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Oxorhenium(V) Dithiolates Catalyze the Oxidation by *tert*-Butyl Hydroperoxide of Sulfoxides and Sulfides, Including 4,6-Dimethyldibenzothiophene

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tert-Butyl hydroperoxide (TBHP) efficiently converts a wide variety of sulfides to sulfoxides and sulfones. The method offers the advantage that one product or the other can be obtained in high purity by a modest variation of conditions. The reactions occur smoothly at 25–50 °C in chloroform and, to the extent studied, in toluene and methylene chloride. A catalyst is required; the most extensively studied was MeReO(mtp)PPh_3, **1**, where $mtpH_2$ is 2-(mercaptomethyl)thiophenol. Other chelating dithiolate ligands can be used with comparable results. These oxidations were tested for dialkyl, alkyl–aryl, and diaryl sulfides; thiophenes; and thianthrene. Even the "hard" sulfide, 4,6-dimethyldibenzothiophene (DMDBT) was *quantitatively* oxidized to the dioxide with TBHP:DMDBT 3.0–3.5 and 0.05–3.8 mol % **1**. The mechanism was explored in kinetics studies carried out only for methyl tolyl sulfide. The product buildup curve was complex, with an induction period followed by a rapid growth phase. The kinetic data could be modeled adequately but not perfectly by allowing five rate constants to refine. Their values are consistent with the chemical sense of the mechanism.

Introduction

The conversion of organic sulfides to sulfoxides and sulfones holds interest from several points of view, to which both laboratory and biologically related perspectives apply.[1] Sulfide oxidation and sulfoxide reduction are the reverse of one another in oxygen atom transfer (OAT) reactions. This means that a given catalyst will be effective in either direction depending on stoichiometric source or sink of the oxygen atom. Sulfoxide reduction in nature is catalyzed by the molybdenum-containing enzyme DMSO-reductase. It also metabolizes aryl alkyl sulfoxides and other dialkyl sulfoxides.[2−4]

Certain oxorhenium(V) compounds[5−9] such as MeReO(dithiolate)PPh_3 catalyze OAT reactions with remarkable kinetic efficiency. Their general formula is MeReO(dithiolate)PZ_3, PZ_3 representing a general alkyl, aryl phosphine, as depicted in Chart 1. In this study, we have concentrated on MeReO(mtp)PPh_3, **1**, where $mtpH_2$ is 2-(mercaptomethyl)thiophenol. Many aspects of the reaction chemistry of **1** are now coming to be understood.[10,11] Among such reactions are bimolecular ligand *displacements*.[10] In the case at hand, the reactions can be referenced to $L_i = PPh_3$ and $L_j = SRR'$, $OSRR'$, $OPPh_3$, *tert*-butyl hydroperoxide (TBHP), or tmtu (1,1,3,3-tetramethyl-2-thiourea).

$$\mathrm{MeReO(mtp)}L_i + L_j \rightarrow \mathrm{MeReO(mtp)}L_j + L_i \qquad (1)$$

Our studies of OAT have included catalyzed sulfoxide reductions[12] and, as reported here, sulfide oxidations with

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(1) Oae, S. In *Organic Sulfur Chemistry: Structure and Mechanism*; CRC Press: Boca Raton, FL, 1991; pp 203−291.
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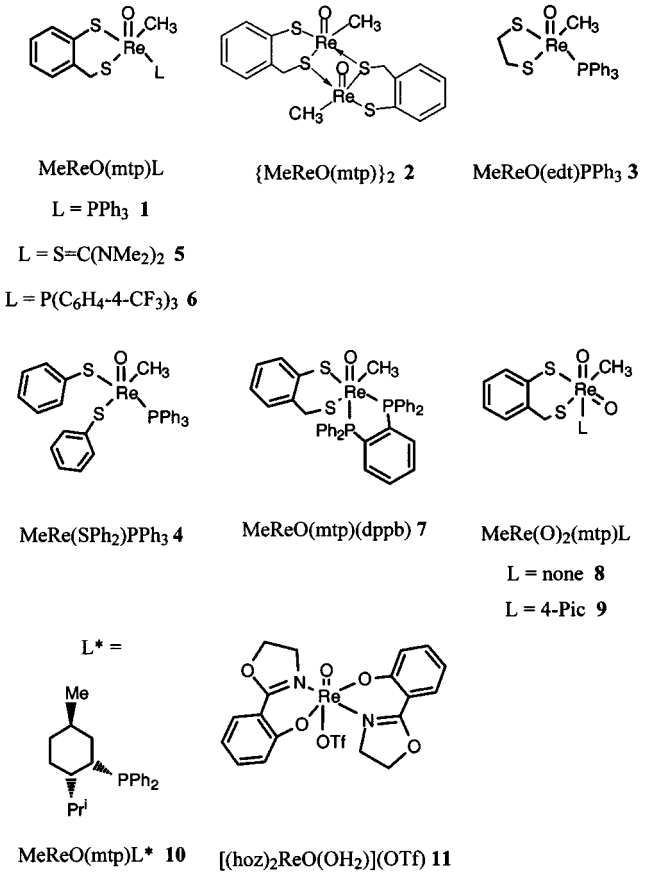
Chart 1



TBHP as the stoichiometric oxidizing agent. The mechanisms show considerable similarities between the rhenium compounds and the molybdenum and tungsten enzymes and their synthetic models.[4,13−22] Rhenium, on the other hand, has been relatively little investigated, but recent work with the catalyst $[ReO(hoz)_2]^+$ (hozH = 2-(2′-hydroxyphenyl)2-oxazoline) has pointed the way.[23]

