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A STUDY OF THE MECHANISM AND APPLICATIONS OF COPPER CATALYSED FREE RADICAL REACTIONS.

A Thesis
presented for the Degree of
Doctor of Philosophy
in the
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by

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I would also like to thank Professor G.M. Badger for his interest and advice and other members of the department for helpful discussion.

STATEMENT

The work described in this thesis incorporates no material previously submitted for a degree in any University, and to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference is made in the text.

(Geoffrey W. Evans)

CONTENTS

page

INTRODUCTION

DISCUSSION

(a) Mechanistic Studies

EXPERIMENTAL

SUMMARY

An investigation into metal-ion catalysed reactions between organic peroxy compounds and active hydrogen-atom donor substrates has shown that transient free radicals undergo oxidation and reduction by the metal ions during the course of these reactions.

The extent to which a given substrate radical can be oxidized by cupric ions is dependent upon several factors. The experiments have shown that these factors include the stability of the free radical, the stability of the carbonium ion which would result from such an oxidation, and the availability of the unpaired electron at the free-valency site. This last criterion is clearly dependent upon the influence of substituent groups adjacent to the free-valency site.

In nearly all the peroxy reactions studied in this work, the copper ion catalyst always acts as a <u>true</u> catalyst, whereby only a trace of the copper salt is required to catalyse every reaction to completion. This surely indicates that the catalyst is being continuously oxidized and reduced throughout the course of the reaction. The initial step in all these peroxy reactions is the reduction of the peroxy compound by cuprous ions. Invariably the identity of the peroxy compound was such that this initial step resulted in

the formation of *t*-butoxy radicals. The *t*-butoxy radicals were required to abstract the active hydrogen-atom from the substrate molecule, hence substrate molecules, in which the C-H bond dissociation energy is high, are not successful participants in these oxidation reactions.

Certain free radicals which were very unstable, *e.g.* those derived from formate esters (CCXIII, CCXV, CCXX, CCXXXI, CCXXXVII), were found to decompose more rapidly than to undergo oxidation. The relatively stable decomposition products were then oxidized by the cupric ions.

There was evidence, also, of a carbonium ion (CCVIII) preferentially decomposing into more stable products rather than reacting with added anions. In general, however, a given free radical did not readily oxidize by an electron-transfer mechanism if the resultant carbonium ion was very unstable. Such a radical could readily be oxidized by a ligand-transfer mechanism, however.

The nature and mechanism of the specific acyloxylation of olefinic substrates with *t*-butyl peresters in the presence of cuprous salts was investigated. The apparent isomerization of all non-terminal double bonds to the terminal position, and also the lack of isomerization of terminal double bonds during these reactions, was explained by the difference in energy of the two possible transition states (CLXXV and CLXXVI). Since copper ion-olefin π-complexes are less stable when the double bond is sterically hindered by substituent groups, the transition state with a non-terminal double bond (CLXXV) was considered to be of higher energy than the transition state with the terminal double bond (CLXXVI). This hypothesis was supported by experiments with cycloalkenes, where the double bond always migrated to the least sterically hindered position. All acyloxylations of olefins are believed to proceed by a ligand-transfer mechanism.

The mechanism and synthetic scope of metal-ion catalysed hydroperoxide reactions in the presence of substrate was also studied. Such reactions, when carried out in the presence of added anions, gave an unlimited range of ester products, depending upon the substrate used and the added anion. This was an advantage over the corresponding catalyse perester reactions which were confined to the formation of acetates and benzoates.

The use of these metal-ion catalysed peroxy reactions as a synthetic tool in the steroid field was also examined.

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INTRODUCTION

(a) GENERAL

Since the early days of organic chemistry, transition metal salts have been used to catalyse reactions of organic peroxides. Fenton[1] originally found that tartaric acid was readily oxidized by aqueous-hydrogen peroxide in the presence of a trace of ferrous sulphate. A mechanism for this induced-decomposition of hydrogen peroxide by ferrous ions was later suggested by Haber and Weiss[2] as follows:

$$H_2O_2 + Fe^{2+} \longrightarrow \cdot OH + OH^- + Fe^{3+} \qquad (1)$$

$$\cdot OH + Fe^{2+} \longrightarrow OH^- + Fe^{3+} \qquad (2)$$

$$\cdot OH + H_2O_2 \longrightarrow H_2O + HO_2\cdot \qquad (3)$$

$$HO_2\cdot + H_2O_2 \longrightarrow \cdot OH + H_2O + O_2 \qquad (4)$$

Only in the last twenty five years, however, has there been serious study devoted to this and related reactions. Indeed, before this period, the existence of free radicals in solution as transient-intermediates in reactions was accepted by very few chemists.[3] The presence of organic free-radicals in the vapour-phase had been proved several years earlier when Paneth and Hofeditz[4] obtained free methyl radicals from the thermal-decomposition of lead tetramethyl. This discovery followed the much earlier observation of Gomberg[5,6] who treated triphenylmethyl chloride solutions with zinc dust or silver powder in an attempt to prepare hexaphenylethane, but instead obtained very reactive transient-intermediates. He concluded that the hexaphenylethane had dissociated into triphenylmethyl-radicals.

$$(C_6H_5)_3.C.C.(C_6H_5)_3 \rightleftharpoons 2(C_6H_5)_3.C. \qquad (5)$$

The catalytic effect of transition-metal salts upon free radical reactions is essentially one of oxidation and reduction. In such reactions organic free-radicals are either reduced to anions or oxidized to cations depending upon the valency-state of the metal-catalyst and the type of radical in question.

$$R. + M^{n+} \longrightarrow R^{+} + M^{(n-1)+} \qquad (6)$$

$$R'. + M^{n+} \longrightarrow R'^{-} + M^{(n+1)+} \qquad (7)$$

The Fenton-reaction, the Sandmeyer-reaction and the Meerwein-arylation reaction all involve this basic principle of oxidation and reduction of free-organic radicals. Since all three reactions are conducted in aqueous solution, the conditions are most favourable for electron-transfer between the metal-ions and substrate-radicals. As will be shown later, however, the oxidation and reduction of organic free-radicals by metal-ions can occur in non-polar solvents by a ligand-transfer process.

The mechanism suggested by Haber and Weiss[2] for the Fenton-reaction (1-4) was the first such mechanism to imply that metal-ions can oxidize or reduce free radicals. In this example, hydroxyl-radicals are reduced to hydroxide-ions by ferrous sulphate.

Evans *et al*[7,8] studied the behaviour of methyl acrylate and acrylonitrile in the presence of hydrogen peroxide and ferrous sulphate. Their experiments supported the Haber-Weiss mechanism and showed that under these conditions, polymerization of the olefin occurred and very little oxygen was evolved. The following sceme was suggested

$$H_2O_2 + Fe^{2+} \longrightarrow \cdot OH + OH^- + Fe^{3+} \qquad (1)$$

$$\cdot OH + CH_2{:}CHR \longrightarrow HO.CH_2.\dot{C}HR \qquad (8)$$

$$HO.CH_2.\dot{C}HR \longrightarrow \text{polymers} \qquad (9)$$

Subsequent work by Merz and Waters,[9,10] Mackinnon and Waters,[11] and Baxendale and Magee[12] also supported the Haber-Weiss mechanism and demonstrated the versatility of the Fenton-reaction.

Mackinnon and Waters[11] suggested that free radicals and their corresponding ions could form thermodynamically-reversible oxidation-reduction systems.

$$R\cdot \rightleftharpoons R^{+} + e, \quad E(-e) \qquad (10)$$

$$R'\cdot + e \rightleftharpoons (R'{:})^{-}, \quad E(+e) \qquad (11)$$

They concluded that free radicals formed by the Fenton-reaction from suitable substrates and having $E(-e)$ much lower than that of the $Fe^{3+} - Fe^{2+}$ system, should be oxidized readily by ferric ions to the appropriate carbonium ions. Thus primary alcohols yielded aldehydes (12), and secondary alcohols produced ketones (13).

$$RCH_2.OH \xrightarrow{.OH} R\dot{C}H\cdot OH \xrightarrow{Fe^{3+}} R\overset{+}{C}H\cdot OH \longrightarrow RCHO \qquad (12)$$

$$R_2CH\cdot OH \xrightarrow{\cdot OH} R_2\dot{C}\cdot OH \xrightarrow{Fe^{3+}} R_2\overset{+}{C}\cdot OH \longrightarrow R_2CO \qquad (13)$$

Similarly, aldehydes were obtained from ethers and amino acids, while hydroxy acids yielded α-keto acids. All these oxidations proceeded by a chain-mechanism, in which a trace-amount of ferrous salt readily catalysed the reaction to completion. Merz and Waters[9,10] represented this chain-oxidation process by the following steps:

$$Fe^{2+} + H_2O_2 \longrightarrow Fe^{3+} + \cdot OH + OH^- \qquad (1)$$

$$Fe^{2+} + \cdot OH \longrightarrow Fe^{3+} + OH^- \qquad (2)$$

$$RH + \cdot OH \longrightarrow R\cdot + H_2O \qquad (14)$$

$$R\cdot + H_2O_2 \longrightarrow ROH + \cdot OH \qquad (15)$$

The oxidation step (15) was later replaced by a two-step sequence:[13,14]

$$R\cdot + Fe^{3+} \longrightarrow R^+ + Fe^{2+} \qquad (16)$$

$$R^+ + H_2O \longrightarrow ROH + H^+ \qquad (17)$$

These workers also found that all the compounds which underwent this chain-oxidation in the Fenton-reaction, also readily reduced mercuric ions and molecular iodine to mercurous ions and iodide ions respectively.

$$CH_3\cdot\dot{C}H\cdot OH + Hg^{2+} \longrightarrow CH_3\cdot\overset{+}{C}H\cdot OH + Hg^{+} \tag{18}$$

$$CH_3\cdot\overset{+}{C}H\cdot OH \longrightarrow CH_3\cdot CHO + H^{+} \tag{19}$$

$$2CH_3\cdot\dot{C}H\cdot OH + I_2 \longrightarrow 2I^{-} + 2CH_2\cdot\overset{+}{C}H\cdot OH \tag{20}$$

Mackinnon and Waters[11] suggested that the redox potentials of the $Fe^{3+} - Fe^{2+}$, $Hg^{2+} - \frac{1}{2}(Hg_2)^{2+}$, and $\frac{1}{2} I_2 - I^{-}$ systems were so close, that each system was capable of oxidizing the same radicals.

Merz and Waters[9] found that compounds which contained electron-attracting groups failed to undergo chain-oxidation in the Fenton-reaction. These reactions needed large quantities of ferrous salt to complete the oxidation and in all cases the radical-intermediates failed to reduce mercuric ions or molecular iodine.

It was suggested that the chain-continuing steps (15,16,17) did not occur in these reactions. Instead, the substrate-radical combined with a hydroxyl-radical (21) or dimerized (22)

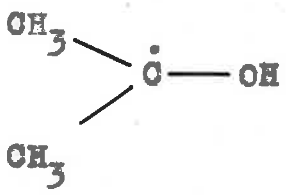
$$R\cdot + \cdot OH \longrightarrow ROH \qquad (21)$$

$$2R\cdot \longrightarrow RR \qquad (22)$$

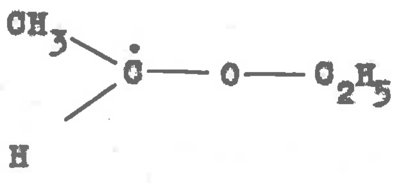
Compounds which failed to undergo chain-oxidation included chloral hydrate, esters, carboxylic acids and amines. Thus ethyl acetate, propionic acid, and diethylamine each yielded acetaldehyde when treated with ferrous sulphate (1 mole).

The failure of this latter group to react by equations (15-20) was attributed to a much higher value of E(-e) for the appropriate radicals.

The differences in the redox potentials between these two classes of radicals were ascribed to the polar-effects of substituent-groups. Merz and Waters[9] suggested that the inductive effect of alkyl groups would increase the availability of the unpaired-electron at the free valency site.

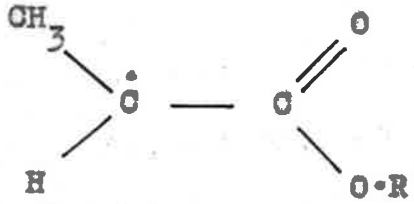


(I)



(II)

Conversely, the strong electron-attracting character of carboxylic acid groups and ester groups would reduce the availability of the odd-electron at the free valency site.

