# Electron Transfer with Aliphatic Substrates. Oxidations of Cycloaliphatic Substrates with Cobalt(III) and Manganese(III) Ions Alone and in the Presence of Oxygen

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The oxidation of cycloaliphatic substrates with cobaltic and manganic acetates was investigated. Hydrocarbons studied include cyclohexane, methylcyclohexane, 1,1-dimethylcyclohexane, *cis*-1,2-dimethylcyclohexane, ethylcyclohexane, and cyclohexene. Reaction products include the corresponding ketones, alcohols, esters (ROAc and RCH$_2$OAc), geminate diesters, keto esters, dimers, and some acids. Their selectivity depends on the metal ion oxidant, experimental conditions, and the structure of the substrate. Added nucleophiles (KOAc or NaOAc) had no effect on product distribution in the cobalt system, but in combination with manganese gave rise to radical derived products (RCH$_2$OAc and RCH$_2$COOH) which increased with rising concentration of added acetate. In both bases, oxidation rates were enhanced. Added cupric acetate oxidizes intermediate cyclohexyl radicals to cyclohexene which reacts further to form cyclohexenyl acetates as major products. The use of Co–Cu and Mn–Cu ion combinations may present a route to olefinic derivatives from saturated substrates. With cobalt and in the presence of oxygen, dicarboxylic acids are formed predominantly, but with manganese this reaction is not favored. Pronounced selectivity with cobalt is attributed to steric factors which limit the attack of bulky and heavy-liganded cobaltic ions to noncrowded sites.

Oxidations of alkylbenzenes with Co(III),[1-3] Mn(III),[3] and Ce(IV)[4] salts in acetic acid or acetonitrile were reported to proceed via radical cation intermediates. This mechanism, however, was proposed for π systems exclusively. Earlier we reported results on the oxidation of *n*-butane[5] and cyclohexane[6] in the cobalt system. Reactions of these paraffins followed a pattern identical with that observed in the oxidation of aromatics. We concluded that σ bonds per se were able to donate electrons to metal ions. This paper deals with the oxidation of cyclohexane with cobaltic and manganic acetates in greater detail, showing participation of various mechanisms depending on experimental conditions. Additional substrates studied include methylcyclohexane, 1,1-dimethylcyclohexane, and *cis*-1,2-dimethylcyclohexane. In the presence of both cobalt and oxygen, methylcyclohexane, ethylcyclohexane, 1,1-dimethylcyclohexane, as well as several oxygenated methylcyclohexane derivatives (ketones and alcohol), were also briefly studied.

## Results

Experiments with metal salts in the presence or absence of oxygen are summarized in Tables I–V. The reaction was followed in each case by analyzing the neutral residue (~60–75% of product) after removing solvents and unreacted substrate by conventional procedures. In some experiments acidic products were isolated and characterized. Material balance on Co(III) ions consumed ranged from 45 to 70%. Cobaltic salts were prepared either from cobaltous acetate and *tert*-butyl hydroperoxide (method 1) or cobaltous acetate and MEK–O$_2$ (method 2), affording essentially identical results. Most reactions with metal salts were carried out under nitrogen. Experiment 2, however, was run with exposure to air, with essentially no effect on the selectivity of the reaction.

### Oxidation of Cyclohexane with Cobaltic Acetate.
The oxidation of cyclohexane with cobaltic acetate, prepared by either of the two methods, afforded three major products in the neutral fraction: cyclohexylmethyl acetate, cyclohexyl acetate, and 2-acetoxycyclohexanone in molar ratios of 50, 32, and 10%, respectively (65% of total product). Minor products consisted of varying amounts of cyclohexylidene diacetate, cyclohexanone, cyclohexanol, and bicyclohexyl and dicyclohexylmethane dimers. Occasionally

**Table I**
**Oxidation Products of Cyclohexane$^a$**

| Expt no. | Reactants, $M$ | | | | | Rxn time, days$^b$ | Product distribution, molar ratio$^c$ | | |
|---|---|---|---|---|---|---|---|---|---|
| | $C_6H_{12}$ | Co(OAc)$_3$ | Cu(OAc)$_2 \cdot$ H$_2$O | KOAc | NaOAc$\cdot$ 3H$_2$O | | C$_6$-H$_{11}$-OAc | C$_6$H$_{11}$-CH$_2$-OAc | Misc$^g$ |
| 1 | 1.5 | 0.4 | | | | 2.1$^i$ | 26 | 51 | 23 |
| 2$^d$ | 1.5 | 0.4 | | 0.6 | | 1.2 | 23 | 54 | 23 |
| 3 | 1.5 | 0.4 | | 1.6 | | 0.8 | 26 | 58 | 16 |
| 4 | 1.3 | 0.16$^e$ | | | | 3.9 | 34 | 53 | 13 |
| 5 | 1.3 | 0.16$^e$ | 0.16 | | | 3.9 | 4 | | 96$^h$ |
| 6 | 1.3 | 0.16 | 0.0011 | | | 1.7 | 6 | | 94$^h$ |
| 7 | 0.9 | 0.16$^f$ | | | | 0.8 | 37 | 47 | 16 |
| 8 | 0.9 | 0.16$^f$ | | | 0.7 | 0.8 | 34 | 50 | 16 |
| 9 | 0.9 | 0.16 | 0.16 | | | 0.8 | 8 | | 92$^h$ |
| 10 | 1.6 | 0.16 | 3.3 | | | 0.7 | 2 | | 98$^h$ |
| 11 | 0.9 | | 0.4 | | | 5.3 | | | |

