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A Kinetic Study of Sulfide Oxidation by Sodium Hypochlorite Using Phase-Transfer Catalysis

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Abstract: The use of sodium hypochlorite as a synthetically useful oxidizing agent is reported for the oxidation of lipophilic organic sulfide substrates employing phase-transfer catalysis (PTC). The PTC results in nearly complete oxidation of the substrate in 20 min, with high selectivity to the sulfoxide, compared to 5 h in its absence. Kinetic studies show the reaction occurs via transfer of OCl^- into the organic phase. Under certain conditions the transfer is rate limiting. The addition of a transition-metal catalyst (TPPMnCl) further increased the rate and led to the complete conversion of the sulfide to the sulfone, illustrating that NaOCl(aq) is a potent oxidizing agent in these biphasic systems.

Hypochlorite is a potent oxidizing agent that has been shown to operate by an oxygen atom transfer mechanism in the oxidation of aqueous nitrite ion.[1] However, the insolubility of hypochlorite salts in hydrocarbons and organic solvents has prevented the use of this material as a reagent for the selective oxidation of organic substrates.

Phase-transfer catalysis, PTC, is a very useful technique for bringing an anionic reactant from one phase into another in which it is normally insoluble, thus permitting reaction. Enhanced reactivity of reagents over that observed in water also often occurs, resulting in reduced consumption of organic solvents, milder reaction conditions, greater specificity of reactions catalyzed, and more control over reaction rates and yields.[2a] Much of the current literature contains data on the use of phase-transfer catalysis in displacement reactions,[2b] with fewer reports on the oxidation of olefins,[3] alcohols,[4] amines,[5] and aromatic hydrocarbons.[6] Some detailed studies employing phase transfer of permanganate salts[7-9] have appeared.

Oxygen atom transfer from an X–O functional group, in high valent metal-oxo and nonmetallic oxygen atom transfer agents, occurs[10] via nucleophilic attack on the oxygen with two-electron transfer to the leaving group X. The strength of the oxygen atom transfer agent should be related to the stability of the X^- group displaced (which in the case of OCl^- is Cl^-). The reaction is specific because the oxidized substrate usually is a poorer nucleophile than the starting material.

We are interested in the oxidation of dialkylsulfides as probe substrates to demonstrate oxygen atom transfer mechanism. Davis et al.[11] have reported that oxidation of organic sulfides and sulfoxides by oxaziridines occurs via an SN^{-2} nucleophilic attack on oxygen. The sulfur donor atom in the sulfide is considerably more basic than that in the sulfoxide toward sigma Lewis acids. By controlling the stoichiometry of the reactants, selectivity to sulfoxide or sulfone should occur with oxygen atom transfer oxidants.

In order to phase transfer OCl^-, we chose quaternary ammonium salts for their advantages of high activity, ready availability, relatively good thermal stability (up to ~150 °C), and low cost.[2] A variety of R groups can be used in the general formula $R_4N^+Cl^-$ to achieve the desired characteristic of the PTC for specific applications. Our results illustrate the usefulness of phase-transfer catalysts in leading to the use of inexpensive sodium hypochlorite solution as an oxygen atom transfer agent. Many oxygen atom transfer reactions from iodosobenzene and its derivative can be catalyzed by metal complexes that will not activate O_2. Phase-transferred hypochlorite is a potential, inexpensive substitute for this more expensive reagent in many of these reactions. Our results should advance the utilization of OCl^- as a synthetic reagent.

Results and Discussion

Our main purpose in this study was to examine the usefulness of phase-transfer catalysis for utilizing hypochlorite as an oxidant for lipophilic substrates. This objective led to our choice of *n*-butyl sulfide as the substrate to oxidize. Methyltri-*n*-octylammonium chloride (Aliquat 336) was selected as the phase-transfer catalyst and is reported to give relatively high rates in a variety of reactions.[1,2,9] On the basis of preliminary phase distribution studies of hypochlorite between the aqueous phase and various organic solvents (toluene, tetrachloroethylene, and methylene chloride), methylene chloride was selected because the phase transferred OCl^- concentration in this solvent remains relatively constant during several hours of stirring with Aliquat 336 present.