The rhenium-catalyzed reactions hold particular interest because they are rapid and yield clean sulfoxides; under minimally different conditions, sulfones are instead formed cleanly and quantitatively. Both procedures are conveniently implemented, as will be described. The sequential net reactions are (TBA is *tert*-butyl alcohol)

$$RSR' + TBHP \rightarrow RS(O)R' + TBA \quad (2)$$

$$RS(O)R' + TBHP \rightarrow RS(O)_2R' + TBA \quad (3)$$

Sulfide oxidation provides the usual laboratory route to sulfoxides. A useful reaction must proceed with 100% selectivity, avoiding overoxidation to sulfones which has sometimes been reported.[24,25] Sulfones are also important intermediates in organic reactions; again, quantitative conversions and 100% sulfone selectivity are needed.[1,26] The methods described here offer the further advantage that one product or the other can be obtained at will. The method is also applicable to thiophenes, which are inherently more difficult to oxidize.[27] Note, for example, the ease with which RSR′ is oxidized by H_2O_2 with $MeReO_3$ (MTO) as the catalyst,[28] as compared to thiophenes.[29] To be specific, MeSPh and dibenzothiophene are oxidized by $MeRe(O)_2(\kappa^2\text{-}O_2)$; the respective rate constants are 2.65×10^3 and 10.2 L mol^{-1} s^{-1}. 2,5-Dimethyl thiophene reacts more slowly yet; an estimate gives $k \sim 0.2$ L mol^{-1} s^{-1}.[29]

We wish particularly to point out that these procedures are applicable even to 4,6-dimethyldibenzothiophene (we designate this particular isomer as DMDBT; its monoxide and dioxide are, respectively, DMDBTO and $DMDBTO_2$). It is a so-called "hard" sulfide that cannot be removed from petroleum by current hydrodesulfurization (HDS) technology. Perhaps DMDBT cannot make close contact with the surface of the cobalt−molybdate HDS catalyst.[30] The same reason was invoked for the failure of bacterial bio-oxidation processes, which work for other dimethylated-DBT isomers.[31] DMDBT may now become the focus of more stringent regulatory requirements because its sulfur content eventually fouls catalytic converters. The value of oxidative chemistry in this regard has been noted.[32−34]

Experimental Section

Materials. Chloroform was used as the solvent in most cases. Methylene chloride and toluene were also used for the oxidation of DMDBT. The sulfides were used as received from commercial sources because their ^1H NMR spectra showed no impurities. TBHP was obtained as a 5−6 M solution in nonane. The dimer {MeReO(mtp)}$_2$, **2**, was synthesized from $MeReO_3$[35] and $mtpH_2$.[5] Reaction of **2** overnight with a ligand L (PPh_3, tmtu, or $P(C_6H_4\text{-}4\text{-}CF_3)_3$)

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resulted in the respective mononuclear compounds MeReO(mtp)L: **1**, **5**, and **6**. The first two of these are already known,[5−7] and the latter was characterized by its ^{1}H and ^{31}P NMR spectra. Addition of hexane precipitated the product, which was filtered and washed with hexane to produce MeReO(mtp)L in >90% yield. Compound **7** was obtained as a brown solid by adding 2.1 equiv of 1,2-bis(diphenylphosphinobenzene), dppb, to a toluene solution of **2** that had first been treated with 6 equiv of 4-(*tert*-butyl)pyridine. The product was obtained after allowing the solution to stand overnight.[36] Compounds **3** and **4** were prepared as reported earlier.[9] Compound **10** was synthesized from **2** and 2.1 equiv (+)-neomenthyldiphenylphosphine (Aldrich). The NMR spectrum of **10** in $CDCl_3$, recorded on a Bruker DRX 400 MHz spectrometer, is characterized by these resonances: ^{1}H δ (ppm) 8.00 (m, 2H), 7.53−7.66 (m, 6H), 7.19−7.32 (m, 6H), 4.98 (d, 1H, J = 12 Hz), 4.23 (m, 1H), 1.60−2.20 (m, 9H), 2.90 (d, 1H, J = 12 Hz), 2.45 (d, 3H, Re−CH_3, J = 8 Hz), 1.23 (d, 3H, J = 8 Hz), 0.62 (d, 3H, J = 8 Hz), 0.18 (d, 3H, J = 8 Hz); ^{31}P δ 28.86.

General Procedure for Sulfoxides. The rhenium catalyst was usually **1**, but others were tested as well. Just 2.05 mmol of TBHP was added to 2 mL of chloroform containing 2.0 mmol of sulfide. A solution of **1** in 1−2 mL of chloroform was added to provide the desired catalyst concentration. In some cases, the solution of **1** was introduced slowly by syringe pump, and in others, it was added all at once. Likewise, experiments were carried out at 25 or 50 °C. The progress of the reaction was monitored in a tiny sample that was withdrawn periodically and checked by TLC or by ^{1}H NMR spectroscopy. When the reaction was found to be complete, the solvent and TBA were evaporated. The ^{1}H and ^{13}C NMR spectra of the products were determined in comparison with literature values,[37,38] which sufficed for their identification because they are all known materials. High-purity sulfoxides were obtained by flash chromatography with ethyl acetate as the eluent.

General Procedure for Synthesizing Sulfones. TBHP (2.0 mmol, but usually 3.0 mmol, an excess) was added to 1.0 mmol of sulfide in 3 mL of chloroform. Catalyst **1** contained in 1 mL of chloroform was added by syringe pump over 2 h at 50 °C, as the reaction was intermittently monitored by TLC. Upon completion, the sulfones were obtained by evaporation and again identified by comparison with the reported NMR spectra.[39,40]

Oxidative Cycloaddition of 2,5-Dimethylthiophene with *N*-Phenylmaleimide. TBHP (2.00 mmol) was added to 3 mL of a chloroform solution of 2,5-dimethylthiophene (112 mg, 1.00 mmol) at 50 °C) and *N*-phenylmaleimide (320 mg, 1.85 mmol). The latter was added to trap the otherwise labile thiophene monoxide. Catalyst **1** (6.3 mg, 1%) dissolved in 1 mL of chloroform was added by syringe pump over 2 h. The reaction was further stirred 1 h and then evaporated to yield the product, *N*-phenyl-1,4-dimethyl-7-thiabicyclo[2.2.1]hept-5-ene-2,3-dicarboxamide 7-oxide, which was separated by flash chromatography using 2:1 hexane/ethyl acetate as eluent. The product (78%) was identified from ^{1}H and ^{13}C NMR data and from its mass spectrum in comparison with literature values.[41]