$^a$ 80°, ~99% HOAc, under N$_2$. $^b$ Reaction followed visually; color of solution changes from dark green to pink. $^c$ Neutral products only (60–80% of total). $^d$ Reaction exposed to air. $^e$ Cobaltic acetate prepared from cobaltous acetate and *tert*-butyl hydroperoxide. $^f$ Cobaltic acetate prepared from cobaltous acetate, MEK, and oxygen. Results with Co(III) oxidants prepared by two methods appear identical. Thus, both methods of preparation were used interchangably. $^g$ Products in varying amounts include 2-acetoxycyclohexanone, cyclohexylidene diacetate, C$_{12}$H$_{22}$ and C$_{13}$H$_{24}$ dimers, cyclohexanol, cyclohexanone, and occasionally cyclohexylmethanol. $^h$ Products in the presence of Cu(II) consist of 3-cyclohexenyl acetate (~98+%) and 1-cyclohexenyl acetate. $^i$ In absence of RH, Co(III) solutions were stable from 4 to 6 days under reaction conditions.

some cyclohexylmethanol and several unidentified compounds were formed in small amounts. Acidic materials (35% of total product) consisted largely of cyclohexylacetic acid and some cyclohexanecarboxylic acid in a 4:1 or higher ratio. Products isolated accounted for 55% of Co(III) ions consumed.

### Oxidation of Methylcyclohexane with Cobaltic Acetate.
Major product types in this reaction were the corresponding ROAc, RCH$_2$OAc, methylcyclohexanones, and cyclohexanols in molar ratios of 40, 20, 15, and 20%, respec-

## Table II
## Oxidation Products of Cyclohexane[a]

| Expt no. | | Reactants, $M$ | | | | Rxn time, days[b] | Product distribution, molar ratio[c] | | |
|---|---|---|---|---|---|---|---|---|---|
| | $C_6H_{12}$ | Mn- (OAc)$_3$ | Cu(OAc)$_2$· H$_2$O | KOAc | NaOAc· 3H$_2$O | | $C_6$- H$_{11}$- OAc | $C_6H_{11}$- CH$_2$- OAc | Misc[d] |
| 12 | 1.8 | 0.5 | | | | 12.8[f] | 86 | 3 | 11 |
| 13 | 1.8 | 0.5 | | 0.7 | | 10.8 | 76 | 19 | 5 |
| 14 | 1.8 | 0.5 | | 1.9 | | 7.1 | 52 | 41 | 7 |
| 15 | 1.4 | 0.15 | 0.16 | | | 14.3[g] | 63 | | 37 |
| 16 | 1.3 | 0.4 | 0.16 | | 0.6 | 14[g] | 30 | 3 | 67[e] |

[a] 80°, ~99% HOAc, under N$_2$. [b] Reaction followed visually; color of solution changes from dark brown to almost colorless. [c] Neutral products only. Some runs contained detectable amount of cyclohexylacetic acid and cyclohexylcarboxylic acid which were qualitatively identified. [d] Products in varying amounts include 2-acetoxycyclohexanone, cyclohexanol, cyclohexanone, and C$_{12}$H$_{22}$. [e] Products in the presence of Cu(II) consist largely of 3-cyclohexenyl acetate (98+%). [f] In absence of RH, Mn(III) solutions were stable for about 14 days under reaction conditions. [g] Arbitrary reaction time.

dards to determine the isomeric composition of products were not available. Likewise, acidic products formed, if any, were not determined.

**Oxidation of Cyclohexene with Cobaltic Acetate.** Reaction of olefin with cobaltic acetate gave 3-cyclohexenyl acetate as the major product (~80%), along with an unknown (~20%), which is thought to be the unsaturated ketocyclohexyl acetate ($C_8H_{10}O_3$, $m/e$ 154.0626).

**Oxidation of Cyclohexane with Manganic Acetate.** Reaction of cyclohexane with manganic acetate afforded three major products: cyclohexyl acetate (~86%), 2-acetoxycyclohexanone (~9%), and cyclohexylmethyl acetate (~3%). Minor products included traces of cyclohexanol, cyclohexanone, and bicyclohexyl. Products are identical with those obtained with cobalt salts, but their selectivities are different. Cyclohexylacetic acid formed in this experiment was only qualitatively detected.

**Effect of Added Acetate Ions.** Oxidation of cyclohexane with cobaltic acetate in the presence of added KOAc or NaOAc (expt 2, 3, 8) decreased the time required for reduction of the oxidant, but had no effect on selectivity. With manganic acetate, however, addition of KOAc (expt 13, 14) not only reduced the reaction time, but also changed prod-

## Table III
## Oxidation Products of Cycloaliphatic Substrates[a]

| Expt no. | Substrate, $M$ | Oxidant, Co$^{3+}$ or Mn$^{3+}$, $M$ | Cu(OAc)$_2$· H$_2$O, $M$ | KOAc, $M$ | NaOAc· 3H$_2$O, | Product distribution, molar ratio[b,c] | | | Remarks |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | ROAc | RCH$_2$OAc | Misc | |
| 17 | MCH, 1.3 | Co(III), 0.2 | | 0.6 | | 39 | 20[d] | 41 | Misc = alcohols, ketones, etc. |
| 18 | MCH, 0.7 | Co(III), 0.12 | 0.15 | | | 12 | | 88 | 82% methylcyclohexenyl acetates |
| 19 | 1,1-DMCH, 0.8 | Co(III), 0.13 | | | 1.0 | 66 | 7 | 27 | Alcohols, ketones |
| 20 | 1,1-DMCH, 0.6 | Co(III), 0.13 | 0.15 | | | 23 | | 77 | 68% dimethylcyclohexenyl acetates, several unknowns |
| 21 | MCH, 1.2 | Mn(III), 0.3 | | 1.6 | | 36 | 10 | 44 | |
| 22 | cis-1,2-DMCH, 1.5 | Co(III),[e] 0.5 | | | 1.3 | 40 | 8 | 52 | Alcohols, ketones, and several unknowns |

