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Activation of Molecular Oxygen:  
Kinetic Studies of the Oxidation of Hindered Phenols  
with Cobalt-Dioxygen Complexes

by

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ABSTRACT

Mechanistic studies of the oxidation of various substituted phenols by Co(II) bis(salicylidene- $\gamma$ -iminopropyl)methylamine, CoSMDPT are reported. The reaction is first order in ( $O_2$ ), [substrate] and [Co]. A series of experiments are reported to provide strong support for a mechanistic scheme that involves reaction of coordinated dioxygen. Coordination of  $O_2$  to this cobalt(II) complex enhances the ability of the dioxygen to abstract hydrogen atoms and to react with phenoxy radicals. The mechanism provides a rationale for the influence of several variables on the reaction and suggests steps that were taken to retard catalyst deactivation.

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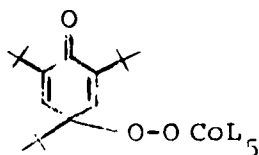
## INTRODUCTION

Determining the ways dioxygen can be activated by a metal center is important for understanding both biological and commercial systems.<sup>[1,2]</sup> Though homogeneous catalytic oxidations have been classified in many different fashions,<sup>[3,4]</sup> they can be separated into four broad categories: (1) free radical autoxidations using simple metal salts; (2) attack by various oxygen-containing nucleophiles on coordinated substrates; (3) oxygen atom transfers from high oxidation state elements; (4) epoxidation of olefins using metal catalysts and alkyl hydroperoxides. Major goals in this field involve controlled, highly selective, oxidations of substrates and demonstration of oxidation capabilities by metal bound  $O_2$ .

We became interested in investigating the possibility of catalyzing oxidations with metal-dioxygen adducts. There are many complexes that reversibly bind dioxygen,<sup>[5]</sup> and the bonding is now understood in terms of the spin-pairing model.<sup>[6]</sup> Upon coordination of cobalt(II) to dioxygen,<sup>[7]</sup> partial electron transfer from cobalt to oxygen occurs ranging from  $0.1e^-$  to  $0.8e^-$  depending on the ligand field surrounding the cobalt.<sup>[8]</sup> This should provide for variation in the reactivity of the bound  $O_2$ . Of the many reported oxidations by  $O_2$ , the oxidation of phenols appeared most attractive as a candidate for a process that involves metal coordinated  $O_2$ . Numerous reagents and catalysts oxidize phenols and these reactions have been reviewed extensively in the literature.<sup>[9-11]</sup> Generally, phenols can be oxidized to quinones, coupled products (diphenoquinones), or polymers, depending

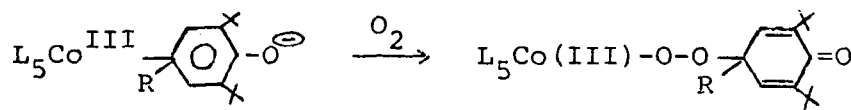
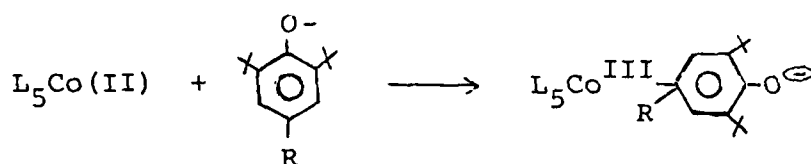
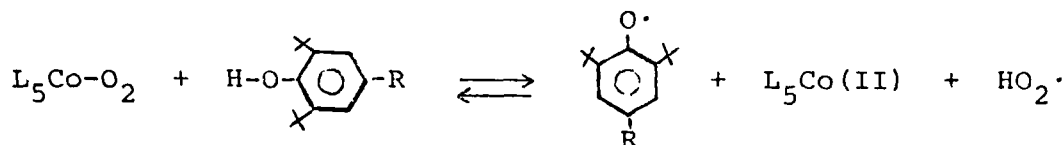
on the choice of catalyst or reagent. The oxidation of hindered phenols by cobalt-salen-dioxygen complexes was first described in 1967 by vanDort and Guerson.<sup>[12]</sup> High yields of the corresponding benzoquinone, BQ, were obtained using phenols which were not substituted in the para position. Several workers<sup>[13,14]</sup> have investigated the effect of various reaction conditions on the product distribution and hypothesize that the monomeric Co-O<sub>2</sub> species produces BQ while the  $\mu$ -peroxo dimer yields DPQ. While it is true that reaction conditions will affect the monomer-dimer equilibrium, Kothari and Tazurma cite evidence to indicate<sup>[15]</sup> that the active species leading to both BQ and DPQ is the mono-nuclear adduct. Cobalt phthalocyanine,<sup>[15]</sup> CoSMDPT,<sup>[16]</sup> Co-acacen,<sup>[17]</sup> and cobaloxime derivatives<sup>[18]</sup> all form dioxygen adducts and have been found to be active catalysts for this oxidation.

Nishinaga<sup>[19]</sup> has reported the majority of the recent work on this subject. He has demonstrated<sup>[20]</sup> that the monomeric cobalt-dioxygen complex can abstract a hydrogen atom from a 2,4,6-trisubstituted phenol by showing the simultaneous disappearance of the Co-O<sub>2</sub> EPR signal with the appearance of a phenoxy radical signal when the oxygen supply is limited. The product of the reaction of the phenoxy radical with the cobalt(II) complex and O<sub>2</sub> has been isolated and characterized as the following species.<sup>[21]</sup>



Nishinaga proposes that this product arises from O<sub>2</sub> attack on a

cobalt(III) phenolate complex. Nishinaga's proposed mechanism is summarized as follows:



Many unanswered questions remain concerning this important reaction. To date, the reaction schemes presented are based on chemical intuition supported by relatively little mechanistic data. Also, the catalyst undergoes about seventy turnovers and then becomes relatively ineffective for reasons that are unknown. Thus, we began a kinetic investigation to provide insight for both the oxidation of the substrate and the deactivation of the catalyst. We hoped to gain an understanding of the mechanism of this reaction to determine if indeed a true dioxygen-activation pathway was operative, and with this understanding evaluate the potential of this catalytic system for more difficult oxidations.

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## EXPERIMENTAL

### General

The EPR spectra were collected on a Varian Model E-9 spectrometer equipped with a Hewlett Packard frequency counter. NMR spectra were obtained on a Varian 390 spectrometer. Mass spectra were run by the Mass Spectroscopy Lab at the University of Illinois on a CH-5 instrument. All elemental analyses were performed by the Microanalytical Lab at the University of Illinois.

### Materials

The preparation of CoSMDPT, Co(II)bis(salicylidene- $\gamma$ -iminopropyl)-methylamine, by published procedures<sup>[22]</sup> was verified by elemental analysis. All phenols were obtained from Aldrich and used without further purification. All solvents were stored over 3A molecular sieves.

### Deuterated 2,6-dimethylphenol

A deuterated sample of 2,6-dimethylphenol was prepared by reaction of the starting phenol with methyl-iodide magnesium Grignard reagent, followed by subsequent workup in D<sub>2</sub>O. Its mass spectrum showed 70% substitution of OD. The OD stretch is observed at 2520 cm<sup>-1</sup>.