Oxidation of DMDBT to $DMDBTO_2$ and DMDBTO. DMDBT (0.105 g, 0.50 mmol) was dissolved in 2 mL of toluene which was brought to reflux. To this was added TBHP (1.75 mmol, 3 equiv) and **1** (6.3 mg, 0.05%) in 0.2 mL of toluene. The solution was refluxed for 2 h, during which time a white solid precipitated. It was filtered and washed with cold dichloromethane to eliminate the trace of catalyst. The dioxide was isolated in 96% yield by this procedure and was characterized by its known ^{1}H NMR spectrum.[42] For DMBTO, DMDBT (0.42 g, 2.0 mmol) and TBHP (2.5 mmol) were dissolved in 5 mL of $CHCl_3$ at room temperature. Catalyst **1** (39 mg, 3.0 mol %) was dissolved in 2 mL of $CHCl_3$ and added to the solution. The reaction was stirred for 1.5 h. The solvent was then evaporated, and DMDBTO was isolated by flash chromatography using 1:1 hexane/ethyl acetate as eluent (52%). The ^{1}H and ^{13}C spectra were determined; no literature report could be found. NMR: ^{1}H δ 7.60 (d, 2H, J = 8 Hz), 7.46 (t, 2H, J = 8 Hz), 7.23 (d, 2H, J = 8 Hz), 2.74 (s, 6H); ^{13}C δ 18.7, 119.5, 124.8, 131.0, 132.7, 137.6, 139.2, 142.7.

Results

Sulfides to Sulfoxides. Useful amounts of the pure sulfoxides could be obtained by defined laboratory procedures. These reactions, when catalyzed by **1** in chloroform (except for DMDBT where methylene chloride and toluene were also used), gave excellent conversions of RSR′ selectively to the sulfoxide RS(O)R′ in essentially quantitative yields when carried out on a 2 mmol scale. Several protocols were explored. A syringe pump was used to introduce **1** slowly as the reaction was intermittently monitored by TLC until it had reached completion. Comparable results and reaction times were realized in many cases with the same quantity of **1** added at the outset. Typically, we used 1−3 mol % (6−40 mg) of **1** and found reaction times of 40 min−2.5 h at 25 °C. A mild increase in temperature to 50 °C was helpful. To prevent sulfone formation, an excess of TBHP was strictly avoided in experiments at 50 °C.

This procedure was tested for 14 sulfides: (a) dialkyl (R, R′ = Me, R = Me, R′ = *tert*-butyl; R = R′ = *tert*-butyl; *cyclo*-C_4H_8); R = Me, R′ = Bn; (b) alkyl, aryl (R = Me, C_6H_4-4-X, X = Me, NO_2, Br, AcO, and CN); (c) diaryl (R = R′ = Ph); (d) R = Ph, R′ = vinyl); (e) dibenzothiophene; and (f) thianthrene. Table 1 presents the results. In every case, the sulfoxide was obtained almost quantitatively.

This method proved tolerant of the tested functional groups. Vinyl phenyl sulfoxide was formed without an epoxidation side product.[43,44] In the workup, the TBA produced evaporated with the solvent. The ^{1}H NMR spectrum showed sulfoxide but not sulfone. That was true even for diphenyl sulfide, where overoxidation can occur.[24,25] In no case did the unreacted sulfide exceed 5%, and generally, it was absent. This method avoids an aqueous workup, which is often required when peracids are used,[24] and is thus particularly useful for water-soluble sulfoxides.

Convenience is also a factor. The attractive features of **1** are its convenient synthesis, long shelf life (>3 months), and stability toward the humid air of an Iowa summer. Not only is the catalyst a forgiving one, but the catalytic reactions themselves can also be carried out on the benchtop. At room

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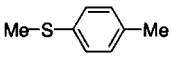
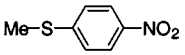
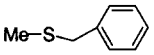
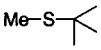
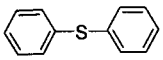
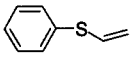
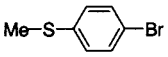
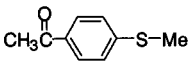
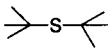
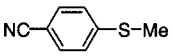
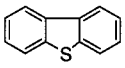
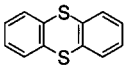
(44) Su, W. *Tetrahedron Lett.* **1994**, *35*, 4955−4958.

Table 1. Oxidation of Sulfides to Sulfoxides by TBHP, Catalyzed by 1[a]

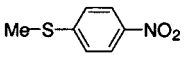
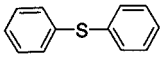
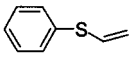
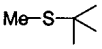
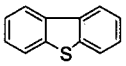
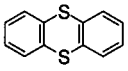
Entry	Compound	**1** (mol %)	Temp / °C	Time / h	% Yield [b]
1	Me–S–Me	3	0	0.7	100
		1	0	2	100 [c]
2		1	25	1	100
		1	25	1	100 [c]
3		1	25	2.5	99 (95)
		0.05	50	0.8	98 (95) [c, d]
4		1	25	1.5	100 (93)
5		1	25	1.5	100 (95)
6		2	25	2.5	100
7		1	25	2	100 (92)
8		1.5	25	2	100 (97)
9		1.5	25	3	100 (95)
10		1.5	25	2	97 (90)
11		1.5	25	2.5	98
12		2	25	2	100 (96)
13		3	25	6	89
		1	25	3	96 [c]
14		1	25	2	96 [e]

[a] At 25 °C in $CHCl_3$; TBHP (2.05 mmol) was added to 2.0 mmol of sulfide in 2 mL chloroform; catalyst **1** in 1−2 mL $CHCl_3$ was added by syringe pump (or all at once, if so noted). [b] Yields are NMR yields of the crude product after solvent and TBA evaporation. NMR yields were determined by integration. The samples were very pure by NMR, so this is a satisfactory procedure. In a few cases, the method was checked by GC-MS. The isolated yield is given in parentheses. [c] The catalyst was added all at the beginning. [d] 2.00 mmol TBHP. [e] Other materials are 5,10-thianthrene dioxide (2%); 2% unconverted thianthrene was also present.

temperature, they proceed in an hour or two, depending on several factors: temperature and the concentrations of **1** and TBHP.

