The infrared spectra of VIc from the two sources were identical.

17β-Benzoyloxy-5-chloro-4-oxaandrostan-3-one (VII).—A solution was made of the keto-acid (IIa, 1.03 g.) in benzene (10 ml.) and this was treated at 10° with cold thionyl chloride (5 ml.). The resulting solution was allowed to stand at 2–3° for 2 days and then the solvent and excess reagent were removed under vacuum. Trituration of the residue with a small volume of cold acetone followed by filtration gave 0.83 g. (77%) of a white powder, m.p. 179–182°. Recrystallization from a large volume of acetone gave the analytical sample as stout needles, m.p. 184–189°, $[\alpha]_D$ +61°; λ_{max} 5.69, 5.86 and 13.34 μ.

Anal. Calcd. for $C_{25}H_{31}ClO_4$: C, 69.67; H, 7.25; Cl, 8.23. Found: C, 69.69; H, 7.35; Cl, 8.22.

17β-Benzoyloxy-5-methoxy-4-oxaandrostan-3-one (VIIIa).—The pseudoacid chloride (VII, 0.28 g.) was dissolved with heating in pyridine (5 ml.) and methanol (5 ml.). The solution deposited thick needles on standing at room temperature for 90 hours. The solid was filtered (0.13 g.) and the filtrate was poured into water. The aqueous suspension was ether extracted and the extracts were washed with water, dried over sodium sulfate and evaporated to leave a gummy residue which on trituration with methanol gave more solid (0.06 g.). Two crystallizations of the combined solids from methanol–methylene chloride gave 0.124 g. (47%) of analytically pure material, m.p. 234–238°, $[\alpha]_D$ +72°, λ_{max} 5.75 and 5.85 μ.

Anal. Calcd. for $C_{26}H_{34}O_5$: C, 73.21; H, 8.04. Found: C, 72.95; H, 8.26.

17β-Benzoyloxy-5-allyloxy-4-oxaandrostan-3-one (VIIIb).—The pseudoacid chloride (VII, 0.32 g.) in pyridine (5 ml.) was treated with freshly distilled allyl alcohol (5 ml.) and allowed to stand 3 days at room temperature. No product had precipitated so the reaction was worked up as described for the methyl pseudoester VIIIa. The crude solid which formed on trituration with methanol was combined with that from another run (starting with 0.28 g. of VII) and crystallized from methanol–methylene chloride and petroleum ether–methylene chloride. The product, 0.06 g. (14%), had m.p. 162–164.5°. An analytical sample obtained by a further crystallization showed no improvement of m.p. and had $[\alpha]_D$ +67°, λ_{max} 5.71 and 5.82 μ.

Anal. Calcd. for $C_{28}H_{36}O_5$: C, 74.30; H, 8.02. Found: C, 74.63; H, 7.85.

17β-Benzoyloxy-5-benzyloxy-4-oxaandrostan-3-one (VIIIc).—17β-Benzoyloxy-5-chloro-4-oxaandrostan-3-one (VII, 0.60 g.) was dissolved in pyridine (8 ml.) and benzyl alcohol (8 ml.) with heating and was then allowed to stand 3 days at room temperature. The reagents were removed under vacuum and the residue was taken into ether. The ether solution was washed with water, dried over sodium sulfate and evaporated. The residue on trituration with methanol gave a solid which was crystallized from petroleum ether–methylene chloride to yield 0.04 g. (6%) of product, m.p. 223–227°. A second crystallization gave the analytical sample, m.p. 230–236°, $[\alpha]_D$ +67°, λ_{max} 5.73 and 5.82 μ.

Anal. Calcd. for $C_{32}H_{38}O_5$: C, 76.46; H, 7.62. Found: C, 76.78; H, 7.59.

Acid Hydrolysis of 17β-Benzoyloxy-5-chloro-4-oxaandrostan-3-one (VII).—The pseudoacid chloride (VII, 0.112 g.) and pyridine (0.021 g.) were refluxed in *t*-butyl alcohol (24 ml.) and water (5 ml.) for 2 hours. After standing at room temperature overnight the *t*-butyl alcohol was removed under vacuum until two phases were present. Water was added and the emulsion was ether extracted. The extracts were dried over sodium sulfate and evaporated to leave an oily product. Crystallization from methanol–water gave the following crops: crop 1, 0.042 g., m.p. 129–145°; crop 2, 0.033 g., m.p. 105–108.5°; crop 3, 0.014 g., m.p. 103–105.5°.

Crop 1 after two recrystallizations gave 0.023 g. (21%) of pure *t*-butyl 17β-benzoyloxy-5-oxo-3,5-seco-A-norandrostan-3-oate (IIc), m.p. 154–157°, $[\alpha]_D$ +78°, λ_{max} 5.81 μ (shoulder 5.87).

Anal. Calcd. for $C_{28}H_{40}O_5$: C, 73.65; H, 8.83. Found: C, 73.88; H, 8.62.

Crops 2 and 3 were combined and crystallized from methanol–water. Material melting at 143.5–174.5° was obtained. When placed on the block at 160° it completely melted then resolidified and remelted 173–175.5°. The infrared spectrum was identical to that of 17β-benzoyloxy-5-hydroxy-4-oxaandrostan-3-one (IIIa) obtained directly from ozonization of testosterone benzoate.

Methyl 17β-Benzoyloxy-5-oxo-3,5-seco-A-norandrostan-3-oate (Ib).—The methyl pseudoester (VIIIa, 0.102 g.) was dissolved in methanol (100 ml.) with heating. After cooling to 40°, 1 drop of concd. sulfuric acid was added and the solution was allowed to stand for 22 hours at room temperature. Water was added and the methanol was removed under vacuum. The organic material was extracted into chloroform and the extracts were washed twice with water and evaporated. The gummy product was chromatographed on silica gel (6.4 g.). A colorless oil was eluted with benzene–ethyl acetate 19:1 which had $[\alpha]_D$ +87°; $\lambda_{max}^{CHCl_3}$ 5.84, 7.79, 8.89, 10.47 μ. The infrared absorption spectrum in chloroform was identical with that of the normal methyl ester prepared by diazomethane treatment of 17β-benzoyloxy-5-oxo-3,5-seco-A-norandrostan-3-oic acid (IIa) and distinctly different from that of the starting material.

CHICAGO 80, ILL.