Table I. Initial Rates of *n*-Butyl Sulfoxide Formation with No PTC

expt	amounts of reactants, mmol[a] Bu_2S[b]	OCl^-[c]	initial rate × 10^5, M s^{-1}
1	17.2	34.44	89
2	17.2	8.6	22
3	34.4	8.6	29

[a] Reactions followed out in air at ambient temperature (~25 °C) with 50.0 mL of CH_2Cl_2 and variable volumes of bleach. [b] Bu_2S was dissolved in 50.0 mL of CH_2Cl_2. [c] Bleach concentration was 0.71 M in OCl^-.

Equations 1 and 2 illustrate the overall stoichiometry of the oxidation reaction.

$$CH_3(CH_2)_3S(CH_2)_3CH_3 + OCl^- \xrightarrow[CH_2Cl_2/H_2O]{} CH_3(CH_2)_3SO(CH_2)_3CH_3 + Cl^- \quad (1)$$

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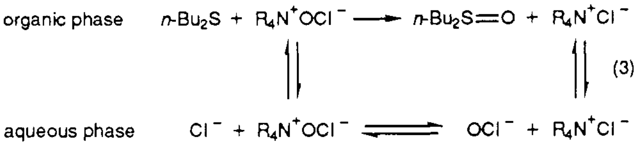
$$CH_3(CH_2)_3SO(CH_2)_3CH_3 + OCl^- \xrightarrow[CH_2Cl_2/H_2O]{} CH_3(CH_2)_3SO_2(CH_2)_3CH_3 + Cl^- \quad (2)$$

The various equilibria involved in the phase transfer catalyzed system are illustrated in eq 3. The PTC at the solvent interface



forms $R_4N^+OCl^-$, which, because of the lipophilic character of the quaternary cation, allows the transfer of the oxidant OCl^- into the organic phase where oxidation of the lipophilic substrate occurs. The product $R_4N^+Cl^-$ species is in equilibrium with the aqueous phase where its reaction with NaOCl permits the transfer of more OCl^- into the organic phase. Equilibria involving hydroxide are omitted.

Because of the multiple equilibria involved in phase-transfer catalysis, the kinetics of these systems are complicated. Much of the published work deals with the kinetics of anion-displacement reactions rather than oxidation reactions.

1. Results When No PTC Was Used. In order to establish a blank for the phase transfer catalyzed system, the reaction rate for the oxidation of *n*-butyl sulfide by hypochlorite in the biphasic system was studied without the phase-transfer catalyst present. Table I shows the amounts of reactants and initial rates of formation of *n*-butyl sulfoxide. The initial rates were determined from the graph of *n*-butyl sulfoxide product formed versus time (Figure 1). Even though very little hypochlorite ion is extracted into the CH_2Cl_2 phase and very little Bu_2S is soluble in the aqueous phase, the Bu_2S is oxidized to the sulfoxide. Since the two phases are immiscible, a classical rate-law analysis is not appropriate here; however, the comparison of initial rates does provide valuable data. Comparing experiments 1 and 2, when the amount of Bu_2S was kept constant, a 4-fold increase in the amount of OCl^- resulted in a 4-fold increase in the initial rate. Comparing Experiments 2 and 3, when the amount of OCl^- was kept constant, a 2-fold increase in the amount of Bu_2S resulted in an initial rate only 1.3 times faster.

There are several possible paths for the reaction of hypochlorite ion with Bu_2S when no phase transfer agent is used. One is a reaction at the interface of the two phases. These types of reactions tend to be limited not only by the concentration of the reactants at the interface, but also by the interfacial area available and hence the stirring rate.[2] When the stirring rate was decreased to half the rate previously used, there was a decrease in the initial rate of formation of the sulfoxide. Some contribution to the observed reaction may come from the very slight solubility of di-*n*-butyl sulfide in the aqueous phase. Gas chromatographic analysis of aqueous-phase samples show trace amounts of CH_2Cl_2 and Bu_2S. Alternately small amounts of oxidant end up in the organic phase, via the very slight solubility of water in the methylene chloride solvent or perhaps as HOCl. Iodometric titration[8] of CH_2Cl_2 samples show trace amounts of OCl^-. The sulfoxide formed in the organic phase can also behave as a PTC by coordinating Na^+ and solubilizing Na^+OCl^- in the organic phase. The observed reaction orders in Bu_2S and OCl^- suggest that the rate-limiting process is the transfer of oxidant into the organic boundary of the interface with reaction occurring in the organic phase.