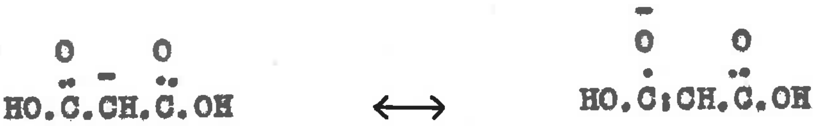


(III)

It was concluded that radicals derived from alcohols (I) and ethers (II) were more likely to be oxidized by the chain process (15-17) than would radicals derived from acids and esters (III) whose unpaired-electron is not readily available. Indeed Drummond and Waters[15] suggested that the strong (-I) contributions of the carboxylic acid groups in the malonic acid-radical (IV) could favour reduction of this radical. The resultant anion (V) would be stabilized by resonance.

$$\cdot CH\cdot(CO_2H)_2$$

(IV)



$$HO.\overset{O}{\ddot{C}}.\overset{-}{CH}.\overset{O}{\ddot{C}}.OH \longleftrightarrow HO.\overset{\overset{-}{O}}{\dot{C}}:CH.\overset{O}{\ddot{C}}.OH$$

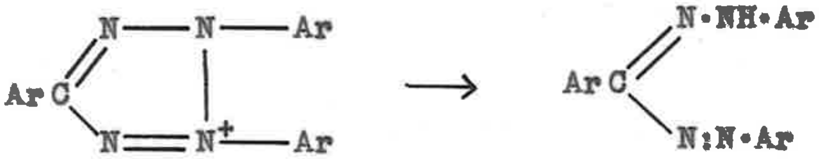
(V)

The experiments of Merz and Waters[9] were supported by those of Kolthoff and Medalia[13] who found that radicals derived from alcohols and aldehydes reduced ferric ions under Fenton-conditions, whereas radicals derived from acetone or acetic acid oxidized ferrous ions.

Haines and Waters[16] later substantiated the preceding suggestions when they found that radicals derived from nitriles (VI) did not reduce triaryltetrazolium salts (VII) unlike the radicals (I) derived from alcohols.

$CRR'.(CN)\cdot$

(VI)



(VII)

Collinson and Dainton[17] later found that polyacrylonitrile-radicals and polyacrylamide-radicals readily reduced ferric perchlorate, whereas polymethylmethacrylate-radicals reacted slowly, if at all. They concluded that the oxidation potentials $E(-e)$ of the polyacrylonitrile- and polyacrylamide-radicals were less positive, while the potential $E(+e)$ for the polymethylmethacrylate-radical was more positive than the potential of the $Fe^{2+} - Fe^{3+}$ system under the conditions used.

The Sandmeyer-reaction and the Meerwein-arylation reaction are two further examples where a metal-ion catalyst, in these cases the copper ion, acts as an oxidizing or reducing agent for transient-radicals. Although there was, at first, some controversy as to the nature of the mechanism of the Sandmeyer-reaction,[18] a mechanism similar to that originally proposed by Waters[19] (23-25) is now accepted.

$$Cu^+ + Ar\,N{\vdots}N^+ \longrightarrow Cu^{2+} + Ar\cdot + N_2 \qquad (23)$$

$$Ar\cdot + Cl^- \longrightarrow ArCl + e \qquad (24)$$

$$Cu^{2+} + e \longrightarrow Cu^+ \qquad (25)$$

This mechanism of Waters[19] readily explained the action of the cuprous ion to produce aryl-radicals from diazonium cations. To avoid postulating the liberation of free-electrons (24), Nonhebel and Waters[20] suggested the following chlorine-transfer mechanism.

$$ArN_2^+ + Cu^+Cl \longrightarrow Ar\cdot + N_2 + Cu^{2+}Cl \longrightarrow ArCl + Cu^+ \qquad (26)$$

They thought that the reaction could take place inside a solvent cage from which very few aryl-radicals could escape. However, Kochi[21] showed that aryl-radicals were abundant and suggested the following three-step process for the Sandmeyer reaction:

$$ArN_2^+ + CuCl_2^- \longrightarrow ArN_2CuCl_2 \qquad (27)$$

$$ArN_2CuCl_2 \longrightarrow Ar\cdot + CuCl_2 + N_2 \qquad (28)$$

$$Ar\cdot + CuCl_2 \longrightarrow ArCl + CuCl \qquad (29)$$

The formation of the complex between $CuCl_2^-$ and the diazonium cation as in (27) was first proposed by Cowdrey and Davies[22] in 1949.

Koelsch and Boekelheide[23] were the first workers to suggest a free-radical mechanism for the Meerwein-arylation reaction. More recent work[21,24-27] suggests a very similar pathway to that of the Sandmeyer-reaction; again the role of the copper ions is probably to oxidize or reduce transient-radicals.

As a result of the basic work of Waters *et al*[9-11] and the more recent work of De La Mare *et al*,[28] it is now possible to summarize many of the factors which dictate whether a given free-radical will be oxidized or, alternatively, reduced by metal ions. These factors also decide the degree of such oxidations or reductions. The work of Waters and his colleagues has already been examined. De La Mare *et al*[28] extensively studied the oxidation of free-radicals by metal salts in aqueous media. The radicals examined included methyl, ethyl, *n*-butyl, *t*-butyl, allylic and acetyl radicals. Both cupric chloride and cupric sulphate were used as oxidizing agents.

From the results of these various workers the following conclusions can be drawn:

(a) Whether or not a free-radical will be oxidized or reduced by metal ions depends, very greatly, upon the value of E(-e) and E(+e) for that radical.

Such values depend upon the substituent-groups adjacent to the free-valency site, the stability of the radical and the stability of the resultant carbonium ion.

(b) The value of the redox potential for the metal ion is important in determining whether oxidation or reduction of the radical will occur.

(c) Cupric salts fail to oxidize thiyl- and oxy-radicals. The fact that alkoxy-radicals with available β-hydrogen-atoms are not oxidized by cupric salts suggests that the removal of the electron from the free-valency site is a necessary criterion for these oxidation reactions.

When conditions are favourable for the oxidation of a radical, the oxidation step can proceed through one of two paths: (i) ligand-transfer, and (ii) electron-transfer.

(i) Ligand-transfer oxidation processes occur directly through a ligand-bridge as in (30).

$$R\cdot + MX_n^m \longrightarrow RX + MX_{n-1}^m \qquad (30)$$

Kochi[21] showed that such a process occurred in the Sandmeyer-reaction and also during chain-termination of polymerization-processes by metal halides.[29,30]

Originally Taube and Meyers[31] had obtained evidence that such oxidation-reduction reactions occurred in inorganic systems. They also showed that the anion was transferred from the oxidizing-agent to the reducing-agent.

The recent experiments of De La Mare _et al_[28] have shown that oxidation of radicals by cupric chloride proceeds by a ligand-transfer mechanism. It was found that, under these conditions, alkyl-radicals were substituted with the chlorine-ligand to yield alkyl chlorides.

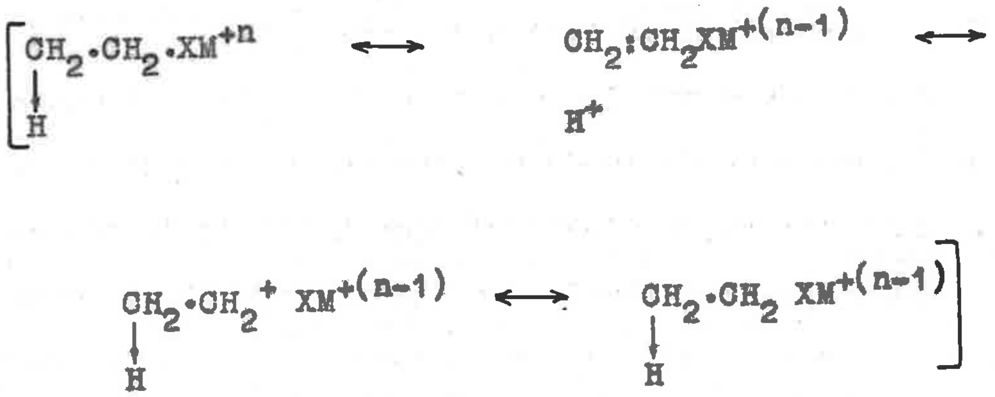
(ii) Electron-transfer oxidation processes require the formation of a transient-carbonium ion from the substrate-radical by the transfer of an electron from the free-radical to the metal (31).

$$R^{\cdot} + MX_n^m \longrightarrow R^+ + MX_n^{m-1} \qquad (31)$$

Kochi[32] suggested that such a process would occur in systems where the resultant carbonium ions were stabilized by resonance, or where the metal-salt in question exhibited poor ligand-transfer properties. Corresponding inorganic one-electron-transfer processes were extensively studied by Taube and his colleagues.[33-36]

The results of De La Mare _et al_[28] demonstrated that oxidation of radicals by cupric sulphate proceeds by an electron-transfer process. The carbonium ions, so produced, underwent elimination to give olefins, or solvolysis to yield substitution-products. These workers were essentially concerned with alkyl-radicals, and they found that, during the electron-transfer mechanism, the stability of the initial radical and also the resultant carbonium ion, determines whether elimination or solvolysis will occur. Thus olefin-formation occurred predominantly with ethyl-radicals, while tertiary-alkyl-radicals and allylic-radicals underwent solvolysis.

It was concluded[28] that ligand-transfer and electron-transfer processes were extreme forms of oxidation and were often competing reactions. These workers suggested that both processes could proceed through the allied transition-states (VIII).



$$\left[\begin{matrix}\mathrm{CH_2{\cdot}CH_2{\cdot}XM^{+n}}\\ \downarrow\\ \mathrm{H}\end{matrix}\longleftrightarrow\begin{matrix}\mathrm{CH_2{:}CH_2XM^{+(n-1)}}\\ \mathrm{H^+}\end{matrix}\longleftrightarrow\begin{matrix}\mathrm{CH_2{\cdot}CH_2^{+}\ XM^{+(n-1)}}\\ \downarrow\\ \mathrm{H}\end{matrix}\longleftrightarrow\begin{matrix}\mathrm{CH_2{\cdot}CH_2\ XM^{+(n-1)}}\\ \downarrow\\ \mathrm{H}\end{matrix}\right]$$

(VIII)

The choice of which transition-state would be involved in a given oxidation-reaction is determined by (i) the nature of the free radical involved, (ii) the particular transition-metal used, and (iii) the type of ligand or anion associated with that metal.

The importance of (i) and (iii) was demonstrated by Kochi and Rust[37] when they attempted to oxidize radicals which contained electron-attracting groups (-CN, $-CO_2H$ etc.) and which could not, therefore, readily accommodate a positive charge. They found that these free-radicals could not be oxidized by cupric sulphate in alcohol or water, to yield products containing the groups -OR or -OH. However, these same radicals were readily oxidized by a ligand-transfer mechanism with the use of cupric chloride (32). Under these conditions, the formation of an intermediate-carbonium ion was unnecessary.

$$R\dot{C}H\cdot CN + CuCl_2 \longrightarrow RCHCl\cdot CN + CuCl \qquad (32)$$

This extensive ligand-transfer property of metal halides had previously been established by several workers.[28-30,32,38-42]

Kochi and Rust[37] also showed that the addition of 5-(methoxycarbonyl)-pentyl radicals (IX) to olefins which contained electron-withdrawing groups ($-CN$, $-CO_2H$, $-CO_2R$ etc.) in the presence of cupric sulphate resulted in extensive polymerization (34). No oxidation of the adduct-radical occurred. When the oxidizing agent was cupric chloride, however, no polymerization took place. Instead the adduct-radical was oxidized by a ligand-transfer mechanism to the corresponding chloride (35).

$$\underset{\text{(IX)}}{MeO_2C\cdot(CH_2)_5\cdot} + CH_2{:}CH\cdot CN \longrightarrow MeO_2C\cdot(CH_2)_6\cdot\dot{C}H\cdot CN \qquad (33)$$

$$MeO_2C\cdot(CH_2)_6\cdot\dot{C}H\cdot CN \quad \xrightarrow{CuSO_4} \quad \text{polymers} \qquad (34)$$

$$MeO_2C\cdot(CH_2)_6\cdot\dot{C}H\cdot CN \quad \xrightarrow{CuCl_2} \quad MeO_2C\cdot(CH_2)_6CHCl\cdot CN \qquad (35)$$

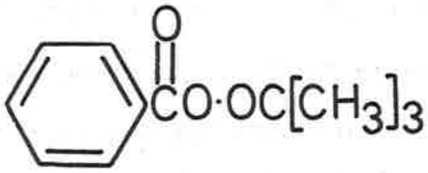
(b) PERESTER-OLEFIN REACTIONS

Since 1950 an impressive volume of work has been carried out on peroxide-reactions catalysed by transition-metal salts. Before 1950 the only peroxide to be seriously studied was hydrogen peroxide, but in recent years many organic-peroxides, -peresters and -hydroperoxides have been treated with transition-metal ions in the presence of various substrates including olefins, ketones, aldehydes, ethers, esters and amides. Indeed, any substrate containing a reasonably labile-hydrogen atom has generally proved quite suitable for these reactions.