[CONTRIBUTION FROM THE GENERAL ELECTRIC RESEARCH LABORATORY]

The Effect of Cobaltous Ions on Cumene Autoxidation[1]

BY HARRY S. BLANCHARD

RECEIVED AUGUST 20, 1959

The α,α′-azodiisobutyronitrile initiated autoxidation of cumene in acetic acid was studied at 60° in the presence and in the absence of cobaltous ions. Rates of initiation were measured and found to be unaffected by cobaltous ions in the range 0–0.0041 *M*. The over-all rates of autoxidation, however, were increased in this concentration range, indicating that the cobaltous ions catalize either the reaction between cumyl peroxy radicals and cumene or the reaction between cumyl radicals and oxygen. Above 0.0041 *M* the rates of initiation increased and concomitantly the yields of hydroperoxide decreases, suggesting that the increased initiation results from decomposition of the hydroperoxide by the metal ions. In the absence of an added free radical initiator, cumene autoxidation was found to be dependent on the purity of the reagents. The results of the study support the idea that in the presence of metal ions but in the absence of added initiator, initiation results from free radicals formed, either from decomposition of hydroperoxides by the metal ions or from reaction of the metal ions with impurities also resulting in free radicals. The so-called "direct" reaction between hydrocarbon, oxygen and cobaltous ions, at least in the case of cumene, was found to be immeasurably slow under our experimental conditions.

The mechanism of the free radical initiated autoxidation of hydrocarbon has received considerable attention in recent years[2] and as a result is now well understood. The detailed mechanism of how heavy-metal ions affect autoxidizing systems,

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[1] Presented in part before the Organic Chemistry Division at the 134th Meeting of the American Chemical Society, Chicago, Ill., September, 1958. A preliminary account of this work appeared in *Chemistry & Industry*, 598 (1959).

[2] (a) J. L. Bolland, *Quart. Rev.*, **3**, 1 (1949); (b) L. Bateman, *ibid.*, **8**, 147 (1954); (c) G. A. Russell, THIS JOURNAL, **77**, 4583 (1955); *ibid.*, **78**, 1047 (1956).

however, is less well understood, although it is common practice to add such ions as oxidation "activators." Indeed, the intense activity of certain metal ions (such as those of iron, cobalt and manganese) as oxidation catalysts is a matter of considerable technological as well as scientific interest. The purpose of this report is to present the results of a study concerning the effect of cobaltous ions on the initiated autoxidation of cumene. From these results it is possible to draw certain conclusions regarding the function of heavy-metal ions in autoxidation systems.

Results and Discussion

The mechanism of the α,α'-azodiisobutyronitrile (AIBN) initiated autoxidation of hydrocarbons is generally formulated as

$$(CH_3)_2C(CN)\text{—}N\text{=}N\text{—}(CN)C(CH_3)_2 \longrightarrow 2eR'\cdot + N_2$$

$$R'\cdot + O_2 \xrightarrow{k_1} R'OO\cdot$$

$$R'OO\cdot + RH \longrightarrow R'OOH + R\cdot$$

$$R\cdot + O_2 \longrightarrow ROO\cdot$$

$$ROO\cdot + RH \xrightarrow{k_p} ROOH + R\cdot$$

$$2ROO\cdot \xrightarrow{k_t} \text{non-radical products} + O_2$$

For the case where R is a *prim-* or *sec-*peroxy radical, Russell[3] has shown that the termination reaction should be formulated

$$2R_2\,CHOO\cdot \longrightarrow R_2\,CHOH + R_2\,CO + O_2$$

the reaction proceeding *via* a cyclic transition state. In the case where R is a *t*-peroxy radical, it was recently shown[4] that these radicals undergo a non-terminating interaction yielding alkoxy radicals. Termination then results in the formation of di-alkyl peroxide presumably *via* the dimerization of the alkoxy radicals.

$$2ROO\cdot \longrightarrow 2RO\cdot + O_2$$

$$2RO\cdot \longrightarrow ROOR$$

Thus, the mechanism of initiated autoxidations in the absence of metal ions is now understood in a rather detailed manner.

It has long been recognized that heavy-metal ions can have a profound effect on autoxidizing systems; particularly on the rates of oxygen absorption and on the nature of the final products. It is generally agreed that one function of the heavy-metal ions is to act as a catalyst for the decomposition of the hydroperoxides formed in the above reaction scheme. Indeed, several investigators[5] have shown in non-autoxidizing systems that the rates of decomposition of many hydroperoxides are greatly enhanced by the presence of metal ions. In this connection the results of Woodward and Mesrobian[5a] are of immediate interest to the present discussion since they related their results on the metal-ion catalized decomposition of tetralin hydroperoxide directly to the role of the same metal ions in the autoxidation of tetralin. From their study they concluded that the major function of the metal ions was to catalyze the decomposition of the hydroperoxide, apparently *via* the following reaction sequence as postulated by Bawn,[6] *et al.* The net result

$$\begin{array}{c} CO^{++} + ROOH \longrightarrow RO\cdot + CO^{+++} + OH^- \\ CO^{+++} + ROOH \longrightarrow ROO\cdot + CO^{++} + H^+ \\ \hline 2ROOH \longrightarrow RO\cdot + RO_2\cdot + H_2O \end{array}$$

of these reactions is the same as that postulated for the bimolecular decomposition of the hydroperoxide itself and the catalytic effect of the metal ions is apparent.[2b]

Similarly, but somewhat earlier, Bawn, Pennington and Tipper[6] concluded from their study of the metal-ion catalyzed autoxidation of trimethylethylene that the sole function of the metal-ions is to decompose the intermediate hydroperoxide. This is a particularly significant finding since in this system independent experiments under non-autoxidizing conditions showed that cobaltic ions were capable of undergoing the following electron-transfer reaction even at room temperature.

$$CO^{+++} + RH \longrightarrow CO^{++} + R\cdot + H^+$$

However, under autoxidizing conditions the reaction of cobaltic ions with hydroperoxide is so much faster that this reaction is of little importance as an initiating process.

More recently Uri[7] studied the autoxidation of methyl stearate and related compounds in the presence of various cobaltous salts. He concluded that the major function of the cobaltous ions was to act as a chain initiator *via* the following reaction sequence. In this system the metal ion is assigned

$$Co^{++} + O_2 \longrightarrow CoO_2^{++}$$

$$CoO_2^{++} + RH \longrightarrow Co^{+++}R^- + HO_2\cdot$$

$$HO_2\cdot + RH \longrightarrow HO_2H + R\cdot$$

essentially the role of an oxygen carrier and little or no importance is attached to its ability to catalyze the decomposition of the hydroperoxide. Moreover, the metal ion in this system is functioning as an initiator while it is in the divalent state. By way of contrast, Bawn and Jolley[8] found in their study of the autoxidation of benzaldehyde that the metal ions acted as an initiator but only in the trivalent state.

$$Co^{+++} + RCHO \longrightarrow Co^{++} + RCO + H^+$$

Thus it appears that the exact role of metal ions in autoxidizing systems is dependent on the substrate and probably on the experimental conditions. As to whether or not cobaltous ions assume any role other than catalyzing the decomposition of hydroperoxides in the autoxidation of aralkyl hydrocarbons appears not to have been adequately answered.