2. Phase-Transfer and Metal-Complex Catalysis. This kinetic study examined the reaction rates for the oxidation of Bu_2S by hypochlorite when the PTC Aliquat 336 was used. In addition, an experiment was conducted with both the PTC and a transition-metal catalyst, (5,10,15,20-tetraphenyl-21*H*,23*H*-porphine)manganese chloride, TPPMnCl.

In order to carry out these kinetic studies, a decrease in concentration of the reactants was necessary so a new blank (no PTC) for these lower concentrations in the absence of the PTC was run and is shown in Figure 2. With no PTC present, an induction period of 30 min is observed and 5 h are required for complete reaction. We speculate that during the induction period the sulfoxide formed in the organic phase behaves as a PTC and coordinates to the sodium ion, facilitating the transport of hypochlorite into the organic phase. No sulfone was produced in this experiment. This could be an important mechanism in heterogeneous oxidation reactions and suggests that crown ethers or other ligands for Na^+ that are soluble in organic solvents and stable to OCl^- could function as phase-transfer catalysts for OCl^-.

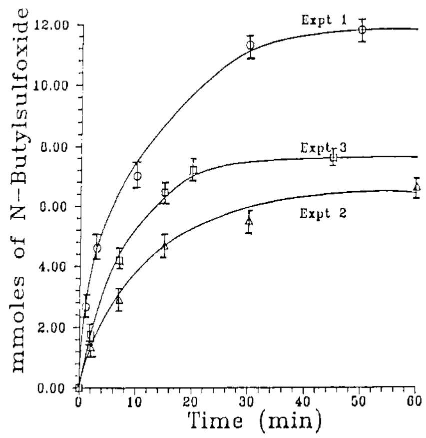


Figure 1. Production of *n*-butyl sulfoxide versus time for experiments 1–3. In experiment 1 the sum of the millimoles of *n*-butyl sulfoxide and *n*-butyl sulfone formed in 1 h totaled approximately 15 mmol (~90% oxidation of sulfide). The sulfone began to form after 10 min and after 24 h the product mixture was two-thirds sulfone and one-third sulfoxide. In experiments 2 and 3 no *n*-butyl sulfone was formed. In both experiments 2 and 3 the amount of *n*-butyl sulfoxide formed after 24 h was approximately 8 mmol, corresponding to nearly complete consumption of OCl^-.

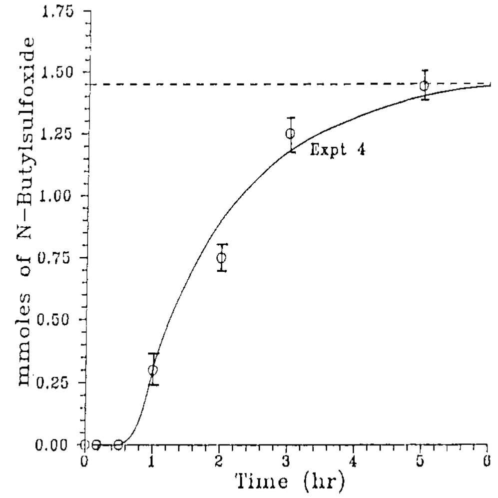


Figure 2. Production of *n*-butyl sulfoxide versus time for experiment 4 (0.029 M Bu_2S). The dashed line indicates complete reaction of di-*n*-butyl sulfide.

Table II. Initial Rates of *n*-Butyl Sulfoxide Formation with PTC

	amounts of reactants, mmol[a]				initial rate × 10^5,
expt	Bu_2S[b]	OCl^-[c]	PTC	TPPMnCl	M s^{-1}
4	1.45	1.45	2.9	0	0.40[d] ± 0.06
5	1.45	1.45	2.9	0.62	1.7 ± 0.3
6	1.45	1.45	2.9	0.62	0.006011 ± 2

[a] Reactions carried out in air at ambient temperature (~25 °C) with 50.0 mL of CH_2Cl_2 and 4.0 mL of aqueous hypochlorite. [b] The Bu_2S was dissolved in 50.0 mL of CH_2Cl_2 with Aliquat 336. [c] The OCl^- concentration was 0.71 M. [d] The net reaction is slower than this because this rate is calculated after the induction period has occurred. Initial rates were determined from the graphs of *n*-butyl sulfoxide formed versus time (Figures 2 and 3).