[a] 80–90°, ~98% HOAc, under N$_2$. Reactions were followed visually by a change in color of solution. [b] Neutral products only. No attempt was made to isolate acidic product formed (if any). [c] Isomeric distribution of products not determined. [d] =CHCH$_2$OAc/=CCH$_3$CH$_2$OAc ratio, ~3; i.e., 25% attack at the tertiary carbon. [e] Cobaltic acetylacetonate (The Harshaw Chemical Co.).

tively. GLC analysis of the product mixture showed the predominance of the 3-methyl- and the 4-methylcyclohexyl derivatives. Based on the ratio of the 3.8- and 4.0-ppm peaks in the NMR spectrum (=CHCH$_2$OAc vs. =C-CH$_3$CH$_2$OAc), 20–25% of the initial attack on RH occurred at the tertiary hydrogen site. Treatment of product with LiAlH$_4$ gave methylcyclohexanols (4-, 37%; 3-, 19%; 2-, 20%; and 1-, 24%), representing 70% of product.

**Oxidation of cis-1,2-Dimethylcyclohexane with Cobaltic Acetylacetonate.** The reaction of this substrate with Co(acac)$_3$ (Harshaw Chemical Co.) gave three major products: ROAc, ROH, and RCH$_2$OAc (molar ratios of 40, 46, and 8%, respectively). Treating the mixture with acetyl chloride converted alcohol to ROAc, doubling the amount of the latter on the chromatogram. The presence of RCH$_2$OAc adduct was detected by NMR. No attempt was made to determine the isomeric composition of products as standards were not readily available.

**Oxidation of 1,1-Dimethylcyclohexane with Cobaltic Acetate.** This substrate on oxidation gave ROAc and RCH$_2$OAc as identifiable products in molar ratios of 67 and 8%, respectively. The remainder of neutral fraction consisted of dimethylcyclohexanones, and several unidentified compounds which are thought to be dimethylcyclohexylidene diacetates and acetoxydimethylcyclohexanones, in analogy to the products of cyclohexane oxidation. Stan-

## Table IV
## Oxidation Products of Cyclohexene[a]

| Expt no. | Reactants, $M$ | | | | Product distribution, molar ratio[b] | | |
|---|---|---|---|---|---|---|---|
| | $C_6H_{10}$ | Co(OAc)$_3$ | NaOAc· 3H$_2$O | Cu(OAc)$_2$ ·2H$_2$O | ⟨⟩—OAc | ⟨⟩—OAc | Misc |
| 23 | 0.5 | 0.12 | 0.35 | | 78 | 2 | 20[c] |
| 24 | 0.5 | 0.12 | | 0.12 | 98 | 2 | |

[a] 80–85°, 98–99% HOAc, under N$_2$. [b] No acidic products were detected. Products isolated accounted for 45% of Co(III) consumed. [c] Unsaturated keto ester; $m/e$ 154.0626 ($C_8H_{10}O_3$).

uct selectivity. The magnitude of both effects was a function of the concentration of added nucleophile.

**Effect of Added Cupric Acetate.** The presence of cupric acetate in the oxidation of cycloaliphatic substrates with either Co(III) or Mn(III) acetates led in all instances to a dramatic change in the nature of the product. Products obtained were largely the saturated esters, which are normally derived from the oxidation of olefinic substrates only.

**Oxidation of Cycloaliphatic Substrates with Cobalt Salts and Oxygen.** Oxidation of cyclohexane in this system was earlier reported to give adipic acid. Methylcyclo-

## Table V
### Oxidation of Cycloaliphatic Substrates with Cobalt Salts and Oxygen[a,b]

| Expt no. | Substrate | 3-Methyl-adipic acid | 2-Methyl-adipic acid | Adipic acid | 3-Methyl-glutaric acid | 2-Methyl-glutaric acid | Glutaric acid | Methyl-succinic acid | Succinic acid |
|---|---|---|---|---|---|---|---|---|---|
| 25 | Methylcyclohexane[c] | 51.1 | 12.8 | Trace | 6.9 | 3.6 | 5.1 | 10.1 | 2.4 |
| 26 | 2-Methyl-cyclohexanone | | 22.8 | | | 11.7 | 20.3 | 23.8 | 11.4 |
| 27 | 3-Methyl-cyclohexanone | 45.3 | 15.9 | | (17.1) | | | 3.2 | 7.3 |
| 28 | 4-Methyl-cyclohexanone | 67.3 | | | | | | | |
| 29 | 3-Methyl-cyclohexanol | 51.5 | 22.7 | | (12.1) | | | Trace | Trace |
| 30 | 1,1-Dimethyl-cyclohexane | 52.9[d] | 21.4[e] | | | | | | |
| 31 | Ethylcyclohexane[c] | 51.8[f] | 10.6[g] | 10.3 | | | 12.2 | | 12.0 |

[a] 100–105°, 20 atm $O_2$, 1–3 hr. [b] Only major products were identified (wt %). They accounted for 77–91% of unrecovered substrate. [c] In the presence of a cooxidant, *n*-butane or *n*-pentane. RH conversions ranged from 35 to 51%. [d] 3,3-Dimethyl isomer. [e] 2,2-Dimethyl isomer. [f] 3-Ethyl isomer. [g] 2-Ethyl isomer.

hexane, 1,1-dimethylcyclohexane, and ethylcyclohexane were oxidized in the same system in present work to give the corresponding adipic acids as major products. 2-Methyl-, 3-methyl-, and 4-methylcyclohexanone and 3-methylcyclohexanol were also included in this study.

