Thiol–Olefin Cooxidation (TOCO) Reaction. 9. A Self-Consistent Mechanism under Nonradical-Inducing Conditions

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The rate of oxygen consumption and the product distribution in the TOCO reaction under various experimental conditions are investigated and a self-consistent mechanism for the reaction under nonradical-inducing conditions is proposed that takes into consideration the observed structural and catalytic effects. Some interesting similarities between hydrogen bromide–olefin and thiol–olefin systems are discussed.

Introduction

The thiol–olefin cooxidation (TOCO) reaction[1] has been studied extensively in this laboratory.[2-6] A self-consistent mechanism for this reaction under conditions that avoid an intentional formation of free radicals proposed here is based on a series of observations that deal, first of all, with the fact that the distribution of the products (TOCO products, thiol–olefin adduct, and disulfide derived from the thiol) as well as the rate of oxygen consumption is a function of the following experimental conditions: (1) the total concentration of equimolar quantities of thiol and olefin; (2) the structural effects of olefin and thiols; (3) the temperature of the reaction mixture; (4) the solubility of oxygen in the reaction mixture; and (5) the effects of catalysts. Other observations relevant to the mechanism under discussion are (6) the secondary, inverse isotope effect; (7) the stereochemistry of the TOCO products derived from indene; (8) the solvent effects; and (9) the kinetic order of the rate of oxygen consumption as a function of the concentration of either olefin or thiol. Finally, there are also some peripheral observations that contribute to the understanding of the thiol–olefin–oxygen reaction, namely: (10) the chemical shift of the sulfhydryl proton of a thiol in the presence of different solvents, including certain olefins;[7] (11) the solvent effects on the rate of the reaction of thiols with oxygen;[8] and (12) the evidence for thiol–olefin complex formation based on electronic spectra.[9]

An overview of the various pathways by which a thiol and olefin can interact with each other and with oxygen to give the above-mentioned three major classes of products is shown in Scheme I, together with approximate rate constants that are either reported in the literature or obtained in the course of this work. Not included in Scheme I, however, is the solvation of the reacting species and intermediate complexes.

The original pathway proposed by Kharasch[10] is represented by k_1, k_4, k_3, and k_6 for the formation of the TOCO products; k_1, k_4, and k_8 for the formation of the anti-Markovnikov adducts, and k_1 and k_5 for the formation of the disulfide. This mechanism has been previously discussed in detail.[10] However, Fava[11] in 1967 observed that there was a vast difference in rates at which exchange (between thiol and disulfide) reactions and TOCO reactions occur, even though their proposed mechanisms had the same initiation step and that the rates of the TOCO reaction was strongly dependent on the structure of the olefin. In order to reconcile with these observations he proposed the charge-transfer complex **2** (K_2) and the abstraction of a hydrogen atom from this complex (k_2) as the initiation step for the TOCO reaction. Extensive investigations of this reaction by Szmant and co-workers[1] found that this proposal was not only consistent with all but also necessary to explain some of the observations. Thus, the second pathway represented by K_2, k_2, k_3, and k_6 to form the TOCO products is incorporated into the scheme. This pathway, together with the pathway also incorporated into this scheme for the formation of the addition products represented by K_1 and k_7 as described in detail, is consistant with all the observations in this reaction as well as with the observations in the preceding two papers. The proposed charge-transfer complex **2** and hydrogen-bonded complex **3** resemble those proposed to explain the temperature- and concentration-dependent product distribution of the reaction between hydrogen bromide and olefin.[12] We shall return to this resemblence after the description of our own observation regarding the cause and effect relationship in the TOCO reaction.

The evidence that has a bearing on the mechanism of the thiol–olefin–oxygen reaction is discussed under the following headings: 1. Importance of the preequilibrium in the choice of reaction paths by the thiol–olefin–oxygen reactants. 2. Importance of the thiol–molecular oxygen reactivity with respect to the TOCO reaction mechanism. 3. Product distribution as a function of temperature. 4. Product distribution as a function of concentration. 5. Kinetics of oxygen consumption in the thiol–olefin–oxygen reaction. 6. The effect of catalysts on the TOCO reaction. 7. Structural effects in the TOCO reaction. 8. Similarity between the hydrogen bromide–olefin and thiol–olefin systems.

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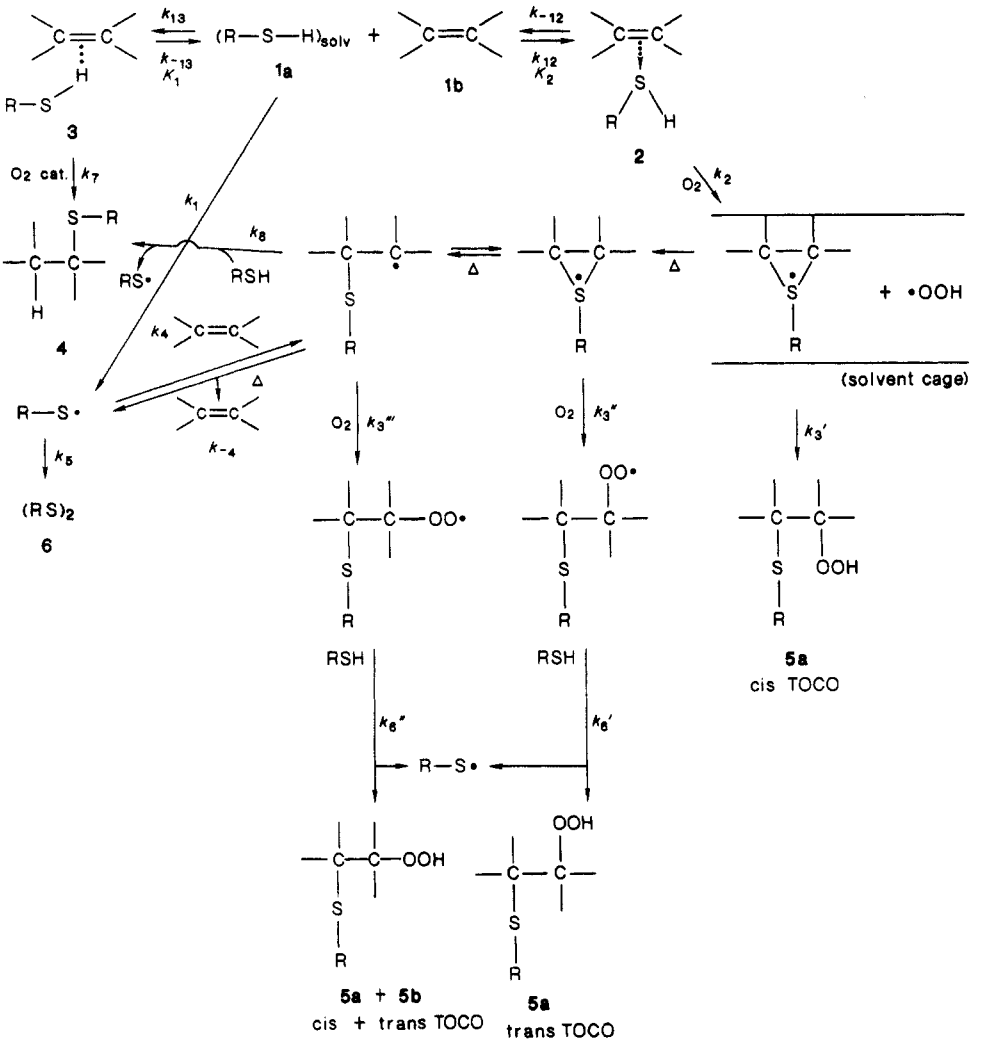
(1) For a complete description and a survey of the literature of the TOCO reaction, see: Szmant, H. H.; Mata, A. J.; Namis, A. J.; Panthananickal, A. M. *Tetrahedron* **1976**, *32*, 2655.
(2) Szmant, H. H.; Rigau, J. J. *Tetrahedron Lett.* **1967**, *34*, 3337.
(3) Szmant, H. H.; Rigau, J. J. *J. Org. Chem.* **1972**, *37*, 447.
(4) Szmant, H. H.; Nanjundiah, R. *Org. Prep. Proc. Int.* **1977**, *9(1)*, 35.
(5) Szmant, H. H.; Nanjundiah, R. *J. Org. Chem.* **1978**, *43*, 1835.
(6) Szmant, H. H.; Baeza, H., J. *J. Org. Chem.* **1980**, *45*, 4092.
(7) D'Souza, V. T.; Nanjundiah, R.; Baeza H., J.; Szmant, H. H. *J. Org. Chem.*, first paper in a series of four in this issue.
(8) D'Souza, V. T.; Iyer, V. K.; Szmant, H. H. J. Org. Chem., previous paper in this issue.
(9) Ma, M. M. M.S. Thesis, University of Detroit, 1970.
(10) (a) Kharasch, M. S.; Nudenberg, W.; Mantell, G. J. *J. Org. Chem.* **1951**, *16*, 524. (b) Kellogg, R. M. *Methods in Free-Radical Chemistry*; Huyser, E. S., Ed.; Marcel Dekker: New York, 1979; Vol. 2, p 1. (c) Oswald, A. A.; Wallace, T. J. *Organic Sulfur Compounds*; Kharasch, N., Meyers, C. Y., Eds.; Pergamon: Oxford, 1966; Vol. 2, p 224. (d) Beckwith A. L. J.; Wagner, R. D. *J. Org. Chem.* **1981**, *46*, 3638.
(11) Fava, A.; Reichenbach, G.; Peron, U. *J. Am. Chem. Soc.* **1967**, *89*, 6696.
(12) Sergeev, G. B.; Stepanov, N. F.; Leenson, I. A.; Smirnov, V. V.; Pupyshev, V. I.; Tyurina, L. A.; Mashyanov, M. N. *Tetrahedron* **1982**, *38*, 2585.
(13) Hoffman, M. Z.; Hayon, E. J. *J. Am. Chem. Soc.* **1972**, *94*, 7950.