Table II shows the amounts of reactants employed and the initial rates for the formation of *n*-butyl sulfoxide when the

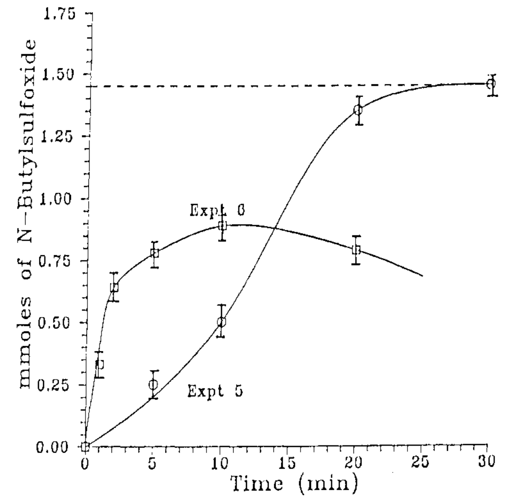


Figure 3. Production of *n*-butyl sulfoxide versus time for experiments 5 and 6. In experiment 6 both sulfoxide and sulfone were produced. After 30 min all of the sulfide had been oxidized. The sulfone began to form after 6 min and after 6 h all the sulfoxide had been converted to the sulfone. In experiment 5 no *n*-butyl sulfone was formed.

Table III. Initial Rates of *n*-Butyl Sulfoxide Formation with PTC

	amounts of reactants, mmol[a]			
expt	Bu_2S[b]	OCl^-[c]	PTC	initial rate × 10^5, M s^{-1}
5	1.45	2.9	0.62	1.7 ± 0.3
7	2.9	2.9	0.62	2.6 ± 0.5
8	1.45	5.8	0.62	3.3 ± 0.8
9	1.45	2.9	3.1	17 ± 3
10	2.9	2.9	3.1	33 ± 7

[a] Reactions carried out in air at ambient temperature (~25 °C) with 50.0 mL of CH_2Cl_2 and 4.0 or 8.0 mL of bleach. [b] The Bu_2S was dissolved in 50.0 mL of CH_2Cl_2 with Aliquat 336. [c] The OCl^- concentration was 0.71 M.

phase-transfer catalyst and a metal complex oxidation catalyst are added to the system.

Since the amounts of Bu_2S and OCl^- are the same in all three experiments, a comparison of the initial rates allows an evaluation of the effectiveness of adding the two types of catalysts. The improved transport of OCl^- into the organic phase by the addition of 0.62 mmol (0.25 g) of PTC to the 50.0 mL of CH_2Cl_2 increased the initial rate over 4-fold. The actual benefit is even larger because this comparison is based on initial rates that were calculated after the 30-min induction period. Figure 3 illustrates the results with PTC present. With no induction period, half the Bu_2S was oxidized in about 15 min, leading to about a 9-fold increase in oxidation effectiveness by using the phase-transfer catalyst. The reaction is now essentially complete in 20 min compared to 5 h. When the reaction was carried out with both the PTC and a transition-metal catalyst (TPPMnCl) present, there was a 6-fold increase in initial rate over the PTC reaction, and over a 25-fold increase over the completely uncatalyzed reaction (see Table II). This reaction began producing a significant amount of *n*-butyl sulfone after about 15 min, and after 6 h, all the sulfoxide had been converted to the sulfone. No sulfone was produced in the uncatalyzed reaction or in the PTC reaction under the conditions used.

Influence of Reactant and PTC Concentrations on the Rate. The amounts of Bu_2S, OCl^-, and PTC were systematically varied in order to determine the rate dependence on each species. Table III contains a summary of the results of these experiments. The initial rates were determined from the graphs of *n*-butyl sulfoxide product formed versus time (Figures 3–5).

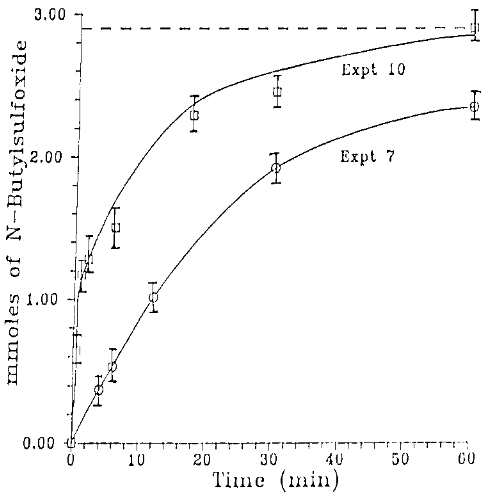


Figure 4. Production of *n*-butyl sulfoxide versus time for experiments 7 and 10. In experiments 7 and 10 no sulfone was produced. In experiment 7, 2.9 mmol of sulfoxide were produced after approximately 5 h. In experiment 10, 2.9 mmol of sulfoxide were produced after 1 h.