**Oxidation of Cyclohexane with Manganese Salts and Oxygen.** The reaction of cyclohexane with manganous acetate and oxygen, under conditions employed with cobalt, did not proceed readily. The reaction started, but after only 10–15 min, oxygen adsorption stopped. Analysis showed only traces of adipic acid. The major product was a mixture of neutral compounds consisting of cyclohexanone (~6%), cyclohexanol (~50%), cyclohexyl acetate (~35%), and smaller amounts of unidentified materials, corresponding to a cyclohexane conversion of <1%. It appears, therefore, that manganese salts are not effective oxidants for conversion of hydrocarbons to carboxylic acids under our mild conditions.
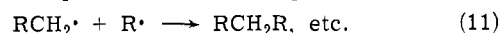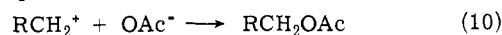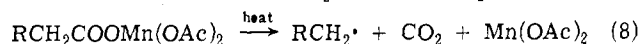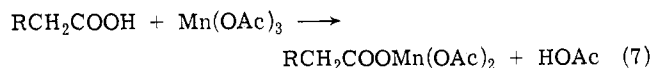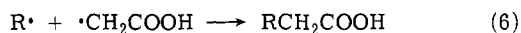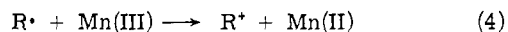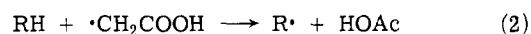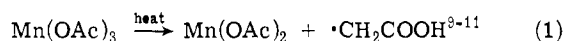
### Discussion

Liquid phase oxidations of aliphatic hydrocarbons with oxygen, in the presence of large amounts of cobalt salt dissolved in acetic acid, proceed at higher rates and lower temperatures than observed in classical autoxidations. Products of reaction are the corresponding carboxylic acids which contribute little to the understanding of the reaction mechanism. Interest in optimizing the oxidation of cyclohexane to adipic acid with cobalt acetate and oxygen led us to study the reaction of cyclohexane with Co(III) and also Mn(III) salts alone. Similar $\rho$ values for the reaction of alkylaromatics with cobaltic acetate in the presence or absence of oxygen (−2.4[1] vs. −2.66[8]) indicate identical rate-controlling steps in both systems. A similar situation was expected to exist in cycloaliphatic series on the basis of identical reactivities in the presence or absence of oxygen (Table VI).

Cycloaliphatic substrates react with metal oxidants to afford the corresponding ketones, alcohols, keto esters, geminate diesters, esters, some acids, and dimeric products. The ratio of products depend on the substrate, metal oxidant, and experimental conditions. Several mechanisms by which these products could arise have been previously reported.[6] We have now established cyclohexylmethyl acetate as the major product of the reaction between cyclohexane and cobaltic acetate. This ester ($C_9H_{16}O_2$, *m/e* 156.1134) was isolated by chromatography and character-

ized by NMR and ir by comparing the spectra with those of an authentic sample [$CCl_4$, $Me_4Si$: 3.85 ppm (d, 2 H, $-CH_2O-$), 2.0 (s, 3 H, $-OAc$), and 0.7–1.9 (m, 11 H, ring protons)]. 2-Acetoxycyclohexanone, earlier believed to be the major product, is also present, but only as a minor component ($C_8H_{12}O_3$, *m/e* 156.0794). In contrast, oxidation of cyclohexane with manganic acetate produced mostly cyclohexyl acetate with only minor amounts of $RCH_2OAc$ adduct, indicative of different pathways with the two salts.

Cyclohexylacetic acid and some cyclohexanecarboxylic acid constituted the acid product isolated from cyclohexane oxidation with cobalt or manganese salts. Their mechanism of formation is in question. Coupling of cyclohexyl and carboxymethyl radicals is one possibility.[22]

Isolation and identification of most of the reaction products allows a reasonable conclusion to be made with regards to reaction mechanism. Based on the literature, the following steps appear reasonable with manganic acetate as oxidant.

$$Mn(OAc)_3 \xrightarrow{heat} Mn(OAc)_2 + \cdot CH_2COOH^{9-11} \quad (1)$$

$$RH + \cdot CH_2COOH \longrightarrow R\cdot + HOAc \quad (2)$$

$$2R\cdot \longrightarrow R-R \quad (3)$$

$$R\cdot + Mn(III) \longrightarrow R^+ + Mn(II) \quad (4)$$

$$R^+ + OAc^- \longrightarrow ROAc \quad (5)$$

$$R\cdot + \cdot CH_2COOH \longrightarrow RCH_2COOH \quad (6)$$

$$RCH_2COOH + Mn(OAc)_3 \longrightarrow$$
$$RCH_2COOMn(OAc)_2 + HOAc \quad (7)$$

$$RCH_2COOMn(OAc)_2 \xrightarrow{heat} RCH_2\cdot + CO_2 + Mn(OAc)_2 \quad (8)$$

$$RCH_2\cdot + Mn(III) \longrightarrow RCH_2^+ + Mn(II) \quad (9)$$

$$RCH_2^+ + OAc^- \longrightarrow RCH_2OAc \quad (10)$$

$$RCH_2\cdot + R\cdot \longrightarrow RCH_2R, etc. \quad (11)$$

Similar reactions could occur with the cobalt oxidant, but involving thermolysis of a different nature.[1]

$$Co(OAc)_3 \longrightarrow Co(OAc)_2 + CH_3\cdot + CO_2 \quad (12)$$

$$CH_3\cdot + HOAc \longrightarrow CH_4 + \cdot CH_2COOH \quad (13)$$
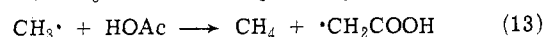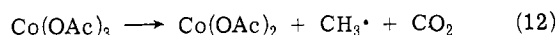
These mechanisms are controlled by thermolysis, consistent with results from manganese salt reactions in which oxidation rates parallel those of thermolysis. With an acetic acid solution of 0.4 *M* Mn(III) and 1.5 *M* $C_6H_{12}$, for exam-