If initiation takes place by some scheme akin to that postulated by Uri or in fact by any process involving the metal ions and free radicals, it should be possible to measure its rate. In order to obtain this information we have studied the AIBN initiated rate of oxidation of cumene in the presence

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(3) G. A. Russell, THIS JOURNAL, **79**, 3871 (1957).

(4) H. S. Blanchard, *ibid.*, **81**, 4548 (1959).

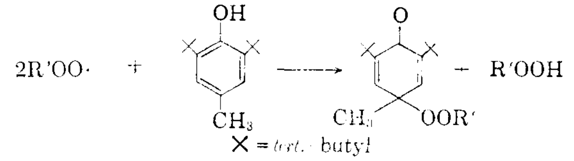
(5) (a) A. E. Woodward and R. B. Mesrobian, *ibid.*, **75**, 6189 (1953); (b) M. H. Dean and D. Skirrow, *Trans. Faraday Soc.*, **54**, 849 (1958); (c) E. Dyer, K. R. Carle and D. E. Weiman, *J. Org. Chem.*, **23**, 1464 (1958).

(6) (a) C. E. H. Bawn, A. A. Pennington and C. F. H. Tipper, *Faraday Soc. Disc.*, **10**, 282 (1951); (b) C. E. H. Bawn, *ibid.*, **14**, 181 (1953).

(7) N. Uri, *Nature*, **177**, 1177 (1956).

(8) C. E. H. Bawn and J. E. Jolley, *Proc. Roy. Soc.* (*London*), **237**, 297 (1956).

and in the absence of cobaltous ions. Since it is possible to measure accurately the rates of initiation by AIBN alone, this should provide a means for measuring accurately the effect of cobaltous ions on the rate of free radical production. This phase of the investigation was carried out essentially by the technique of Boozer, Hammond[9] and co-workers who showed that the general mechanism of autoxidation is modified as follows when an efficient inhibitor such as 2,6-di-*t*-butyl-4-methylphenol (DBPC) is present. Thus, the radicals formed from the initiator react preferentially with the



inhibitor (*vide infra*). Following the complete consumption of the inhibitor the normal oxidation is observed. This then provides an accurate measure of the rate of free radical production in the absence of metal ions. The same experiments can be also carried out in the presence of metal ions. If the metal ions increase the rate of free radical production, then the lengths of the inhibition periods will be diminished. Moreover, the amount by which the inhibition periods are diminished will provide an accurate measure of the rate of free radical production caused by the metal ions.

Previously we have shown[4] that in chlorobenzene solution, the kinetics of cumene autoxidation rigorously obey equation 1. In this expression, R_i,

$$-\mathrm{d}[\mathrm{O_2}]/\mathrm{d}t = k_p[\mathrm{RH}][R_i]^{1/2}/(2k_t)^{1/2} + R_i/2 \quad (1)$$

the rate of initiation, $= 2ek_i[\mathrm{AIBN}]$. Under the conditions of 0.097 *M* AIBN, R_i is calculated to be 1.32×10^{-6} mole l.$^{-1}$ sec.$^{-1}$ based on a value of 1.15×10^{-5} sec. for k_i and a value of 0.60 for *e*, the efficiency of radical production from AIBN. The value of k_i was determined from a compilation of all of the available literature data[10] while the value of *e* appears established at about 0.6 by the data of Hammond, Sen and Boozer,[11] at least for the case of aromatic solvents.

In the past cobaltous compounds of rather ill-defined composition, such as the commercial naphthenates, have frequently been employed as the source of cobaltous ions. In the present investigation, cobaltous acetate was chosen as the source of cobaltous ions since it can be obtained in a state of reasonable purity. However, since cobaltous acetate is quite insoluble in non-polar solvents, it was necessary to choose a more polar solvent and for this reason acetic acid was selected as the reaction medium.

In Table I data on the rate of oxidation and the yield of hydroperoxide are collected. As was found in the case of autoxidations of cumene in chlorobenzene solution, the yield of hydroperoxide is a function of the kinetic chain length.[4] Independent experiments showed that cumene hydroperoxide was completely stable under the experimental conditions. Moreover, acetophenone was also isolated and identified as an oxidation product although it was not possible to analyze for this quantitatively as had been done for the oxidations in chlorobenzene solution (see Experimental). Further, unlike the oxidations in chlorobenzene solutions, as evidenced by the data in column 4 of Table I, equation 1 is not obeyed rigorously as the solvent is changed from cumene to acetic acid. This may indicate an influence of solvent upon the rate constants of the autoxidation mechanism. Since one of the main objectives of the work was to measure rates of initiation, it was imperative to establish that the acetic acid had no effect on the decomposition of the AIBN and hence on the rates of initiation. For example, although *e* appears established as 0.6 for aromatic solvents, it might well be different in such a solvent as acetic acid.[11,12]

TABLE I

OXIDATION OF CUMENE IN ACETIC ACID AT 60° IN THE PRESENCE OF α,α'-AZODIISOBUTYRONITRILE (0.097 *M*)

[Cumene], mole l.$^{-1}$	Kinetic chain length[a]	Rate,[b] mole l.$^{-1}$ sec.$^{-1}$ × 10^5	Rate, $R_{1/2}$/[RH] [AIBN]$^{1/2}$ × 10^5	Yield ROOH,[c] %
0.72	2.3	0.31	1.06	60
1.05	3.0	.40	0.99	71
2.10	5.3	.70	.95	85
3.15	7.4	.98	.92	88
3.50	8.1	1.08	.92	89
4.20	10.3	1.36	1.01	91
5.25	14	1.84	1.06	93
6.30	18	2.39	1.17	95
6.90[d]	20	2.68	1.20	96
6.90[d,e]	29	1.90	1.21	97
6.90[d,f]	66	0.86	1.24	97

[a] Kinetic chain length = d[O$_2$]/d*t*/R_i. [b] Corrected for nitrogen evolution from the AIBN. [c] Calculated as percentage of oxygen absorbed. [d] Pure cumene. [e] 0.05 *M* AIBN. 0.01 *M* AIBN.