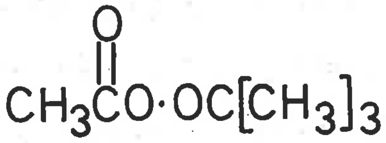
Several metal-ion catalysts have been successfully used. These include iron, copper, cobalt[43-49], manganese[15,44,46-48,50], nickel[44,46], chromium[46], silver[46], and antimony[51].

The reactions of t-butyl perbenzoate (X) with many substrates, in these catalytic oxidation-reduction systems, has been extensively studied. This relatively stable perester was first prepared by Milas and Surgenor[52] in 1946 and the kinetics of its decomposition was studied[53-55] in 1951.

Bartlett and Hiatt[56] studied the uncatalysed, thermal-decomposition of several peresters in chlorobenzene and identified many gaseous and volatile products. Thus t-butyl peracetate (XI) at 140° yielded large quantities of carbon dioxide and acetone, and lesser amounts of methane and acetic acid. No t-butanol was identified.



(X)



$CH_3\overset{O}{\overset{\|}{C}}O \cdot OC[CH_3]_3$

(XI)

The acetone and methane undoubtedly resulted from the thermal-decomposition of the t-butoxy radicals[57] (36) which, in turn, were formed by the cleavage of the peroxide linkage of the perester (37).

$$Me_3CO\cdot \longrightarrow Me_2CO + Me\cdot \qquad (36)$$

$$MeCO_2\cdot OCMe_3 \longrightarrow Me_3CO\cdot + MeCO_2\cdot \qquad (37)$$

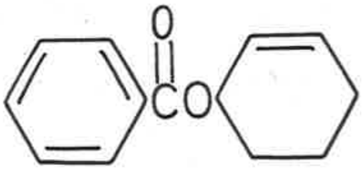
The catalysed-decomposition of t-butyl peresters with cuprous salts yields entirely different products, however.[58] Thus t-butyl perbenzoate (X) yields only small quantities of carbon dioxide but large amounts of benzoic acid. The following sceme was suggested[58] to account for these products.

$$C_6H_5\cdot CO_2\cdot OC(CH_3)_3 + Cu^+ \longrightarrow C_6H_5\cdot CO_2Cu^{2+} + (CH_3)_3CO\cdot \qquad (38)$$

$$(CH_3)_3CO\cdot \longrightarrow (CH_3)_2C{:}O + \cdot CH_3 \qquad (39)$$

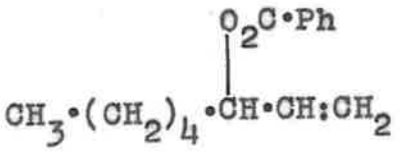
$$C_6H_5\cdot CO_2\cdot CO(CH_3)_3 + \cdot CH_3 \longrightarrow C_6H_5\cdot CO_2\cdot CH_3 + (CH_3)_3CO\cdot \qquad (40)$$

The catalytic-reduction of *t*-butyl peresters by transition-metal ions in the presence of olefins, has been extensively studied since 1958. There has been some controversy, however, as to the nature of the mechanism of these reactions. In 1958 Kharasch and Sosnovsky[59] reported that the induced-decomposition of *t*-butyl perbenzoate by cuprous bromide, in the presence of cyclohexene, yielded large quantities of cyclohex-2-en-1-yl benzoate (XII). A kinetic investigation of this reaction was later attempted.[60]



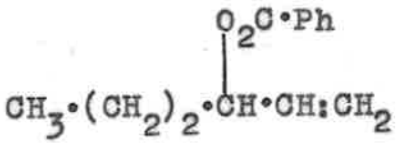
(XII)

Similarly oct-1-ene yielded 1-pentylallyl benzoate (XIII) and hex-1-ene yielded 1-propylallyl benzoate (XIV).



$$CH_3\cdot(CH_2)_4\cdot\overset{O_2C\cdot Ph}{\overset{|}{C}}H\cdot CH{:}CH_2$$

(XIII)



$$CH_3\cdot(CH_2)_2\cdot\overset{O_2C\cdot Ph}{\overset{|}{C}}H\cdot CH{:}CH_2$$

(XIV)

These workers found no evidence for the formation of oct-2-en-1-yl benzoate (XV) or hex-2-en-1-yl benzoate (XVI) and, therefore, concluded that these reactions were unique in that they were stereospecific. In related uncatalysed-reactions, olefins react with free-radicals to produce mixtures of isomeric allylic compounds[49,61,62] presumably due to resonance of the allylic-radical (XVII).

$CH_3\cdot(CH_2)_4\cdot CH{:}CH\cdot CH_2\cdot O_2C\cdot Ph$ $CH_3\cdot(CH_2)_2\cdot CH{:}CH\cdot CH_2\cdot O_2C\cdot Ph$

(XV) (XVI)

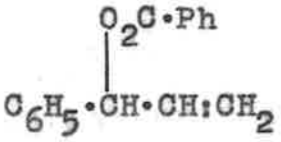
$$R\ \dot{C}H\cdot CH{:}CH_2 \longleftrightarrow R\ CH{:}CH\cdot CH_2\cdot$$

(XVII)

Kharasch and his colleagues later reported[58] that allylbenzene (XVIII) reacted with t-butyl perbenzoate (X) and cuprous bromide to yield mainly the unrearranged 1-phenylallyl benzoate (XIX). They also found that oct-2-ene similarly formed a mono-benzoate without isomerization.

$C_6H_5{\cdot}CH_2{\cdot}CH{:}CH_2$

(XVIII)



$C_6H_5{\cdot}\overset{O_2C\cdot Ph}{CH}{\cdot}CH{:}CH_2$

(XIX)

These workers suggested the following mechanism for these reactions:

$$C_6H_5{\cdot}CO_2{\cdot}OC(CH_3)_3 + Cu^{+} \longrightarrow C_6H_5{\cdot}CO_2\ Cu^{2+} + (CH_3)_3\ CO{\cdot} \qquad (38)$$

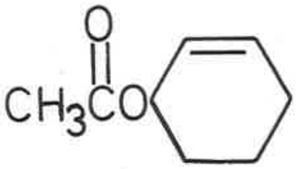
$$(CH_3)_3CO{\cdot} + RH \longrightarrow R{\cdot} + (CH_3)_3C{\cdot}OH \qquad (41)$$

$$R{\cdot} + C_6H_5{\cdot}CO_2\ Cu^{2+} \longrightarrow C_6H_5{\cdot}CO_2R + Cu^{+} \qquad (42)$$

(RH = olefin)

They suggested that the perester was initially reduced by cuprous ions (38). Since no isomerization of the double bonds occurred, they proposed that the replacement of the allylic-hydrogen by the benzoyloxy-radical (41 and 42) took place in a concerted manner.

Kharasch and his colleagues also found that *t*-butyl peracetate (XI) gave products analogous to those obtained with *t*-butyl perbenzoate (X). They also established that when cyclohexene was dissolved in glacial acetic acid and treated with *t*-butyl perbenzoate in the presence of cuprous bromide, cyclohex-2-en-1-yl acetate (XX) was produced instead of cyclohex-2-en-1-yl benzoate (XII).

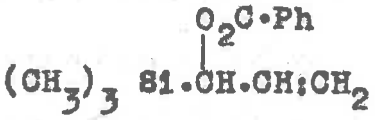


(XX)

When Sosnovsky and O'Neill[63] treated *t*-butyl perbenzoate (X) with 3-trimethylsilylprop-1-ene (XXI) in the presence of cuprous bromide, they obtained 1-trimethylsilylallyl benzoate (XXII). No isomerized product was found. Under identical conditions 3-trimethylsiloxyprop-1-ene (XXIII) yielded 1-trimethylsiloxyallyl benzoate (XXIV) and no rearranged product.

$(CH_3)_3\,Si\cdot CH_2\cdot CH{:}CH_2$

(XXI)

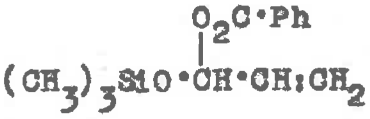


$(CH_3)_3\,Si\cdot\overset{\overset{O_2C\cdot Ph}{|}}{C}H\cdot CH{:}CH_2$

(XXII)

$(CH_3)_3SiO\cdot CH_2\cdot CH{:}CH_2$

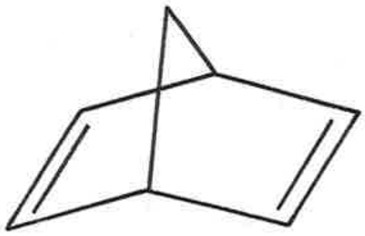
(XXIII)



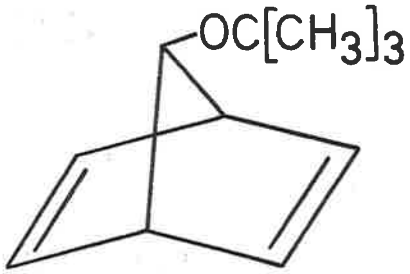
$(CH_3)_3SiO\cdot\underset{}{\overset{O_2C\cdot Ph}{\overset{|}{C}H}}\cdot CH{:}CH_2$

(XXIV)

The reaction between norbornadiene (XXV), *t*-butyl perbenzoate (X) and cuprous bromide,[64,65] contrasts with the preceding olefin reactions in that no benzoyloxy derivative was obtained. The sole product proved to be 7-*t*-butoxynorbornadiene (XXVI).



(XXV)



(XXVI)

When Denney *et al*[66] treated cyclohexene with *t*-butyl perbenzoate-carbonyl-O^{18} in the presence of cupric ions, they found that the label was completely equilibrated between the two oxygen atoms of the resultant cyclohex-2-en-1-yl benzoate. They concluded that the equilibration occurred during the formation of the ester and therefore only a concerted mechanism involving the perester, catalyst and olefin was acceptable.

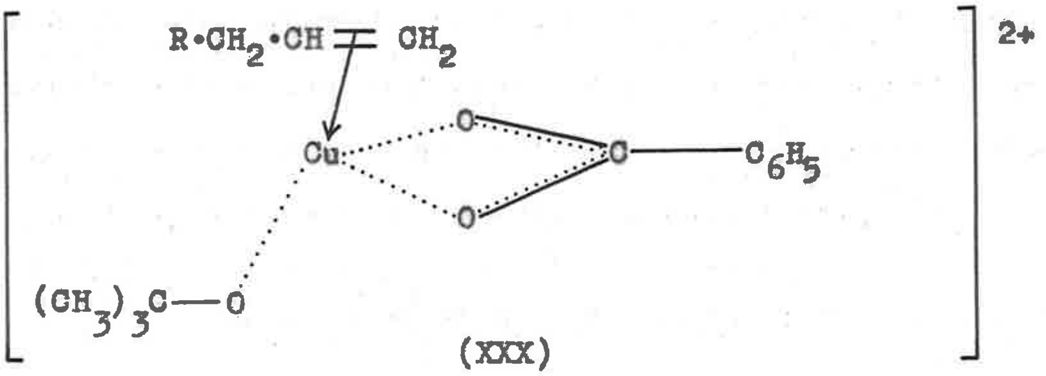
A further reaction between *t*-butyl perbenzoate and 3-deuterio-3-phenylprop-1-ene (XXVII) in the presence of cupric ions, followed by a deuterium-analysis of the products, indicated that simple hydrogen-abstraction from the allylic position by t-butoxy radicals was not occurring. These workers also found that β-methylstyrene (XXVIII) yielded only cinnamyl benzoate (XXIX) in these reactions.

$C_6H_5{\cdot}CHD{\cdot}CH{:}CH_2$ (XXVII)

$C_6H_5{\cdot}CH{:}CH{\cdot}CH_3$ (XXVIII)

$C_6H_5{\cdot}CH{:}CH{\cdot}CH_2{\cdot}O_2C{\cdot}Ph$ (XXIX)

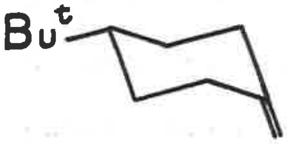
In order to explain these results, Denney et al[66] suggested that the t-butyl perbenzoate and copper-ion reacted to give a copper-ion complex containing a t-butoxy-radical and a benzoyloxy-radical. This complex could then coordinate with the olefin to give the intermediate transition-state (XXX) which is resonance stabilized.



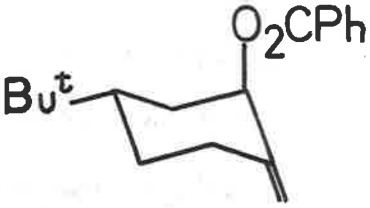
(XXX)

Subsequent hydrogen-abstraction by the complexed t-butoxy-radical, followed by rapid combination of the olefinic radical and the benzoyloxy group within the copper-complex were then suggested, with the resultant formation of the required product.