0022-3263/87/1952-1729$01.50/0

Scheme I



typical rate constants

this work (*p*-chlorothiophenol in Freon 113 at 30 °C)

$k_1 = 7 \times 10^{-7}$ s^{-1}

from ref 10d

$k_3 = 1 \times 10^{8}$ M^{-1} s^{-1}

$k_4 = 10^{4}$-10^{7} M^{-1} s^{-1}

$k_{-4} = 2 \times 10^{5}$ s^{-1}

$k_6 = 5 \times 10^{3}$ M^{-1} s^{-1}

$k_8 = 10^{7}$ M^{-1} s^{-1}

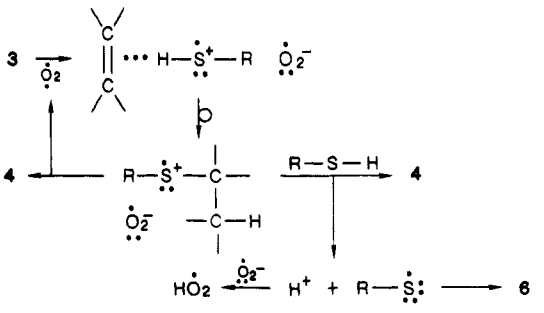
from ref 13

$k_5 = 10^{9}$-10^{10} M^{-1} s^{-1}

Results and Discussion

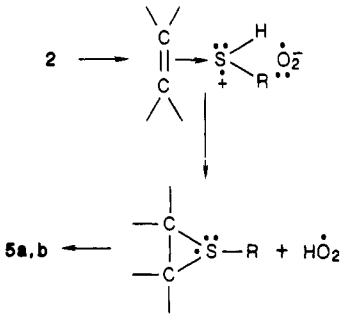
1. The Importance of Preequilibria in the Choice of the Reaction Paths by the Thiol–Olefin–Oxygen Reactants. The evidence for the existence of equilibria between the "free" and associated thiol and olefin is presented elsewhere.[7] Assuming the validity of a competitive formation of charge-transfer and hydrogen-bonded complexes, one can speculate how these preequilibria affect the product distribution in the TOCO reaction. The hydrogen-bonded complex **3** is expected to shield the sulfhydryl proton from an attack by oxygen, and thus the anti-Markovnikov adduct formation (**4** in Scheme I) would be enhanced (Scheme II) as is indeed shown experimentally.[6] On the other hand, the increased electron density of the exposed sulfhydryl proton in the charge-transfer complex **2** should promote a reaction with molecular oxygen[8] (Scheme III). The resulting pair of radical species leads to the temperature-dependent formation of cis or trans hydroperoxy sulfides (**5a,b** in Scheme I) on the way to the eventually isolated TOCO products.[1]

Scheme II



In view of the increasing recognition of the ubiquitous one-electron-transfer mechanisms,[14] such steps can be invoked to explain the formation of **4** and **5** as shown in

Scheme III



Schemes II and III. However, the authors have not made a detailed study of thiylation of olefins under nonradical-inducing conditions and further work is necessary to substantiate Scheme II.

The observations consistent with this mechanistic picture are (1) the reluctance of isolated olefins such as cyclohexene and cyclopentene to give TOCO products, and the exclusive or preferred formation of anti-Markovnikov adduct (Table I), and (2) the ability of conjugated, styrene-like olefins to give quantitative yields of TOCO products (Tables II–V).

Schemes II and III are useful to explain the remarkable aspects of the TOCO reaction, namely, the dependence of the distribution of reaction products on both the total equimolar concentration of thiol and olefin and on the reaction temperature (Table II) as well as the dependence of the rates of the TOCO reaction on the structure of various olefins (Table VI).

The conclusions with regard to the preequilibria that generate the relatively weak thiol–olefin complexes **2** and **3** from the solvated or self-associated reactants, and the dependence of the rate-determining steps of the major competitive processes on the presence of these fragile complexes, are supported by the "negative activation energy" of the TOCO reaction (ref 1). As discussed in greater detail below, there seems to be a significant difference in the relative magnitudes of the two competing equilibria and also in their temperature coefficients. Thus, at higher temperatures, $K_2 > K_1$ (Scheme I) so that the formation of the anti-Markovnikov adduct is hardly observed. On the other hand, the rate of the reaction (as evidenced by oxygen consumption) not only increases with a decrease in the temperature but, at the same time, the formation of the adduct **4** becomes more competitive relative to the formation of the TOCO products.

2. The Importance of Thiol–Molecular Oxygen Reactivity with Respect to the TOCO Reaction Mechanism. The sensitivity of the abstraction of the sulfhydryl hydrogen from either the solvated or complexed thiol by molecular oxygen to the chemical environment is discussed elsewhere,[8] but it is noteworthy that the reaction is relatively slow in the absence of bases or transition metals. In the absence of an olefin, the thiyl radical dimerizes to give a disulfide, whereas the TOCO products are formed via a bridged sulfur radical or an open carbon radical (Scheme I). The similarity between the TOCO reaction and the oxidation of a thiol in an inert solvent or in the presence of a benzenoid cosolvent can be seen by the comparison of Schemes III and IV. The relatively higher reactivity of the thiol–olefin complexes toward oxygen in the presence of conjugated olefins (indene and substituted styrenes) as compared to the thiol–benzenoid complexes can be attributed to the greater stabilization by the larger π system of the incipient radical cation **7** in the transition state.

Fava and collaborators explained[11] the assistance of olefins in the abstraction of the sulfhydryl hydrogen by oxygen by means of such complexes. Also, the formation of the olefin–thiol complexes is reminescent of the molecule-assisted-homolysis of a sulfhydryl hydrogen suggested by Pryor.[15] The kinetic evidence for the involvement of both the thiol and olefin in the rate-determining step of

Table I. Effect of Olefin Structure on the Rates of Oxygen Absorption by Mixtures of Olefins and *p*-Chlorothiophenol[a] at 24 ± 4 °C

olefin (mol)[b]	$t_{1/2}$, h	O_2 absorption, % theory	products (%)	10^5k, s^{-1}
cyclohexene (0.002)	85	100[b]	$(RS)_2$ (100)	0.22
cyclohexene (0.004)	85	100[b]	$(RS)_2$ (100)	0.22
cyclopentene (0.002)	80	86[c]	TOCO (45) addn (40)	0.24
cyclopentene (0.004)	48	70[c]	TOCO (65) addn (30)	0.40
none	18	100[b]	$(RS)_2$ (100)	1.06

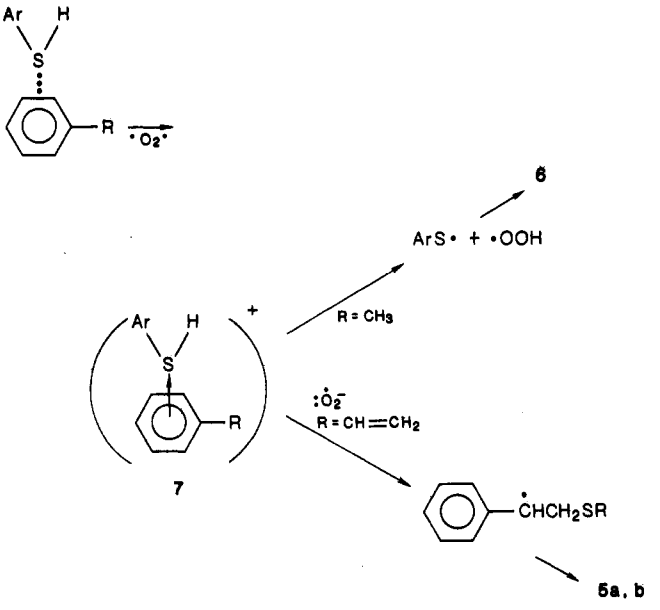
[a] *p*-Chlorothiophenol and olefin concentrations are 0.057 M in hexane. [b] Based on 100% yield of disulfide. [c] Based on 100% yield of TOCO products unless stated otherwise.

Table II. Effects of Total Concentration and Temperature on the Product Distribution in the TOCO Reaction of Indene and *p*-Chlorothiophenol in Hexane

indene, M	thiol, M	yield,[a] %	temp, °C	addn, %	TOCO, %
0.3	0.3	81	0	26	74
0.6	0.6	81	0	37	63
1.6	1.6	79	0	80	20
0.3	0.3	82	30 ± 3	5	95
0.6	0.6	84	30 ± 3	7	93
1.6	1.6	79	30 ± 3	22	78
5.3	5.3	85	30 ± 3	100	0[b]

[a] Total yield of addition and TOCO products. [b] In isooctane solution.

Scheme IV



(14) (a) Ashby, E. C.; Park, W. *Tetrahedron Lett.* **1967**, 6695. For a description of the radical cation formed by one-electron transfer in the oxidation of sulfides, see: (b) Asmus, K.-D. *Acc. Chem. Res.* **1979**, *12*, 436. (c) Asmus, K.-D. presented before the Division of Petroleum Chemistry Inc., American Chemical Society Anaheim, September 1986.