### Kinetic studies

The reaction progress was monitored by following the O<sub>2</sub> consumption. The procedure and apparatus for conducting the oxidation at atmospheric pressure has been described previously.<sup>[23]</sup> Oxidations performed at elevated pressures were conducted in a Parr pressure bottle fitted with a pressure gauge and placed in a temperature controlled oil bath. Typically, a 250 ml pressure bottle was charged with a 50 ml solution of the phenol (concentrations given in text) and magnetic stir bar. The solid cobalt

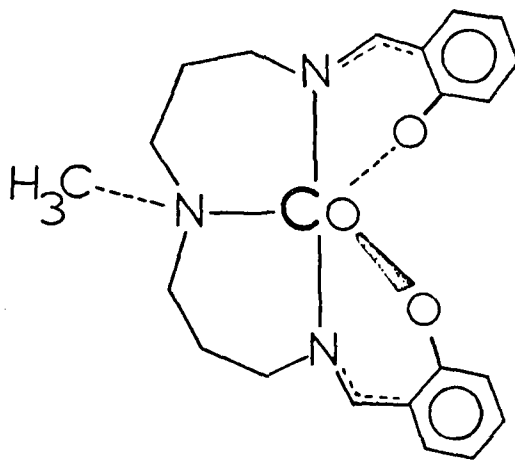
catalyst would be floated on the solution in a plastic cap. The system was purged several times with  $O_2$  and allowed to equilibrate at the appropriate temperature and pressure (usually 30 min.). Reaction began by stirring the solution and spilling the solid catalyst into the solution. All reactions were stirred at a sufficient rate to ensure mass transfer of dioxygen in the solvent was not rate limiting. The  $O_2$  consumption was found to correlate with product formation. This method gave reproducible results within  $\pm 1$  psi. Reported rates reproducible to within 5% were taken from maximum slopes of the oxygen uptake curves.

Products for the 2,6-di-*t*-butylphenol oxidation were analyzed by NMR integration of the *t*-butyl group.<sup>[24]</sup> After completion of the reaction,  $CHCl_3$  was added to insure all products were in solution.



## RESULTS

The cobalt complex used in our study was Co(II) bis(salicylidene- $\gamma$ -iminopropyl)methyl amine, or CoSMDPT. A representation of the complex is shown below;



### Kinetic studies

The reaction orders for cobalt, phenol, and  $O_2$  were obtained by independently varying the concentrations of each and monitoring  $O_2$  uptake. All oxidations were conducted in benzene. The  $O_2$  uptake at atmospheric pressure for the reaction at various cobalt concentrations is shown in Figure 1. A plot of  $\ln[Co]$  vs.  $\ln[d[O_2]/dt]$  yields a straight line with a slope of '1 (Figure 2) indicating the reaction is first order in  $[Co]$  as long as the catalyst is completely dissolved. First order kinetics are observed for phenol concentrations less than 0.09 M (Figure 3). When the ratio of phenol to cobalt becomes greater than 20/1, the rate becomes pseudo zero order in substrate. The reaction was conducted at three different  $O_2$  pressures, while maintaining all other conditions constant. Figure 4 shows the dependence of the rate of the reaction

on the oxygen pressure. The initial rates observed at 60 psi (4.1 atm) and 120 psi (8.2 atm) are approximately 4 and 8 times faster, respectively, than the rate of oxidation at atmospheric pressure, indicating a first order dependence on the  $O_2$  concentration.

When a sample of 2,6-dimethyldeuterophenol was employed as the substrate at 30°C the reaction rate was identical, within experimental error, to the undeuterated sample throughout the duration of the reaction. To ensure that the reaction conditions did not convert some of the deuterated phenol to undeuterated phenol since HOD is produced, a reaction was run with excess  $D_2O$  (2 ml, .11 moles) present with the deuterated phenol. The same rate was found for both the deuterated phenol-water and the undeuterated phenol-water experiment, thus indicating an absence of a deuterium isotope effect for this system.

Various phenols were oxidized with CoSMDPT in benzene at 30°C (Table I). In the absence of the steric effects encountered in the 2,4,6-trisubstituted phenols or the 2,6-di-t-butylphenol, the rate increases as the oxidation potential of the phenol decreases. Unsubstituted phenol is oxidized by CoSMDPT in dimethylformamide at higher temperatures and pressures (Table I).

Increasing temperatures up to 50°C results in a faster oxidation of 2,6-dimethylphenol as seen in Figure 5. Temperatures above 70°C have little or no effect on the rate. This behavior indicates the complexity of the reaction mechanism since this increased rate contrasts with the decreased amount of cobalt-dioxygen adduct expected at the higher temperature. [25]

Solvent variation also yields complicated behavior where the rate in chloroform > toluene > benzene > methylene chloride > methanol > DMF.

### Catalyst Deactivation

In a typical oxidation with excess phenol,  $O_2$  uptake slows substantially by 70 turnovers and declines to almost zero, in roughly the next 20 turnovers. The deactivation of the catalyst (evidenced by the decrease in reaction rate) is accompanied by the precipitation of a brown solid. Chemical analysis of this solid indicates that a considerable increase in the oxygen content of the spent catalyst has occurred compared to CoSMDPT. Typically a 6/1 ratio of O/Co is found in the former.

Studies were initiated to determine the factors that lead to decline in catalytic activity. The change in catalyst lifetime for different conditions is indicated in Table II by the number of turnovers. In these experiments an oxidation was run at 60 psi with a large excess of phenol to cobalt. Uptake is monitored to 30 psi, and then recharged to 60 psi. This cycle is repeated until a noticeable decrease in rate is observed.

The EPR spectrum of a reaction mixture was monitored during the course of an oxidation to determine the correlation of the Co- $O_2$  signal with catalyst deactivation. Aliquots of the reaction mixture taken at various intervals of  $O_2$  uptake show only a Co- $O_2$  signal. Interestingly, this signal remains at relatively the same intensity throughout the reaction; even after the noticeable drop in catalyst activity that occurs at 70 turnovers. This result implies that a product of the oxidation causes a decline in catalytic activity without initially destroying the Co- $O_2$  species. This period is followed by the subsequent oxidation of cobalt(II) to cobalt(III) and the disappearance of the EPR signal. The major products of the oxidation, BQ and  $H_2O$ , do not inhibit the  $O_2$  uptake as shown in Table II. However, acids are found to inhibit cata-

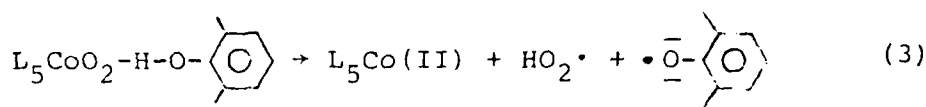
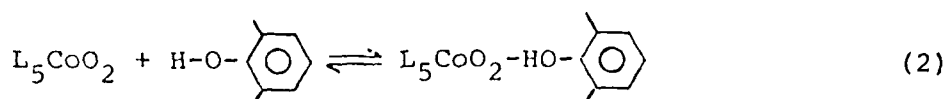
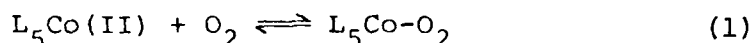
lytic activity. Adding a solution of benzene, saturated with dry HCl, to a solution in the midst of an oxidation reaction results in an immediate end to the  $O_2$  uptake. Inhibition is obtained when solutions of trifluoroethanol or benzoic acid are added. When a weaker acid such as unsubstituted phenol is added to the oxidation reaction, the rate decreases and a large amount of the coupled product DPQ is generated. The EPR of the solution containing TFE and phenol show characteristic Co- $O_2$  signals, while solutions containing benzoic acid or HCl do not show an EPR signal because rapid oxidation of the cobalt occurs.