TABLE II

INHIBITED OXIDATIONS OF CUMENE AT 60° IN THE PRESENCE OF α,α'-AZODIISOBUTYRONITRILE (0.0097 *M*)

Cumene, mole l.	Rate,[a] mole l.$^{-1}$ sec.$^{-1}$ × 10^6	INH,[b] mole l.$^{-1}$ × 10^3	Time, min. Obsd.	Time, min. Calcd.
		Acetic acid		
1.05	4.00	..	2	...
1.05	4.10	1.22	32	30.5
1.05	4.00	2.43	62.5	61
1.05	4.00	4.86	124	122
1.05	4.00	1.77	46	44.5
1.05	4.10	3.54	91.5	89
		Benzene		
2.30	9.80	..	...	...
2.30	9.80	1.69	45	45
		Chlorobenzene[c]		
2.30	9.90	..	...	...
2.30	9.70	1.69	32	30.5
2.30	9.80	3.38	63	61

[a] Corrected for nitrogen evolution from the AIBN. [b] Inital concentration of DBPC. [c] These results are from ref. 8 at 62.5°.

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(9) C. E. Boozer, G. S. Hammond, C. E. Hamilton and J. N. Sen, THIS JOURNAL, **77**, 3233 (1955).

(10) See footnote 3 in ref. 3 for the data used.

(11) G. S. Hammond, J. N. Sen and C. E. Boozer, THIS JOURNAL, **77** 3244 (1955).

(12) As shown in ref. 11, *e* varies from a low of 0.43 in carbon tetrachloride to a high of 0.75 in nitromethane and nitrobenzene.

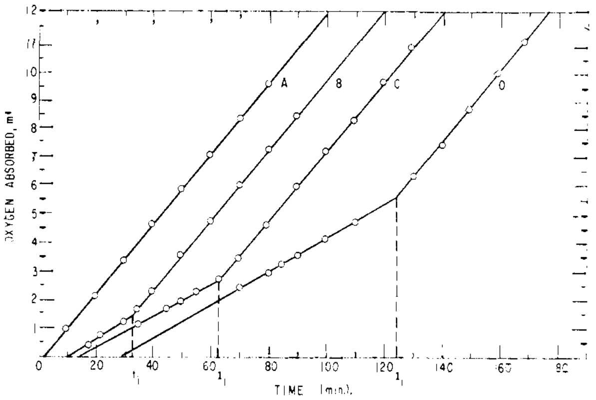

Fig. 1.—The AIBN (0.097 M) initiated, DBPC-inhibited autoxidation of cumene (0.08 M) in acetic acid at 60°, corrected for nitrogen evolution from the AIBN: A, no DBPC; B, 1.22 × 10^{-3} M DBPC; C, 2.43 × 10^{-3} M DBPC; D, 4.86 × 10^{-3} M DBPC.

That such is not the case is clearly shown by the data in Table II. The observed times were determined graphically as illustrated in Fig. 1. Here the point of intersection determines the length of the inhibition period. At this point all of the inhibitor is consumed and the normal oxidation is observed. In the case of the runs in acetic acid a small (2 min.), reproducible induction period was observed even in the absence of added inhibitor, regardless of how stringently the acetic acid was purified. That this induction period is due to some trace impurity rather than to lack of thermal equilibrium is indicated by the fact that it is completely absent in the cases of benzene and chlorobenzene. It is observed that doubling the inhibitor concentration exactly doubles the length of the inhibition period, thus providing an exact measure of the rate of free radical production. Moreover, the rates of oxidation in the absence of inhibitor are identical with those in the presence of inhibitor, thus providing assurance that the products of the inhibition reaction are not complicating the ultimate oxidation.

The calculated times reported in Table II were determined by use of equation 2. This expression

$$\begin{array}{lll} t_i & = k[\mathrm{DBPC}]/R_i & \\ [\mathrm{DBPC}] & = \text{initial concentration} & \\ R_i & = \text{rate of initiation} & \\ k & = 2 \text{ (ref. 9)} & \qquad (2) \end{array}$$

is the expected one under conditions where the rate of initiation is constant and where the inhibitor can compete efficiently with the hydrocarbon for peroxy radicals. The excellent agreement between the observed and calculated times show these conditions are fulfilled. Moreover, the efficiency, e, must also be the same in acetic acid as it is in a number of aromatic solvents as is evident by the comparison of the data reported for benzene and chlorobenzene.

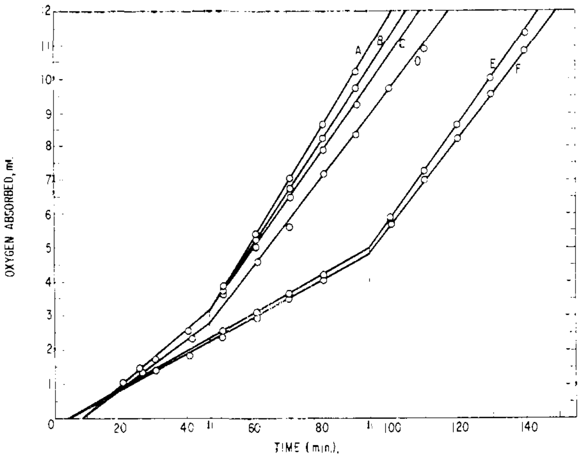

Fig. 2.—The AIBN (0.097 M) initiated, DBPC-inhibited autoxidation of cumene (1.08 M) in acetic acid at 60°, corrected for nitrogen evolution from the AIBN: A, 4.11 × 10^{-3} M $Co(OAc)_2$, 1.77 × 10^{-3} M DBPC; B, 2.82 × 10^{-3} M $Co(OAc)_2$, 1.77 × 10^{-3} M DBPC; C, 1.41 × 10^{-3} M $Co(OAc)_2$, 1.77 × 10^{-3} M DBPC; D, no $Co(OAc)_2$, 1.77 × 10^{-3} M DBPC; E, 1.41 × 10^{-3} M $Co(OAc)_2$, 3.54 × 10^{-3} M DBPC; f, no $Co(OAc)_2$, 3.54 × 10^{-3} M DBPC.

If cobaltous ions are capable of increasing the rate of free radical production, then the lengths of the inhibition periods will be diminished since the rate of free radical production will now exceed 1.32 × 10^{-6} mole l.$^{-1}$ sec.$^{-1}$. The results of a number of experiments in the presence of cobaltous ions are collected in Table III and typical oxidation curves are shown in Fig. 2.