Table III. Effect of Total, Equimolar Concentrations on Product Distribution in the Reaction between Indene and *p*-Chlorothiophenol in the Presence of an Excess of Oxygen[a]

concn of reactnt, 10^2M	amt of reactnt mol × 10^3	initl phase[b] time, h	product distribution: disulfide mol × 10^3	disulfide % yield	addition product mol × 10^3	addition product % yield	TOCO product mol × 10^3	TOCO product % convn	TOCO product % yield
1	0.79	18.0	0.076	19	0	0	0.64	81	100
2	4.6	8.2	0.28	13	0	0	3.98	88	98
4	3.0	1.41	0.092	6	0	0	2.8	93	99
4	6.1	50	0.65	21	0	0	4.6	75	94
8	6.1	1.13	0.06	2	0	0	5.9	97	99
16	4.0	36	0.157	8	0.12	3	3.6	89	100
16	4.0	0.25	0	0	0.16	4	3.8	95	99

[a] In Freon 113 at 30 °C. [b] The slow oxygen-absorbing phase.

Table IV. Effect of Total, Equimolar Concentrations on Product Distribution in the Reaction between Benzocyclohex-1-ene and *p*-Chlorothiophenol in the Presence of an Excess of Oxygen[a]

concn of reactnt, 10^2M	amt of reactnt, mol × 10^3	initl phase[b] time, h	product distribution: disulfide mol × 10^3	disulfide % yield	addition product mol × 10^3	addition product % yield	TOCO product mol × 10^3	TOCO product % convn	TOCO product % yield
1	0.77	27	0.15	38	0	0	0.47	61	100
2	1.5	22	0.25	34	0	0	0.99	66	99
2	1.5	126	0.41	55	0	0	0.63	43	92
4	6.0	20	0.94	33	0	0	3.6	64	87
4	3.0	16	0.33	22	0	0	2.3	77	98
8	4.0	8	0.087	4	0	0	3.8	95	99
16	4.0	2	traces		0.14	4	3.8	95	98

[a] In Freon 113 at 30 °C. [b] The slow oxygen-absorbing phase.

Table V. Effect of Total, Equimolar Concentrations on the Product Distribution in the Reaction between Benzocyclohept-1-ene and *p*-Chlorothiophenol in the Presence of an Excess of Oxygen[a]

concn of reactnt, 10^2M	amt of reactnt, mol × 10^3	initl phase[b] time, h	product distribution: disulfide mol × 10^3	disulfide % yield	addition product mol × 10^3	addition product % yield	TOCO product mol × 10^3	TOCO product % convn	TOCO product % yield
1	0.76	144	0.11	28	0	0	0.54	71	100
2	1.57	77	0.145	19	0	0	1.27	81	99
2	1.5	254	0.313	41	0	0	0.88	58	100
4	6.0	71	0.119	4	0	0	5.74	96	99
8	4.0	22	traces		0	0	3.96	99	100

[a] In Freon 113 at 30 °C. [b] The slow oxygen-absorbing phase.

Table VI. Effect of Olefin Structure on the Rates of Oxygen Absorption by Equimolar Mixtures of Olefins and *p*-Chlorothiophenol[a] at 24 ± 4 °C

olefin	O_2 absorption, % theory[b]	10^2k, M^{-1} s^{-1}
styrene	90	8.70
p-tert-butylstyrene	88	21.0
p-fluorostyrene	89	6.9
p-bromostyrene	83	3.7
3,5-dimethylstyrene	80	14
p-methylstyrene	87	12
p-chlorostyrene	85	4.30
p-methoxystyrene	88	10
p-phenoxystyrene	70	2.8
indene	96	2.30
indene-*1,3,3-d*$_3$	88	6.90
indene[c]	126	11.00[d]

[a] The total concentration of the equimolar mixture is 0.057 M in hexane. [b] Based on 100% yield of TOCO products. [c] The total concentration is 0.04 M in Freon 113 at 30 °C. [d] Third-order autocatalytic rate constant; units are M^{-2} s^{-1}.

the TOCO reaction (conceivably the abstraction of the sulfhydryl hydrogen) is presented below.

3. Product Distribution as a Function of Temperature. The course of the reaction of oxygen with the radical formed by the abstraction of hydrogen atom from the thiol–olefin complex is dependent on the solvent and temperature. As proposed previously,[1] at low temperatures the collapse of the radical pair in the solvent cage leads to relatively large amounts of the cis TOCO products (**5a** in Scheme I). At relatively higher temperatures the escape of the hydroperoxy radical from the solvent cage results in bridged radicals that are attacked by oxygen or hydroperoxy radicals preferentially from the backside to give the trans TOCO products. However, a further increase in the temperature of the reaction mixture shifts the equilibrium between the bridged radical and the open, "classical" radical in favor of the latter and now oxygen can attack it from either side of the molecular plane to give nearly equal amounts of cis and trans TOCO products. Furthermore, at the relatively higher temperatures, the classical carbon radicals tend to dissociate to give free thiyl radicals and the olefin, and the thiyl radicals then dimerize to give disulfide. Thus, at relatively higher temperatures when the formation of the cis TOCO product increases due to the nonstereoselective addition of oxygen to the classical carbon radical, this shift in the stereochemistry of the TOCO reaction is accompanied by higher yields of disulfide.

Table II indicates that the amount of addition product increases as the temperature of the TOCO reaction is lowered. Although no attempt was made to account for the exact changes of oxygen concentration in solution at different temperatures; by assuming Gay–Lussacs Law, the

(15) Pryor, W. A. presented before the Division of Petroleum Chemistry, Inc., American Chemical Society, Houston, March 1980.

above observation indicates that the formation of oxidation product in the TOCO reaction does not depend only on the concentration of oxygen in solution.

The explanation of the formation of increasing amounts of addition products at relatively low temperatures (Table II) is found in the shift of the preequilibria in favor of the hydrogen-bonded complex. Such a shift can be rationalized on the basis of a tighter association, i.e., the relatively shorter bond distance, resulting in a loss of internal freedom in **3** and a consequently more negative entropy of association in hydrogen bonding as compared to that of the less-congested donor–acceptor complexes. Also, the enthalpy of hydrogen-bond formation is more favorable because of stronger bonding than that of charge-transfer complex formation. The above-mentioned arguments are supported by thermodynamic parameters found in the literature[16] for the interaction of thiols with electron donors, and one can hypothesize a plot of log K vs. $1/T$ (Figure 1)[17] that shows the relative stability of the hydrogen-bonded complexes to increase at the lower temperatures. Such a plot implies a greater concentration of both complexes at the lower temperatures and thus an increased rate of reaction at lower temperatures in agreement with the "negative activation energy" that is actually observed.[1]

4. Product Distribution as a Function of Concentration. A remarkable aspect of the TOCO reaction is the change in the distribution of reaction products when the total concentration of equimolar amounts of thiol and olefin is varied even though an excess of oxygen is present at all times. Under the concentration conditions employed traditionally for preparative purposes (i.e., 0.2–0.3 M of both thiol and olefin in an inert paraffinic solvent like hexane), one can isolate an essentially quantitative yield of the β-hydroxy sulfoxides provided that the thiols and olefin reactants are chosen judiciously (aromatic thiols and styrene-like olefins, Tables III, IV, and V). We shall now discuss the changes in the distribution of the reaction products as one varies the total concentration of the equimolar reactants.

An increase in the equimolar concentrations of the same reactants under similar solvent and temperature conditions causes a decreased yield of the TOCO products, and a quantitative yield of addition product is obtained (Table II) at concentrations higher than 5 M. On the other hand, a decrease in the equimolar concentrations of the olefinic and thiol reactants, say from 0.2 to 0.01 M, yields an increasing amount of disulfide at the expense of the TOCO products (Tables III, IV and V). These concentration effects are believed to be a direct consequence of the preequilibria discussed in the preceding section of this paper.

In a solution of indene and *p*-chlorothiophenol in Freon 113 at 25 °C, $K_2 > K_1$ (Scheme I) as evidenced by the ^{1}H NMR results.[7] Thus, at the optimum concentration range for the formation of TOCO products (0.2 to 0.3 M), the charge-transfer complex **2** seems to be the predominant species, and the abstraction of the sulfhydryl hydrogen by oxygen or hydroperoxy radical leads to the desired TOCO products. However, an increase in the total concentration of the olefinic and thiol reactants brings about a relatively increased presence of the hydrogen-bonded complex.

This conclusion is supported by calculations using a model in which one assumes that the relative stabilities of two complexes differ by 3 orders of magnitude (i.e., if $K_2' = 10^{-2}$ and $K_1' = 10$). The ratio of the concentrations of the more stable and less stable species, i.e., X_1/X_2, can then be shown to decrease significantly as the total concentrations of the reactants increases from, say, 0.01 to 10 M (A in Figure 2).[17] The results of similar calculations based on other relative stability ratios and different concentration ratios are also included in Figure 2.[17] The results of these calculations demonstrate that the greatest concentration difference between the two species is at *low* concentrations of the reactants, and not, unexpectedly, as the difference in the relative magnitude of the associations increases. Lower temperatures also enhance the relatively greater presence of the weaker complex. Philosophically speaking, this is analogous to a societal situation: in times of scarcities the strong tend to survive better than the weak, whereas in times of plenty even the weaker have a good chance to succeed. On the basis of this model it can be visualized that an increase in the total concentration of the olefin and thiol reactants increases the relative presence of the less-favorable hydrogen-bonded complex, and this then could be the reason for the formation of high yields of the addition product.

The relative yields of TOCO products and of the anti-Markovnikov adduct actually depend not only on the equilibrium concentrations of the appropriate complexes **2** and **3** but also on the relative rates of the two reactions:

$$d(\text{TOCO})/d(\text{adduct}) = k_2[O_2][\mathbf{2}]/k_7[\mathbf{3}]$$

The conversion of the hydrogen-bonded complex **3** to the anti-Markovnikov adduct under nonhomolytic conditions is extremely slow, but it is subject to catalysis by oxygen. This was demonstrated by experiments carried out over a period of 1 year during which NMR tubes filled in the absence of air with neat mixtures of indene and various thiols, and kept in the dark, were examined periodically for the formation of the expected adduct.[8] No reaction could be detected after 45 days. Then, the tubes were opened to air for 2 min and the observations were continued. After 6 months only *m*-(trifluoromethyl)thiophenol was seen to have produced some addition product.