Increase turnovers are obtained when the reaction is run in the presence of  $Na_2CO_3$  as seen in Table II. The addition of 2,6-lutidine or polystyrene bound tertiary amine,<sup>[27]</sup> also increases turnovers with the  $Na_2CO_3$  slurry being most effective. Peroxides formed from decomposition of metal-dioxygen complexes<sup>[28]</sup> or from  $HO_2$  were suspected as side products that could cause ring cleavage and lead to organic acids that decompose the catalyst. When an aqueous  $H_2O_2$  solution is added to a methanol solution of catalyst,  $O_2$  gas is evolved. When a 30% aqueous  $H_2O_2$  solution is added to a 2,6-dimethylphenol oxidation in methanol solvent the pressure drop is monitored from the initial increased value of pressure from  $H_2O_2$  decomposition. A decline in the number of turnovers (Table II) is reserved.

If  $H_2O_2$  is used as the only oxygen source (the reaction with phenol is run under argon), CoSMDPT catalyzes the decomposition of  $H_2O_2$  to  $H_2O$  and  $O_2$  with the simultaneous irreversible oxidation of the cobalt center and no benzoquinone is formed. Thus, the presence of  $H_2O_2$  inhibits the conversion of phenol to quinone.

# DISCUSSION

The results of this study clearly indicate that a metal bound dioxygen is an active species in the oxidation of phenol. The following steps are implicated:



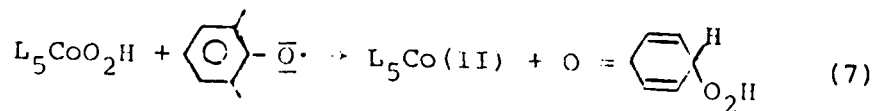
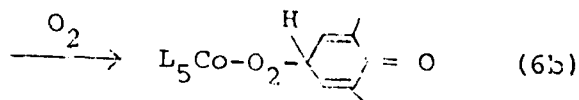
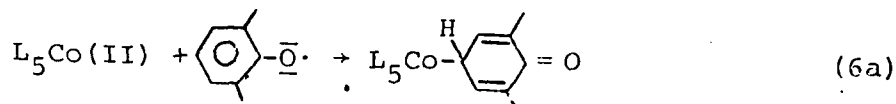
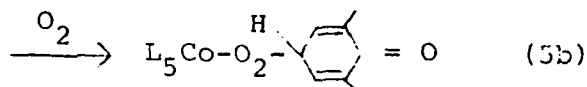
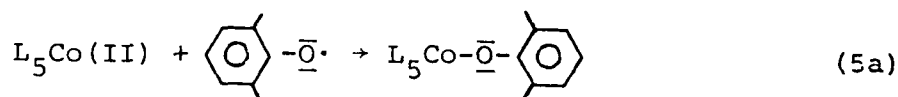
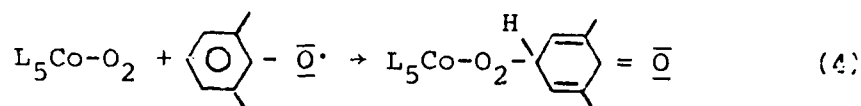
Step 2 is supported by earlier studies in which it is conclusively shown<sup>[25]</sup> that trifluoroethanol, TFE, undergoes a hydrogen bonding interaction with the terminal oxygen of the cobalt-dioxygen adduct. Although TFE is a stronger acid than 2,6-dimethylphenol,<sup>[29]</sup> they are close enough in acidity to expect the interaction in equation 2 to occur. Step 3 receives support from the EPR identification of the phenoxy radical formed when 2,4,6-tri-t-butylphenol is oxidized with this catalyst.

There are several paths by which the phenoxy radical can be converted to the quinone. The reaction of the phenoxy radical with free  $O_2$  to form benzoquinone (BQ) is ruled out since the free radical reacts faster with itself in the presence of  $O_2$  to form diphenohydroquinone and subsequently diphenoquinone, DPQ, than it reacts with  $O_2$ .<sup>[9]</sup> The reaction of the phenoxy radical with  $HO_2$  was proposed earlier in a scheme to account for the products of the reaction.<sup>[3]</sup> This proposal does not seem plausible for the following reason. When  $HO_2$  radicals are intermediates in

autoxidations, large deuterium isotope effects are observed<sup>[30]</sup> and this is not the case in our system. Since HO<sub>2</sub> is reported<sup>[31]</sup> to decompose at diffusion controlled rates and the slow step in this reaction occurs subsequent to step 3, vide infra, the fate of HO<sub>2</sub> is decomposition:



The following possible reactions of the phenoxy radical with cobalt complexes remain to be considered for the next step:



The kinetic orders found in this study are consistent with several of the reactions listed above. Rate expressions can be derived whose reaction orders are consistent with step 2, or more likely 3, being rate controlling and 4, 5, 6, or 7 fast. Since no deuterium isotope effect was observed on the rate of oxidation, we can eliminate steps 2 or 3 as the rate controlling step. Mechanisms in which steps 4, 5a, and 6a are rate controlling are also consistent with the observed rate law if a steady state con-

centration of phenoxy radicals is assumed. Rate controlling steps for 5b and 6b can be eliminated for they would lead to a second order dependence on  $O_2$ . A rate controlling step 7 is not reasonable in view of the short lifetime of an  $L_5CoO_2H$  species<sup>[32]</sup> and because peroxides have not been observed in the reaction medium.<sup>[21]</sup>

Furthermore, if 7 were a key step, catalysis of the hydroxylation of 2,4,6-trimethylphenol by CoSMDPT would have been observed.

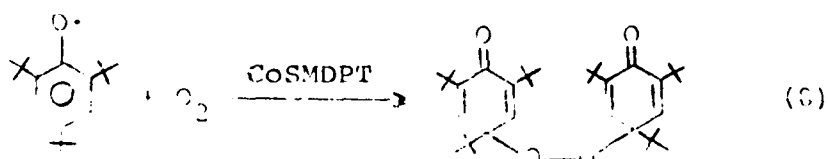
Several indirect pieces of evidence suggest that in addition to the hydrogen atom abstraction of the first step, there is involvement of an  $L_5CoO_2$  species in a subsequent reaction with the phenoxy radical; (Equation 4). The ratio of BQ to DPQ is very informative in this connection. If this step under consideration (4, 5a or 6a) is inhibited, the phenoxy radical concentration will increase, these radicals will couple to form diphenohydroquinone and be oxidized to diphenoquinone. Data reported earlier<sup>[23]</sup> on the catalysis of this oxidation by polystyrene bound CoSMDPT suggests subsequent cobalt involvement (steps 4, 5a or 6a). The BQ/DPQ ratio is a function of the cobalt loadings in polymer. At high loadings, where the generated radical has a high probability of encountering another cobalt-dioxygen center, large ratios of BQ/DPQ are obtained. At low cobalt concentrations the ratio is reduced substantially. Encounter of phenoxy radical with a cobalt center leads to BQ while failure to encounter one leads to DPQ. Several reagents including solid  $PbO_2$  will generate phenoxy radicals.<sup>[33]</sup> When  $PbO_2$  and  $Co(II)$  (acetylacetonate)<sub>2</sub> (which does not form a dioxygen adduct under these conditions) catalyzed oxidation of 2,6-dimethylphenol, only diphenoquinone is produced. This result

suggests that the phenoxyl radical needs to encounter a  $\text{Co-O}_2$  species as shown in step 4 for the production of the quinone. If, as shown in step 5, a cobalt(II) species were sufficient,  $\text{Co}(\text{acac})_2$  could have fulfilled this requirement.

When competitive hydrogen bonding agents are added to the reaction medium for a 2,6-dimethylphenol,  $\text{CoSMDPT}$  catalyzed oxidation, the results are readily rationalized in terms of step 4. When unsubstituted phenol, a slightly stronger acid than 2,6-dimethylphenol, is added to the reaction mixture, the rate of reaction is decreased and the BQ/DPQ ratio is decreased. With the phenol competitively hydrogen bonding to  $\text{L}_5\text{CoO}_2$ , the phenoxy radical attack on this species is inhibited and DPQ is formed at the expense of BQ.