In Fig. 2 curves D and F are for runs in the presence of AIBN alone, *i.e.*, they are the standard. Curves A, B, C, D, E show that cobaltous ions in the concentration range 0–0.00411 M have no effect on the rate of free radical production. This finding is of particular significance since as is evident from the oxidation curves (Fig. 2), the rates of oxygen absorption are enhanced in the presence of cobaltous ions. Since the rate of free radical production is the same in the presence as it is in the absence of cobaltous ions, this rate enhance-

TABLE III

INHIBITED OXIDATIONS OF CUMENE (1.05 M) IN ACETIC ACID AT 60° IN THE PRESENCE OF α,α'-AZODIISOBUTYRONITRILE (0.097 M) AND COBALTOUS IONS

Co^{++},[a] mole l.$^{-1}$ × 10^3	DNPC,[b] mole l.$^{-1}$ × 10^3	Rate,[c] mole l.$^{-1}$ sec.$^{-1}$ × 10^5	Inhibition period, min. Obsd.	Calcd.	Yield ROOH, %
...	..	4.06	2.0	..	71
1.34	1.77	4.58	46.5	45	72
2.67	1.77	4.87	46.5	45	72
4.11	1.77	5.26	46.5	45	69
8.22	1.77	5.72	39.5	45	59
12.40	1.77	6.52	37.5	45	48
16.44	1.77	6.96	37.0	45	35
1.34	3.54	4.58	91.0	90	70
4.11	3.54	5.27	91.5	90	72
2.67	2.43	4.86	63.0	61	72
2.67	4.86	4.87	123.0	122	71
8.22	2.43	5.72	53.0	61	56
1.40[e]	2.43	4.60	62	61	70
0.50[e]	2.43	4.14	61	61	69
1.40[f]	2.43	4.96	51	61	63

[a] Initial concentration of cobaltous acetate. [b] Initial concentration of DBPC. [c] Corrected for nitrogen evolution from AIBN. [d] Calculated as percentage of oxygen absorbed found as ROOH. [e] Cumene hydroperoxide (8.5 × 10^{-4} M) added initially. [f] Cumene hydroperoxide (0.015 M) added initially.

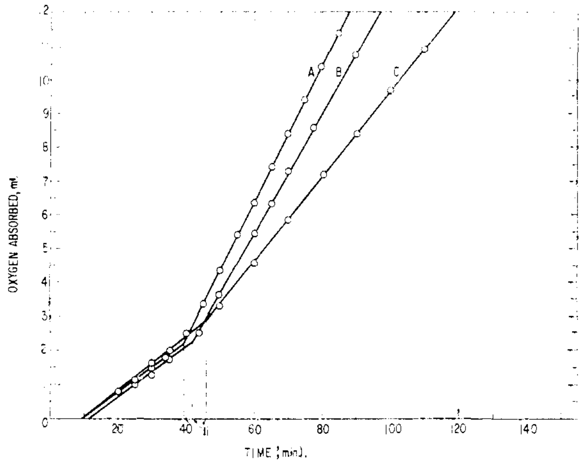

Fig. 3.—The AIBN (0.097 M) initiated, DBPC-inhibited (0.00177 M), autoxidation of cumene (1.08 M) in acetic acid at 60°, corrected for nitrogen evolution from the AIBN: A, 1.24×10^{-2} M $Co(OAc)_2$; B, 8.22×10^{-3} M $Co(OAc)_2$; C, no $Co(OAc)_2$.

ment cannot be attributed to an increase in the rate of chain initiation. Moreover, the yields of hydroperoxides (Tables I and III) in the concentration range 0–0.00411 M cobaltous ions are nearly the same as they are in the absence of the metal ions. From this finding it follows that the enhancement in the rates of oxidation cannot be attributed to decomposition of hydroperoxides. Little can be said at this time as to why the metal ions cause the observed rate enhancement. It is tempting to speculate that the metal ions may be complexing some of the peroxy radicals and thus stabilizing them. If such stabilization did occur it would be expected that these complexed radicals would terminate at a slower rate then uncomplexed radicals. Such an effect would lead to a rate enhancement. However, by the same token, it would be expected that complexed radicals would propagate at a slower rate than uncomplexed radicals thus leading to a diminished rate of oxygen absorption. In view of the profound effects that small amounts of metal ions can have on homolytic reactions, as recently reported by Kharasch and Fono,[13] it is perhaps not surprising that such a rate enhancement is observed even in the absence of hydroperoxide decomposition. Obviously, the final answer to this question will require further study.

Further increases in the cobaltous ion concentration do cause a diminution in the inhibition periods (Fig. 3) and, concomitant with this diminution, the yields of hydroperoxides decrease (Table I and III). This finding supports the idea that the diminution in the inhibition period is due to an increased rate of free radical production through the decomposition of the hydroperoxides by the metal ions. If this is the case, since hydroperoxides are formed from the initiator during the inhibition period, it follows that the cobaltous ion concentration must attain a certain value before this reaction becomes detectable. Moreover, it should be possible to approach this condition by increasing the concentration of the hydroperoxide as well as by increasing the cobaltous ion concentration. That such is the case is evident from the data on the last three runs reported in Table III. In the first two of these runs, sufficient cumene hydroperoxide was added initially to provide the same concentration of hydroperoxide as would be present at the end of the inhibition period. As expected, this had no effect on the length of the inhibition period. However, when sufficient cumene hydroperoxide was added initially to make the solution 0.015 M with respect to hydroperoxide, the length of the inhibition period was diminished considerably. The fact that the cobaltous ion concentration or the hydroperoxide concentration must exceed a certain value before this reaction comes into play as an effective initiating system attests to the probable complexity of this reaction. In this connection it should be pointed out that Dyer, Carle and Weiman[5c] in their study of the cobaltous ion-catalyzed decomposition of tetralin hydroperoxide found that the rate constants varied with the initial concentration of hydroperoxide. Moreover, in some autoxidation systems it has been found that the order of reaction with respect to the metal ions is frequently found to be a function of the metal ion concentration.[6b]

Recently Lippincott and Lloyd[14] have reported results on the inhibited autoxidation of tetralin catalyzed by cobaltous naphthenate. Their data were found to fit the expression

$$t_i = t_i^0 \exp(kX) \qquad (3)$$

where X is the concentration variable, either cobaltous naphthenate concentration or inhibitor concentration. This unexpected result was interpreted by Lippincott and Lloyd to mean that the usual steady-state concentration assumption was not applicable to the kinetics of inhibited autoxidations. Rather, they feel the inhibition periods in the presence of "a strong branching catalyst" should be interpreted in terms of branching chain kinetics and, indeed, the inhibition period kinetics found in the absence of branching catalysts are merely special cases of the branching chain kinetics. In view of these results it appeared of interest to examine the so-called direct reaction between cumene, oxygen and cobaltous acetate in acetic acid solution. Moreover, since the rate of free radical production from AIBN is 1.32×10^{-6} mole $l.^{-1}$ $sec.^{-1}$ it can be calculated that if the rate of initiation by any reaction due to cobaltous ions exceeded 7.5×10^{-8} mole $l.^{-1}$ $sec.^{-1}$, this would have been detectable under the conditions of our experiments. However, small as this rate of initiation may be, if this represents a real value due to a direct initiation by cobaltous ions it should be possible to measure this reaction directly through the use of inhibitors.