Table VII. Stereochemistry of the Adducts Produced from 1,3,3-Trideuterioindene[a] and Substituted Thiophenols under Nonphotochemical Conditions

substit	temp, °C	extent of reactn,[c] %	% trans[d] adduct
p-methoxy	5	56	100
	25	52	100
m-methyl	5	46	100
	25	43	100
p-fluoro	5	23	100
	25	100	100
p-*tert*-butyl	5	100	100
	25	100	100
m-trifluoromethyl	5	49[e]	100[e]
	25	58	100[e]

[a] Deuterium content 96–98%. [b] In NMR tubes protected from light after a reaction period of 375 days. Since no reaction was observed after 45 days when the NMR tubes were prepared with thorough removal of air (see Experimental Section), the tubes were opened to the air for 2 min and the observation of the spectral changes was continued. After 6 months, only the *m*-(trifluoromethyl)thiophenol was seen to have produced some addition product. The samples were not further exposed to air for the remainder of the 375 days. [c] Determined after 375 days by the comparison of the intensity of either the two doublets produced by the 1- or 2-protons of the indene–thiol adduct against the intensity of the 2-proton singlet of unreacted 1,3,3-trideuterioindene. [d] Determined on the basis of the presence of only one doublet observed at approximately δ 3 in a 100-MHz spectrum of the 1,3,3-trideuterioindene–thiol adduct. [e] This result is less certain because of the complexity of the spectrum.

(16) Vinogradov, S. N.; Linell, R. H. *Hydrogen Bonding*; Van Nostrand Reinhold Co.: New York 1971.

(17) See paragraph at the end of paper about supplementary material.

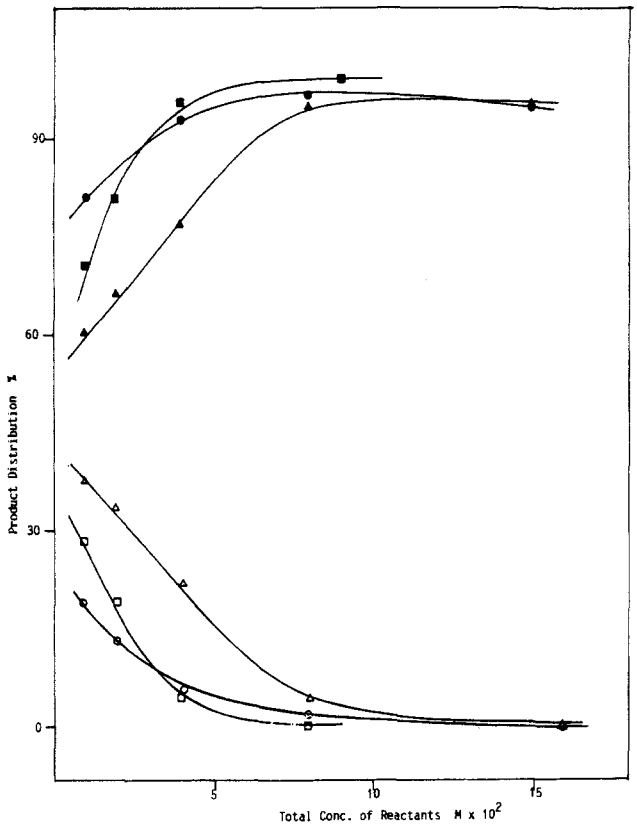
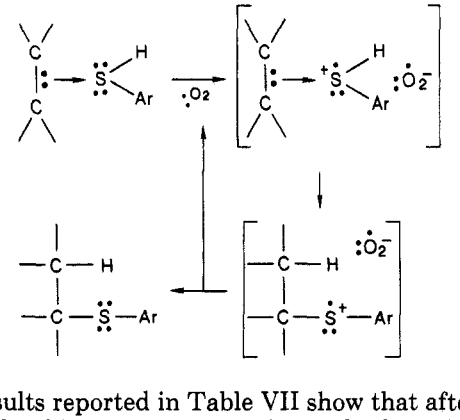


Figure 3. Product distribution as a function of total concentration of equimolar mixtures of *p*-chlorothiophenol and indene, benzocyclohex-1-ene, and benzocyclohept-1-ene in Freon 113 at 30 °C: (○) disulfide, (●) TOCO.

Scheme V



The results reported in Table VII show that after 1 year a considerable amount of reaction had taken place. It is likely that the formation of anti-Markovnikov adduct from **3** involves a momentary one electron transfer by oxygen as shown in Scheme II. This scheme incorporates the previously demonstrated stereoselective formation of the trans-anti-Markovnikov adduct in the reaction of indene and thiols.[6] The reported[6] tendency of some cis adduct formation as a function of the electron-withdrawing substituents present in the thiol can now be explained by invoking the competitive presence of a charge-transfer complex in which the thiol functions as an electron acceptor, and oxygen again plays a catalytic role in the formation of anti-Markovnikov adduct (Scheme V). Eventually, the catalytic traces of oxygen seem to be consumed by side reactions such as the oxidation of the thiol to disulfide or the formation of TOCO products.

The formation of disulfide at the expense of TOCO products at the lower total concentration range of thiol and olefin reactants (0.01–0.2 M) can be explained by the shift in equilibria from the thiol–olefin complexes toward the solvated but not olefin-complexed thiol (**1a** in Scheme I). The oxidation of the solvated thiols by way of thiyl radicals is subject to autocatalysis as evidenced by an acceleration of the otherwise slow consumption of oxygen and a corresponding increased formation of disulfide (Tables III, IV, V, and Figure 3). In line with this rationale is the observation that the relative amounts of disulfide formed in the reaction between equimolar mixtures of *p*-chlorothiophenol and either indene, benzo-1,2-cyclohexene, or benzo-1,2-cycloheptene decrease in the same order as the stability of the corresponding charge-transfer complexes[7] increases.

Table VIII. Effect of Indene Concentration on the Rate of Indene and *p*-Chlorothiophenol TOCO Reaction at 28 ± 2 °C

indene, mol[a]	thiol, mol[a]	$t_{1/2}$, h	O_2 absorption, % theory[b]	$10^5 k_{in.}$, s^{-1}
0.002	0.002	6	96	3.2
0.004	0.002	3	97	6.4
0.008	0.002	1.2	100	16
0.016	0.002	0.5	98	38

[a] In 35 mL of hexane. The solutions were 0.057 M in thiol. [b] Based on 100% yield of TOCO products.

Table IX. Effect of Thiol Concentration on the Rate of the Reaction of Indene[a] and *p*-Chlorothiophenol at 30 ± 2 °C

thiol, mol[b]	O_2 absorption, % theory[b]	$10^5 k_{in.}$, s^{-1}
0.002	96	3.2
0.0025	90	11
0.003	80	12
0.004	90	19

[a] Indene (0.002 mol) is 0.057 M in hexane. [b] In 35 mL of hexane. [c] Based on a 100% yield of cooxidation products.

5. Kinetics of Oxygen Consumption in the Thiol–Olefin–Oxygen Reaction. The rate of oxygen consumption in the reaction between equimolar concentrations of *p*-chlorothiophenol and styrene-like olefins (e.g., indene and substituted styrenes) in the presence of an excess of oxygen in hexane at 30 °C follows a pseudo-second-order rate law. A first-order dependence in olefin was demonstrated by varying the concentration of indene (Table VIII and Figure 4).[17] However, by varying the concentration of thiol a second-order dependence in thiol was estimated (Figure 5),[17] indicating that the thiol probably acts as a dimer at higher concentrations (Table IX). These observations indicate that both indene and *p*-chlorothiophenol are involved in the rate-determining step of the TOCO reaction. Comparing the rates of reactions in Scheme I, the rate-determining step can be identified as the abstraction of the sulfhydryl hydrogen from thiol–olefin complex **2** (k_2), since the rate constant of this step (k_2) is expected to be comparable to k_1 and is the slowest step of the scheme. Thus,

$$-dO_2/dt = k_2[O_2][\mathbf{2}]$$

$$[\mathbf{2}] = K_2[\mathbf{1a}][\mathbf{1b}]$$

$$-dO_2/dt = k_2K_2[\mathbf{1a}][\mathbf{1b}][O_2]$$

Since the concentration of oxygen in the solvent remains constant under the experimental conditions employed in this work, $-dO_2/dt = k_{obsd}[\mathbf{1a}][\mathbf{1b}]$ where $k_{obsd} = k_2K_2[O_2]$.

In our accompanying paper[8] on the noncatalyzed reaction of thiols with molecular oxygen, it is shown that the correlation of the rates of reaction with the dielectric constants of the solvents is greatly improved when the

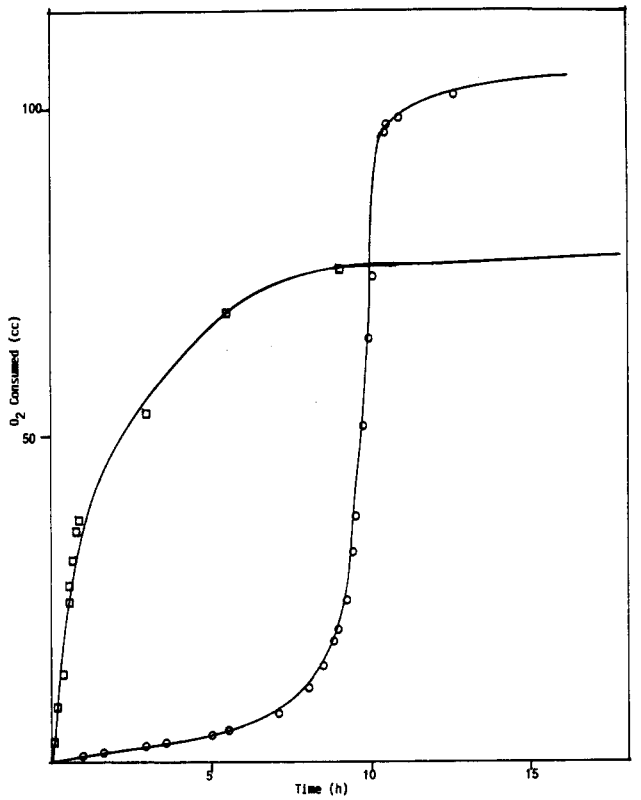


Figure 6. Oxygen consumption during the reaction between equimolar concentrations (0.02 M) of indene and *p*-chlorothiophenol in the presence of excess of oxygen at (○) 30 °C and (□) 0 °C in Freon 113.