A mild increase in temperature to 50 °C permitted the use of a smaller amount of **1** and allowed a shortened reaction time. The amount of TBHP then needed to be even more tightly controlled at ≤RSR′, lest some sulfone also be formed. At the extreme, a much less reactive sulfide, 4-nitrophenyl methyl sulfide, was used with TBHP, 1.0 mmol each. With 0.05 mol % (0.3 mg) of **1**, 95% sulfoxide was

Table 2. Oxidation of Sulfides to Sulfones by 3 equiv of *t*-BuOOH Catalyzed by **1**

Entry	Compound	**1** (mol%)	% Yield [a]
1		0.5	97
		0.05	85
2		0.3	100
		0.3	100 [c]
3		0.5	100
4		0.5	99
5		0.5	100
		0.5	100 [d]
6		0.5	98[b]
7		0.5	97

[a] The yields were determined by taking the ^{1}H NMR of the crude product after evaporation. [b] The balance is thianthrene monoxide. [c] Compound **1** added at the start; complete reaction in 2 h. [d] Compound **1** added at the start; complete reaction in 1 h.

obtained in 1 h. A control reaction lacking **1** showed 2% sulfoxide in that time.

In the absence of sulfide, **1** is decomposed by TBHP. The modes of catalyst decomposition are complex; we represent them by an approximate chemical equation that shows formation of RSSR (the cyclic organic disulfide, mtp) and MTO (which does not catalyze sulfide oxidation by TBHP), in eq 4. This is a simplification, however, because some Ph_3-PS and other byproducts are formed as well.

$$\mathrm{MeReO(mtp)PPh_3} + 3\mathrm{TBHP} \rightarrow \mathrm{MeReO_3(MTO)} + \mathrm{RSSR} + 3\mathrm{TBA} + \mathrm{Ph_3PO} \quad (4)$$

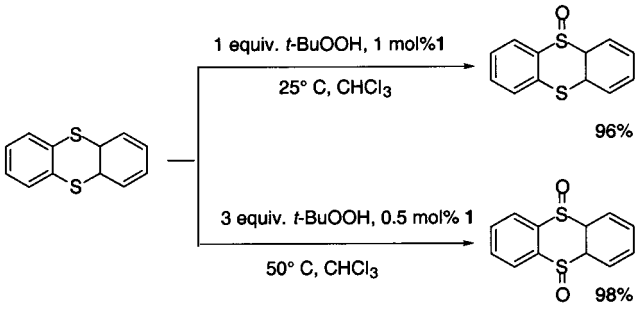
Sulfides to Sulfones, via Sulfoxides. This transformation requires working at 50 °C. The syntheses were done with 3:1 TBHP/RSR′, because with 2 equiv of TBHP, only partial (75%−85%) conversions to sulfones were obtained. Sulfones were obtained in excellent yields in 2 h with only 0.3−0.5 mol % of **1**. Six sulfides were tested to demonstrate tolerance to functional group variations, including the vinylic group in phenyl vinyl sulfide, which remained unchanged. These results are summarized in Table 2. With syringe pump addition of **1**, all of the oxidations were complete within 2 h. The amount of **1** could be further reduced to 0.05 mol % at the expense of a longer reaction time, ∼4 h, although the yield of some sulfones was reduced to 85%.

Table 3. Oxidation of Methyl Tolyl Sulfoxide (MTSO) to Sulfone by TBHP under Different Conditions[a]

MTSO/mmol	TBHP/mmol	**1** (mol %)	$MTSO_2$, %
1.0	2.0	1.0	100
1.0	2.0	0	12
1.0	1.5	1.0	82

[a] At 50 °C in 3 mL of chloroform.

Scheme 1. Oxidation of Thianthrene



During this procedure, sulfides were found to have disappeared within 15−30 min. To no surprise, the reaction starting with a sulfide is a sequential one, with a sulfoxide intermediate. To show whether **1** is needed for the second oxidation, methyl tolyl sulfoxide (MTSO) was used. We obtained the sample commercially, lest some adventitious rhenium be present in a sample that we had prepared. With 1 mol % of **1**, a reaction between TBHP (2.0 mmol) and MTSO (1.0 mmol) at 50 °C in chloroform gave a 100% yield of $MTSO_2$ in 2 h. Without **1**, only 12% sulfone was formed. Recognizing that the 2:1 molar ratio represents an excess, the reaction was repeated stoichiometrically, 1.5:1 TBHP/MTSO, yielding 82% $MTSO_2$. The data in Table 3 suggest that **1** does indeed catalyze the sulfoxide-to-sulfone step but that this step, unlike sulfide-to-sulfoxide, occurs slowly on its own.

Oxidation of Thianthrene. Several products can be formed in principle, but only two were found, thianthrene 5-oxide (SSO) with 1:1 TBHP and RSR′, and thianthrene 5,10-dioxide (SOSO) with a 3:1 ratio. No trace was found of 5,5-dioxide (SSO_2), 5,5,10-trioxide ($SOSO_2$), or 5,5,10,-10-tetraoxide (SO_2SO_2). No other oxidation products were detected. The results (Table 2) are summarized in Scheme 1.