Cross and Whitham[67] treated a conformationally fixed olefin, 1-methylene-4-t-butylcyclohexane (XXXI), with t-butyl perbenzoate and cuprous chloride and obtained the benzoate of 2-methylene-trans-5-t-butylcyclohexanol (XXXII) as the major epimer. A small quantity of the equitorial allylic substitution-product was also found, which favoured the Denney intermediate (XXX).



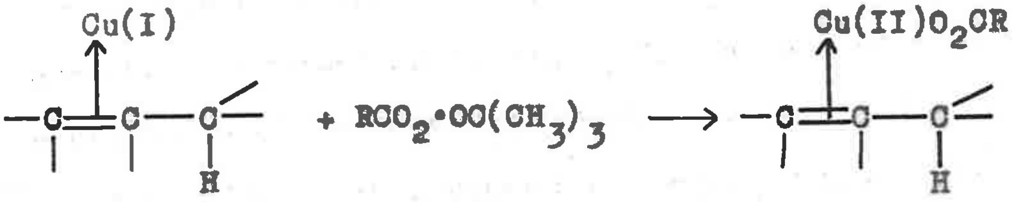
(XXXI)



(XXXII)

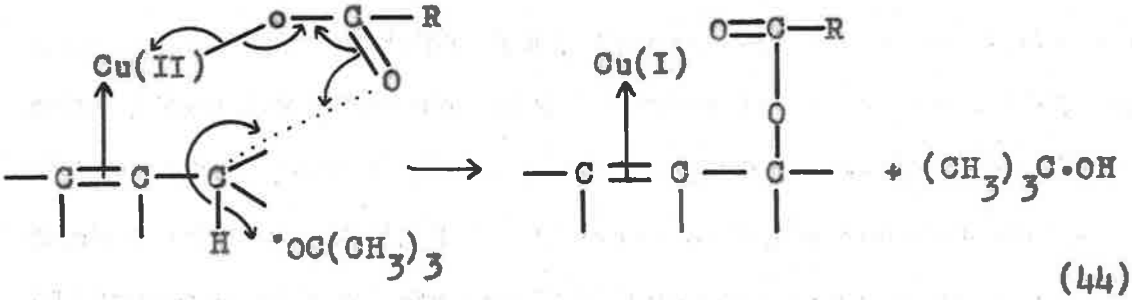
At the time when Denney et al[66] published their copper-complex intermediate (XXX), the nature of the mechanism of these stereospecific olefin reactions was still very obscure. The existence of the complex proposed by Denney et al had yet to be proven, and other possible mechanisms remained to be examined.

About this period, therefore, work was begun in this laboratory to study the mechanism of these reactions. After a few preliminary experiments we conceived a mechanism to explain the stereospecific nature of these olefin-perester reactions.[68] Our observation that the *t*-butoxy radicals were, in fact, free, led us to believe that these reactions proceeded by a mechanism which was not concerted. Our mechanism was based on the assumption that no double-bond can migrate if it is complexed to a metal-ion. We suggested, therefore that a π-complex would, initially, be formed between the cuprous ion and the double-bond of the olefin. This complex was then expected to reduce the perester (43) to a cupric carboxylate-olefin complex (XXXIII) and free *t*-butoxy-radicals. A series of one-electron shifts could then give the acyloxylated olefin in which the double-bond had not migrated (44).



(XXXIII)

+ $(CH_3)_3CO\cdot$ (43)



(44)

It was well after this mechanism had been published, and several experiments had been completed to prove its authenticity, that Kochi[32,69] discovered that the terminal double bonds of olefins are certainly fixed but that non-terminal double bonds almost completely isomerize during these reactions. Our mechanism, therefore, appeared to be invalid, for it was designed to explain the non-isomerization of all double bonds, whether terminal or not. It will be shown in a later section of this thesis, however, that this mechanism, suggested by us, is, in fact, still acceptable.

Kochi[32,69] studied the cuprous salt-catalysed decomposition of _t_-butyl perbenzoate (X) in the presence of isomeric butenes. Regardless of which butene isomer was used (but-1-ene (XXXIV) or but-2-ene (XXXV)), 1-methylallyl benzoate (XXXVI; R = Ph·CO_2) comprised 88% of the total ester products in each case. When _t_-butyl peracetate (XI) was similarly treated with but-1-ene or but-2-ene, 1-methylallyl acetate (XXXVI; R=CH_3·CO_2)

was the main product in each case.

$CH_3\cdot CH_2\cdot CH{:}CH_2$ $\qquad$ $CH_3\cdot CH{:}CH\cdot CH_3$ $\qquad$ $CH_3\cdot CHR\cdot CH{:}CH_2$

(XXXIV) $\qquad$ (XXXV) $\qquad$ (XXXVI)

Koehi pointed out that these isomer-distributions were unique. He showed that reactions involving classical carbonium-ion transition-states yielded equal quantities of each isomer. The nitrous acid deamination of the isomeric butenylamines was one such example.

During true free radical reactions involving butenyl radicals, the products contain a predominance of the crotyl isomer.[70] Thus the isomeric butenes react with t-butyl hypochlorite (XXXVII) at low temperatures to produce mainly crotyl chloride (XXXVIII).

$(CH_3)_3\,CO\,Cl$ $\qquad$ $CH_3\cdot CH{:}CH\cdot CH_2Cl$

(XXXVII) $\qquad$ (XXXVIII)

Kochi[32] conceived a mechanism to explain the predominance of the α-methallyl isomer over the crotyl isomer in these perester reactions. He suggested that the first step was the same as that put forward by Kharasch et al[58] (38) whereby the perester was reduced by the cuprous ion to a cupric carboxylate and t-butoxy-radicals. Isomeric butenyl-radicals (XXXIX) were then expected to be formed by the abstraction of the allylic hydrogen-atoms of the butene isomers with the t-butoxy-radicals.

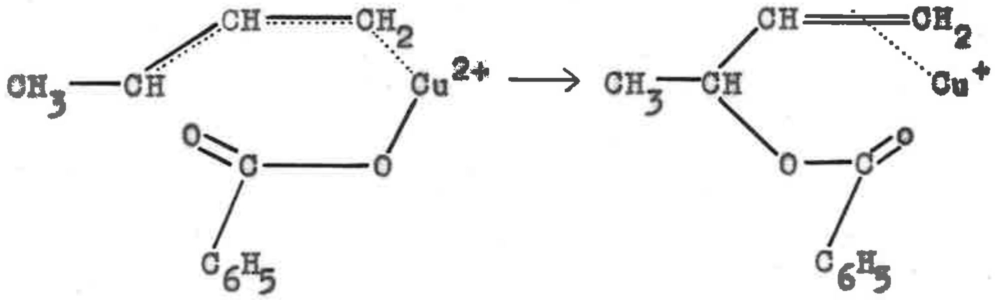
$$\left.\begin{array}{l} CH_3CH{:}CH\cdot CH_3 \\ \\ CH_2{:}CH\cdot CH_2\cdot CH_3 \end{array}\right] \xrightarrow{Bu^tO\cdot} \cdot CH_2\cdot CH{:}CH\cdot CH_3 \longleftrightarrow CH_2{:}CH\cdot\dot{C}H\cdot CH_3 \qquad (45)$$

(XXXIX)

The existence of these radicals in the free-state could then account for the apparent isomerization of the non-terminal double bond in but-2-ene into the terminal position.

Koohi suggested that benzoyloxylation of the butenyl-radical (XXXIX) could involve two extreme processes of oxidation, viz. ligand-transfer and electron-transfer. It was shown in part (a) of this section that cupric chloride and cupric sulphate oxidize radicals by ligand-transfer and electron-transfer respectively.

The benzoyloxylation of the butenyl-radicals by a ligand-transfer mechanism was suggested, by Kochi,[32] to involve the formation of an intermediate complex (XL) between the cupric carboxylate and butenyl-radical. A cyclic ligand-transfer-reaction within this complex would then yield the required product with the terminal double bond (XLI).



(46)

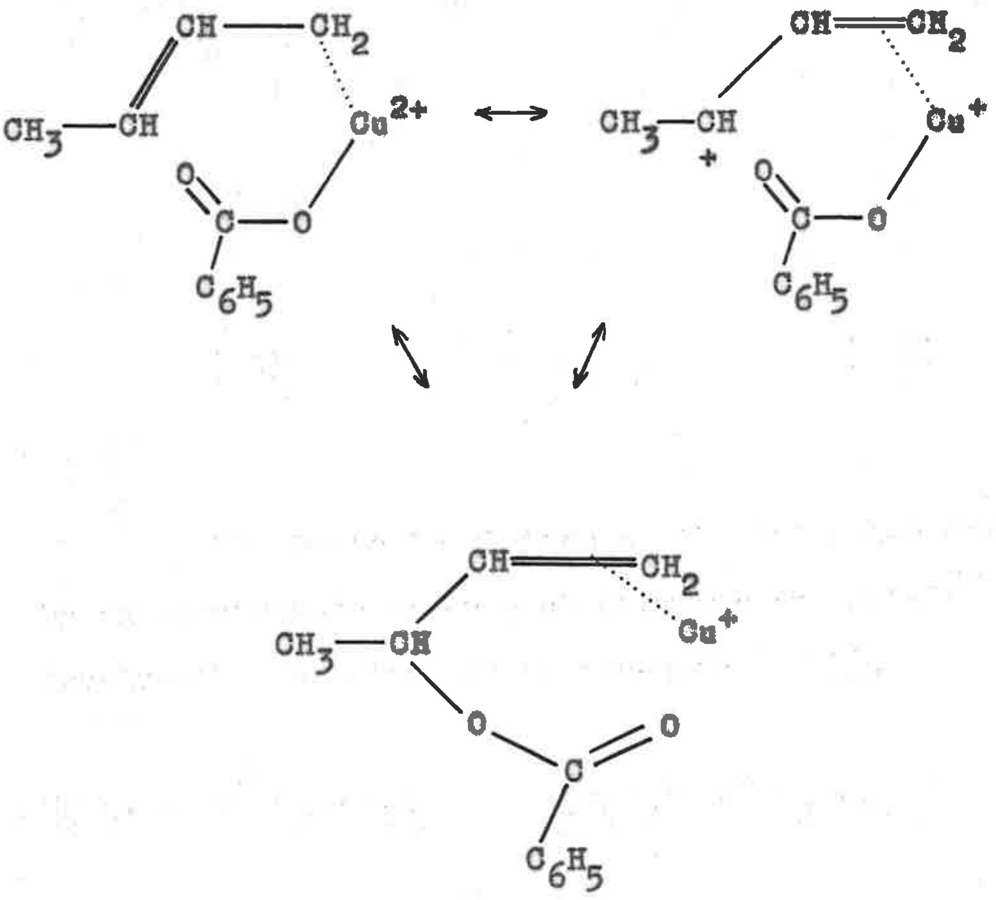
(XL) (XLI)

The benzoyloxylation of the butenyl-radicals by an electron-transfer mechanism was suggested[32] to involve the formation of an ion-pair (XLII).

$$C_4H_7\cdot + Cu^{2+}O_2C\cdot C_6H_5 \longrightarrow (C_4H_7^+ \; Cu^+ \; O_2C\cdot C_6H_5) \qquad (47)$$

(XLII)

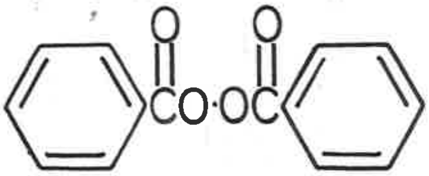
Kochi produced evidence to suggest that the transition-state had both ligand-transfer and electron-transfer properties since the unusual isomer distribution could not be explained exclusively by one or the other of these processes. He represented the most probable transition-state by (XLIII) where the ligand-transfer mechanism was operating in a system containing considerable carbonium ion character.



(XLIII)

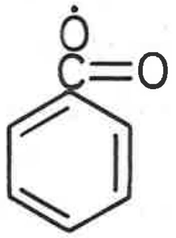
This transition-state therefore explained the high yield of α-methallyl benzoate in each reaction. The driving-force for substitution at the 3-position was assumed to be due to the greater stability of a double bond-cuprous ion complex in the terminal position of the olefin. Kochi mentioned that such a complex would be more stable than a non-terminal double bond complex.

In contrast to the preceding results are the reactions between benzoyl peroxide (XLIV), olefins, and copper salts. Kharasch and Fono[71] treated oct-1-ene and oct-2-ene with benzoyl peroxide (XLIV) in the presence of cuprous salts and obtained, in each case, a mixture of 1-pentylallyl benzoate (XIII) and oct-2-en-1-yl benzoate (XV) in similar amounts. They also found that these reactions yielded considerably more benzoic acid and less carbon dioxide than the corresponding uncatalysed reaction. A great reduction in the yield of high-molecular weight adducts in the catalysed reactions infered that the cuprous salt facilitated the termination reaction.