A reaction in progress can be stopped by adding the stronger acid TFE. Since radicals can be generated by  $\text{Co}(\text{III})$ , vide infra, this suggests a role of other than a radical initiation step for  $\text{L}_5\text{CoO}_2$  and we propose equation 4. When stronger acids such as benzoic acid or  $\text{HCl}$  are added, the reaction stops immediately and this is accompanied by oxidation of cobalt(II) to cobalt(III).

Nishinaga<sup>[19]</sup> has ruled out the possibility of step 4 being important on the basis of the following experiment: bubbling  $\text{O}_2$  through a solution of  $\text{CoSMDPT}$  and 2,4,6-tri-*t*-butylphenoxy radical produced only the coupled product that resulted from the reaction of the radical with free  $\text{O}_2$ .

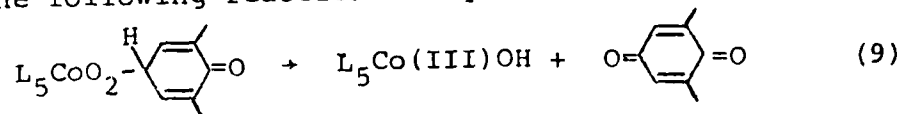




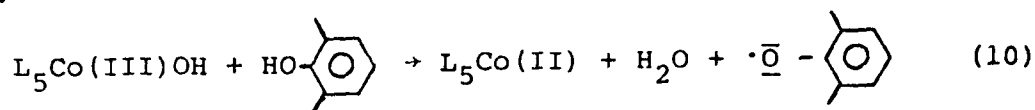
Although experimental details are lacking, there may be two potential drawbacks to this conclusion. First, the concentration of free phenoxy radicals in the oxidation of 2,6-dimethylphenol is extremely low under catalytic reaction conditions (as mentioned above), making the reaction in equation 8 much less probable. Second, the concentration of  $\text{Co-O}_2$  in the above experiment is expected to be lower than that in the phenol oxidation because it has been shown that the equilibrium in step 1 is enhanced<sup>[25]</sup> by the addition of hydrogen bonding substrates via step 2. Thus, the concentration of  $\text{L}_5\text{CoO}_2$  in a solution of phenoxy radicals is considerably less than what is found in a typical phenol oxidation. Instead of step 4, steps 6a and 6b are proposed<sup>[19]</sup> as the mechanism for quinone formation. Formation of a Co-C bond is followed by subsequent  $\text{O}_2$  insertion to produce the cobalt-peroxy-quinone compound. We prepared the cobalt-peroxy-quinone complex of 2,4,6-tri-*t*-butylphenol reported by Nishinaga<sup>[20]</sup> and observed a very interesting phenomena in the EPR. If a toluene/ $\text{CH}_2\text{Cl}_2$  glass of this complex is prepared, the EPR spectrum in Figure 6 is observed. It displays overlapping spectra of the free phenoxy radical and  $\text{Co-O}_2$  signal. Thus, the phenoxy radical plus  $\text{L}_5\text{CoO}_2$  are in equilibrium with the cobalt-peroxo-quinone. This is most readily visualized as occurring via the reverse reaction of step 4 and would support the direct pairing of radicals in the oxidation as opposed to an unprecedented reversible  $\text{O}_2$  insertion (the reverse of step 6).

The remaining problem involves the step for converting  $\text{L}_5\text{Co-O}_2$ -=O to the quinone and regenerating the catalyst. There is no direct information bearing on this problem. By

analogy with the decomposition of an organic hydroperoxide, we propose the following reaction for quinone formation:



The Co(II) species could be regenerated by phenol oxidation as follows:



The fate of the  $HO_2$  generated in step 3 is worth considering further. The rate of self reaction of  $HO_2$  approaches the diffusion controlled limit in nonpolar solvents.<sup>[31]</sup> It could be converted to hydrogen peroxide by hydrogen atom abstraction from phenol and the peroxide can be decomposed into water and  $O_2$  by the cobalt(II) complex. Minor side reactions involving small amounts of  $HO_2$  radical or hydrogen peroxide are probably implicated in the catalyst degradation reaction. Carboxylic acids formed from ring opening reactions would block step 2 above and stop oxidation by inhibiting formation of the phenoxy radical. The observation of a cobalt- $O_2$  EPR of undiminished intensity in the deactivated catalyst is consistent with such a hydrogen bonded carboxylic acid-cobalt dioxygen adduct. Carboxylic acids can arise by attack of  $HO_2$  on quinones or via Baeyer-Villiger type attacks of peroxides on ketones. Experiments designed to test this speculation led to a very significant improvement in catalyst lifetime. Addition of base to the reaction mixture greatly extended the number of turnovers by the catalyst. The most basic material,  $Na_2CO_3$ , was most effective. The role of a base is not well established, however, since the  $pK_a$  of  $HO_2$  is 4.9 it should be converted into a

superoxide anion by the addition of these bases.<sup>[34]</sup> Thus we propose that equations 1, 2, 3, 4, 9 and 10 constitute the reaction both for the formation of quinone, and the regeneration of the catalyst.

The metal plays two important roles in the catalysis of this oxidation: (1) coordination activates the  $O_2$  molecule and enhances its ability to abstract hydrogen atoms; (2) coordination enhances the activity of the  $O_2$  molecule in a free radical reaction with organic molecules. There are many aspects of the mechanism of this oxidation reaction that remain speculative. We have, however, presented results that rule out many of the possible paths. Our proposed mechanism is summarized in Figure 7. The extension of a reaction pathway for a given system to other substrates is always a dangerous practice and this lack of generality is one of the shortcomings of kinetic investigations. In this study, we have been able to provide a scheme for the oxidation of 2,6-dimethylphenol that is consistent with the known reactivity of this and analogous substrates. We have also been able to demonstrate that coordination of dioxygen to a metal enhances the rate at which it undergoes the spin-pairing reaction with organic free radicals.

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TABLE I

| PHENOL                          | (OP) <sub>O</sub> [26] | ΔP (psi) | Time (min) | Total <sup>a</sup> turnovers | Turnovers per hour |
|---------------------------------|------------------------|----------|------------|------------------------------|--------------------|
| 1. 2,4,6 TRIMETHYL <sup>c</sup> | .67                    | 26       | 1190       | 20.4                         | 1.6                |
| 2. 2,6 di-t-Butyl               | .68                    | 33       | 310        | 24.9                         | 4.8                |
| 3. 2,3,5,6 tetramethyl          | .71                    | 40       | 97         | 27.7                         | 13.6               |
| 4. 2,6 diisopropyl              | .74                    | 40       | 188        | 30.1                         | 15.4               |
| 5. 2,6 dimethyl                 | .76                    | 43       | 131        | 32.3                         | 14.8               |
| 6. 2,5 di-t-Butyl               | .83                    | 12       | 1415       | 9.1                          | .4                 |
| 7. 3,5 dimethyl                 | .86                    | 15       | 930        | 11.3                         | .4                 |
| 8. phenol <sup>d</sup>          | .92                    | 18       | 1060       | 14.1                         | .8                 |
| 9. 2,6 dichloro                 | —                      | 0        | 300        | 0                            | 0                  |

All oxidations were .49M in phenol and .0146M in CoSMDPT, 50ml of benzene used as solvent, temperature = 30°C, initial pressure of O<sub>2</sub> = 60 psi.

<sup>a</sup> Total turnovers = moles O<sub>2</sub> consumed/mole Co before rate of O<sub>2</sub> uptake begins to decline.