Oxidation of Thiophenes. Heavily substituted thiophenes, such as dibenzothiophene, were successfully oxidized to dibenzothiophene monoxide (Table 1, entry 13) and dibenzothiophene dioxide (Table 2, entry 5), as governed by the TBHP:DBT ratio. On the other hand, with a 1:1 or a 3:1 reagent ratio, 2,5-dimethylthiophene both at room temperature and at 50 °C gave <20% 2,5-dimethylthiophene 1,1-dioxide; unreacted thiophene and unidentified products remained, and the use of additional **1** did not improve matters.

Thiophene oxides lacking attached ring systems are known to cyclize rapidly in solution.[45−47] One can capture the thiophene monoxide by addition of a dienophile trap.[41,48,49]

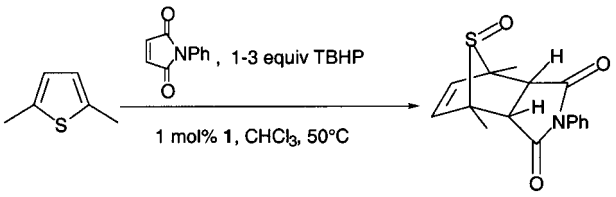
Table 4. Oxidation of 4,6-DMDBT with Different Reaction Conditions and Catalysts[a]

entry	DMDBT (mmol)	TBHP (mmol)	catalyst (mol %)	temp (°C)	time (h)	solvent	"SO" (%)	"SO_2" (%)	"SO" + "SO_2" (%)
1	1.0	2.0	**1** (1.0)	50	2	C	71	20	91
2	2.0	2.5	**1** (3.0)	25	1.5	C	58	3	61
3	2.0	2.5	**2** (3.0)	25	1.5	C	61 (52)	4	65
4	0.5	1.0	**3** (5.0)	50	2.5	C	67	15	82
5	0.5	1.0	**5** (5.0)	50	2.5	C	64	31	95
6	0.5	1.75	**5** (3.8)	50	2	C	0	100 (95)	100
7	0.5	1.75	**5** (5.0)	50	1.5	M	0	100 (92)	100
8	0.5	1.75	**1** (3.8)	50	2	C	0	100 (95)	100
9	0.5	1.75	**1** (3.8)	50	2	T	3	97	100
10	0.5	1.50	**1** (1.0)	50	2.5	T	9	91	100
11	0.5	1.75	**1** (0.5)	70	0.7	T	7	93	100
12	0.5	1.75	**1** (0.05)	111	2	T	0	100 (96)	100
13	0.5	1.75	(0)	111	2	T	7	0	7

[a] Solvents: C = chloroform; T, toluene; M, methylene chloride. "SO" = DMDBTO; "SO_2" = DMDBTSO_2.

In this case, *N*-phenylmalelimide was used. Its adduct was isolated in 78% yield, as described by Scheme 2:

Scheme 2. Oxidation and Trapping of 2,5-Dimethylthiophene Monoxide



Oxidation of DMDBT. This compound proved more difficult to oxidize, but good results were obtained in three solvents with several oxorhenium(V) catalysts. The data are summarized in Table 4. A modest excess of TBHP was needed to ensure complete conversion to the dioxide. Several oxorhenium catalysts were used; of these, **1** and **5** were used the most, and both gave high yields in a reasonable time, ≤2.5 h. The reaction runs well in chloroform, methylene chloride, and toluene; the last is particularly noteworthy in that it represents a nonpolar hydrocarbon environment. Further reductions in the catalyst level could be realized by working at a higher temperature. At the extreme, the reaction proceeded well in refluxing toluene with only 0.05% of the catalyst. The separation of the dioxide proved trivial because it is nearly insoluble in all of these solvents. It precipitates from toluene even at 111 °C.

Product Buildup Curves. The formation of methyl tolyl sulfoxide (MTSO) was monitored as a function of time under several sets of conditions in which methyl tolyl sulfide (MTS) was used as a representative substrate. The curves all showed similar features, most notably a distinct induction period whose length is dependent on several factors. One illustration of the product buildup curve is displayed in Figure 1, and others are illustrated in Figure S-1. In each case, the rate

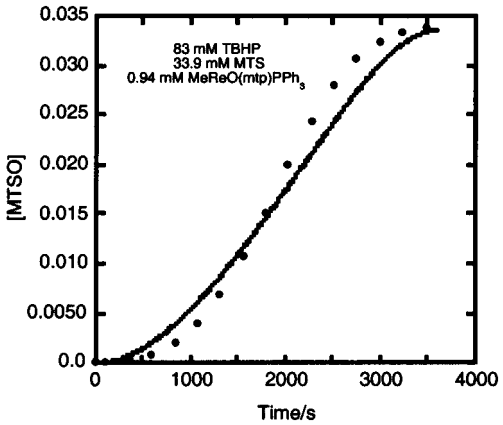


Figure 1. Formation of MTSO, showing fitted vs experimental data during the reaction of 33.9 mM MST and 83 mM TBHP in the presence of 0.31 mM MeReO(mtp)PPh_3, **1**. The experimental progress curve was modeled by a kinetics simulations routine that gave the optimum fit to data from six such experiments. The fitted curve is shown as a smooth curve. Other experiments and their fits are given in Figure S-1.

increased, and the induction period decreased with increasing [TBHP] and [**1**], whereas it slowed dramatically and the induction time grew longer as [MTS] was increased, other concentrations being constant.

Independent of this, PPh_3 on its own is oxidized by TBHP in the presence of catalyst **1** faster than MTS is.[50] When 3% of PPh_3 relative to MTS was added, added [PPh_3] = 1.0 mM, the oxidation of MTS slowed; this phenomenon can be represented by $t_{1/2}$ values of ~3900 and 1900 s, the first for the reaction with phosphine added and the second free of phosphine save for the 0.3 mM PPh_3 introduced as coordinated to **1**. The implications of these variations will be taken up in the Discussion, where an analysis of the reaction mechanism will be presented.