(XLIV)

Kharasch and Fono[71] suggested that the initial step in this reaction was the addition of a benzoyloxy-radical (XLV) to the double bond (48). This occurred whether or not the copper-catalyst was present.



(XLV)

$$C_6H_5\cdot CO_2\cdot + C_8H_{16} \longrightarrow C_6H_5\cdot CO_2\cdot C_8H_{16}\cdot \qquad (48)$$

(XLVI)

In the presence of cuprous salt, the adduct-radical (XLVI) became reversibly "trapped", and readily attacked another benzoyl peroxide molecule (49).

$$C_6H_5\cdot CO_2\cdot C_8H_{16}\cdot Cu^+ + (C_6H_5\cdot CO_2)_2 \longrightarrow$$

$$C_6H_5\cdot CO_2\cdot C_8H_{15} + C_6H_5\cdot CO_2H + C_6H_5\cdot CO_2\cdot + Cu^+ \qquad (49)$$

The reaction of but-1-ene (XXXIV) and but-2-ene

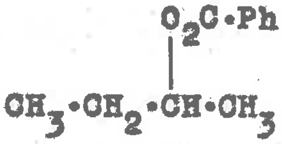
(XXXV) with benzoyl peroxide (XLIV) in the presence of cuprous salt, was later examined by Kochi.[38] He found that but-1-ene yielded mainly *n*-butyl benzoate (XLVII) and crotyl benzoate (XLVIII), with only small quantities of α-methallyl benzoate (XXXVI; $R = Ph\cdot CO_2$). Conversely but-2-ene yielded mainly *s*-butyl benzoate (XLIX) and α-methallyl benzoate (XXXVI; $R = Ph\cdot CO_2$), with only small quantities of crotyl benzoate (XLVIII).

$CH_3\cdot CH_2\cdot CH_2\cdot CH_2\cdot O_2C\cdot Ph$

(XLVII)

$CH_3\cdot CH{:}CH\cdot CH_2\cdot O_2C\cdot Ph$

(XLVIII)



$$\begin{array}{c} \qquad\qquad O_2C\cdot Ph \\ \qquad\qquad | \\ CH_3\cdot CH_2\cdot CH\cdot CH_3 \end{array}$$

(XLIX)

Kochi suggested that the first step in these reactions was the reduction of the benzoyl peroxide by cuprous ions (50). This step is analogous to that suggested[58] for the induced-decomposition of *t*-butyl perbenzoate (X) by copper ions (38). The benzoyloxy radicals (XLV) so formed were then considered to add to the double-bond of the butene isomers (51 and 52). Oxidation of the resultant benzoyloxybutyl-radicals (La and Lb) by cupric ions were expected to yield[72] the butenyl esters (53 and 54).

$$(C_6H_5\cdot CO_2)_2 + Cu^+ \longrightarrow C_6H_5\cdot CO_2Cu^{2+} + C_6H_5\cdot CO_2\cdot \tag{50}$$

$$C_6H_5\cdot CO_2\cdot + CH_3\cdot CH{:}CH\cdot CH_3 \longrightarrow C_6H_5\cdot CO_2\cdot CHMe\cdot \dot{C}H\cdot CH_3 \tag{51}$$

(La)

$$C_6H_5\cdot CO_2\cdot + CH_2{:}CH\cdot CH_2\cdot CH_3 \longrightarrow C_6H_5\cdot CO_2\cdot CH_2\cdot \dot{C}H\cdot CH_2\cdot CH_3 \tag{52}$$

(Lb)

$$C_6H_5\cdot CO_2\cdot CHMe\cdot \dot{C}H\cdot CH_3 + Cu^{2+} \longrightarrow C_6H_5\cdot CO_2\cdot CHMe\cdot CH{:}CH_2 + Cu^+ + H^+ \tag{53}$$

$$C_6H_5\cdot CO_2\cdot CH_2\cdot \dot{C}H\cdot CH_2\cdot CH_3 + Cu^{2+} \longrightarrow C_6H_5\cdot CO_2\cdot CH_2\cdot CH{:}CH\cdot CH_3 + Cu^+ + H^+ \tag{54}$$

Kochi[38] believed that the thermal-decomposition of benzoyl peroxide (55) would compete with the induced decomposition (50), unlike the corresponding reactions of t-butyl peresters.

$$(C_6H_5{\cdot}CO_2)_2 \longrightarrow 2\ C_6H_5{\cdot}CO_2{\cdot} \qquad (55)$$

He suggested, therefore, that reduction of benzoyloxy-radicals (XLV) by cuprous ions (56) could be important in these reactions.

$$C_6H_5{\cdot}CO_2{\cdot} + Cu^+ \longrightarrow C_6H_5{\cdot}CO_2^- + Cu^{2+} \qquad (56)$$

Kochi concluded that the difference in the initiating free-radicals from the benzoyl peroxide-reactions and t-butyl perester-reactions caused the different product-ratios in each case.

The main pathway in the benzoyl peroxide-reactions was one of addition, by the benzoyloxy-radicals, to the olefin. Isomerization of the adduct-radicals was not possible. In the t-butyl perester-reactions, the abstraction of allylic-hydrogens by t-butoxy-radicals was the main reaction path. In this case, isomerization of the allylic-radical was possible, and did occur, to yield the product with a terminal double-bond in every case.

Although *t*-butoxy-radicals usually abstract labile-hydrogens in these reactions, they also can form addition-adducts with certain conjugated systems. Kharasch *et al*[73] have shown that the decomposition of *t*-butyl hydroperoxide (LI) with ferrous ions, in the presence of such dienes as butadiene (LII) and isoprene (LIII), yields dimers, each containing two *t*-butoxy groups.

$(CH_3)_3CO{\cdot}OH$ (LI)

$CH_2{:}CH{\cdot}CH{:}CH_2$ (LII)

$CH_2{:}C\ Me{\cdot}CH{:}CH_2$ (LIII)

These results indicate that the *t*-butoxy-radicals added to the diene systems to form allylic radicals (57), which then dimerize (58).

$$(CH_3)_3CO\cdot + CH_2{:}CH{\cdot}CH{:}CH_2 \longrightarrow (CH_3)_3CO{\cdot}CH_2{\cdot}CH{:}CH{\cdot}CH_2\cdot \qquad (57)$$

$$2(CH_3)_3CO{\cdot}CH_2{\cdot}CH{:}CH{\cdot}CH_2\cdot \longrightarrow \left[(CH_3)_3CO{\cdot}CH_2{\cdot}CH{:}CH{\cdot}CH_2-\right]_2 \qquad (58)$$

Volman and Graven[74] photochemically-decomposed di-*t*-butylperoxide (LIV) in the presence of butadiene (LII) and found that the *t*-butoxy-radicals added to the diene and promoted polymerization.

$$(CH_3)_3CO\cdot OC(CH_3)_3$$

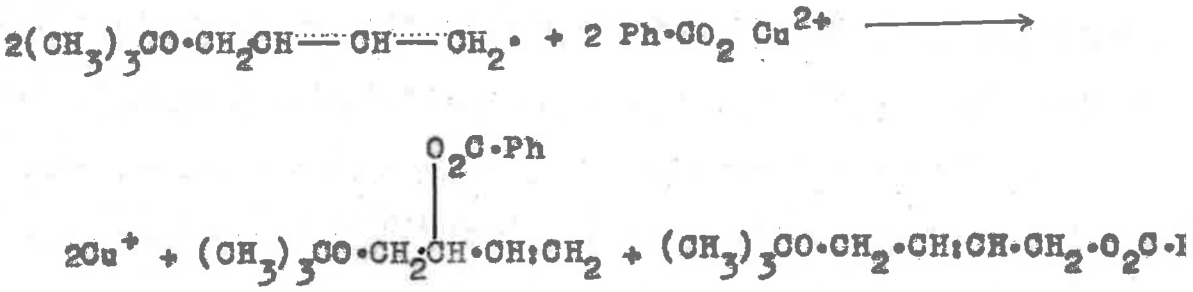
(LIV)

The cuprous ion-catalysed decomposition of *t*-butyl-perbenzoate (X) and - peracetate (XI) in the presence of butadiene (LII) was studied by Kochi.[39] The results indicated that the *t*-butoxy-radicals were again adding to the conjugated diene to form allylic-radicals (LV). Kochi suggested that these allylic adduct-radicals were then oxidized by cupric ions in an identical fashion to the oxidation of the simple butenyl-radicals (XXXIX), previously described. *t*-Butoxybenzoyloxybutenes (LVI) and (LVII) were the products. The sceme was represented as follows:

$$Ph\cdot CO_2\cdot OC(CH_3)_3 + Cu^{+} \longrightarrow Ph\cdot CO_2\ Cu^{2+} + (CH_3)_3CO\cdot \qquad (38)$$

$$(CH_3)_3CO\cdot + CH_2{:}CH\cdot CH{:}CH_2 \longrightarrow (CH_3)_3CO\cdot CH_2\cdot CH\cdots CH\cdots CH_2\cdot$$

(LV) (59)



$$2(CH_3)_3CO\cdot CH_2CH\overset{\cdots\cdots}{—}CH\overset{\cdots\cdots}{—}CH_2\cdot + 2\,Ph\cdot CO_2\ Cu^{2+} \longrightarrow$$

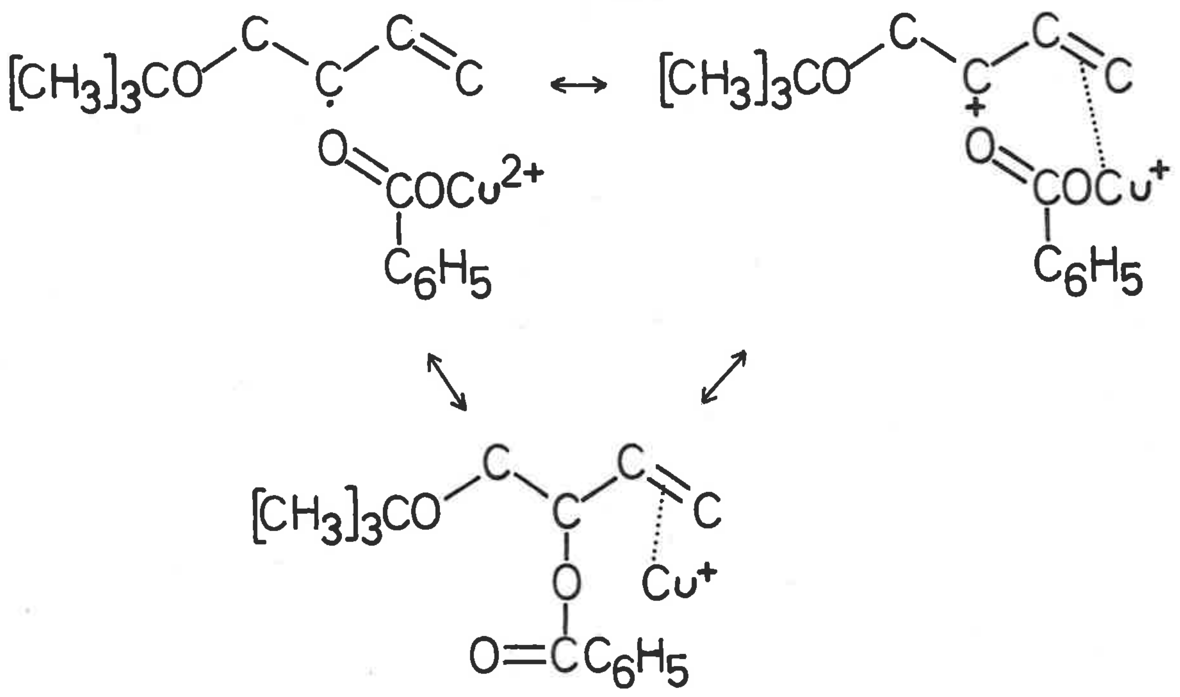
$$2Cu^{+} + (CH_3)_3CO\cdot CH_2\overset{\overset{O_2C\cdot Ph}{|}}{C}H\cdot CH{:}CH_2 + (CH_3)_3CO\cdot CH_2\cdot CH{:}CH\cdot CH_2\cdot O_2C\cdot$$

(LVI) (LVII)

(60)

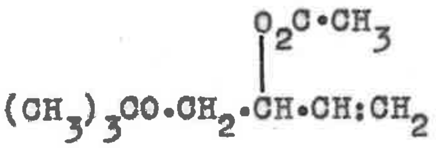
The product consisted of two isomers, 4-*t*-butoxy-3-benzoyloxybut-1-ene (LVI) comprised 80% of the isomer-mixture, and 4-*t*-butoxy-1-benzoyloxybut-2-ene (LVII) made up the remaining 20% of the mixture. Similar results were obtained when *t*-butyl peracetate (XI) was used.