In Fig. 4 typical oxidation curves are shown for the oxidation of cumene as a function of cobaltous acetate concentration. For comparison, the AIBN initiated oxidation of cumene is also included. As is evident from the curves, the reactions in the absence of AIBN show marked induction periods. Moreover, these induction periods are not particu-

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[13] M. S. Kharasch and A. Fono, *J. Org. Chem.*, **24**, 606 (1959); see also W. Treibs and G. Pellmann, *Ber.*, **87**, 1201 (1954).

[14] W. T. Lippincott and W. G. Lloyd, THIS JOURNAL, **79**, 4811 (1957).

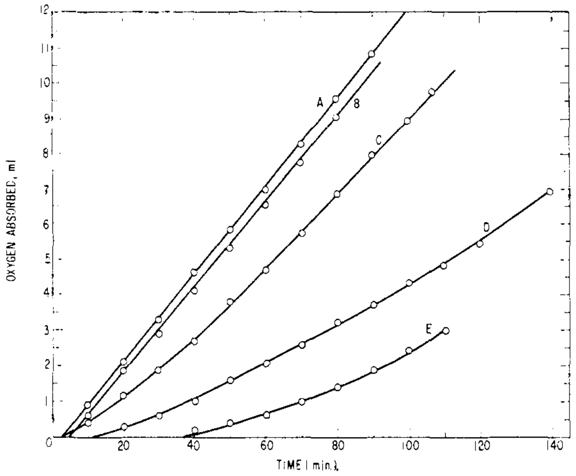


Fig. 4.—The effect of cobaltous ions on the autoxidation of cumene (1.08 *M*) in the absence of AIBN: A, 0.097 *M* AIBN, no $Co(OAc)_2$ (curve corrected for nitrogen evolution from the AIBN); B, 2.75 × 10^{-2} *M* $Co(OAc)_2$; C, 8.9 × 10^{-3} *M* $Co(OAc)_2$; D, 4.32 × 10^{-3} *M* $Co(OAc)_2$; E, 2.88 × 10^{-3} *M* $Co(OAc)_2$.

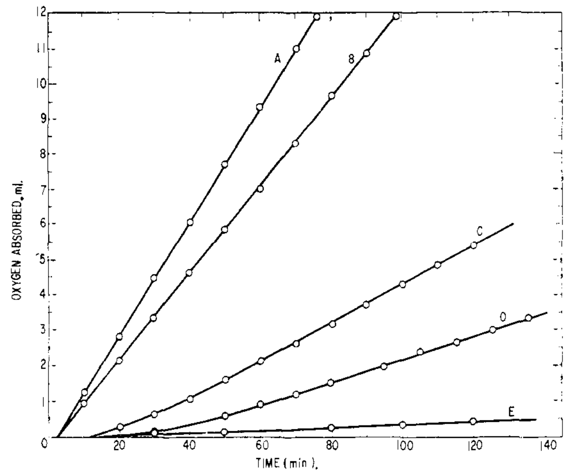


Fig. 5.—Effect of purification of reagents on the autoxidation of cumene (1.08 *M*) in acetic acid at 60°: A, 4.11 × 10^{-3} *M* $Co(OAc)_2$ (recrystallized), 0.097 *M* AIBN (corrected for nitrogen evolution); B, 0.097 *M* AIBN, no $Co(OAc)_2$ (corrected for nitrogen evolution); C, 4.11 × 10^{-3} *M* $Co(OAc)_2$ (recrystallized), no AIBN; E, 4.11 × 10^{-3} *M* $Co(OAc)_2$ (recrystallized), freshly chromatographed cumene, no AIBN.

larly reproducible. As the cobaltous ion concentration is decreased the induction periods increase and simultaneously the autocatalytic character of the curves become more pronounced. Further, it was found that the purity and source of the cobaltous acetate was also important in determining the lengths of the induction period as well as the ultimate rates of oxygen absorption. Interestingly enough, these solutions remain pink throughout the entire oxidation indicating that the cobaltic ion concentration is extremely low. Finally, it was found that the purity of the cumene was important in determining whether or not an oxidation was observed. These effects are illustrated by the typical oxidation curves presented in Fig. 5. Comparison of curves C and D (Fig. 5) shows the effect of purification of the cobaltous acetate. These two runs differ only in the fact that the cobaltous acetate used in obtaining D was purified by recrystallization from aqueous acetic acid. The cumene used in each of those runs was Phillip's 99 mole per cent., which had been rectified but not chromatographically filtered through activated silica gel or alumina. As long as this cumene was used, it was found that oxidation always took place regardless of how stringently the cobaltous acetate was purified although the rate decreased as the cobaltous acetate was further purified. Further, as pointed out above, the source of the cobaltous acetate was also important. That is, when the same amounts of two different samples were used, both the rates of oxidation and the lengths of the induction periods were different. Moreover, one of the samples of cobaltous acetate could never be purified to the point that it would give as low a rate of oxidation as did the other one. Curves A, B and E should be considered as a family since they were obtained using highly purified reagents, including cumene which had been chromatographically filtered through activated silica gel just prior to oxidation. Here, curve B shows the AIBN initiated autoxidation of cumene in the absence of metal ions. Curve A shows the rate enhancement caused by the cobaltous ions. It should be noted that this curve was obtained at a cobaltous ion concentration at which neither the length of the inhibition period nor the yield of hydroperoxide is affected by the metal ions. Finally, curve E shows that using these highly purified materials, in the absence of an added free radical initiator, essentially no oxidation takes place. These results, coupled with those obtained on the initiated and inhibited oxidation, lend further support to the idea that the direct reaction between cumene, oxygen and cobaltous ions in acetic acid solution is immeasurably slow when highly purified reagents are employed. Obviously, since in the absence of added inhibitor the induction periods were rather unreproducible, it seemed hopeless to measure inhibition periods in the presence of DBPC. However, at high cobaltous ion concentrations (commercial cobaltous acetate) and using cumene which had not been freshly chromatographed on alumina, as shown in Fig. 4, the induction periods are quite short and, indeed, under these conditions are even reproducible within ±10%. Therefore, it was of interest to add DBPC to these solutions and measure inhibition periods as Lippincott and Lloyd had done for tetralin. However, although DBPC did inhibit the reactions (indicating that free radicals are involved) it was impossible to obtain reproducible results. Rather, the inhibition periods were completely sporadic and unpredictable, although at very low ($<10^{-3}M$) inhibition concentrations some semblance of order was observed. Thus, doubling the inhibitor concentration did appear to approximately double the inhibition period but even here the reproducibility was no better than ±20%. Finally we tried measuring inhibition periods with DBPC under these same conditions except with known amounts of cumene hydroperoxide added initially. If the following reactions went cleanly and if the DBPC were as effective in trapping the alkoxy radical as it is in trapping the peroxy radical, this would not only give rates of