Comparing Different Rhenium Catalysts. A comparison among several of the catalysts shown in Chart 1 for the conversion of MTS to MTSO is presented in Figure 2. Table 5 shows the time required with different catalysts for 50% conversion of MTS with 1 mol % catalyst. All of these catalysts carry the reaction to completion with rates in the order **2** > **6** > **3** > **1**. Compound **4**, which lacks the stabilization provided by a chelating dithiolate, acts as a

(45) Nagasawa, H.; Sugihara, Y.; Ishii, A.; Nakayama, J. *Bull. Chem. Soc. Jpn.* **1999**, *72*, 1919−1926.
(46) Nakayama, J.; Nagasawa, H.; Sugihara, Y.; Ishii, A. *J. Am. Chem. Soc.* **1997**, *119*, 9077−9078.
(47) Nakayama, J. *Bull. Chem. Soc. Jpn.* **2000**, *73*, 1−17.
(48) Li, Y.; Matsuda, M.; Thiemann, T.; Sawada, T.; Mataka, S.; Tashiro, M. *Synlett* **1996**, 461−464.
(49) Naperstkow, A. M.; Macaulay, J. B.; Newlands, M. J.; Fallis, A. G. *Tetrahedron Lett.* **1989**, *30*, 5077−5080.
(50) Saha, B.; Espenson, J. H. To be submitted for publication.

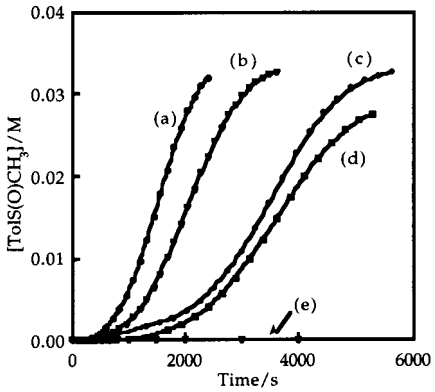


Figure 2. Different oxorhenium(V) compounds in this family serve as catalysts for the oxidation of MTS by TBHP. Data are shown for (a) [**2**] = 0.157 mM; (b) [**6**] = 0.31 mM; (c) [**3**] = 0.31 mM; (d) [**1**] = 0.31 mM; (e) [**7**] = 0.31 mM.

Table 5. Comparisons among Different Oxorhenium(V) Catalysts for the Oxidation of MTS and 4-Nitrophenyl Methyl Sulfide[a]

catalyst	$t_{1/2}$ (h)[b,c]	time (h)[d]	yield[d]
2	0.42	2.5	95
6	0.58		
3	0.97	2.5	95
1	1.05	1	95
4		4	75[e]
5		2.5	97
7	NR		

[a] At 25 °C in $CHCl_3$, 2.0 mmol substrate by TBHP (2.05 mmol). [b] Listed in order of decreasing reactivity for 50% conversion of MTS; the rhenium content, relative to sulfide, is 1 at. %. [c] Substrate is MTS; $t_{1/2}$ is for comparison only, because each progress curve shows an induction period of different length. [d] Time and yield for complete oxidation to 4-$O_2NC_6H_4S(O)Me$. [e] Catalyst **4** has decomposed after 4 h.

catalyst, but it gave only 75% conversion, owing to its eventual decomposition. Table 5 also presents the time needed for the complete conversion of 4-nitrophenyl methyl sulfide to its sulfoxide.

Detection and Characterization of the Re^{VII} Intermediate. A direct reaction between TBHP and **1** was monitored by ^1H NMR spectroscopy at room temperature and at 240−260 K. The room-temperature products were those shown in eq 4 without any intermediate being detected.

Dimer **2** is also a catalyst for sulfoxide formation. Addition of 8.0 mM TBHP to 2.0 mM **2** at 260 K gave a red compound **8**. It was formed nearly quantitatively in about 30 min. Its ^1H NMR spectrum, given in Figure S-2, is characterized by these resonances: δ (ppm): 2.71 (s, 3H, Re−CH_3), 4.55 (d, 1H, J = 8 Hz), 5.36 (d, 1H, J = 8 Hz), and 7.1−7.7 (m, 4H). Its structure is assigned as shown in Chart 1 because the ^1H NMR spectrum showed that TBA had been formed concurrently, signaling that **8** is a Re(VII) compound, for proper redox balance.

In solution, **8** is stable for >1 h. Efforts to obtain it in solid form for further characterization and analysis failed, however, probably because of its reactive nature. These reactions of **8** were characterized, as presented in Scheme 3. With sulfide or phosphine, the dioxorhenium(VII) species is reduced to oxorhenium(V). With 4-picoline, however, reduction is not spontaneous; instead, the simple adduct **9** is formed, as previously reported.[15] The reactions referred to in this paragraph were monitored by ^1H and ^{31}P NMR spectroscopies.

Attempted Chiral Induction. We also used **10** as a catalyst. It bears a chiral phosphine, (+)-neomenthyldiphenylphosphine, a ligand that has been used successfully in asymmetric catalysis.[51,52] The oxidation of MTS to MTSO by 1 equiv of TBHP occurred efficiently and completely, >95%. Chiral induction was not observed in several trials, however, as no enantiomeric excess was obtained as determined by a chiral chromatography.[53]

Discussion

The success of catalysis speaks for itself. Sulfoxides and sulfones can be obtained nearly quantitatively without cross-contamination. Even the least reactive substrates (DMDBT and 4-nitrophenyl methyl sulfide) can be oxidized.

The principal issue at this point is to devise a reaction scheme consistent with the data and with the known chemistry and reactivity of **1**. We have relied upon the new data as well as the information gleaned from our study of rhenium-catalyzed OAT from pyridine *N*-oxides to PAr_3.[54] The latter set of reactions occurs considerably faster than sulfide oxidations do.

Kinetic data were collected for a single sulfide, MTS, that is representative of the class. The buildup of MTSO was followed by ^1H NMR spectroscopy. All of the experiments were characterized by an induction period of varying length, even though 100% conversion to product was recorded with a stoichiometric excess of either MTS or TBHP. Reactions were not followed to the point where either sulfone formation or decomposition of **1** became important.