To account for the stereospecific nature of the products in these reactions, Kochi[39] proposed a transition-state which was analogous to that (XLIII) suggested for the butene-perester reactions.[32] He represented the transition-state (LVIII) as having both ligand-transfer and electron-transfer properties.



(LVIII)

Kochi[39] also decomposed t-butyl hydroperoxide (LI) in the presence of cupric acetate and butadiene (LII). A mixture of acetic acid and benzene was used as the solvent. Examination of the reaction-products showed that a mixture of t-butoxyacetoxybutenes had been formed in 50% yield. The mixture consisted of 80% 4-t-butoxy-3-acetoxybut-1-ene (LIX) and 20% 4-t-butoxy-1-acetoxybut-2-ene (LX). These results indicated that the transition-state, in this reaction, was probably identical to that (LVIII) described for the reaction with t-butyl perbenzoate.



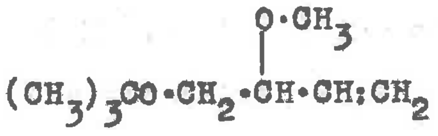
$(CH_3)_3CO\cdot CH_2\cdot \overset{O_2C\cdot CH_3}{CH}\cdot CH{:}CH_2$

(LIX)

$(CH_3)CO\cdot CH_2\cdot CH{:}CH\cdot CH_2\cdot O_2C\cdot CH_3$

(LX)

When Kochi[39] catalytically-decomposed *t*-butyl peresters in the presence of butadiene (LII) using methanol as a solvent, the yield of *t*-butoxybutenyl esters was reduced, but the distribution of isomers remained constant. This reduced yield of esters was compensated by the formation of a mixture of *t*-butoxymethoxybutenes. This mixture consisted of 73% 4-*t*-butoxy-3-methoxybut-1-ene (LXI) and 27% 4-*t*-butoxy-1-methoxybut-2-ene (LXII)



$(CH_3)_3CO\cdot CH_2\cdot \overset{O\cdot CH_3}{CH}\cdot CH{:}CH_2$

(LXI)

$(CH_3)_3CO\cdot CH_2CH{:}CH\cdot CH_2\cdot O\cdot CH_3$

(LXII)

It was suggested[39] that the transition-state involved in the methoxy-substitution would possess more carbonium-ion character than that involved in acyloxy-substitution (LVIII). This would explain the less specific distribution of isomeric *t*-butoxymethoxybutenes.

As previously discussed, the total amount of carbonium-ion character in the transition-state (LVIII) dictates the degree of isomer-distribution in the products. A transition-state containing groups with considerable ligand-transfer properties (acyloxy groups), would thus be much more stereospecific than a transition-state containing more carbonium-ion character (electron-transfer properties) and less ligand-transfer ability. Indeed it was shown[75,76] that solvolysis of crotyl- and α-methallyl-chlorides (XXXVIII and LXIII), which involves pure carbonium-ion intermediates, results in the formation of equal amounts of crotyl- and α-methallyl isomers.

$CH_3{\cdot}CHCl{\cdot}CH{:}CH_2$ $CH_3{\cdot}CH_2{\cdot}CH_2{\cdot}CH{:}CH_2$

(LXIII) (LXIV)

Kochi[77] further proved his theory when he decomposed *t*-butyl peresters in the presence of but-1-ene (XXXIV), but-2-ene (XXXV), pent-1-ene (LXIV) and butadiene (LII) using complex-copper salts as catalysts.

Unlike the results obtained when simple copper catalysts were used with *t*-butyl peresters, the isomer-distribution in these reactions was entirely different. When the oxidation of butenyl-radicals was accomplished with a 1,10-phenanthroline-cupric acetate complex, the isomeric distribution of the butenyl esters could be selected according to the molar-ratio of phenanthroline ligands to copper ions.

Whereas the butenyl ester mixture consisted of 85% α-methallyl isomer (XXXVI) when simple copper-catalysts were used, the use of phenanthroline-copper acetate (equi-molar quantities) as a catalyst, resulted in the formation of only 73% of the α-methallyl isomer (XXXVI) and 27% of the crotyl isomer (LXV); acetonitrile was used as a solvent. In benzene solution, equal quantities of each isomer was obtained.

$$CH_3\cdot CH{:}\,CH\cdot CH_2R$$

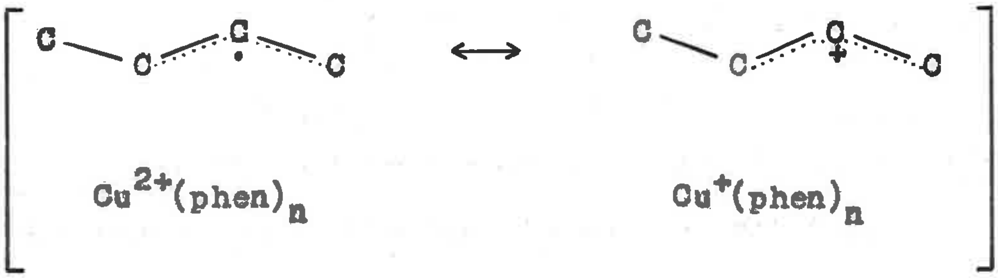
(LXV) (R = $Ph\cdot CO_2$ or OAc)

When the catalyst contained more than two mole equivalents of phenanthroline to copper acetate, the crotyl isomer actually predominated, regardless of solvent. Similar results were obtained with pent-1-ene (LXIV).

The use of these complex copper-catalysts in the reaction between butadiene (LII) and <u>t</u>-butyl peresters, also caused a marked change in isomer-distribution.

Whereas 4-t-butoxy-3-acyloxybut-1-enes (LVI and LIX) had been the main isomers when simple copper-catalysts were employed, the percentage of these isomers was greatly reduced when a complex copper-catalyst was used.

The ratio of isomeric products from these complex-copper catalysed reactions, is closely related to the ratio obtained from conventional carbonium-ion reactions. Kochi[77] suggested that the oxidation of allylic-radicals by cupric-phenanthroline and cupric-bipyridyl complexes is essentially an electron-transfer process in which the transition-state (LXVI) is represented by extensive carbonium-ion character. Ligand-transfer properties in these reactions were very meagre. The transition state was represented as follows:



(LXVI)

(c) PERESTER REACTIONS WITH NON-OLEFINIC SUBSTRATES

The metal-ion catalysed reaction of t-butyl peresters with compounds containing activated hydrogen-atoms (other than olefins), has been extensively studied during the last few years. Often these reactions yield products different from those obtained in the corresponding uncatalysed reactions. Good examples are the reactions with ethers.

When simple ethers react with t-butoxy radicals in the absence of metal catalysts,[78] the α-hydrogen atom of the ether is abstracted and the resultant radical dimerizes. For example, the reaction[78] between di-t-butyl peroxide (LIV) and di-n-butyl ether (LXVII) yields 4,5-di-n-butoxyoctane (LXVIII).

$$CH_3{\cdot}(CH_2)_2{\cdot}CH_2{\cdot}O{\cdot}CH_2{\cdot}(CH_2)_2{\cdot}CH_3 + (CH_3)_3CO{\cdot} \longrightarrow$$

(LXVII)

$$CH_3{\cdot}(CH_2)_2{\cdot}CH_2{\cdot}O{\cdot}\dot{C}H{\cdot}(CH_2)_2{\cdot}CH_3 \qquad (61)$$

$$2\ CH_3{\cdot}(CH_2)_2{\cdot}CH_2{\cdot}O{\cdot}\dot{C}H{\cdot}(CH_2)_2{\cdot}CH_3 \longrightarrow$$

$$\left[CH_3{\cdot}(CH_2)_2{\cdot}CH_2{\cdot}O{\cdot}\overset{|}{C}H{\cdot}(CH_2)_2{\cdot}CH_3\right]_2 \qquad (62)$$

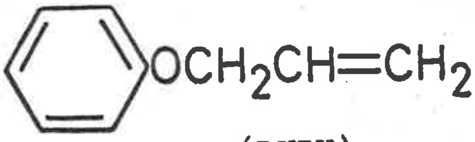
(LXVIII)

The decomposition of t-butyl perbenzoate (X) with cuprous chloride in the presence of simple ethers[79] yields no dimeric-products, however. In every case a benzoyloxy group is introduced into the α-position of the ether. This reaction, therefore, has proved to be an excellent method for preparing the benzoate esters of hemiacetals and hemiketals.

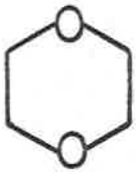
Certain cyclic ethers behave in a similar fashion. Thus phenyl allyl ether (LXIX) and 1,4-dioxane (LXX) react smoothly under these conditions[80,81] to yield 1-phenoxyallyl benzoate (LXXI) and 2-benzoyloxy-1,4-dioxane (LXXII) respectively. This latter product (LXXII) was previously prepared by Cass[82] in an uncatalysed reaction between 1,4-dioxane (LXX) and benzoyl peroxide (XLIV).

Good yields of the benzoyloxy derivatives (LXXIII and LXXIV) were likewise isolated[83] when 2-methyl-2-ethyl-1,3-dioxolane (LXXV) and isochroman (LXXVI) were treated with t-butyl perbenzoate and cuprous salts.

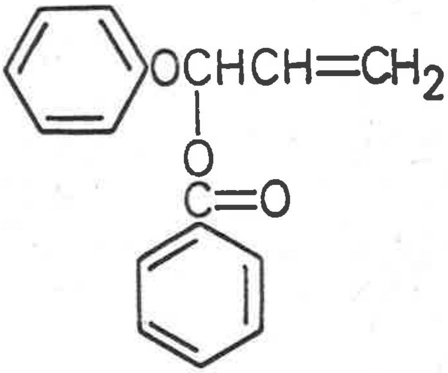
There are many instances, however, where ethers have produced the acyloxy products in poor yields. Tetrahydrofuran (LXXVII), tetrahydropyran (LXXVIII) and n-butyl ether (LXVII) all produced acyloxy products,[81,84-86]



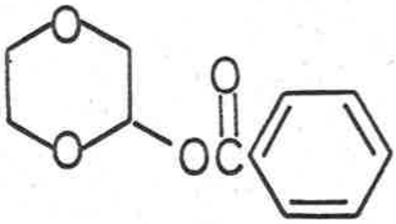
(LXIX)



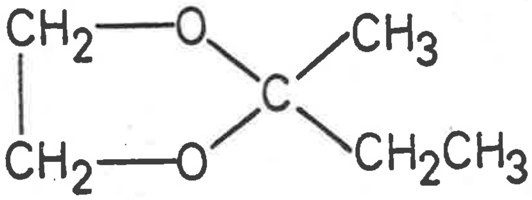
(LXX)



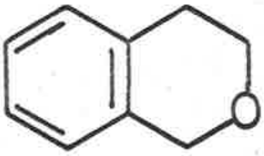
(LXXI)



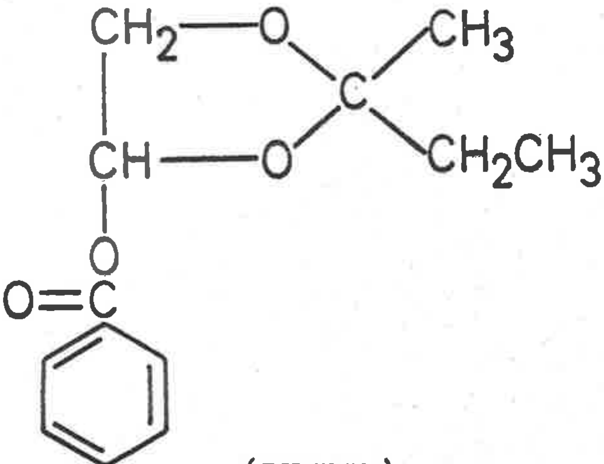
(LXXII)



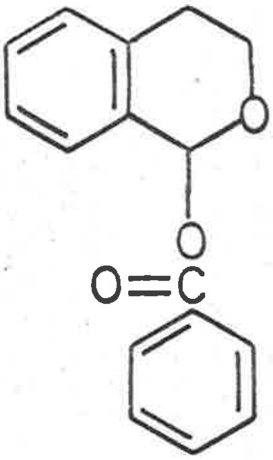
(LXXV)



(LXXVI)



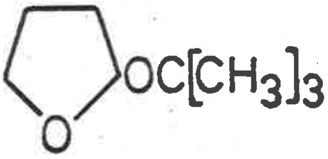
(LXXIII)