$$\mathrm{Co^{++} + ROOH \longrightarrow Co^{+++} + RO\cdot + OH^-}$$
$$\mathrm{Co^{+++} + ROOH \longrightarrow Co^{++} + ROO\cdot + H^+}$$

initiation of cumene autoxidation, but simultaneously the rate of decomposition of cumene hydroperoxide catalyzed by cobaltous ions. Unfortunately, although the inhibition periods were considerably shorter than without the added hydroperoxide, no clear relationship was found between the hydroperoxide concentration and the lengths of the inhibition periods. Again, this is consistant with the idea that the reaction between hydroperoxide and cobaltous ions is probably much more complex than that suggested by the simple equations above.

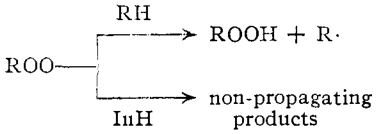
On the basis of the results obtained in this phase of the investigation it seems reasonable to conclude that there is no direct reaction between cobaltous ions, oxygen and cumene. Further, when oxidations in the presence of metal ions but with no added free radical initiator take place, initiation probably results either from reaction between the metal ions and thermally formed hydroperoxide or is due to the presence of impurities in the hydrocarbons or metal salt. In this connection some further comment should be made on the results of Lippincott and Lloyd. Their conclusion that the finding of an exponential relationship in tetralin autoxidation indicates a non-steady state condition is certainly a valid one. However, their assertion that "the concept of dynamic equilibria as developed in the branching-chain kinetics of Semenoff" applies to all inhibited autoxidations warrants careful examination. It seems to us, rather, that the results obtained by Lippincott and Lloyd are precisely those to be expected under conditions where the steady-state assumption does not apply and in no way do they prove the necessity for invoking branching-chain kinetics to inhibition periods in general. Our reasoning is outlined in the following few paragraphs.

In order to obtain well defined inhibition periods which are *directly* proportional to the concentration of the inhibitor two conditions must be met. First, the rate of initiation must be constant. Obviously, if this condition is not met, the steady-state condition will never by obtained. Secondly, the inhibitor must be able to compete effectively with the hydrocarbon for the free radicals formed.[15] Competition between the inhibitor and hydrocarbon for radicals is controlled by the concentrations of the inhibitor and hydrocarbon and by the intrinsic reactivities of the inhibitor and hydrocarbon.

NOTE ADDED IN PROOF, Feb. 2, 1960.—Prof. C. D. Cook (private communication) has found that in DBPC–inhibited, AIBN–initiated autoxidation of Tetralin, the DBPC traps tetralylperoxy radicals exclusively. This finding adds further support to the idea that under autoxidizing conditions tetralin competes quite effectively with DBPC for peroxy radicals.

When the inhibitor is attacked by radicals in preference to the hydrocarbon the length of the inhibition period will be directly proportional to the inhibitor concentration provided that R_i is constant. From the fact that the inhibition periods are directly proportional to the concentration of the inhibitor, and from the fact that the observed and calculated times agree very well, it seems reasonable to believe that both of these requirements have been met in the present work.

Such a complex relationship (equation 3) as that obtained by Lippincott and Lloyd might well be expected to obtain under conditions where R_i is variable and where the hydrocarbon can compete with the inhibitor for free radicals. Their system (tetralin, 70°, cobaltous naphthenate and 2, di-*t*-butyl-4-methylphenol) is well suited for these complications. No attempt was made to maintain a constant rate of initiation and initiation by some primary process involving cobaltous ions, oxygen and/or hydrocarbon was obviously slow. For example, by extrapolation of their data it can be calculated that in the inhibited oxidation of tetralin in the presence of 25 micromoles of cobaltous naphthenate per kilogram of tetralin, that a decrease of inhibitor concentration from 20 to 19 millimoles/kilogram of tetralin would require a period of 12 years. At lower inhibitor concentrations, competition between inhibitor and hydrocarbon for peroxy radicals results. This situation will lead to a fairly rapid build-up of hydroperoxide during the inhibition period. Since the formation of hydroperoxide



in the presence of cobaltous naphthenate is recognized to lead to degenerate chain branching, the autocatalytic destruction of the inhibitor observed by Lippincott and Lloyd is expected. This situation is exactly similar to the autocatalytic rate of autoxidation observed when tetralin is autoxidized in the presence of cobaltous naphthenate. The consequences of this variable rate of initiation which is in part due to the competition between inhibitor and hydrocarbon for peroxy radicals leads to a complex relationship between t_i and the concentration of the inhibitor and/or catalyst. Of course, under these conditions steady-state kinetic assumptions cannot be made but the results obtained are in no way contradictory to predictions made from systems wherein steady-state assumptions have been correctly applied. Finally, it should be pointed out that tetralin being a very reactive hydrocarbon undergoes thermal autoxidation at a faster rate than does cumene and therefore it would be expected to be more difficult to obtain the kind of data obtained on cumene in the present work. However, in view of the result of Hammond, *et al.*,[16] who studied the AIBN initiated, DBPC inhibited autoxidation of tetralin with no apparent complications, coupled with the results of Woodward and Mesrobian[5a] who studied the cobaltous acetate-activated autoxidation of tetralin

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(15) The actual requirement is that for each radical formed, a radical is trapped by the inhibitor.

(16) G. S. Hammond, C. E. Boozer, C. E. Hamilton and J. N. Sen, THIS JOURNAL, **77**, 3238 (1955).

and found the steady-state assumption applicable, it would seem that tetralin would behave the same in our system as does cumene, providing the aforementioned conditions are met.