<sup>b</sup> Turnovers per hour = mole O<sub>2</sub> consumed/mole Co·hr, based on initial rates.

<sup>c</sup> DMF used as solvent.

<sup>d</sup> DMF used as solvent, temperature = 75°C, initial O<sub>2</sub> pressure = 120 psi.

TABLE II

Oxidation of 2,6 Dimethylphenol; Determination of  
Catalytic Activity with Various Additives

|                                                                        | mmoles<br>of Additives | $\Delta P$<br>(psi) | Time<br>(hrs) | Total<br>Turnovers |
|------------------------------------------------------------------------|------------------------|---------------------|---------------|--------------------|
| No Additive                                                            | —                      | 68                  | 20.5          | 76                 |
| 2,6 dimethylbenzoquinone                                               | 10.5                   | 83                  | 17.5          | 93                 |
| 2,6 dimethylbenzoquinone                                               | 33.0                   | 86                  | 18            | 96                 |
| 2,6 dimethylbenzoquinone + H <sub>2</sub> O                            | 33.0                   | 82                  | 18            | 92                 |
| Na <sub>2</sub> CO <sub>3</sub> slurry <sup>a</sup>                    | 36.7                   | 56                  | 20.5          | 249                |
| Fe(acac) <sub>3</sub> Cl                                               | 36.7                   | 70                  | 20.5          | 78                 |
| MeOH (solvent) <sup>b</sup>                                            | —                      | 48                  | 20.5          | 200                |
| H <sub>2</sub> O <sub>2</sub> in MeOH <sup>b</sup>                     | 17.6                   | 51                  | 20.5          | 46                 |
| H <sub>2</sub> O <sub>2</sub> in MeOH plus<br>2,6 dimethylbenzoquinone | 17.6                   | 21                  | 20.5          | 24                 |

All oxidations were conducted in 50 ml of benzene, unless stated otherwise, with  $7.37 \times 10^{-2}$  moles of 2,6 dimethylphenol, and  $4.88 \times 10^{-4}$  moles CoSMDPT, temperature = 30°C. <sup>a</sup>Small amount of a crown ether added as well to act as a phase transfer catalyst, but was later found not to be necessary. <sup>b</sup> $1.24 \times 10^{-4}$  moles CoSMDPT to accomodate the large number of turnovers at comparable phenol concentrations.

## FIGURE CAPTIONS

Figure 1. Oxygen uptake curves for oxidation of 2,6-dimethylphenol ( $4.0 \times 10^{-2}$  M), with CoSMDPT. Cobalt concentrations are (1)  $4.014 \times 10^{-2}$  M, (2)  $2.996 \times 10^{-2}$  M, (3)  $2.202 \times 10^{-2}$  M, (4)  $2.00 \times 10^{-2}$  M, (5)  $1.252 \times 10^{-2}$  M, (6)  $1.014 \times 10^{-2}$  M, (7)  $0.620 \times 10^{-2}$  M.

Figure 2. Plot of  $\ln[dO_2/dt]$  versus  $\ln[Co]$  (from Figure 1). Slope indicates reaction order for cobalt = 1.

Figure 3. First order kinetic plot for oxidation of 2,6 dimethylphenol with CoSMDPT ( $4 \times 10^{-3}$  M in Co) in 25 ml of benzene.

Figure 4. Oxidation of 2,6 dimethylphenol ( $.494$  M) with CoSMDPT ( $.0146$  M) in 50 ml of benzene. Temperature =  $30^\circ\text{C}$ , O initial pressure 120 psi,  $\bullet$  initial pressure 60 psi.

Figure 5. Oxidation of 2,6 dimethylphenol at various temperatures  $[Co] = .0146$  M  $[phenol] = .49$  M in 50 ml of toluene.

Figure 6.  $\text{CH}_2\text{Cl}_2$ /toluene frozen glass EPR (x-band) spectrum of  $\text{Co-O}_2$  and phenoxyl radical.

Figure 7. Proposed mechanism for the oxidation of 2,6 dimethylphenol by CoSMDPT.