## Table VI
### Relative Reactivities per Molecule[a]

| Substrate | Co(III), 78° | Co(III), O₂, 100°, 20 atm |
|---|---|---|
| Ethylbenzene | 1.2 (1.3)[c] | 1.2 |
| cis-1,2-Dimethylcyclohexane | | 1.1 |
| Toluene[b] | 1.0 | 1.0 |
| 1,1-Dimethylcyclohexane | 0.8 | |
| trans-1,2-Dimethylcyclohexane | | 0.6 |
| Cyclohexane | 0.5 | 0.5 |
| Cyclohexane-$d_{12}$ | ~0.4 (0.4)[d] | |
| Cumene | (0.3)[c] | 0.2 |
| Methylcyclohexane | 0.2 | 0.2 |
| trans-1,4-Dimethylcyclohexane | | ~0.1 |

[a] Reactivities obtained by competitive oxidations earlier described.[6] Rates were based on disappearance of RH and related to toluene by $k_a/k_b = \log([A]_f/[A]_i)/\log([B]_f/[B]_i)$, where [A] and [B] refer to concentrations of the two substrates before and after the reaction in wt % [~0.4 $M$ Co(III)/HOAc, 0.8 $M$ RH, and 0.4 $M$ chlorobenzene as internal standard.] [b] Assumed standard, reactivity 1.0. [c] From ref 1, 65°. [d] In the presence of 0.2 $M$ Cu(OAc)₂·H₂O, 70°.

ple, it required 13 days for the oxidant to be consumed (80°), approximately the same time as in the absence of RH. With cobalt acetate, however, reactions 12 and 13 cannot be the sole or major contributors, as oxidation are at least twice as fast as thermolysis. It took only 2 days for a 0.4 $M$ Co(III) solution to be reduced in the presence of $C_6H_{12}$ (1.4 $M$), while 4–6 days were needed for complete reduction without substrate. While the data could be consistent with a free-radical pathway, propagation through cobalt cannot be excluded (eq 14).

$$C_6H_{12} + Co^{3+} \longrightarrow C_6H_{11}{}^{\cdot} + Co^{2+} + H^{\cdot} \quad (14)$$
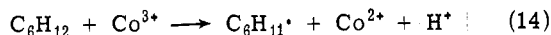
In addition to thermolysis, electron transfer may also be assumed, leading to products identical with those from thermolysis. Waters et al.[23] found the oxidation of cyclohexane with Co(III) ions and oxygen to follow the same rate law as simple alkylbenzenes,[8] with rates being of comparable order. This is believed to be indicative of σ-bond involvement as condensed polycyclic aromatics—biphenyl, naphthalene, and phenanthrene—reacted at rates several orders of magnitude greater than toluene, most likely involving π electrons instead. The rates of Co(III) disappearance and oxygen consumption in this system for the cycloaliphatic[7] and alkylaromatic[14] substrates both followed the expression $-d[Co(III)]/dt = k_1[RH][Co(III)]^2/[Co(II)]$ and $-d[O_2]/dt = k_2[RH][Co(III)]^2/[Co(II)]$. Since electron transfer is now an accepted concept for the oxidation of aromatic substrates, to assume the same for cycloaliphatic hydrocarbons is not considered unreasonable.[24]

Results in Tables I and II show that oxidation of cyclohexane with manganic acetate is more selective than with cobalt. We confirm that cyclohexyl acetate is the major product from cyclohexane oxidation with manganic acetate.[12] Selectivity is attributed to slow formation of radicals with manganic acetate (reaction 1). Cobaltic acetate is a more powerful oxidant and therefore less selective. With Co(III), radicals can be generated by both electron transfer and thermolysis at higher rates and in higher concentrations than with manganese to afford a more complex product. Increasing the concentration of radicals in the manganese system through addition of nucleophiles causes product ratios to approach those with cobalt. Addition of acetates (KOAc or NaOAc) in cyclohexane oxidations with Co(III) led to rate enhancement, but had no appreciable ef-

fect on product distribution. With manganese, however, both rate and amount of RCH₂OAc adduct increased with rising acetate ion concentration. Such an effect was earlier reported for oxidations of alkylbenzenes with both cobalt and manganese. Results are comparable to those with the cycloaliphatic substrates. They are in agreement with an electron transfer pathway for cobalt, and a free-radical one for manganese. In analogy to work reported with lead salts,[13] a Mn(OAc)₄⁻ complex was suggested in the presence of added acetate ions, assumed to be more active than Mn(OAc)₃ alone.[10] The same is also true of cobalt.[14]

We also compared cyclohexane oxidations with cobalt to those with manganese salts in the presence of cupric acetate. Cu(II) ions were earlier shown to be effective radical terminators, the rate of termination of simple alkyl radicals being diffusion controlled. Copper oxidizes stable radicals (allyl, benzyl, and tert-butyl) to carbonium ions, and converts less stable radicals to olefins.[15] If thermolysis were involved in initiation with cobalt, methyl radicals produced would be trapped by Cu(II), as no products of cyclohexane can be formed. Initiation by electron transfer, however, produces cyclohexyl radicals directly which can be oxidized by Cu(II) to form cyclohexane-derived products. On this basis, data in Tables I–III suggest electron transfer as the sole or dominating mechanism operating in cyclohexane oxidation with cobaltic acetate. Electron transfer in oxidation of cyclohexane with manganic acetate is a probable contributor, at least in experiments with added nucleophiles. Increased formation of cyclohexylmethyl acetate in the absence of copper, and olefin formation in its presence, can be rationalized by assuming this pathway.