The ligand *displacement* (not dissociation) reactions of eq 1 (the 5 ligands give a set of 10 equilibrium reactions, 4 of which are independent) occur more rapidly than sulfide oxidation. Catalyst **1** was the only rhenium species detected by NMR spectroscopy during oxidation catalysis. Phosphine coordinates to Re(V) much more strongly than do any of the other Lewis bases present. As a result, one important kinetic barrier is the step in which TBHP displaces PPh_3. Our analysis starts with this premise: ligand displacement steps other than phosphine displacement remain at equilibrium. This is one of the assumptions we have made to reduce the kinetic steps to a tractable number.

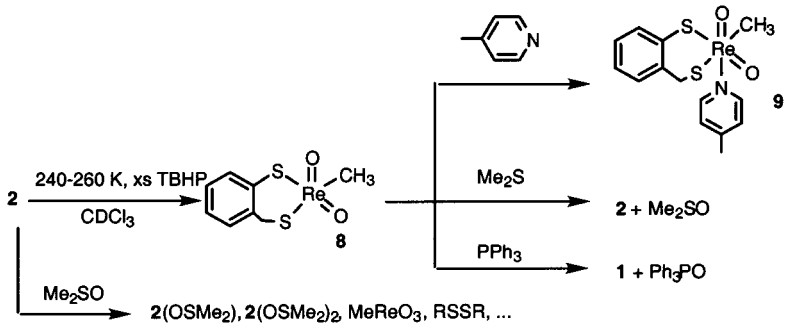
Insofar as the chemistry critical to catalysis is concerned, another kinetic barrier arises at the step in which a dioxorhenium(VII) intermediate is formed by elimination of TBA from an intermediate containing coordinated hydroperoxide:

$$\mathrm{MeReO(mtp)(TBHP)} \rightarrow \mathrm{TBA} + \mathrm{MeRe(O)_2(mtp)} \quad (5)$$

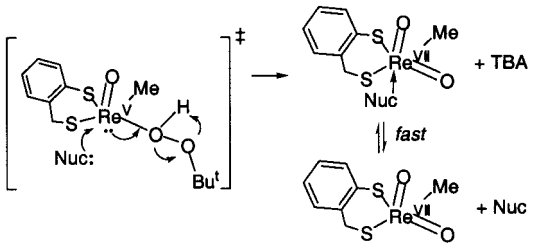
The oxidation of phosphines by pyridine *N*-oxides requires, from an analysis of the kinetic data, that a nucleophile assist

(51) Zim, D.; de Souza, R. F.; Dupont, J.; Monteiro, A. L. *Tetrahedron Lett.* **1998**, *39*, 7071−7074.
(52) Morrison, J. D.; Burnett, R. E.; Aguiar, A. M.; Morrow, C. J.; Phillips, C. *J. Am. Chem. Soc.* **1971**, *93*, 1301−1303.
(53) We are grateful to Prof. D. A. Armstrong, J. Anderson, and T. Xiao for these determinations.
(54) Wang, Y.; Espenson, J. H. Submitted for publication.

Scheme 3. Formation and Reactions of Dioxorhenium(VII)



Scheme 4. Proposed Nucleophilic Assistance in the Formation of Dioxorhenium(VII)



this reaction. Each one of phosphine, pyridine *N*-oxide, pyridine, tetrabutylammonium bromide, and tmtu was able to do so.[54]

$$\mathrm{MeReO(mtp)O(OPy)} + \mathrm{Nuc} \rightarrow \mathrm{Py} + \mathrm{MeRe(O)_2(mtp)Nuc} \quad (6)$$

On the basis of that work, it seems likely that a nucleophile assists reaction 5 as well. In this instance, the nucleophiles present are PPh_3 (except in one instance, however, it was present only at the level of the catalyst), MTS, MTSO, TBHP, and TBA. This suggestion is depicted in Scheme 4. The rationale is that this is a step in which the d^2 electrons of Re(V) are removed by oxidation.

The dioxorhenium(VII) product of eq 5−6, like other oxorhenium(VII) compounds, is believed to be in rapid equilibrium with Lewis bases. Rapid equilibration between ligands and rhenium(VII) has been shown to be the case not only here but with $MeReO_3$ in its coordination with pyridine and pyridine *N*-oxide.[55] Equilibrium between the rhenium product shown and $MeRe(O)_2(mtp)$ occurs on a submillisecond time scale. In reaction 6, the nucleophile can be any of PyO, Py, or $[Bu_4N]Br$.

In the step that follows, MTS abstracts an oxygen atom from the dioxorhenium(VII) intermediate. We also show this reaction as two steps occurring in sequence, on the basis of results from molybdenum chemistry.[21,22]

$$\mathrm{MeRe(O)_2(mtp)} \xrightarrow{\mathrm{MTS}} \{\mathrm{MeReO(mtp)(MTSO)}\} \xrightarrow{\mathrm{MTS},\, k_4} \mathrm{MeReO(mtp)MTS} + \mathrm{MTSO} \quad (7)$$

This is not the complete story, however, because it would lead to the smooth conversion of MTS to MTSO, without the distinct induction period. The latter appears to arise from two effects: the aforementioned low rate of displacement of coordinated PPh_3 and the partial loss of phosphine due to oxidation. We therefore introduce a step well-known from our earlier studies of PyO chemistry. This involves the oxidation of phosphine by the dioxorhenium(VII) intermediate:

$$\mathrm{MeRe(O)_2(mtp)} + 2\mathrm{PPh_3} \rightarrow \mathrm{MeReO(mtp)(PPh_3)}\ [\mathbf{1}] + \mathrm{Ph_3PO} \quad (k_5) \quad (8)$$

