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UNUSUAL ANTIOXIDANT BEHAVIOR OF HINDERED CHLOROPHENOLS IN METAL-CONTAINING SYSTEMS

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Studies by previous workers have indicated that the antioxidant properties of chlorophenols and alkylphenols are qualitatively similar.[2] In contrast to expectations based on these results, certain chlorophenols have now been found to have remarkably good antioxidant properties in some systems containing transition metals. The present communication describes these effects and suggests a reasonable explanation for their occurrence.

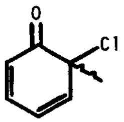
Experiments 1--9 (Table I) show that the hindered *o*- and *p*-chlorophenols **4**--**6** are much better antioxidants than the hindered alkylphenols **1**--**3** for cumene oxidations initiated by metal--hydroperoxide combinations. Analogous results were obtained in a parallel series of experiments employing 4-vinylcyclohexene as the oxidizable substrate. Significantly, *m*-chlorophenols did not show the unusual inhibitory effect (*cf*. expt 10), and the methyl ether of **6** had no antioxidant activity under these conditions. Furthermore, vpc and mass spectral analyses showed that the *o*- and *p*-chlorophenols were not completely consumed during the long induction periods they produced. Under the conditions of Table I, even a fourfold increase in the initial concentration of **1** did not produce the dramatic effects observed with compounds **4**--**6**. However, these effects are apparently limited to metal-containing systems; this conclusion is supported by previous work[2a] and by our observation of roughly comparable t_{ind}'s for phenols **1**, **4**, and **5** in cumene oxidations initiated with 2,2´-azobis[2-methylpropionitrile] at 50°.

From the preceding observations it appears that the antioxidant chloro-substituent effect does not result from (a) entrapment of an unusually large number of radicals per antioxidant molecule consumed, (b) operation of an *ad hoc* termination mechanism, involving complexed radicals, which does not require phenol consumption, (c) reductions in rates of initiation due to complexation of metal ions by the phenols, or to the incursion of a phenol-catalyzed hydroperoxide decomposition process which does not produce free radicals.[3] Instead, the data suggest the operation of a novel autosynergistic inhibition mechanism involving catalyst deactivation. According to this hypothesis, the deactivating agents are chlorocyclohexadienones (partial

TABLE I. Inhibited Autoxidations[a] of Cumene

Expt no.	Metal[b] (g-atom x 10^7)	Phenol	t_{ind},[c] hr
1	Co(2.03)	2,6-di-*t*-Bu-4-Me (1)	0.2 ± 0.1[d]
2	Mn(2.28)	1	0.6 ± 0.1[e]
3	Co(2.03)	2,4,6-tri-*t*-Bu (2)	0.3--0.5
4	Co(2.03)	2-*t*-Bu-4-Me (3)[f]	0.35 ± 0.05[g]
5	Co(2.03)	2-*t*-Bu-6-Cl-4-Me (4)	>23.7,[h] >22.3[h]
6	Mn(2.28)	4	>21.7[h]
7	Co(2.03	2,6-di-*t*-Bu-4-Cl (5)[i]	>71.1,[h] >18.2[h]
8	Mn(2.28)	5[i]	>19.8[h]
9	Co(2.03)	2-*t*-Bu-4-Cl-5-Me (6)	>22.5,[h] >17.2[h]
10	Mn(2.28)	2-*t*-Bu-5-Cl-4-Me (7)	1.7

[a] Temp = 50 ± 0.2°, O_2 = 1 atm, cumene = 5.0 ml, *t*-BuOOH = 2.64×10^{-4} mol, phenol = 2.27×10^{-5} mol unless noted otherwise. [b] Naphthenate. [c] Time required for detectable O_2 uptake. Deviations are primarily due to slight deterioration of stock solutions on aging. [d] Eight runs. [e] Three runs. [f] 2.30×10^{-5} mol. [g] Two runs. [h] Experiment was terminated arbitrarily at this time. [i] 2.31×10^{-5} mol.



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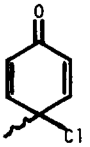

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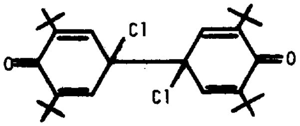

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structures 8 and 9) formed from the *o*- and *p*-chlorophenols by conventional radical reactions[2a] during the induction periods. These dienones contain reactive (allylic) halogen and are thus able to undergo reactions (see below) which convert the metal ions into insoluble metallic chlorides having minimal catalytic activities. The chlorocyclohexadienones formed from *m*-chlorophenols contain unreactive (vinylic) halogen; thus *m*-chlorophenols do not show the unusual inhibitory effect.