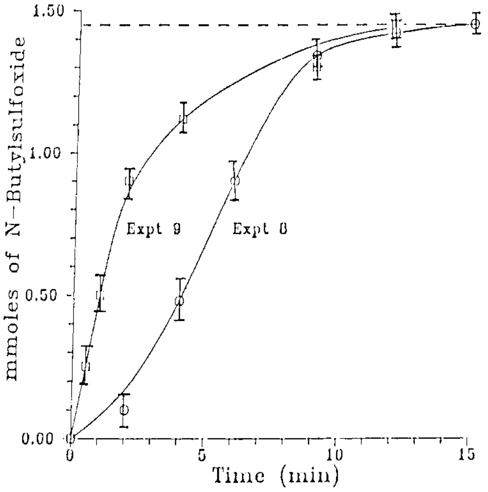


Figure 5. Production of *n*-butyl sulfoxide versus time for experiments 8 and 9. In experiment 8 no sulfone was observed in the first hour, but all the sulfoxide was oxidized to the sulfone after approximately 12 h. In experiment 9 no sulfone was produced in the first 15 min.

A comparison of the initial rates of sulfoxide formation for experiments 5 and 7 reveals that doubling the amount of Bu_2S increases the rate by a factor of 1.5. This is higher than the 1.3 factor observed when no PTC was used (see experiments 2 and 3). In experiments 5 and 8, doubling the amount of OCl^- does in fact double the rate, the same dependence that was observed with no PTC present.

Comparing experiments 7 and 10, we see that a 5-fold increase in the amount of PTC increases the rate more than 10-fold. Finally a comparison of experiments 9 and 10 shows that with the substantially larger amount of PTC, doubling of the amount of Bu_2S does double the rate of the oxidation.

It appears that the rate-limiting step in this reaction sequence is the anion-transfer step (with the sulfide oxidation being very rapid). This would explain the increasing sulfide dependence of 1.3, 1.5, and 2 based on no PTC, a small amount of PTC, and a large amount of PTC.

Increasing the amount of PTC increases the initial rate dramatically as shown in the comparison of experiments 5 and 9 and 7 and 10. From these results we conclude that the substrate oxidation is occurring in the organic phase utilizing phase-transferred hypochlorite. The oxidation reaction is first order in sulfide and hypochlorite when reagent transfer is not limiting.

3. Results with Neat *n*-Butyl Sulfide. Next we decided to investigate the effects of PTC on the heterogeneous oxidation of *neat* Bu_2S with aqueous OCl^-. The techniques employed were the same as those in previous kinetic studies except that smaller round-bottom flasks were used because the CH_2Cl_2 was not present. The oxidations were conducted with and without

Table IV. Initial Rates of *n*-Butyl Sulfoxide Formation with Neat Bu_2S

	amounts of reactants, mmol[a]			
expt	Bu_2S[b]	OCl^-[c]	PTC[d]	initial rate × 10^5, M s^{-1}
11	34.4	8.6	0	83 ± 15
12	34.4	8.6	0.62	440 ± 60

[a] Reactions carried out neat, in air, at ambient temperature (~25 °C). [b] The neat Bu_2S (6.0 mL) was the organic phase. [c] Aqueous hypochlorite (12.0 mL) concentration was 0.71 M. [d] Methyl tri-*n*-octylammonium chloride (Aliquat 336).