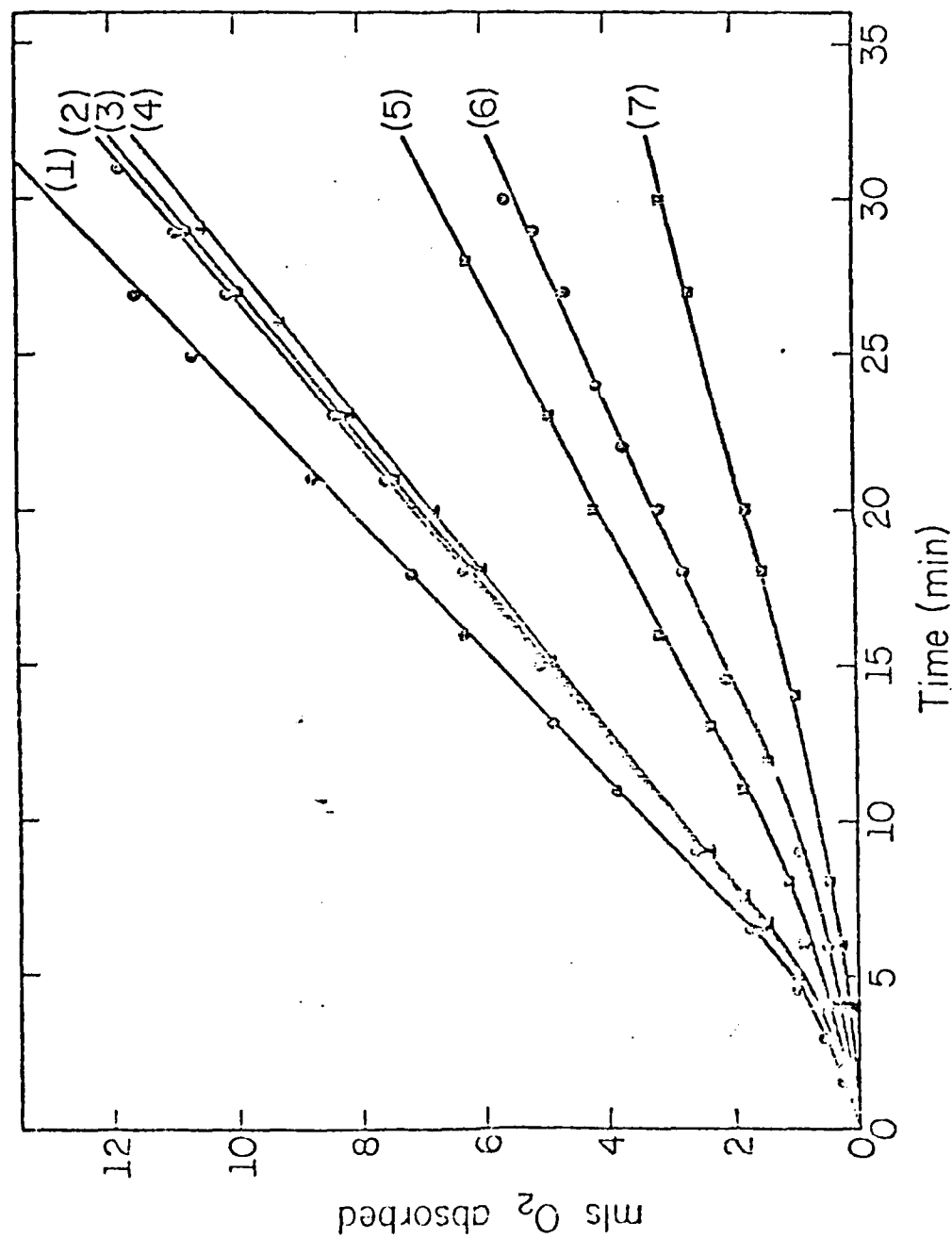


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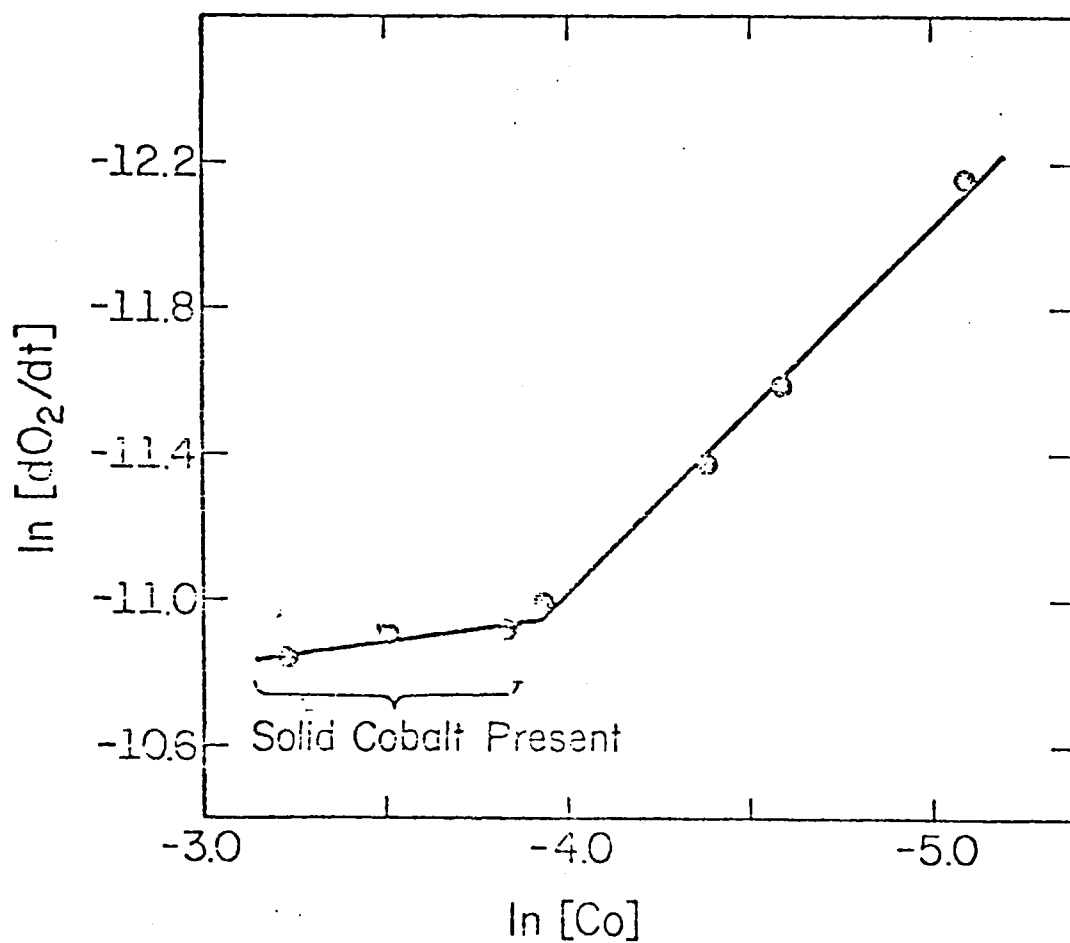


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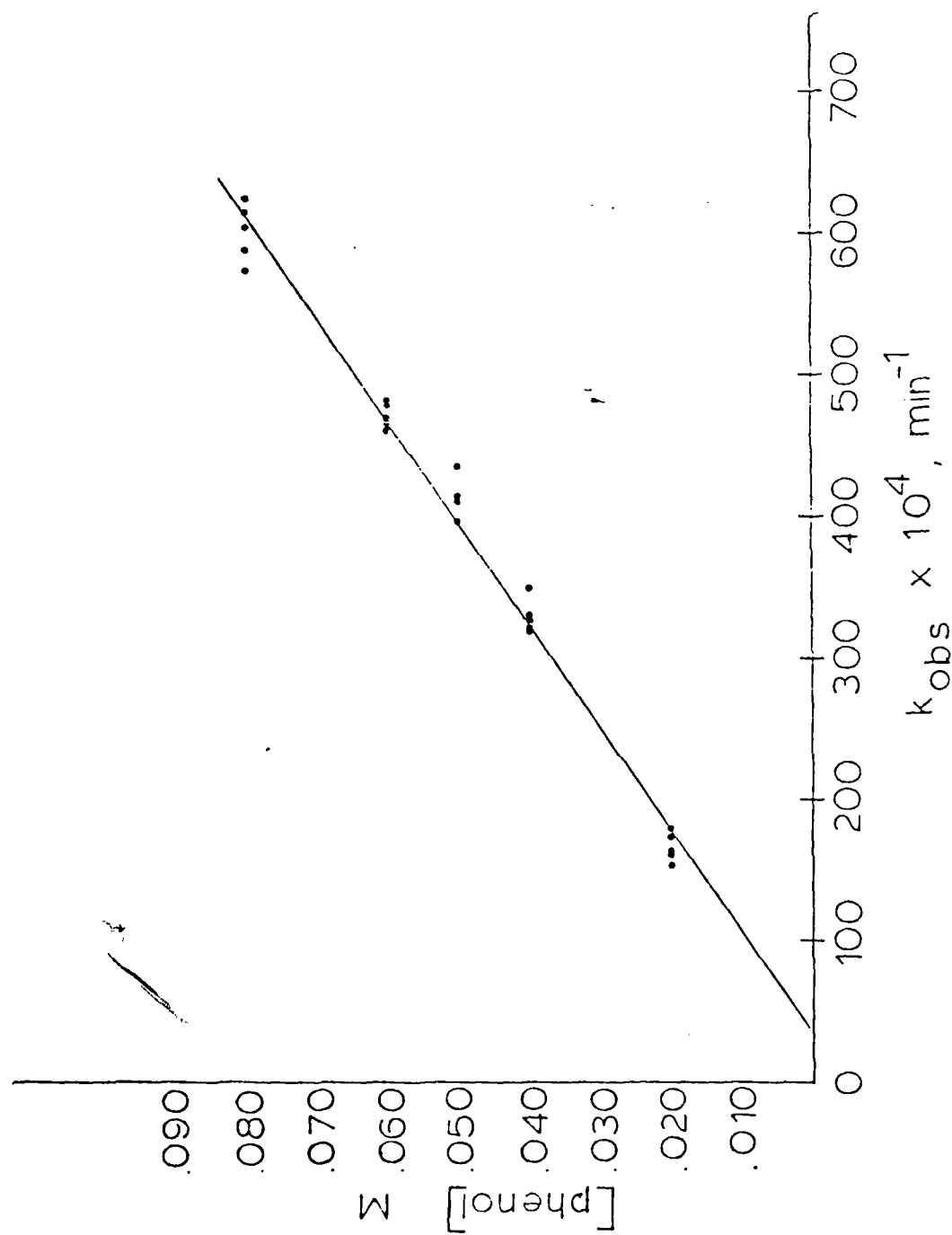