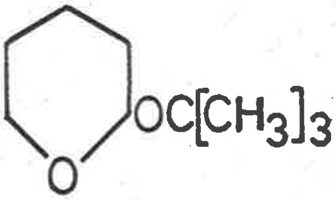
(LXXIV)

(LXXVII)

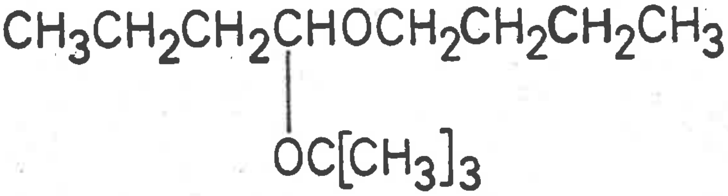
(LXXVIII)



(LXXIX)

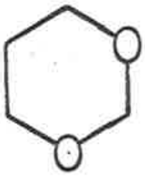


(LXXX)

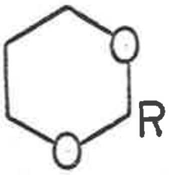


$$\underset{\displaystyle OC[CH_3]_3}{CH_3CH_2CH_2CH}OCH_2CH_2CH_2CH_3$$

(LXXXI)



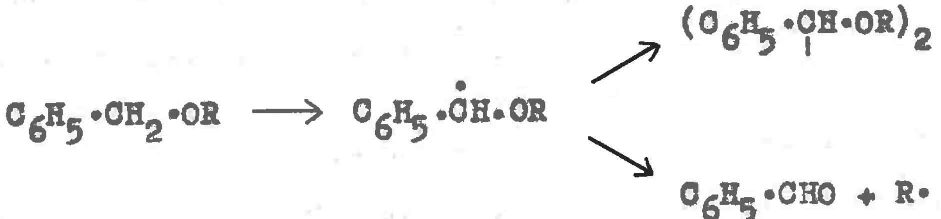
(LXXXII)



(LXXXIII)

but in poor yield. In all three cases acetals proved to be the main products; thus 2-t-butoxytetrahydrofuran (LXXIX), 2-t-butoxytetrahydropyran (LXXX) and 1-t-butoxy-1-n-butoxybutane (LXXXI) were isolated. When 1,3-dioxane (LXXXII) was treated under the same conditions,[83] the acetal (LXXXIII; R = $(CH_3)_3CO$) and the acylal (LXXXIII; R = $C_6H_5{\cdot}CO_2$) were both formed, the latter in greater yield.

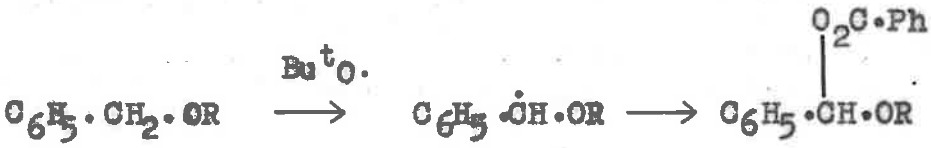
When benzyl ethers (LXXXIV) react with di-t-butyl peroxide (LIV) in the absence of cuprous ions,[87-89] a benzylic-hydrogen is always abstracted by the t-butoxy-radicals. The resultant radical (LXXXV) then, either, dimerizes or decomposes.



$$\begin{tikzcd} & & (C_6H_5{\cdot}\underset{|}{C}H{\cdot}OR)_2 \\ C_6H_5{\cdot}CH_2{\cdot}OR \arrow[r] & C_6H_5{\cdot}\dot{C}H{\cdot}OR \arrow[ur] \arrow[dr] & \\ & & C_6H_5{\cdot}CHO + R{\cdot} \end{tikzcd} \qquad (63)$$

(LXXXIV) (LXXXV)

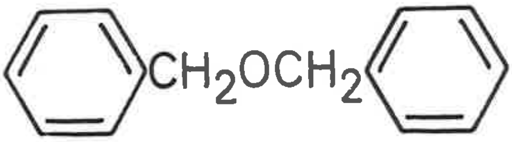
Benzyl ethers readily accommodate a benzoyloxy group when treated with t-butyl perbenzoate (X) and cuprous ions.[90,91] Lawesson and Berglund[90,91] suggested the following sceme



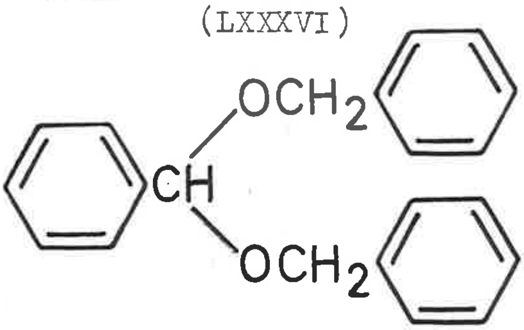
$$C_6H_5{\cdot}CH_2{\cdot}OR \xrightarrow{Bu^tO\cdot} C_6H_5{\cdot}\dot{C}H{\cdot}OR \longrightarrow C_6H_5{\cdot}\overset{O_2C\cdot Ph}{\overset{|}{C}H}{\cdot}OR \qquad (64)$$

These workers found that no dimerization or decomposition occurred. The resultant benzoyloxy compounds proved to be unstable to light and oxygen.

In contrast to these results, dibenzyl ether (LXXXVI) did not form an acylal derivative under the conditions used. The main product was shown to be the dibenzylacetal of benzaldehyde (LXXXVII).

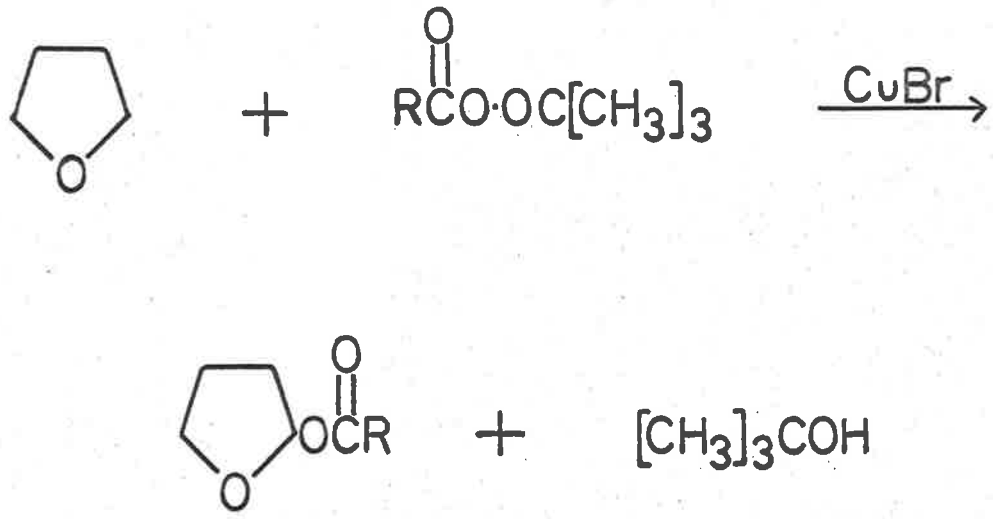


(LXXXVI)



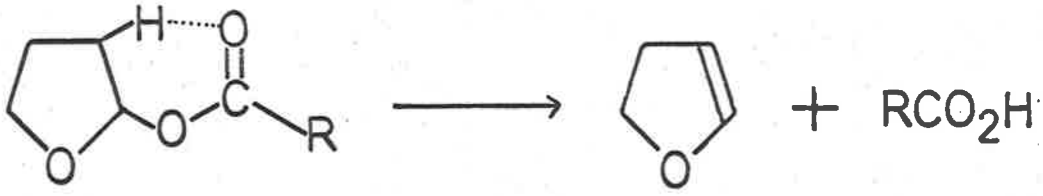
(LXXXVII)

Several workers have tried to explain the anomalous products obtained in these reactions of ethers. Sosnovsky[81] showed that the α-acyloxy ethers could often be decomposed into the appropriate α,β-unsaturated compounds. He suggested that the unsaturated ethers, so formed, could then react with t-butanol in the reaction mixture to yield acetals. Sosnovsky[92] formulated the reaction by the equations (65-67).

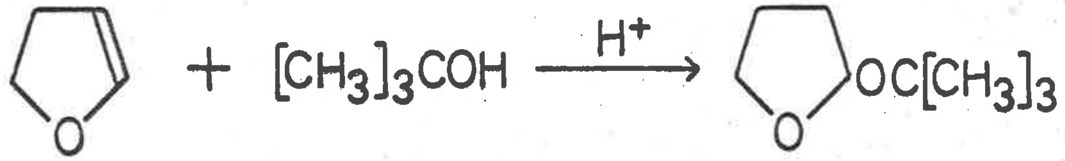


(65)

(LXXXVIII)



(66



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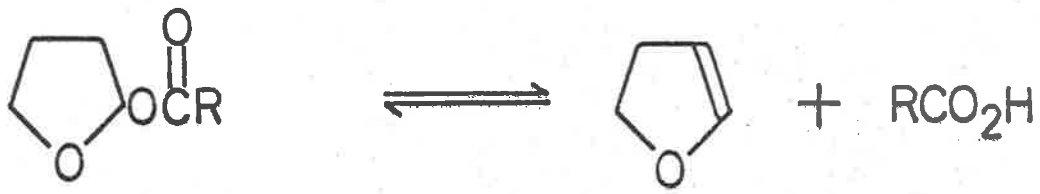
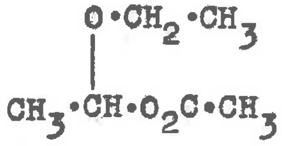


(68

Sosnovsky found that the acyloxy derivatives (LXXXVIII) could be isolated in much better yield when the reactions were stopped immediately after all the perester had been consumed.

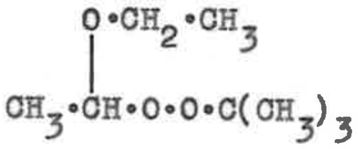
Lawesson and Berglund[85] suggested that an equilibrium could exist between the ether and the acid (68), the acid being produced upon rise in temperature.

These workers[83] later suggested that the formation of t-butoxy derivatives involved solvolysis with t-butanol, proceeding by alkyl-oxygen heterolysis of the ester. A somewhat similar mechanism was also advanced by Rieche and Bischoff[93] for the reaction of t-butyl hydroperoxide (LI) with α-ethoxyethyl acetate (LXXXIX) which yields the peroxide (XC).



$CH_3 \cdot \overset{O \cdot CH_2 \cdot CH_3}{CH} \cdot O_2C \cdot CH_3$

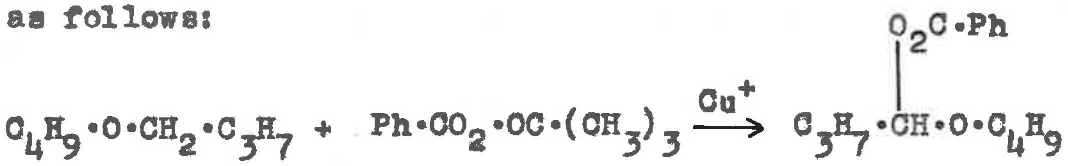
(LXXXIX)



$CH_3 \cdot \overset{O \cdot CH_2 \cdot CH_3}{CH} \cdot O \cdot O \cdot C(CH_3)_3$

(XC)

Support for this hypothesis was obtained when Lawesson and Berglund[78,85,94] treated ethers with t-butyl perbenzoate and cuprous salts in an excess of alcohols other than t-butanol. Di-n-butyl ether (LXVII) reacted, under these conditions, to yield a symmetrical acetal[78,94] as follows:



$$C_4H_9\cdot O\cdot CH_2\cdot C_3H_7 + Ph\cdot CO_2\cdot OC\cdot(CH_3)_3 \xrightarrow{Cu^+} C_3H_7\cdot\overset{O_2C\cdot Ph}{CH}\cdot O\cdot C_4H_9$$

(LXVII) (69)

$$C_3H_7\cdot\overset{O_2C\cdot Ph}{CH}\cdot O\cdot C_4H_9 \xrightarrow{RCH} C_3H_7\cdot CH(OR)\cdot O\cdot C_4H_9 \qquad (70)$$

$$C_3H_7\cdot CH(OR)\cdot O\cdot C_4H_9 \xrightarrow{ROH} C_3H_7\cdot CH(OR)_2 \qquad (71)$$

In a similar reaction, di-*iso*-propyl ether (XCI) gave symmetric ketals of acetone (XCII), according to the following scome:

$$(CH_3)_2\cdot CH\cdot O\cdot CH\cdot(CH_3)_2 + Ph\cdot CO_2\cdot OC(CH_3)_3 \xrightarrow{Cu^+}$$

(XCI)

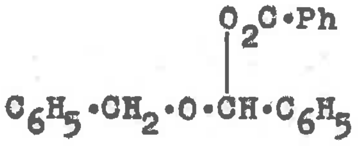
$$(CH_3)_2\cdot CH\cdot O\cdot C(CH_3)_2\cdot O_2C\cdot Ph \qquad (72)$$

$$(CH_3)_2\cdot CH\cdot O\cdot C\cdot(CH_3)_2\cdot O_2C\cdot Ph \xrightarrow{ROH} (CH_3)_2\cdot CH\cdot O\cdot C\cdot(CH_3)_2\cdot OR \qquad (73)$$

$$(CH_3)_2\cdot CH\cdot O\cdot C\cdot(CH_3)_2\cdot OR \xrightarrow{ROH} (CH_3)_2\cdot C\cdot(OR)_2 \qquad (74)$$

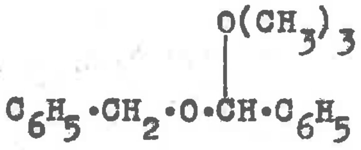
(XCII)

Lawesson and Berglund[78] extended the above mechanism to explain the formation of the dibenzylacetal of benzaldehyde (LXXXVII) from dibenzyl ether (LXXXVI). They suggested that benzyl alcohol could displace the benzoyloxy group of the acylal (XCIII) to produce the observed product (LXXXVII). Alternatively, the unsymmetrical acetal (XCIV) could be initially formed by the action of t-butanol on the acylal (XCIII) and subsequent reacetalization[95] with benzyl alcohol could then give the product (LXXXVII). Although the presence of benzyl alcohol appears not to have been reported in the products of this reaction, the corresponding reaction between t-butyl perbenzoate (X), di-n-butyl ether (LXVII) and cuprous ions has been shown[78] to yield n-butanol.