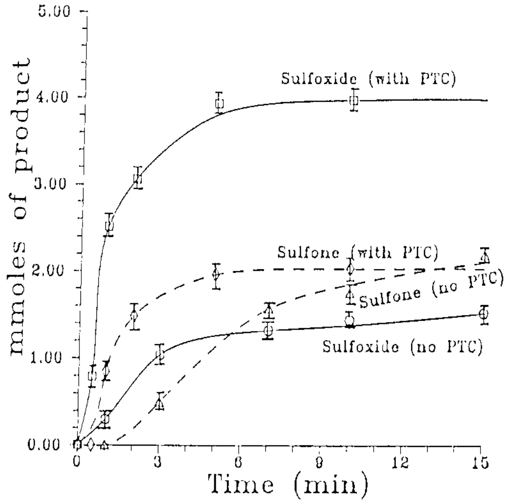


Figure 6. Production of *n*-butyl sulfoxide and *n*-butyl sulfone versus time for experiments 11 and 12. In experiment 12 essentially all of the OCl^- has reacted in 7 min. In the system without PTC (expt 11), reaction is not complete even after 45 min (The 45-min points were measured and showed that 1.9 mmol of sulfoxide and 2.4 mmol of sulfone were produced but are not shown on the graph).

phase-transfer catalyst present. Table IV shows the amounts of reactants and initial rates of formation of *n*-butyl sulfoxide. The initial rates were determined from the graphs of *n*-butyl sulfoxide product formed versus time (Figure 6).

With the same amounts of Bu_2S and OCl^- in both experiments, a comparison of the initial rates allows an evaluation of the effectiveness of adding a phase-transfer catalyst. Addition of 0.62 mmol (0.25 g) of PTC to the reaction system increased the initial rate more than 5-fold. This result is similar to that seen when methylene chloride was used as the organic solvent (experiments 4 and 5). Since both the sulfone and sulfoxide are found in the organic phase, with little in the aqueous phase, the rate increase is due primarily to the transport of OCl^- into the Bu_2S by the PTC. This supports our speculation that oxidized sulfide may act as a phase-transfer catalyst.

As expected, the rates in the neat system are considerably faster than those in CH_2Cl_2 with comparable amounts of reactants. In experiment 3 the initial rate was 29 × 10^{-5} M s^{-1} (Table I), while in experiment 11 (Table IV) the rate is 83 × 10^{-5} M s^{-1}. A major factor contributing to this difference is the lower interfacial concentration of Bu_2S in the CH_2Cl_2 solution. The neat Bu_2S reactions were quite exothermic, exhibiting a 10–15 °C temperature rise within the first few minutes of reaction, which probably accelerated the rate of reaction.

In both of the experiments using neat Bu_2S, a significant amount of *n*-butyl sulfone was formed relatively early in the course of the reaction. When no PTC was used, about 1.5 times as much sulfone as sulfoxide was produced; however, in reactions containing the PTC about half as much sulfone as sulfoxide was produced.

Conclusions

We have demonstrated that phase-transfer agents greatly enhance oxidation of lipophilic substrates by hypochlorite ion. We conclude that the oxidation occurs in the organic phase with phase-transferred hypochlorite ions. When mass-transfer conditions are not limiting, the reaction is first order in substrate and hypochlorite. This result is consistent with a mechanism in which a nucleophilic sulfur attacks an oxygen, leading to oxygen atom transfer. Selectivity is manifested when mass transfer is not limiting, as expected from the weaker nucleophilicity of the sulfoxide. The addition of metalloporphyrins as catalysts resulted in an order of magnitude increase in the rate of oxidation and catalyzed the oxidation of the sulfide all the way to the sulfone.

Experimental Section

The kinetic studies were carried out at ambient temperature (~25 °C) in round-bottom flasks on magnetic stirrers by first adding the CH_2Cl_2 solvent, *n*-butyl sulfide, Aliquat 336, and an internal standard. Standard household bleach solution (0.71 M in OCl^- and pH ~12) was added last. Small samples of the organic phase were then analyzed on a Varian 3700 gas chromatograph (FID) using a 6 ft, stainless steel, packed FFAP column after showing the virtual absence of sulfide, sulfoxide, and sulfone in the aqueous phase. An internal standard (*n*-octane) was used in all reactions and calibration curves for the oxidation products of *n*-butyl sulfoxide and *n*-butyl sulfone were prepared so that the number of moles of each product could be determined at various reaction times.

The *n*-butyl sulfide and Aliquat 336 were obtained from Aldrich, the *n*-octane was from Alfa Products, and the NaOCl solution was standard household bleach. The bleach was standardized with a standard thiosulfate solution in an iodometric titration.

Samples which were not run on the GC immediately were stored briefly in a refrigerator freezer or in liquid nitrogen (for the faster reactions).

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