The most pronounced effect of copper on the course of reaction is elimination of the RCH₂OAc adduct and formation of unsaturated esters with both cobalt and manganese. Oxidation of cyclohexane with cobaltic acetate and copper led to the formation of 3-cyclohexenyl acetate (~94%), 1-cyclohexenyl acetate (~2%), and cyclohexyl acetate (~4%). With manganese and copper, however, 3-cyclohexenyl acetate and cyclohexyl acetate were formed in 37 and 61% yield, respectively. Unlike with cobalt, considerable amounts of cyclohexyl acetate are still formed with added cupric acetate when manganic acetate is the oxidant. This suggests an additional pathway immune to the radical scavenger, and as yet not elucidated.

Formation of unsaturated esters in the presence of copper proceeds through cyclohexene. With cobaltic acetate, reaction involves radical cations,[16] but with manganese, a direct allylic abstraction.[17]
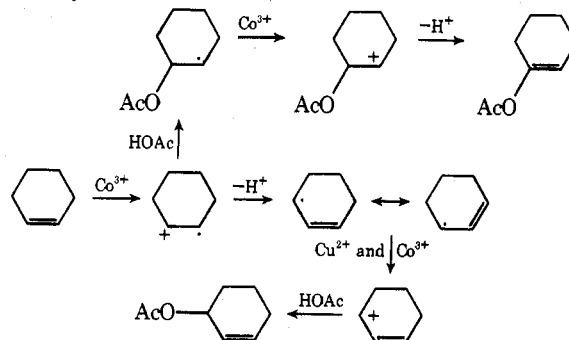


Results with copper ions as cooxidant appear significant from a practical as well as theoretical point of view. Conversion of aliphatic substrates to olefinic derivatives by this route may have general preparative value.

## Conclusion

Our postulate that electron transfer is at least a contributing and most likely the dominant mechanism in the oxi-

<div align="center">

**Table VII**
**Characterization of Major Products**[b]

</div>

| Compd | Formula | Mol wt P⁺, m/e[c] | NMR (CCl₄, Me₄Si) |
|---|---|---|---|
| Cyclohexylmethyl acetate | $C_9H_{16}O_2$ | 156.1150 156.1134 | 3.85 (d, 2 H, CH₂O), 2.0 (s, 3 H,OAc), 0.7–1.9 (m, 11 H, ring) |
| Cyclohexyl acetate | $C_8H_{14}O_2$ | 142.0994 142.0982 | 4.7 (s, 1 H, ═CHO); 2.0 (s, 3 H, OAc), 1.0–1.9 (m, 10 H, ring) |
| 2-Acetoxycyclohexanone | $C_8H_{12}O_3$ | 156.0786 156.0794 | 4.85–5.4 (m, 1 H, ═CHO–), 2.3 (m, 2 H, CH₂CO), 2.1 (s, 3 H, OAc), 1.3–2.0 (m, 6 H, ring) |
| Cyclohexylacetic acid | $C_8H_{14}O_2$ | 142.0994 142.0987 | (Me₂SO-$d_6$, Me₄Si): 1.0–2.7 (broad multiplet with some fine structure) |
| Cyclohexanecarboxylic acid | $C_7H_{12}O_2$ | 128.0837 128.0858 | 0.6–2.6 (broad multiplet with some fine structure, 11 H, ring), 11.6 (s, 1 H, COOH, exchangeable) |
| 3-Cyclohexenyl acetate[a] | $C_8H_{12}O_2$ | 140.0837 140.0842 | 5.9 (m, 2 H, olefin), 5.3 (s, 1 H, ═CHO), 2.0 (s, 3 H, OAc), 1.0–1.9 (m, 6 H, ring) |

[a] Major product isolated from a comparable run in the presence of 0.001 $M$ Cu(OAc)₂. [b] Minor products were detected by doping with standards. They included cyclohexanone, cyclohexanol, cyclohexylidene diacetate, and some dimers. [c] Calculated over found.

dation of cycloaliphatic substrates with cobalt is based on manifestations such as high rates at low temperature, high product selectivity, and relative inactivity of tertiary hydrogen, observations among others closely paralleling those with aromatic substrates. Free-radical processes must also occur and experimental conditions will determine their contribution. The extent to which electron transfer contributes will depend on the oxidation potential of the metal ion couple, the ionization potential of RH, experimental conditions in general, and, in the presence of oxygen, on the ability to regenerate the higher valency state of the metal. The requirements for electron transfer to operate with cycloaliphatics and cobalt appear to be well met in the light of these criticalities.

## Experimental Section

Oxidations at elevated pressure were carried out in a 1-l., 316 stainless steel, magnetically stirred autoclave which was equipped with a Dispersomax stirrer, a heating mantle, and cooling coils (Autoclave Engineers, Inc., Erie, Pa.). Molecular oxygen was used as the oxidant, introduced into the reactor through a medium porosity, 2-in. o.d., stainless steel sparger and was supplied at the rate at which it was consumed. Experiments with metal salts alone were carried out in standard laboratory glassware under nitrogen. Concentrations of metal ions were determined by iodometric titration. Products of reaction were analyzed by GLC by doping with standards and confirmed by mass spectrometry. Carboxylic acids were analyzed as trimethylsilyl derivatives on Varian 1520, T. C. detector, chromatograph (6 ft × 0.25 in., OV-1 column, programmed from 50 to 275° at 10°/min). Other analyses were carried out on a 5 ft × 0.25 in. 20% Carbowax 20M column at 65°. The NMR spectra were obtained on a Varian T-60 spectrometer. Chemical shifts are in δ units, in parts per million.