Table X. Rate Constants for Oxygen Consumption by Equimolar Amounts of *p*-Chlorothiophenol and Olefins in the Presence of an Excess of Oxygen at 0 °C in Freon 113

olefin reacted	concn of olefin and thiol, 10^2M	10^2K, M^{-1} s^{-1}
indene	2	3.2
indene	4	11.3
indene	8	29.4
benzocyclohex-1-ene	2	4.0

solubility of oxygen in a given solvent is taken into consideration. In this context it is of interest to note that the relative rates of oxygen consumption during the TOCO reaction in Freon 113 were actually smaller than in hexane in spite of the much larger solubility of oxygen in the former solvent.[18] This unexpected behavior can be attributed to a solvation of thiyl hydrogen by Freon 113, $-S-H\cdots Cl_2CF-CClF_2$, that shields the hydrogen from the rate-determining attack by oxygen.

In the course of the work that employed Freon 113 solutions of equimolar amounts of *p*-chlorothiophenol and indene at 0 °C, the oxygen consumption followed a second-order rate law (Table X). On the other hand, at 30 °C (Figure 6) the reaction of the same thiol and indene, or benzo-1,2-cyclohexene, or benzo-1,2-cycloheptene passed through an intial, slow oxygen-consumption phase that obeyed a pseudo-first-order rate law. This phase was followed by a relatively fast oxygen-consumption phase that obeyed a pseudo-third-order, autocatalytic rate law (Figure 7 and Tables XI–XIII). The slow oxygen-consumption phase seems to be more prominent at dilute concentrations of olefin and thiol (0.01 to 0.08 M) and at concentrations above 0.16 M this induction period becomes

(18) Wessler, E. P.; Illis, R.; Clark, L. C. *J. Fluorine Chem.* **1977**, *9*, 137.

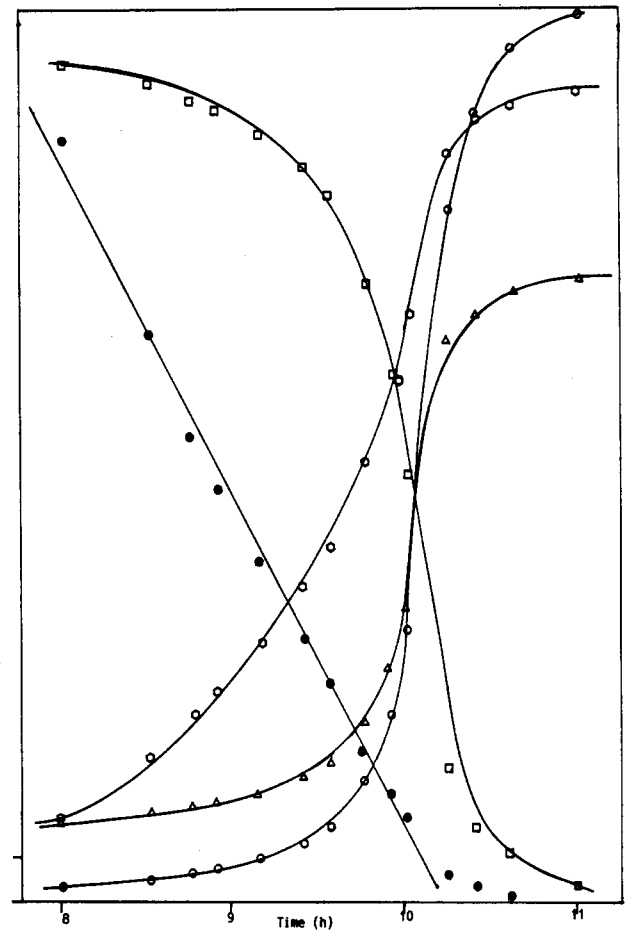


Figure 7. Kinetic treatment of the data for the rate of oxygen consumption during the reaction between equimolar concentrations (0.02 M) of indene and *p*-chlorothiophenol in the presence of excess of oxygen in Freon 113 at 30 °C. Plots are for (□) 1st, (△) 3/2, (○) 2nd (○) 2nd autocatalytic, and (●) 3rd autocatalytic (see Appendix B) order.

negligible (Figure 8). An examination of aliquots taken from the reactions carried out at 30 °C in Freon 113 showed that most of the disulfide (12% out of the total of 19% produced) was formed during that initial phase of the reaction. This phase is characterized by a slow and small consumption of oxygen (approximately 18% of the total volume) and a small yield of TOCO products (15% out of the total of 81%). Consistent with these results is the fact that the amount of disulfide formed in the reaction is proportional to the length of the slow oxygen-absorbing phase (Figure 9). Thus, it can be concluded that the disulfide and hydroperoxide formed during the initial slow reaction phase catalyze the fast oxygen-consumption phase to produce the observed autocatalytic, third-order rate law behavior. While the greater duration of this slow oxygen-consumption phase can be attributed to the lower concentration of the charge-transfer complex involved in the rate-determining step, the third-order autocatalytic rapid phase indicates the initiation of a radical chain reaction induced by disulfide. The latter conclusion is supported by results described in the section that follows.

6. The Effect of Catalysts on the TOCO Reaction. The slow, oxygen-consumption phase described in the preceding section was shortened by the addition of bis(*p*-chlorophenyl) disulfide, cumene hydroperoxide, pentamethylene sulfide, and pyridine. A shortening of the initial, slow oxygen-absorbing phase by chloride and bromide ions had previously been reported by Bredereck[19] without an explanation. This catalytic effect was confirmed in this

Table XI. Oxygen Consumption in the Reaction between Indene and *p*-Chlorothiophenol in the Presence of Oxygen at 30 °C in Freon 113

concn of reactnt, 10^2M	amt of reactnt, mol × 10^3	total O_2 consumed, mol × 10^3	initial phase[a]					second phase[b]		
			O_2 consumed					O_2 consumed		
			mol × 10^3	%	time, h	$t_{1/2}$, h	10^5k_1, s^{-1}	mol × 10^3	%	k_2, M^{-2} s^{-1}
1	0.79	1.28	0.16	20	18	10	1.9	0.82	103	
2	4.5	4.8	0.48	10	8.2	7.8	2.4	4.5	100	2.7
2	4.0				36					
2	1.5				96					
4	3.0	3.78	0.12	4	1.41	0.63	30.0	3.1	103	0.11
4	6.1	5.46	0.32	5	50	40	0.47	5.1	83	
8	6.1	6.4	0.2	3	1.13	0.35	55	6.2	101	0.04
16	4.0	3.8	0.12	3	36	17.5	1.1	3.6	90	
16	4.0	4.1	0.06	2	0.25	0.15	128	4.0	100	0.0087

[a] Initial, slow oxygen-absorbing phase. [b] Rapid oxygen-absorbing phase.

Table XII. Oxygen Consumption in the Reaction between Benzocyclohex-1-ene and *p*-Chlorothiophenol in the Presence of Excess Oxygen at 30 °C in Freon 113

concn of reactnt, 10^2M	amt of reactnt, mol × 10^3	total O_2 consumed, mol × 10^3	initial phase[a]					second phase[b]		
			O_2 consumed					O_2 consumed		
			mol × 10^3	%	time, h	$t_{1/2}$, h	10^5k_1, s^{-1}	mol × 10^3	%	k_2, M^{-2} s^{-1}
1	0.77	1.1	0.16	20	27	18	1.0	0.73	94	
2	1.5	1.8	0.18	12	22	16	1.2	1.47	98	1.74
2	1.5	1.7	0.08	5	126	102	19	1.46	97	
4	6.0	5.6	0.32	5	20	15	1.3	5.2	86	
4	3.0	2.9	0.17	5	16	11	1.7	2.7	90	1.26
8	4.0	4.5	0.12	3	8	4	4.8	4.44	110	0.08
16	4.0	4.0	0.12	3	2	0.58	33	3.9	98	0.395

[a] Initial, slow oxygen-absorbing phase. [b] Rapid oxygen-absorbing phase.

Table XIII. Oxygen Consumption in the Reaction between Benzocyclohept-1-ene and *p*-Chlorothiophenol in the Presence of Excess Oxygen at 30 °C in Freon 113

concn of reactnt, 10^2M	amt of reactnt, mol × 10^3	total O_2 consumed, mol × 10^3	initial phase[a]					second phase[b]		
			O_2 consumed					O_2 consumed		
			mol × 10^3	%	time, h	$t_{1/2}$, h	10^5k_1, s^{-1}	mol × 10^3	%	k_2, M^{-2} s^{-1}
1	0.76	1.26	0.40	52	144	71	0.27	0.81	106	
2	1.57	1.89	0.4	25	77	60	3.0	1.48	94	
2	1.5	2.0	0.88	58	254	185	0.10	1.11	74	
4	6.0	6.7	0.8	13	71	57	0.33	5.8	86	1.19
8	4.0	4.7	0.28	7	22	14.5	1.3	4.0	100	0.233

[a] Initial, slow oxygen-absorbing phase. [b] Rapid oxygen-absorbing phase.