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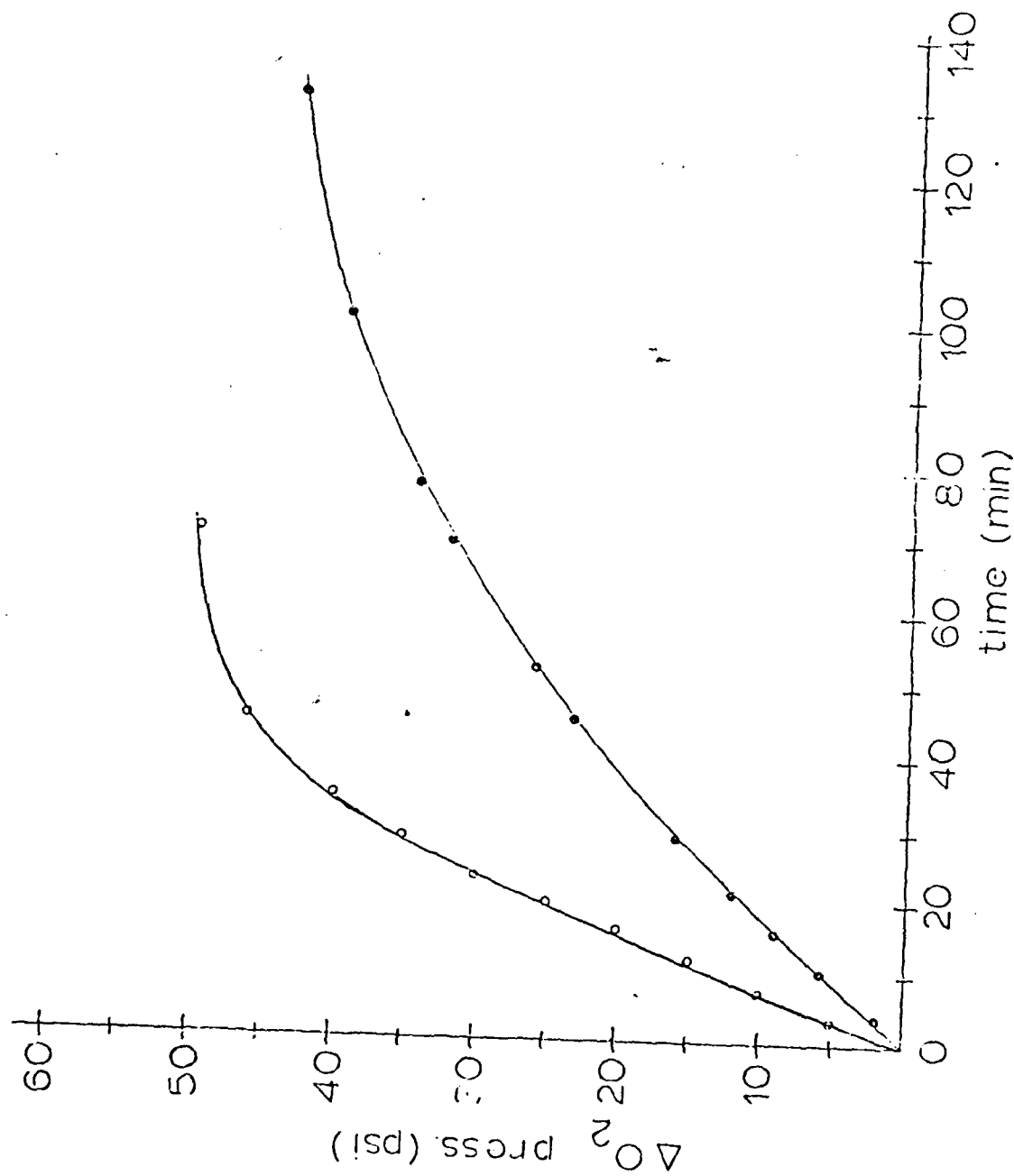


Figure 4. Oxidation of 2,6 dimethylphenol (.494 M) with COSMDPT (.0146 M) in 50 ml of benzene. Temperature = 30°C, O initial pressure 120 psi, ● initial pressure 60 psi.