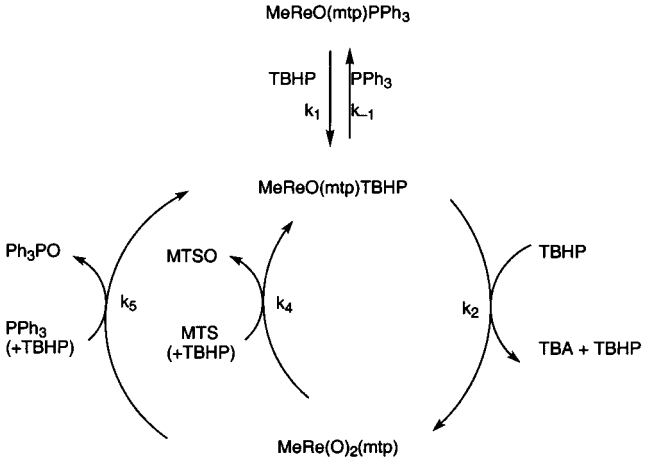
The initial supply of phosphine is no greater than that of the starting concentration of **1**. Thus, any PPh_3 oxidized in reaction 8 reduces the proportion of the rhenium catalyst present in the phosphine form **1** (which is most stable of all with respect to ligand displacement equilibria). Other $MeReO(mtp)L_j$ species are formed as a consequence. They are undoubtedly more reactive catalysts, because their thermodynamic barrier relative to the generation of the reactive species MeReO(mtp)TBHP in eq 5 is lowered. As phosphine is oxidized, therefore, the rate increases with time. This is the essence of the chemistry underlying the induction period. For $L_i = PPh_3$ and $L_j = Me_2S$, pK = 5.3. From the kinetic modeling, as given subsequently, we can deduce an estimate pK = 3.8 for $L_i = PPh_3$ and L_j = TBHP. The binding of TBHP is thus favored over that of MTS, which supports the selection of that step for the modeling.

Kinetic Modeling. To approach this complex system, it proved desirable to reduce the number of conceivable steps because none of the rate constants are known directly. For example, the kinetics and equilibria of the different ligands that participate in eq 1 were ignored, save for the case $L_i = PPh_3$ and L_j = TBHP. Reaction 6 was successfully included with TBHP as the nucleophile, but a parallel step with PPh_3 as the nucleophile proved insignificant, no doubt because phosphine remains at a very low concentration. Reaction 6 produces the Re(VII) compound $MeRe(O)_2(mtp)$, **8**, which can react with MTS (higher concentration, lower rate constant) in competition with PPh_3 (vice versa) to restore MeReO(mtp)L, L = TBHP, PPh_3. These reactions are the minimum set needed to reproduce the kinetic data. They are shown in the form of a catalytic cycle in Scheme 5, where fast steps (e.g., the second step of eq 7 and others) have been omitted.

The success of a model is measured by the extent to which the calculated and experimental curves agree. Its plausibility is judged by the chemical scheme itself and the fitted values

(55) Wang, W.-D.; Espenson, J. H. *J. Am. Chem. Soc.* **1998**, *120*, 11335−11341.

Scheme 5. Catalytic Cycle Used for Kinetic Modeling



of the rate constants. In this scheme, there are five constants to be determined from the six experiments, each with 16−41 concentration−time values. The fitting to this model by the program ZiTa[56] was satisfactory but not fully precise; see Figures 1 and S-1. The fitted rate constants are summarized in Table 6. More critical, however, is the result that the semiquantitative features were properly modeled. Thus, the occurrence of an induction period, the variation of its length with concentration, the rapid increase to a maximum rate, and the result that all of the limiting reagent is converted to product are indications that the model is satisfactory, in essence at least.

(56) Peintler, G. *ZITA 5.0., A comprehensive program package for fitting parameters of chemical reaction mechanisms, Version 3.1*; Institute of Chemistry, JATE: Szeged, Hungary, 1999. The first use of this program was described: Peintler, G.; Nagypal, I.; Epstein, I. R. *J. Phys. Chem.* **1990**, *94*, 2954.

Table 6. Chemical Equations[a] and the Fitted Values[b] of Their Rate Constants at 25° in $CDCl_3$

chemical equation	k/L mol^{-1} s^{-1}
$MeReO(mtp)PPh_3 + TBHP \rightarrow MeReO(mtp)TBHP + PPh_3$	$k_1 = 9.8 \pm 1.8 \times 10^{-4}$
	$k_{-1} = 6.7 \pm 1.4$
$MeReO(mtp)TBHP + TBHP \rightarrow MeRe(O)_2(mtp) + TBA + TBHP$	$k_2 = 2.2 \pm 0.3$
$MeRe(O)_2(mtp) + MTS\ (+ TBHP) \rightarrow MeReO(mtp)TBHP + MTSO$	$k_4 = 40 \pm 16$
$MeRe(O)_2(mtp) + PPh_3\ (+ TBHP) \rightarrow MeReO(mtp)TBHP + Ph_3PO$	$k_5 = 2.5 \pm 1.0 \times 10^2$

[a] A species shown in parentheses is not a part of the rate law, but it completes the stoichiometry. [b] The program ZiTa was used for data fitting.[56]

The fitted rate constants, although of low precision (see Table 6), deserve comment. As anticipated, k_1 ($=1 \times 10^{-3}$ L mol^{-1} s^{-1}) is small. It can be compared to the value for another weak nucleophile, with $k = 7 \times 10^{-3}$ L mol^{-1} s^{-1} estimated for pyridine. Values for reactions in which PPh_3 displaces a more weakly bound ligand include $k_{-1} = 7$ L mol^{-1} s^{-1} for TBHP and $k \sim 80$ L mol^{-1} s^{-1} for Py (after a significant extrapolated from data in ref 10). As anticipated, k_1 is quite low, 10^{-3} L mol^{-1} s^{-1}. Also, $k_5 > k_4$, although the margin is not high: 250 versus 40 L mol^{-1} s^{-1}. This reflects the selectivity of phosphine over sulfides, consistent with their nucleophilic strengths.

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Supporting Information Available: Additional figures (S-1−3), including plots of kinetic data and NMR spectra. This material is available free of charge via the Internet at http://pubs.acs.org.

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