Table XIV. Rate Constants of Oxygen Consumption by Equimolar (0.04 M) Mixtures of *p*-Chlorothiophenol and Indene in Freon 113 at 30 °C in the Presence of Bis(*p*-chlorophenyl) Disulfide and Cumene Hydroperoxide

catalyst added	time,[a] h	catalyst, equiv	k, M^{-2} s^{-1}
none			0.11
bis(*p*-chlorophenyl) disulfide	0	1	1.56
bis(*p*-chlorophenyl) disulfide	22	2	2.5
cumene hydroperoxide	1	1	4.0
cumene hydroperoxide	1	2	5.0
cumene hydroperoxide	0	1	4.4
bis(*p*-chlorophenyl) disulfide + cumene hydroperoxide [b]	0 1.5	0.5 1.0	5.6

[a] Time after initiation of the reaction when the catalyst was added causing the induction period to be cut short and the fast oxygen-absorption phase to begin. [b] Added sequentially.

Table XV. Effect of Various Catalysts on the Induction Period in Freon 113 at 30 °C

catalyst	induction period eliminated	remarks *a*; *b*
hydrogen peroxide	no	(0.04); 1
cumene hydroperoxide	yes	(0.04); 1 and 2
2,2,6,6-tetramethylpiperidinyloxy radical	no	(0.04); 1
chloride ion	yes	*c*
bromide ion	yes	*c*,*d*
iodide ion	no	*d*
pyridine	yes	(0.04); 1
bis(*p*-chlorophenyl) disulfide	yes	(0.04); 1 and 2
pentamethylene sulfide	yes	(0.04); 1 and 2

[a] Concentration (M) of equimolar mixture of indene and *p*-chlorothiophenol in Freon 133 at 30 °C. [b] Amount of catalyst added (equiv). [c] Reference 14. [d] The concentration of equimolar mixture was 0.057 M in hexane. The concentration of the catalyst was variable.

laboratory, but it was found that iodides prolonged the initial phase and decreased its rate. Bis(*p*-chlorophenyl) disulfide and cumene hydroperoxide also accelerated the second, fast, oxygen-consumption phase (Table XIV). On the other hand, no effect was noted by the addition of the 2,2,6,6-tetramethylpiperidinyloxy free radical (Table XV).

Possibly the most surprising result was in the inability of the piperidinyloxy radical to eliminate the lengthy induction period in the reaction of *p*-chlorothiophenol, indene, and oxygen. This observation suggests that the formation of the thiyl radical is not the critical step that initiates the TOCO reaction. The nearly quantitative yield of the disulfide obtained in the presence of the piperidi-

(19) Bredereck, H.; Wagner, A.; Kottenhahn, A. *Chem. Ber.* **1960**, *93*, 2415.

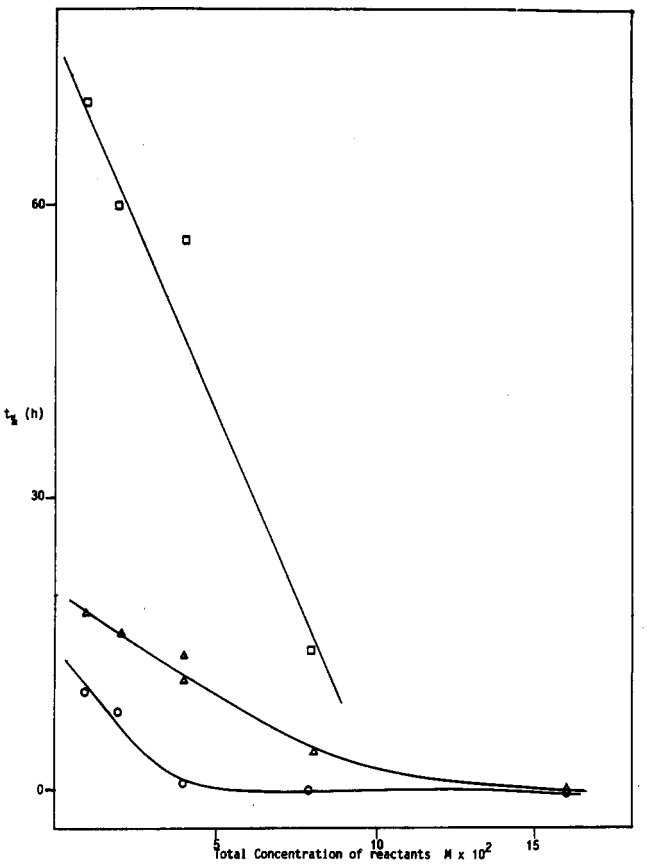
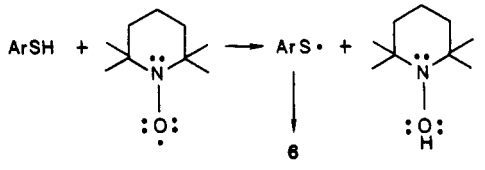


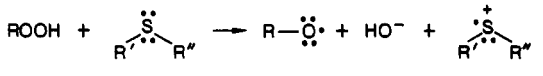
Figure 8. Half-life of the initial, slow oxygen-absorbing phase in the reaction of *p*-chlorothiophenol and (○) indene, (△) benzocyclohex-1-ene, and (□) benzocyclohept-1-ene as a function of the total concentration of equimolar mixtures of thiol and olefin.

nyloxy radical suggests that the thiyl radicals are responsible for the disulfide formed in this reaction:



The catalytic effect of cumene hydroperoxide supports the conclusion that the slow, initial phase of oxygen consumption during the TOCO reaction serves to build up the hydroperoxide derived from the olefin and that the former then catalyzes the second, rapid oxygen-consumption phase presumably by a process represented in Scheme III. The fact that hydrogen peroxide fails to exert a similar catalytic effect indicates that it may be solvating the thiol through hydrogen bonding, thus preventing the formation of the olefin–thiol complex **2** considered essential for the initiation of the TOCO process.

The catalytic effect of the disulfide and sulfide tested in this study is best explained by their ability to trigger the decomposition of the hydroperoxyl-containing substances that build up during the initial phase of the TOCO process:



where R = substituted indane radical in the case of the TOCO reaction of indene and R′ = R″ = pentamethylene or R′ = *p*-chlorophenyl, R″ = *p*-chlorophenylthiyl. The alkoxy radical subsequently catalyzes the TOCO process according to Scheme III. The behavior observed in the

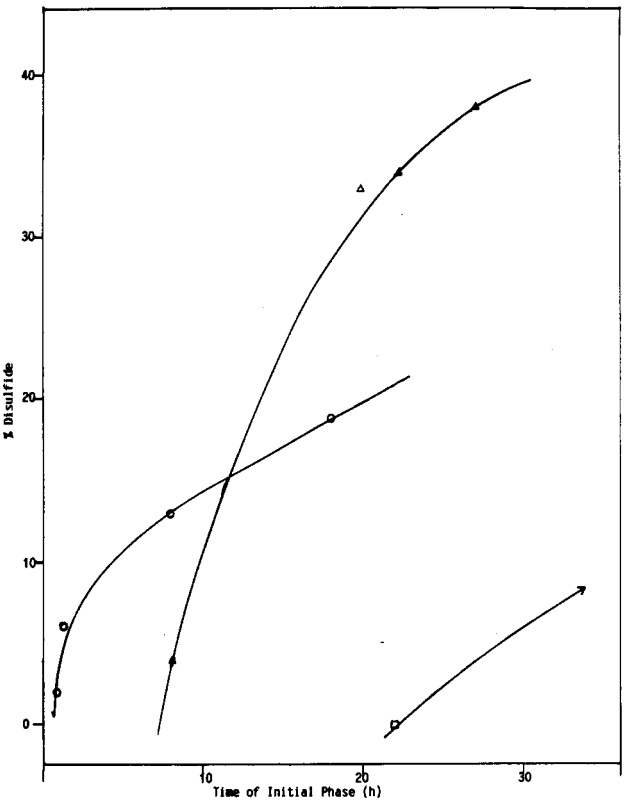
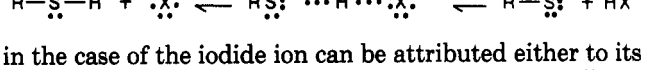


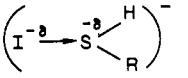
Figure 9. The yield of bis(*p*-chlorophenyl) disulfide in the reaction of *p*-chlorothiophenol, oxygen and (○) indene, (△) benzocyclohex-1-ene, and (□) benzocyclohept-1-ene as a function of the length of the initial, slow oxygen-absorbing phase.

case of the system in which the ineffective disulfide addition was followed by an effective addition of cumene hydroperoxide (Table XIV) mimics the normal course of the noncatalyzed TOCO reaction and is consistent with the autocatalytic phase that can follow a slow, initial phase.

The chloride and bromide ions may function in a similar fashion by promotion of an electron transfer or they may activate the thiol by inducing its polarization discussed elsewhere.[8] In this context, the lack of catalytic activity



in the case of the iodide ion can be attributed either to its failure to function as a Lewis base, its failure to give alkoxy radicals as shown above in the case of sulfide or disulfide (but instead consuming the hydroperoxyl function through a simple oxidation reaction that involves two-electron-transfer steps), or, finally through the formation of charge-transfer complexes in which the reaction of hydrogen with molecular oxygen is inhibited because of stereoelectronic effects.



The catalytic effect of pyridine is attributed to its basicity and consequent promotion of the polarized or ionized thiol as described above for the case of chloride and bromide.