Acknowledgment.—It is a pleasure to acknowledge many stimulating and helpful discussions with Dr. Glen A. Russell.

Experimental

Materials.—Cumene (Phillips 99 mole per cent. minimum) was rectified in a large Podbielniak column (750 plates) and the center fraction collected; b.p. 69–70° at 41 mm., $n^{20}\text{D}$ 1.4910. This fraction was chromatographically filtered through activated silica gel or alumina and stored under nitrogen at 0°. Acetic acid was refluxed with chromium trioxide for 12–15 hours and then distilled through a Vigreux column, the center fraction being collected. The water content of this fraction was determined by Karl Fischer titration following which the theoretical quantity of acetic anhydride was added and the whole heated to reflux for 48 hours. Following this treatment the water content as determined by Karl Fischer titration was 1 mg./ml. At this point the theoretical quantity of boron triacetate necessary to react with the residual water was added and the whole heated to reflux for 16 hours. Finally, the acid was distilled under nitrogen through a Vigreux column and the center fraction collected and stored under nitrogen. Vapor phase chromatography indicated that the acid was pure. Azodiisobutyronitrile (Eastman Kodak Co.) was recrystallized several times from methanal; m.p. 102° dec. 2,6-Di-*t*-butyl-4-methylphenal (Koppers, "food-grade") was purified by 10 successive recrystallizations from *n*-hexane carried out as follows; the phenol was dissolved in *n*-hexane at room temperature following which the solution was cooled with rapid stirring to −60°. This treatment was repeated successively until the mother liquors showed no evidence of color. The final product (m.p. 69.5–70°) was stored under nitrogen at 0°. Commercial cobaltous acetate tetrahydrate was purified by several recrystallizations from 50% aqueous acetic acid. The resulting product was dehydrated by pumping at 80° and 1 mm. for approximately 60 hours. The emission spectrum of the salt showed trace amounts of copper, chromium and manganese to be present. Standard solutions of the anhydrous salt were prepared in anhydrous acetic acid. In every case these solutions analyzed satisfactorily for cobaltous ions and were shown by Karl Fisher titration to contain less than 0.01% water. The solutions were stored under nitrogen until used.

Oxidation Procedure.—The initiator was added to the oxidation flask as a 0.1 *M* solution in benzene. The benzene was removed by evacuating at 15–20 mm. for approximately two hours. The reagents (cumene, acetic acid, standard cobaltous acetate solution, DBPC) appropriate to the run were added by pipet and the oxidation flask, which consisted of a heavy-walled erlenmeyer flask, attached to a reciprocating rack contained in a thermostated oil-bath and the rate of oxygen absorption measured by manual control of the mercury level in the gas buret.

Analytical Procedures. Hydroperoxides.—The yields of hydroperoxide were determined by the stannous chloride procedure of Barnard and Hargrave[17] and carried out as described previously.[4] Blank determinations showed that cobaltous ions had no effect on the procedure.

Isolation of Acetophenone.—Acetophenone was isolated and identified as its DNP derivative, m.p. 248–249°, mixed m.p. 249°; reported[18] 250°. Due to the acetic acid solvent it was not possible to analyze quantitatively for the acetophenone, as had been done in the autoxidations employing chlorobenzene as solvent. However, it was demonstrated conclusively that the acetophenone did not arise by reaction between cumene hydroperoxide and DNP. It was found that these two reagents reacted very slowly under the conditions of the experiments, whereas the addition of DNP reagent to the oxidant gave an almost instantaneous reaction yielding the DNP derivative of acetophenone. In view of the yields of hydroperoxide and considering the earlier results in chlorobenzene solution, the most reasonable conclusion is that acetophenone is a primary oxidation product in the acetic acid system also.

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(17) D. Barnard and K. R. Hargrave, *Anal. Chem. Acta*, **5**, 476 (1951).

(18) R. L. Shriner and R. C. Fuson, "Identification of Organic Compounds," John Wiley and Sons, Inc., New York, N. Y., 1948.

SCHENECTADY, N. Y.

[CONTRIBUTION FROM THE SCHOOL OF CHEMISTRY, UNIVERSITY OF MINNESOTA]

1,2,3,4,7,7-Hexachloro-2-norbornene Derivatives

BY WAYLAND E. NOLAND AND LOWELL R. SMITH

RECEIVED AUGUST 26, 1959

Diels–Alder reactions of hexachlorocyclopentadiene led to the formation of the adducts I from nitroethylene, VI after hydrolysis of the adduct from itaconic anhydride, and X from dimethyl acetylenedicarboxylate. The nitro adduct I was converted to a sodium salt II which yielded the chloro (IVa) and bromo (IVb) derivatives on halogenation. The failure of II to undergo the Nef or related solvolysis reactions is attributed in part to an inductive effect of the chlorine substituents, since the corresponding acid III was shown to be 63 times as strong as the unchlorinated acid. Chemical reduction of I yielded the corresponding amine V. The diacid VI yielded, besides the anhydride VII, a monomethyl ester (VIII) and, under conditions which overcame the much greater steric hindrance of the second carboxyl, the dimethyl ester IX. Saponification of X yielded the diacid XI, which has properties different from a diacid described in the literature to which the same structure previously had been assigned.

The failure of salts of the 5-nitro-2-norbornenes to undergo the Nef reaction, and the novel rearrangement which occurs instead with 5-nitro-2-norbornene,[1] led us to examine the behavior under similar conditions of the partially chlorinated derivative, 1,2,3,4,7,7-hexachloro-*endo*-5-nitro-2-norbornene (I). This derivative was synthesized in 61% yield by the Diels–Alder reaction of hexachlorocyclopentadiene with nitroethylene. In contrast to the more extensive Diels–Alder reactions of cyclopentadiene with nitroölefins,[2] the steric limits of the Diels–Alder reaction of hexachlorocyclopentadiene appear to have been reached in the simplest case, with nitroethylene itself; 2-nitropropene, 1-nitropropene and β-nitrostyrene do not appear to react with refluxing hexachlorocyclopentadiene, and excellent recoveries of hexachlorocyclopentadiene were obtained.

The adduct I forms a sodium salt (II), which was isolated as a hydrate. With this sodium salt all attempts to produce a Nef reaction or a rear-

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(1) W. E. Noland, J. H. Cooley and P. A. McVeigh, THIS JOURNAL, **81**, 1209 (1959).

(2) (a) W. E. Noland and R. E. Bambury, *ibid.*, **77**, 6386 (1955); (b) W. E. Noland, R. E. Counsell and M. H. Fischer, *J. Org. Chem.*, **21**, 911 (1956).