**Cobaltic Acetate (Method 1).** This oxidant was prepared from cobaltous acetate and *tert*-butyl hydroperoxide. To 100 g of Co(OAc)₂·4H₂O in 2 l. of methanol, heated under reflux, was added with stirring over a 1-hr period 38 g of 90% *t*-BuOOH (Lucidol). Reaction was continued for an additional 1 hr and methanol solvent was stripped off on a rotary evaporator and replaced with 1.5 l. of acetic acid. The resulting solution was concentrated to ~350 ml, which was 0.37 $N$ Co(III), or 32%.

**Cobaltic Acetate (Method 2).** This oxidant was prepared from cobaltous acetate, MEK, and oxygen. A mixture containing 100 g of Co(OAc)₂·4H₂O and 15 g of water in 1 l. of acetic acid was heated to 90°. With oxygen being passed through a medium porosity sparger immersed in the solution (~1–2 l./hr), 350 ml of MEK was added over a period of 1 hr. Reaction was continued for 6 hr and the mixture was concentrated to about 360 ml. Titration showed it to be 0.34 $N$ Co(III).

**Oxidation of Cyclohexane with Cobaltic Acetate. Material Balance Run.** In a typical experiment a 1.2 $M$ cyclohexane solution containing 150 mmol of sodium acetate trihydrate, and 100 mmol of cobaltic acetate [28% Co(III)] in 520 ml of acetic acid was

heated at 80° (N₂ atmosphere, 28 hr) until the color of solution changed from dark green to purple. The reaction mixture was cooled and then 3.5 mmol of cyclohexyl chloride was added as an internal standard. The solution was diluted with 500 ml of ethyl ether and extracted three times with cold water (400–500-ml portions), once with 5% NaHCO₃ solution, and water. After drying the organic layer over magnesium sulfate and filtering, the mixture was concentrated in a rotary evaporator and analyzed by GLC. Analysis showed the sample to contain 1.6 mmol of cyclohexylmethyl acetate, 1.3 mmol of cyclohexyl acetate, and 0.6 mmol of 2-acetoxycyclohexanone. The aqueous layer was evaporated to dryness, treated with 25 ml of concentrated hydrochloric acid to release any acidic products tied up with the cobalt, and evaporated to dryness. After adding 3.5 mmol of octanoic acid as internal standard, the residue was extracted with acetone, dried over magnesium sulfate, filtered, and analyzed by GLC. Analysis showed the sample to contain 1.8 mmol of cyclohexylacetic acid and 0.35 mmol of cyclohexanecarboxylic acid. The products thus isolated account for about 65% of Co(III) ions consumed. The aqueous layer contained additional products (cyclohexanone and cyclohexanol) in trace amounts, but these were not isolated.

Identification of products was carried out by GLC by comparing relative retention times to those of authentic samples. Most authentic samples were commercially available. Cyclohexylmethyl acetate and 3-cyclohexenyl acetate were synthesized by a standard acetylation procedure employing acetyl chloride and the commercially available cyclohexylmethanol and 3-cyclohexen-1-ol.

Major components in a product mixture were also collected off the gas chromatographic column and further characterized by mass spectrum, NMR (Table VII), and ir.

**Attempted Oxidation of Methylcyclohexane.** A mixture consisting of 20 g of Co(OAc)₂·4H₂O, 20 g of MEK, 60 g of hydrocarbon, and 400 g of acetic acid was treated with oxygen (105°, 20 atm total pressure, 4 hr) under conditions earlier employed to prepare adipic acid from cyclohexane.[6] Reaction starts as noted by oxygen uptake, but after about 30 min of reaction, whenever MEK is consumed, reaction stops. Continued heating up to 48 hr showed no evidence of any reaction of the substrate.

**Cooxidation of Methylcyclohexane and *n*-Butane.** The above experiment was repeated in the presence of 95 g of butane (105°, 20 atm, 3 hr) to afford 563 g of liquid reaction product. This mixture was diluted with 500 ml of water, recovering unreacted methylcyclohexane by decanting, and then evaporated to dryness in a rotary evaporator. The residue was extracted several times with acetone to afford 42.2 g of dicarboxylic acids. Analysis by GLC showed methyladipic acids (63.9% efficiency), methylglutaric acids (10.5%), and methylsuccinic acid (10.1%) to be major products. Minor products included glutaric acid and succinic acid, but no adipic acid. Conversion of methylcyclohexane was estimated at ~50%. The ratio of the 3-methyladipic acid to its 2-methyladipic isomer was 4:1, and with glutaric acids it was 1.9:1. No material balance on butane was obtained in this experiment. Results were assumed to be comparable to those of our earlier study.[5]

**Oxidation of 4-Methylcyclohexanone.** Forty grams of this ketone was oxidized as above in absence of butane (104°, 17 atm, 1.5 hr) to afford 488 g of liquid product. This product was diluted with

200 ml of water, heated on a steam bath until the color of solution had turned from dark green to pink, and then it was evaporated to dryness. Extraction of residue with acetone gave 41.3 g of product. Analysis by VPC showed this material to be 92% 3-methyladipic acid (67% yield). None of the 2-methyl isomer was detected. Recrystallization from benzene afforded pure product [mp 91–92° (lit.[18] mp 89–91°)]: NMR (Me$_2$SO-$d_6$, Me$_4$Si) 0.9 (d, 3, CH$_3$), 1.5 (m, 2, CH$_2$CH$_2$COOH), 1.8–2.6 (m, 5, –CH=, CH$_2$COOH); neut equiv, 80.8 (calcd, 80).