The erratic behavior of the initial slow oxygen-consumption phase under identical experimental conditions that employed equimolar mixtures of the thiol–olefin reactants (Tables XI, XII, and XIII) can be attributed to trace impurities that cause an irreproducible kinetic behavior. Such erratic behavior of thiols under oxidative

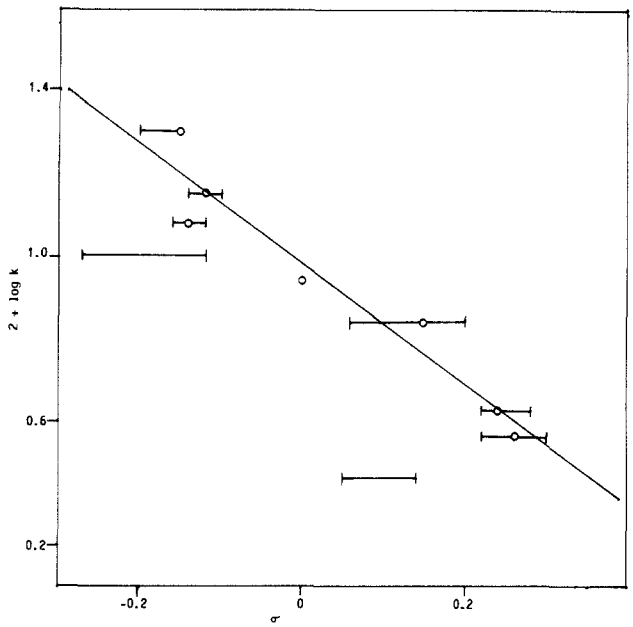


Figure 10. Effect of substituents on the rate of the TOCO reaction between equimolar mixtures of *p*-chlorothiophenol and substituted styrenes in the presence of an excess of oxygen at 24 °C in hexane.

Table XVI. Effect of the Structure of Olefins on the Product Distribution in the Reaction between Equimolar[a] Mixtures of *p*-Chlorothiophenol and Various Olefins in the Presence of an Excess of Oxygen

olefin	yield,[b] %	TOCO, %	disulfide, %
styrene	82	91	9
p-*tert*-butylstyrene	75	89	11
p-fluorostyrene	73	85	15
p-bromostyrene	66	87	13
3,5-dimethylstyrene	59	89	11
p-methylstyrene	65	90	10
p-chlorostyrene	77	93	7
p-methoxystyrene	65	92	8
p-phenoxystyrene	74	94	6
indene	80	100	0
indene-*1,3,3-d*$_3$	77	93	7

[a] Total concentration of the equimolar mixture is 0.057 M in hexane. [b] Total yield of addition and TOCO products.

conditions has been reported previously.[20] For example, it has been demonstrated that the presence of as little as a 10^{-7} M concentration of copper ions had a profound catalytic effect on the rate of thiol oxidation. It seems unlikely that such purity of reactants can be legitimately claimed under ordinary experimental conditions. Since the slow, oxygen-consumption phase of the TOCO reaction has been shown to produce most of the disulfide and also some of the hydroperoxide intermediate that eventually gives the TOCO products, and since these structures have also been shown to catalyze the fast oxygen-consumption phase, the erratic kinetic behavior of the TOCO reaction under conditions that employ relatively low concentrations of thiol and olefin can be reconciled.

7. Structural Effects in the TOCO Reaction. a. Effect of Olefin Structure on the Reaction Rates of the TOCO Reaction. The rate of oxygen consumption in the reaction between equimolar mixtures of *p*-chlorothiophenol and a series of substituted styrenes in the presence of an excess of oxygen was found to follow the Hammett relationship (Table XIV, Figure 10). The relatively large ρ value (−1.45) clearly supports the donor

(20) Cullius, C. F.; Hopton, J. D.; Trim, D. L. *J. Appl. Chem.* **1968**, *18*, 330. Wallace, T. J.; Schriesheim, A. *Tetrahedron* **1965**, *21*, 2271.

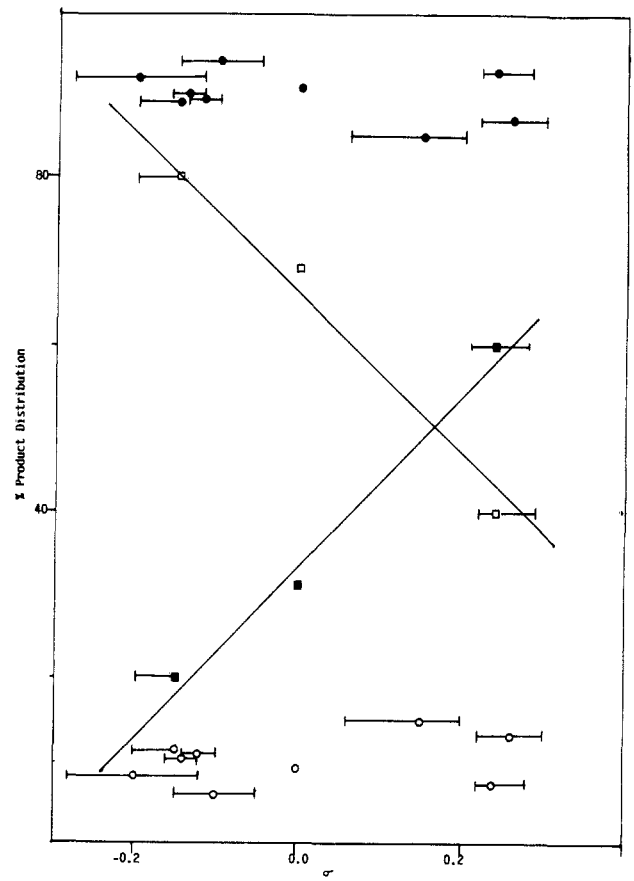


Figure 11. Effect of substituents on the product distribution in the TOCO reaction of *p*-chlorothiophenol and substituted styrenes: (●) % TOCO and (○) % disulfide at low concentrations (0.057 M); (■) % TOCO and (□) % addition at high concentrations (0.3–0.4 M).

role of the olefin in a charge-transfer complex **2** assumed to be the precursor in the formation of TOCO products. The inverse secondary isotope effect (k_H/k_D = 0.33) observed in the reaction between equimolar quantities of *p*-chlorothiophenol and indene or its 1,3,3-trideuterio derivative (Table VI) is also consistent with the greater equilibrium concentration of the complex produced by the deuteriated olefin. It is noteworthy that the oxygen consumption by *p*-chlorothiophenol is retarded by the addition of equimolar amounts of isolated olefins like cyclohexane and cyclopentene (Table I). This result supports the argument that the isolated olefins from predominantly hydrogen-bonded complexes with the thiol and thus hinder the attack of oxygen at the sulfhydryl hydrogen.

b. Effect of Olefin and Thiol Structures on the Product Distribution of the TOCO Reaction. At low concentrations (0.057 M), the product distribution in the reaction between equimolar concentrations of *p*-chlorothiophenol and a series of substituted styrenes in the presence of an excess of oxygen was found to be insensitive to changes in the substituents of styrene (Table XVI, Figure 11). This can be reconciled with the nearly nonexistent formation of hydrogen-bonded complexes at these low concentrations of thiol and olefin. The absence of detectable thiol–olefin adducts which are believed to be formed via hydrogen-bonded complexes also supports this argument. However, the small amounts of disulfide obtained under these conditions indicate that thiyl radicals are formed either in the reaction of oxygen with the solvated, but otherwise uncomplexed thiol (**1a**: k_1 in Scheme I) or by the dissociation of the open, classical carbon radical (k_{-4} in Scheme I).

Table XVII. Effect of Structure of the Reactants on the Distribution of Addition and TOCO Products

olefin[a]	thiophenol[a]	yield,[b] %	temp, °C	addn, %	TOCO, %
indene	*p*-methoxy	80	0		100[c]
indene	*m*-methyl	76	0	8	92[c]
indene	*p*-chloro	81	0	30	70[c]
p-*tert*-butylstyrene	*p*-chloro	86	30	80	20
styrene	*p*-chloro	92	30	69	31
p-chlorostyrene	*p*-chloro	83	30	40	60

[a] Olefin and thiol are 0.3–0.4 M in hexane. [b] Total yield of addition and TOCO products. [c] Values are taken from Panthananickal, A. Ph.D. Thesis, University of Detroit, 1974.

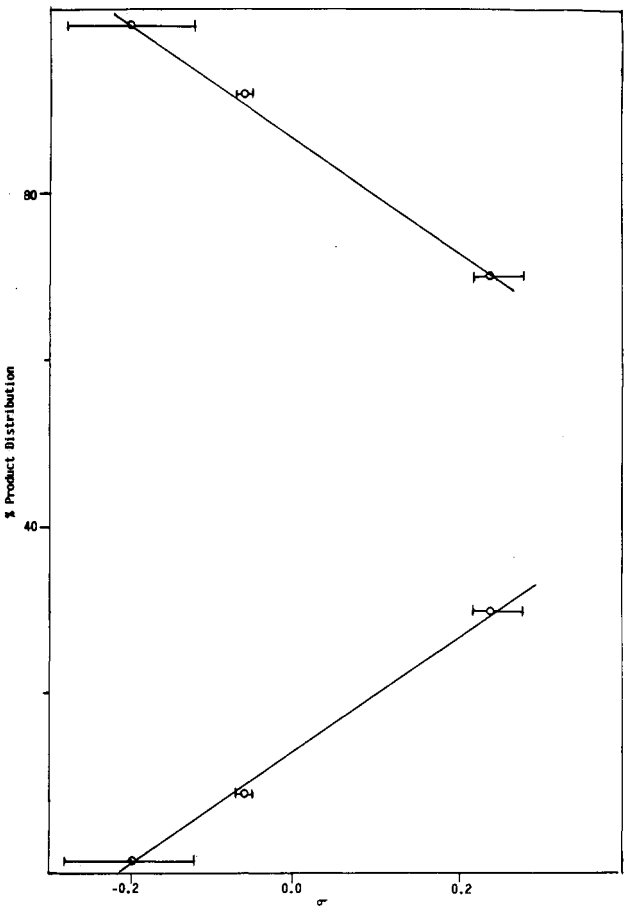
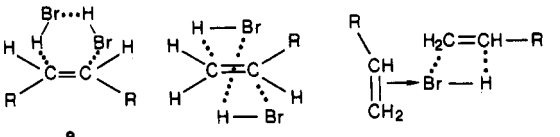


Figure 12. Effect of substituents on the product distribution in the TOCO reaction of indene and substituted thiophenols: (●) % TOCO, (○) % addition.