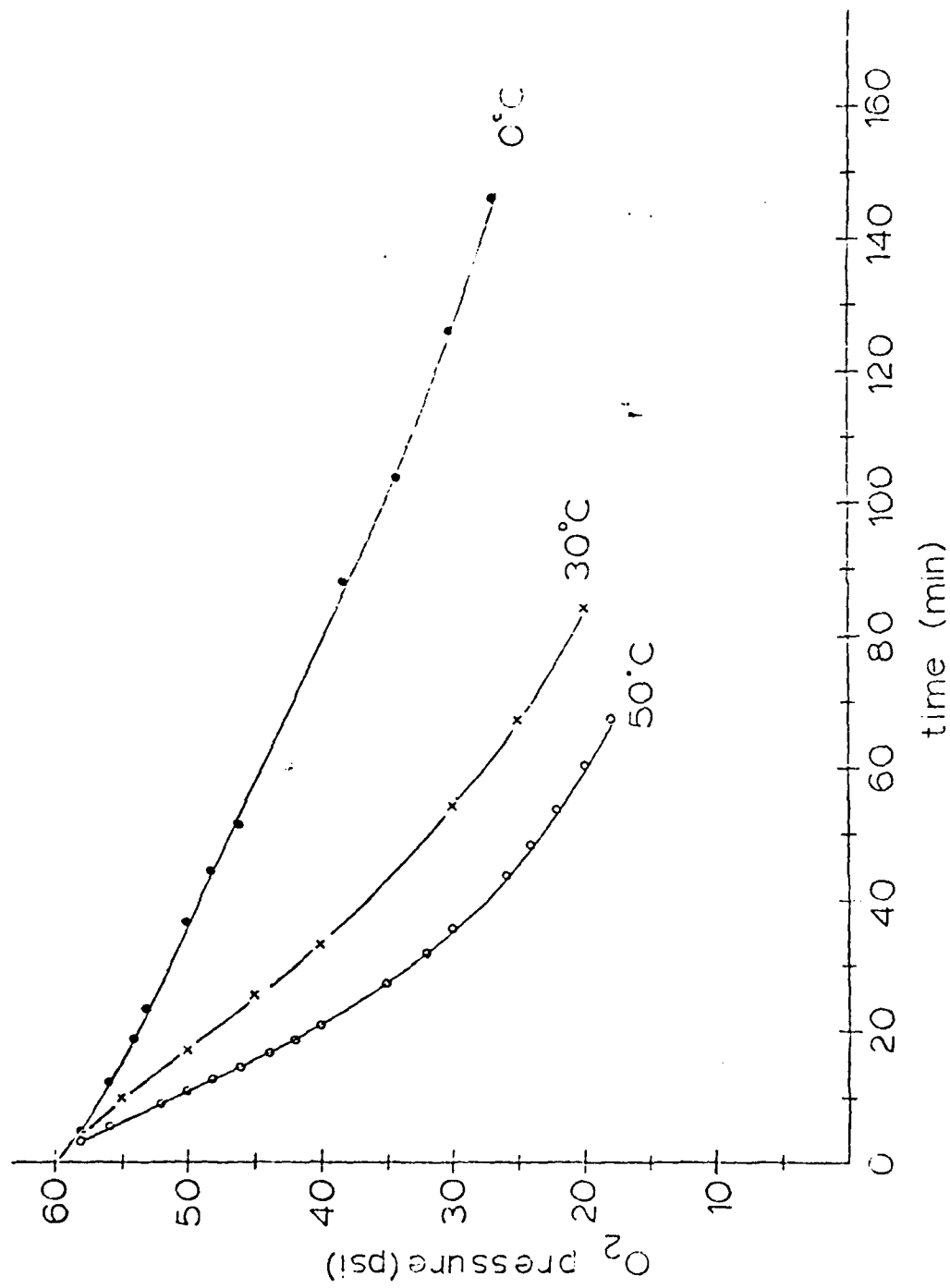


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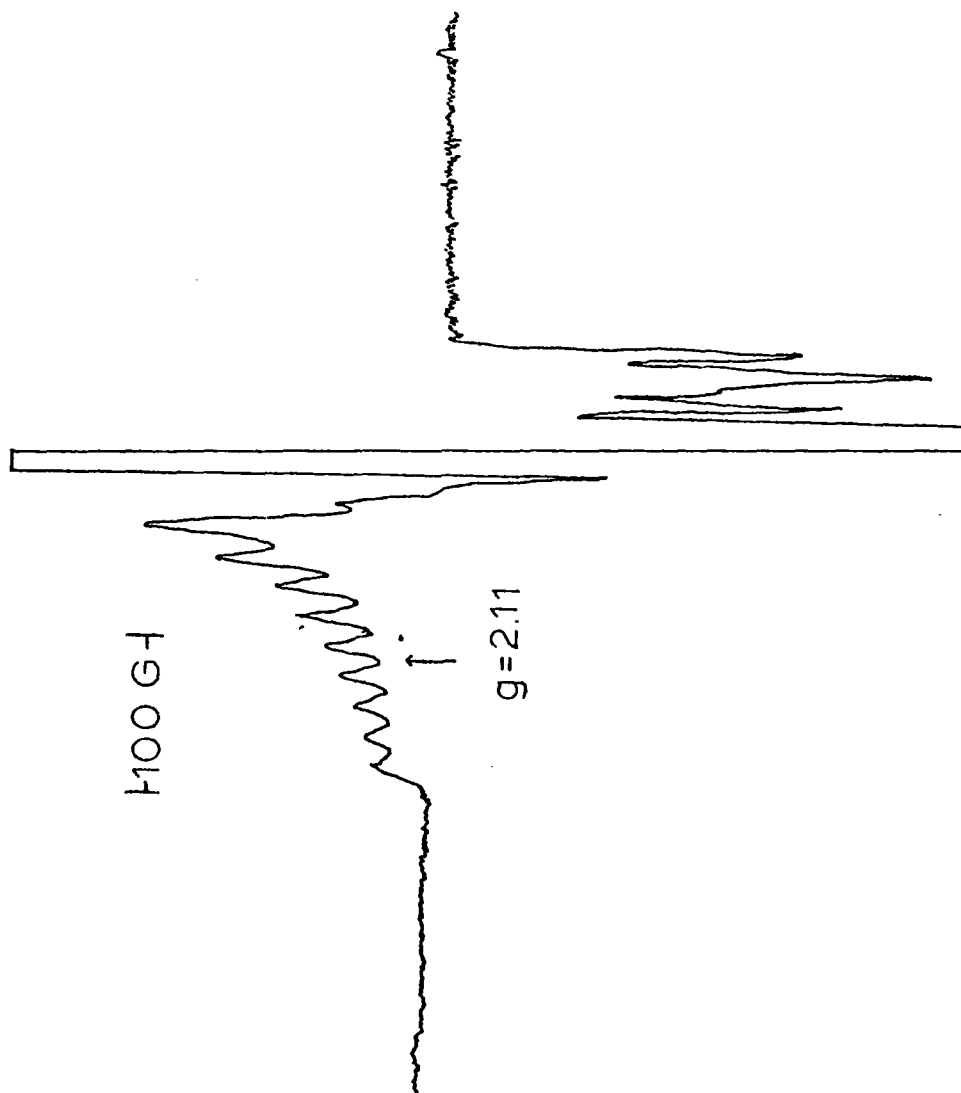


Figure 6.  $\text{CH}_2\text{Cl}_2$ /toluene frozen glass EPR (x-band) spectrum of  $\text{Co-O}_2$  and phenoxyl radical.

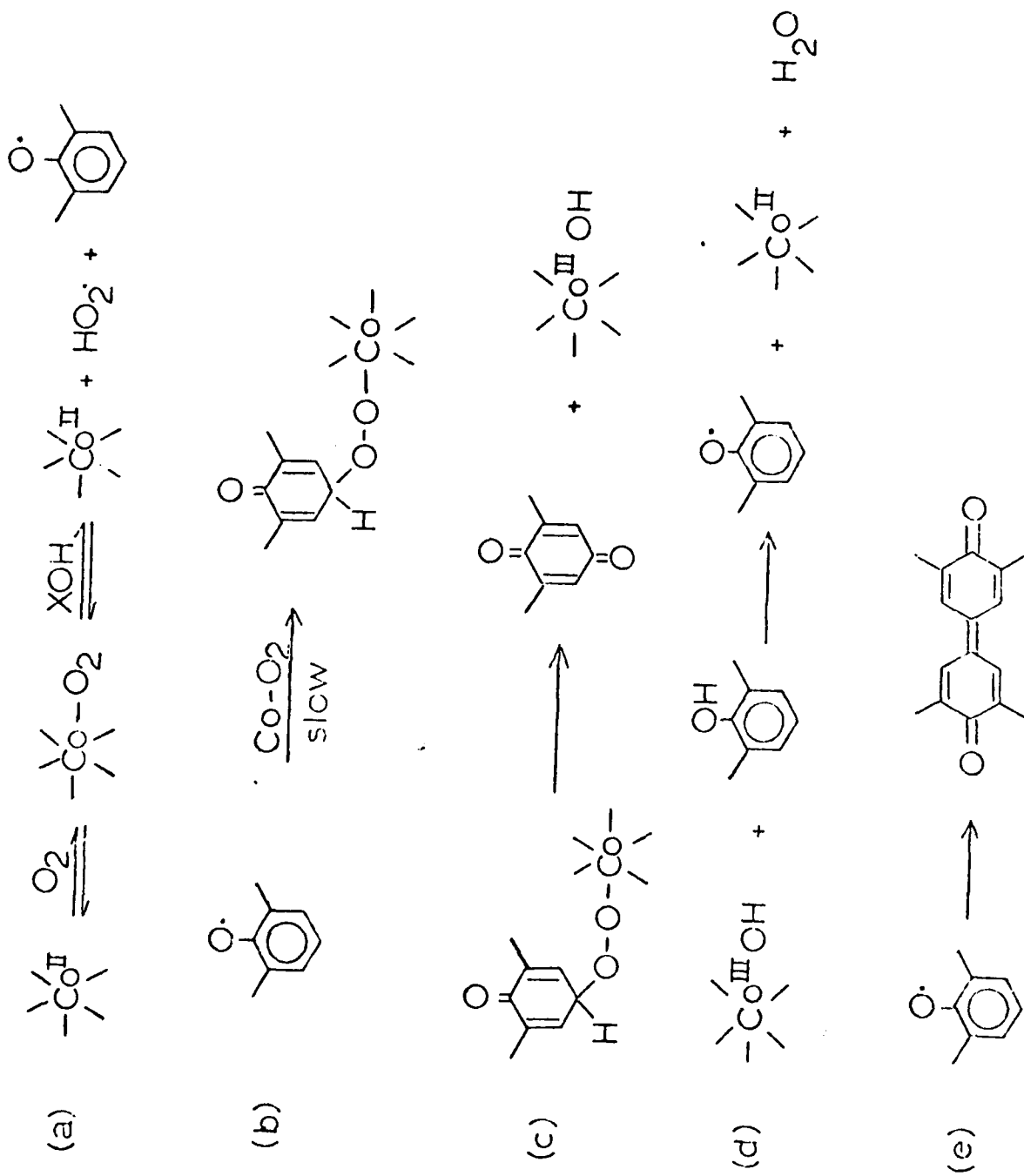


Figure 7. Proposed mechanism for the oxidation of 2,6-dimethylphenol by CoSMDPT