In order to test this proposal, reactions of phenols 4--7 with t-BuOOH (1 mol equiv) and Co(II)or Mn(II) naphthenate (0.1 mol equiv) were carried out on a preparative scale in benzene at 25°. The reactions with 4, 5, and 6 gave precipitates (isolated yields, 28--86%) which were identified as $CoCl_2 \cdot 6H_2O$ and $MnCl_2 \cdot 4H_2O$ by X-ray and elemental analysis. These precipitates were found to be inactive as oxidation catalysts under the conditions of Table I, and similar precipitates were not obtained from 7. Furthermore, separately synthesized allylic chlorocyclohexadienones (e.g., 10) showed considerable antioxidant activity under the conditions of Table I,[4] and mixtures of these dienones with 1 showed very pronounced antioxidant synergism (very long t_{ind}'s) in parallel experiments. These results constitute strong confirmation for the autosynergistic inhibition process described above.

The detailed mechanism of the metal-scavenging process is of considerable interest; preliminary experiments with 10 suggest that this mechanism involves metal-assisted displacement of Cl^- by nucleophiles[5] (t-BuOOH, t-BuOH, water) derived from the initiator system. Benzene solutions of 10 do not react with Co(II) naphthenate alone, or with small amounts of t-BuOH and water in the absence of the metal catalyst. However, 10 reacts very rapidly in benzene with a mixture of Co(II) naphthenate, t-BuOH, and water to form equimolar amounts of 5 and 2,6-di-t-butyl-p-benzoquinone in quantitative yield. As a scavenger for Co(II) in hydrocarbon media, 10 is comparable in reactivity to organic chlorides which are known to yield Cl^- very readily (e.g., trityl chloride), and the cause of this unexpected behavior is currently under investigation.

In summary, we conclude that the antioxidant chloro-substituent effect has now been adequately demonstrated, and that the major factors responsible for its operation have been deduced. In systems suited to their use, hindered o- and p-chlorophenols are among the most effective antioxidants known, and their practical utilization is therefore anticipated.

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(2) See, *inter alia*, (a) E. C. Horswill, J. A. Howard, and K. U. Ingold, *Can. J. Chem.*, **44**, 985 (1966); (b) J. A. Howard and K. U. Ingold, *ibid.*, **41**, 1744, 2800 (1963); **43**, 2724 (1965); (c) E. S. Torsueva, I. A. Shlyapnikova, V. B. Miller, and Y. A. Shlyapnikov, *Vysokomol. Soedin.*, *Ser. B*, **12**, 666 (1970); (d) J. Pospisil, L. Taimr, and L. Kotulak, *Advan. Chem. Ser.*, **No. 85**, 169 (1968); (e) W. G. Lloyd, R. G. Zimmerman, and A. J. Dietzler, *Ind. Eng. Chem. Prod. Res. Develop.*, **5**, 326 (1966); (f) H. Morawetz, *Ind. Eng. Chem.*, **41**, 1442 (1949); (g) E. M. Bickoff, A. L. Livingston, and C. R. Thompson, *J. Amer. Oil Chem. Soc.*, **32**, 64 (1955).

(3) The observed effect is much too large to be explained by (a), and this explanation is also inconsistent with the t_{ind}'s measured in the absence of metals. In fact, in their careful comparative study, Horswill *et al.*[2a] found that the number of radicals trapped per antioxidant molecule consumed was actually *less* for **5** and other *p*-chlorophenols than for the alkylphenols **1**--**3** (1.0--1.7 *vs.* 1.8--2.4, for cumene oxidations initiated with 2,2′-azobis[2-methylpropionitrile] at 65°). Explanation (b) is excluded by the inactivity of the methyl ether of **6**; (c) fails to account for the relatively low activity of *m*-chlorophenols. However, the factors in (c) may be of minor importance, and they could be responsible for the slightly higher activity of **7** as compared to **1**--**3**.

(4) Previous work[2a] suggests that **10** may be the major initial product formed from **5** under these conditions.

(5) *Cf.* E. S. Rudakov and I. V. Kozhevnikov, *Tetrahedron Lett.*, 1333 (1971).