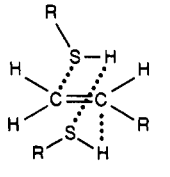
At higher concentrations (0.3–0.4 M) the significant amount of thiol–olefin adducts that are isolated (Table XVII) clearly suggests the existence of competitive hydrogen-bonded complexes. The yields of the addition products are proportional to the electron-donating character of the olefin (Figure 11) and the electron-withdrawing character of the thiol (Figure 12). Figure 2[17] shows that at a certain high concentration of reactants, say 1 M, and for identical differences in equilibrium constants (A, K_1 = 10, $K_2 = 10^{-2}$, and B, K_1 = 1, $K_2 = 10^{-3}$), the ratio of concentrations of the more stable (X_1) and less stable (X_2) species is smaller in the case of the formation of the more stable complexes (A) as compared to when the less stable complexes (B) are formed. The mathematical model is in line with the rationale that at high concentrations the electron-donating substituents on styrene and the electron-withdrawing substituents on thiophenol promote not only the formation of charge-transfer complexes **2** but also that of hydrogen-bonded complexes **3** and that the latter are then present in sufficient concentration to channel the reaction toward the formation of thiol–olefin adducts.

8. The Similarity between the Hydrogen Bromide–Olefin and Thio–Olefin Systems. The formation of two kinds of thiol–olefin complexes as precursors to the addition reaction of the olefin resembles the recently reexamined[12] mechanism of the hydrogen bromide–olefin addition. The authors conclude that the normal (Markovnikov) and the abnormal (anti-Markovnikov) additions involve molecular complexes represented by **8** or **9** and **10**, respectively. These tend to be formed depending on which



8 **9** **10**

of the two reactants is in excess. The product distribution in this system is not only dependent on the concentrations of the reactants but is also sensitive to the temperature of the reaction mixture with a negative temperature coefficient being observed as is also the case in the thiol–olefin reaction. It is noteworthy that complex **10**, believed to be responsible for the anti-Markovnikov addition of HBr, is a charge-transfer complex in which the olefin functions as the electron-donor, and this conclusion is analogous to complex **2** (Scheme I) proposed here. However, in the reaction of indene and styrenes with thiols in the presence of oxygen, the choice of reaction paths is not between the formation of Markovnikov and anti-Markovnikov products. Under the conditions described here the latter regioselectivity prevails and the competition is between the formation of the TOCO products or thiol–olefin adducts. In the thiol–olefin system, the choice between complexes analogous to **8** or **9** is clearly in favor of **9** in view of the trans stereoselectivity demonstrated with the aid of deuteriated reagents[6]. However, the trans-anti-Markovnikov addition in the case of thiol–olefin reaction suggests the reversal of orientation in the predominant complex involving the thiol as represented by **11**. The formation of the minority cis-anti-Markovnikov adduct then corresponds to the hydrogen-bonded complex **3** induced by the more acidic thiols.



11

Experimental Section

Materials. *p*-Chlorothiophenol (Aldrich Chemical Co.) was recrystallized from aqueous ethanol, mp 51–52 °C. ^{1}H NMR spectra and the melting points of the thiol indicated that it was disulfide-free. Indene (Eastman Organic Chemicals) was freshly vacuum-distiled before use, bp 38–39 °C (10 Torr). Substituted styrenes (obtained from Dow Chemical Co. by courtesy of Dr. R.

Dolinski) were freshly vacuum-distilled before use. Benzo-1,2-cyclohexene and benzo-1,2-cycloheptene (obtained from the University of Puerto Rico by courtesy of Professor Oswaldo Cox) were found to be sufficiently pure and peroxide-free to be used without further purification. Cyclohexene and cycloheptene (Aldrich Chemical Co.) were distilled before use.

Determination of Rate of Oxygen Absorption. A three-necked flask containing the solution of known concentration of *p*-chlorothiophenol in a given solvent was connected to a gas buret. The bottom of the buret was connected to a dropping funnel filled with glycerol by means of Tygon tubing. The volume and the pressure in the buret could be controlled by moving the dropping funnel vertically. The system was connected to a U tube that contained glycerol and functioned as a gas manometer. The second arm of the three-necked flask was fitted with a rubber septum. The third arm was fitted with a stopcock. The system was flushed with oxygen and the buret was filled with oxygen and then sealed off by means of the stopcock. The flask was immersed in a Haake circulator set at the appropriate temperature and stirred with an immersed magnetic stirrer. The system was allowed to stabilize for about 2 h.

An accurately measured volume of olefin was injected into the reaction flask. The level of the dropping funnel was adjusted until the manometer indicated that the inside and outside pressures were equal and the volume of oxygen in the buret was read. The volume of oxygen in the buret was recorded at various intervals as the reactions were allowed to run to completion.

Simultaneously, a blank experiment was carried out by using an equal volume of the solvent in the same Haake circulator. The difference between the blank and the reaction buret at a given time was utilized to calculate the rate constants, thus minimizing the errors due to the atmospheric pressure changes.

The order of the reaction was determined by the best fit of the data to the rate equations. The dependence in olefin and thiol was determined from a plot of log of the initial rates of reactions where concentration of one of the reactants was held constant and the concentration of the other reactant (which was in large excess) was varied vs. the log of the concentration of that reactant (Figure 4 and 5).[17] The error limit in rate constants is ±1%.

Separation of the Reaction Products. The reaction mixture was filtered and the filtrate was extracted with 0.1 N NaOH and washed with water to separate the unreacted thiol. The organic layer was mixed with the precipitate and analyzed by column chromatography as described below. The aqueous layer was acidified with 0.1 N HCl and extracted with hexane. This hexane layer was treated with known (excess) volume of 0.1 N iodine solution and back titrated with 0.1 N $Na_2S_2O_3$ to determine the amount of unreacted thiol.

A representative sample (0.500 g) was chromatographed by means of a column 22 × 1 in. using 50 g of J. T. Baker's silica gel, activated overnight at 120 °C. The pack column was first eluted with hexane and then with various mixtures of hexane and toluene, and toluene and ethyl acetate. Finally, the column was washed with pure ethyl acetate. The hexane fraction yielded the disulfide (R_f 1.0 in ethyl acetate), the toluene fractions gave the addition products (R_f 0.90–0.95 in ethyl acetate), and the TOCO products were obtained from the ethyl acetate fractions (R_f 0.52–0.62 in ethyl acetate). These products were identified by IR and NMR as described previously.[1]

^{1}H NMR Study of Addition of Thiophenols to 1,3,3-Trideuterioindene. Equimolar amounts of 1,3,3-trideuterioindene and substituted thiophenols were introduced into NMR tube in an atmosphere of dry nitrogen. The samples were contained in 5-mm o.d. NMR tubes (high resolution type). Using the Firestone valve (Aldrich Chemical Co.) the NMR tubes were evacuated and then the sample tubes were purged with a stream of nitrogen while the sample tubes were kept under vacuum. The process of evacuation and purging with nitrogen was repeated five times to ensure that the NMR tubes were free from oxygen. Subsequently, the NMR tubes were sealed in a stream of nitrogen. The same procedure was followed for all different thiols shown in Table VII. One set of samples (five) was kept at room temperature while another set was kept at 5 °C. All samples were protected from light. Proton magnetic spectra were determined by means of A60A and FT 100-MHz spectrophotometers. Tetramethylsilane was used only as an external standard to calibrate the instrument. The stereochemistry of addition of different aromatic thiols to 1,3,3-trideuterioindene was determined from NMR.

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Registry No. $PhCH{=}CH_2$, 100-42-5; *p*-*t*-$BuC_6H_4CH{=}CH_2$, 1746-23-2; *p*-$FC_6H_4CH{=}CH_2$, 405-99-2; *p*-$BrC_6H_4CH{=}CH_2$, 2039-82-9; 3,5-$Me_2C_6H_3CH{=}CH_2$, 5379-20-4; *p*-$MeC_6H_4CH{=}CH_2$, 622-97-9; *p*-$ClC_6H_4CH{=}CH_2$, 1073-67-2; *p*-$MeOC_6H_4CH{=}CH_2$, 637-69-4; *p*-$PhOC_6H_4CH{=}CH_2$, 4973-29-9; *p*-$MeOC_6H_4SH$, 696-63-9; *p*-ClC_6H_4SH, 106-54-7; *m*-MeC_6H_4SH, 108-40-7; *p*-FC_6H_4SH, 371-42-6; *p*-*t*-BuC_6H_4SH, 2396-68-1; *p*-$CF_3C_6H_4SH$, 937-00-8; *p*-$ClC_6H_4SSC_6H_4$-*p*-Cl, 1142-19-4; 1*H*-indene, 95-13-6; benzocyclohex-1-ene, 119-64-2; benzocyclohept-1-ene, 1075-16-7; cyclohexene, 110-83-8; cyclopentene, 142-29-0; cumene hydroperoxide, 80-15-9.

Supplementary Material Available: Figures 1, 2, 4, and 5 and Appendixes A and B (6 pages). Ordering information is given on any current masthead page.