**Preparation and Dehydration of 3,3-Dimethylcyclohexanol.** About 100 g (0.7 mol) of 5,5-dimethyl-1,3-cyclohexanedione in 600 ml of methanol was reduced in the presence of 20 g of nickel 0104P catalyst (Harshaw) in a 1-l., 316 stainless steel autoclave (200°, 100 atm H$_2$, 6 hr). The crude reaction mixture was filtered to recover the catalyst and methanol was distilled off to give 95 g of colorless liquid product which was mostly alcohol by ir: $n^{20}$D 1.4625 [lit.[19] bp 80–81° (16 mm), $n^{25}$D 1.4569]; NMR (CCl$_4$, Me$_4$Si) 0.89 (s, 3, CH$_3$), 0.93 (s, 3, CH$_3$), 1.1–2.1 (m, 8, CH$_2$), 3.1 (s, 1, exchangeable proton, OH), 3.62 ppm (m, 1, =CH–).

The reaction product was transferred to a 200-ml flask and distilled in the presence of 5 g of p-toluenesulfonic acid. The product distilling in the temperature range of 85–130° was collected, separated from water, dried (MgSO$_4$), and redistilled to give 56 g (71%) of ~35:65 mixture of 3,3- and 4,4-dimethylcyclohexene, bp 114–118° (lit.[20] bp 115.2–116.2°).

**Preparation of 1,1-Dimethylcyclohexane.** About 98 g of olefinic mixture prepared by the above procedure was hydrogenated in the presence of 20 g of nickel 0104P catalyst in 600 ml of methanol (145°, 95 atm, 2 hr). The reaction mixture was filtered, but isolation of 1,1-dimethylcyclohexane by distillation was not successful. Instead, the reaction mixture was diluted with ~2 l. of water and the organic layer was separated, dried (MgSO$_4$), and redistilled to give 86 g (87%) of 1,1-dimethylcyclohexane: bp 116–119° (lit.[21] bp 119.65°); NMR (CCl$_4$, Me$_4$Si) 0.88 (s, 6, CH$_3$), 1.1–1.6 (m, 10, CH$_2$).

**Oxidation of 1,1-Dimethylcyclohexane.** A mixture consisting of 20 g of cobaltous acetate tetrahydrate, 400 g of acetic acid, 20 g of MEK, and 60 g of 1,1-dimethylcyclohexane was oxidized to afford 537 g of crude reaction mixture (106°, 20 atm, 3 hr). This mixture was diluted with 1 l. of water to recover unreacted substrate, heated on a steam bath until solution had turned from dark green to pink, and evaporated to dryness. The residue was extracted with acetone to afford 43 g of acids. Analysis by NMR and VPC showed 3,3-dimethyl- and 2,2-dimethyladipic acid (3:1 ratio, based on areas of two singlet gem-dimethyl groups at 1.05 and 1.18 ppm, respectively) to be the major products of reaction (73%, 57% conversion). Minor products were not characterized.

Other substrates such as ethylcyclohexane, 3-methylcyclohexanone and 3-methylcyclohexanol, and 2-methylcyclohexanone were oxidized under similar conditions and are summarized in Table V.

**Oxidation with Cobaltic and Manganic Salts.** Experiments with metal salts alone were carried out in standard laboratory glassware. Conditions employed, substrates oxidized, and the results obtained are summarized in Tables I–III. After termination of reaction, noted by a change in color resulting solution (green to pink for cobalt, and brown to colorless for manganese), the mixture was taken up in ethyl ether and repeatedly extracted with cold water. The organic layer was dried (MgSO$_4$) and filtered, and the ether was evaporated. After carefully stripping off the unreacted substrate in a rotary evaporator, the residue was subjected to chromatographic analysis. Products of reaction were confirmed by doping with standards whenever possible as well as by mass spectrometry. Manganic acetate was prepared by a published procedure.[3] Concentrations of metal ions were determined by iodometric titration.

**Oxidation of Cyclohexane with Manganic Acetate and Oxygen.** A mixture of 20 g of Mn(OAc)$_3$·4H$_2$O, 20 g of MEK, and 60 g of cyclohexane in 400 g of acetic acid was treated with oxygen (115°, 20 atm) for 3 hr. The autoclave was cooled, depressured, and its content of 505 g withdrawn. This mixture was diluted with an equal volume of cold water, recovering 38 g of unreacted substrate by decanting, and extracted with ethyl ether. The organic layer was washed three times with water and once with dilute sodium bi-

carbonate solution, and dried over MgSO$_4$. On evaporation to dryness, about 1 g of organic residue was recovered. Analysis by GLC showed cyclohexanone (6%), cyclohexanol (50%), cyclohexyl acetate (35%), and smaller amounts of cyclohexylidene diacetate, 2-acetoxycyclohexanone, and several unidentified compounds to be in the residue. The initial aqueous layer was also evaporated to dryness, but the residue from this treatment contained only a trace of adipic acid. For practical purposes, therefore, no reaction occurred. This of course is in contrast to excellent results obtained with cyclohexane in the cobalt system.

**Reactivity Data.** Reactivities were determined by a competitive oxidation procedure.[6] Oxidations with cobaltic acetate were carried out under nitrogen in sealed ampoules [0.4 M Co(III)/ HOAc, 0.8 M RH, and 0.4 M chlorobenzene as internal standard]. Reactivities under oxygen pressure were carried out in an autoclave, generating Co(III) ions in situ from reaction of cobaltous acetate and MEK in the presence of oxygen. A typical charge consisted of 20 g of Co(OAc)$_2$·4H$_2$O, 20 g of MEK, 60 g of n-butane, and 10–15 g of each RH in 450 g of acetic acid. After an induction period of ~30 min at 100° and 20 atm, reaction was continued for ~5 min. Reactivities were based on the disappearance of RH and were related to toluene, an assumed standard.

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