$C_6H_5\cdot CH_2\cdot O\cdot \overset{O_2C\cdot Ph}{CH}\cdot C_6H_5$

(XCIII)



$C_6H_5\cdot CH_2\cdot O\cdot \overset{O(CH_3)_3}{CH}\cdot C_6H_5$

(XCIV)

The above mechanism was further verified when these workers found that the dibenzylacetal of benzaldehyde (LXXXVII) was also formed from the reaction between t-butyl perbenzoate, cuprous chloride and benzyl alcohol. The following sceme was suggested:

$$C_6H_5\cdot CH_2\cdot OH + Ph\cdot CO_2\cdot OC(CH_3)_3 \xrightarrow{Cu^+} C_6H_5\cdot CHOH\cdot O_2C\cdot Ph \qquad (75)$$

$$C_6H_5\cdot CHOH\cdot O_2C\cdot Ph \xrightarrow{ROH} C_6H_5\cdot CHOH\cdot OR \qquad (76)$$

$$C_6H_5\cdot CHOH\cdot OR \xrightarrow{ROH} C_6H_5\cdot CH\cdot (OR)_2 \qquad (77)$$

(where $R=C_6H_5\cdot CH_2$)

It was also found[96] that the benzoyloxy derivative of benzyl ethyl ether (XCV) reacted with ethanol to produce benzaldehyde diethylacetal (XCVI).

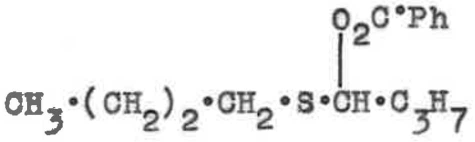
$$\underset{(XCV)}{C_6H_5\cdot CHOEt\cdot O_2C\cdot Ph} \xrightarrow{EtOH} \underset{(XCVI)}{C_6H_5\cdot CH\cdot (OEt)_2} \qquad (78)$$

Although it has been shown that acetals can be prepared by refluxing acylals in alcohols,[78,85,94] there appears to be no report of the catalysed-decomposition of t-butyl perbenzoate (X) in the presence of acylals and acetals. The results of such reactions would certainly help to clarify the mechanism of these reactions with ethers.

Simple thioethers have been shown to react in a similar fashion to their oxygen analogues. In the case of di-n-butyl sulphide (XCVII), the action of t-butyl perbenzoate (X) and cuprous chloride produced[79,86] the expected acylal derivative (XCVIII).

$$CH_3 \cdot (CH_2)_2 \cdot CH_2 \cdot S \cdot CH_2 \cdot (CH_2)_2 \cdot CH_3$$

(XCVII)



$$CH_3 \cdot (CH_2)_2 \cdot CH_2 \cdot S \cdot \overset{\overset{O_2C \cdot Ph}{|}}{C}H \cdot C_3H_7$$

(XCVIII)

In contrast to its oxygen analogue, the acylal (XCVIII) did not produce an acetal when treated with t-butanol. Instead, the α,β-unsaturated sulphide (XCIX) was obtained.

$$CH_3 \cdot (CH_2)_2 \cdot CH_2 \cdot S \cdot CH{:}CH \cdot CH_2 \cdot CH_3$$

(XCIX)

Diethyl sulphide (C), n-propyl sulphide (CI), tetrahydrothiophene (CII) and thioxane (CIII) all react smoothly with t-butyl perbenzoate and cuprous ions to give the expected acyloxy compounds (CIV-CVII) in good yields.[83,97]

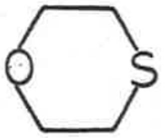
$CH_3CH_2SCH_2CH_3$

(C)

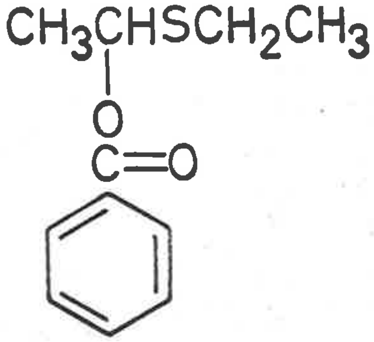
$CH_3CH_2CH_2SCH_2CH_2CH_3$

(CI)

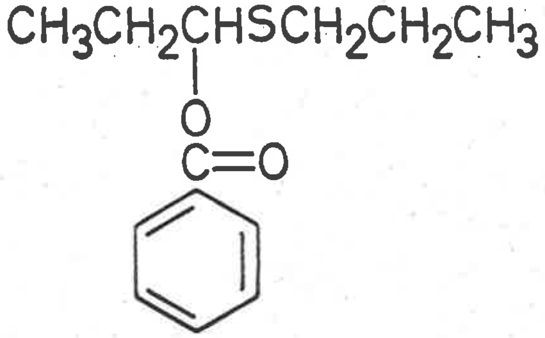
(CII)



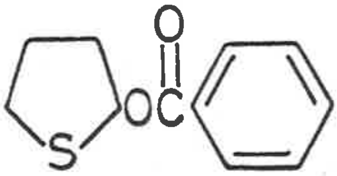
(CIII)



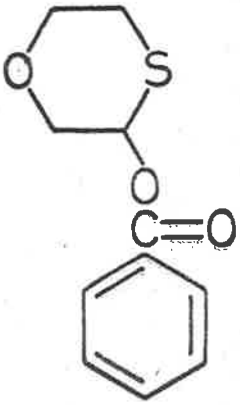
(CIV)



(CV)



(CVI)



(CVII)

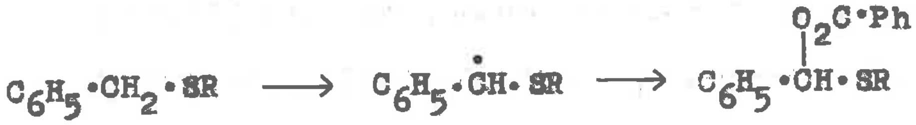
When benzyl sulphides react with *t*-butoxy radicals in the absence of copper salts, the resultant radicals dimerize[96] (*Cf.* benzyl ethers[87]). This was observed in the case of dibenzyl sulphide (CVIII).

$$C_6H_5\cdot CH_2\cdot S\cdot CH_2\cdot C_6H_5 \xrightarrow{Bu^tOH} C_6H_5\cdot CH_2\cdot S\cdot \dot{C}H\cdot C_6H_5 \longrightarrow$$

(CVIII)

$$(C_6H_5\cdot CH_2\cdot S\cdot \overset{|}{C}H\cdot C_6H_5)_2 \qquad (79)$$

Lawesson and Berglund[96] have shown that benzyl sulphides readily form the expected acylal derivatives when treated with *t*-butyl perbenzoate and copper salts.



$$C_6H_5\cdot CH_2\cdot SR \longrightarrow C_6H_5\cdot \dot{C}H\cdot SR \longrightarrow C_6H_5\cdot \overset{O_2C\cdot Ph}{\overset{|}{C}H}\cdot SR \qquad (80)$$

As in the case of their oxygen analogues, these acylal derivatives are relatively unstable. Although dibenzyl ether (LXXXVI) failed to yield an acylal derivative,[91] the corresponding dibenzyl sulphide derivative was isolated,[96] but was too unstable to be purified.

It has long been established[98-100] that α-hydrogen atoms are preferentially abstracted from alcohols during free-radical reactions. The reaction between benzyl alcohol and t-butyl perbenzoate (X) in the absence of copper salts yields benzaldehyde.[96] Bartlett and Nozaki[98] suggested that a hemiacylal (CIX) would be an intermediate of such a reaction; this could then decompose into the carbonyl compound.

$$C_6H_5{\cdot}CHOH{\cdot}O_2C{\cdot}Ph \longrightarrow C_6H_5{\cdot}CHO + C_6H_5{\cdot}CO_2H \qquad (81)$$

(CIX)

Sosnovsky and Yang[80] heated a mixture of t-butyl perbenzoate and cuprous ions in the presence of benzyl alcohol and also obtained benzoic acid and benzaldehyde as products. They likewise proposed an intermediate hemiacylal which subsequently decomposed into the aldehyde and acid.

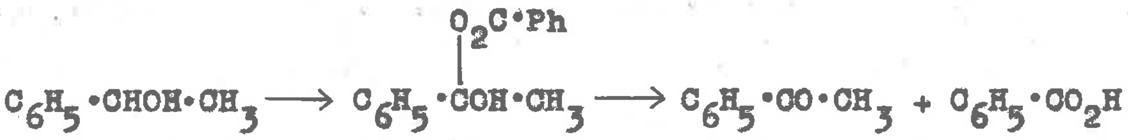
This experiment was later repeated by Lawesson and Berglund[96] who found that the sole product of the reaction with cuprous ions was the dibenzylacetal of benzaldehyde (LXXXVII) (75-77). They came to the conclusion that the cuprous salt prevents the decomposition of the hemiacylal (CIX) into benzaldehyde and benzoic acid.

These workers[101] later studied the cuprous ion-catalysed decomposition of *t*-butyl perbenzoate in the presence of *n*-butanol, *s*-butanol and 1-phenylethanol (CXI). The main product from the *n*-butanol-reaction was *n*-butyraldehyde di-*n*-butylacetal (CX). A hemiacylal was again suggested as an intermediate.

$$CH_3(CH_2)_2CH(OBu^n)_2$$

(CX)

The two secondary alcohols yielded methyl ethyl ketone and acetophenone respectively. Lawesson and Berglund suggested that no ketal was formed and that the decomposition of the hemiacylal went to completion.



$$C_6H_5{\cdot}CHOH{\cdot}CH_3 \longrightarrow C_6H_5{\cdot}\overset{\overset{O_2C{\cdot}Ph}{|}}{C}OH{\cdot}CH_3 \longrightarrow C_6H_5{\cdot}CO{\cdot}CH_3 + C_6H_5{\cdot}CO_2H$$

(CXI) (82)

Cuprous salts have no effect on the reaction[96] between *t*-butyl perbenzoate and benzyl mercaptan (CXII). The *t*-butoxy-radical abstracts the S-H hydrogen and not the C-H hydrogen. Dimerization results, with the formation of the disulphide (CXIII).

$$C_6H_5{\cdot}CH_2{\cdot}SH \longrightarrow C_6H_5{\cdot}CH_2{\cdot}S{\cdot} \longrightarrow C_6H_5{\cdot}CH_2{\cdot}S{\cdot}S{\cdot}CH_2{\cdot}C_6H_5 \quad (83)$$

(CXII) (CXIII)

The active hydrogen-atom of aldehydes is very prone to abstraction by free radicals;[102,103] acyl-radicals are thereby formed. Benzaldehyde and di-*t*-butyl peroxide react[102] to yield *sym*-diphenylethylene glycol dibenzoate (CXIV). The following scheme was suggested.

$$(CH_3)_3CO{\cdot}OC(CH_3)_3 \longrightarrow 2(CH_3)_3CO{\cdot} \qquad (84)$$

$$(CH_3)_3CO{\cdot} + C_6H_5{\cdot}CHO \longrightarrow (CH_3)_3C{\cdot}OH + C_6H_5{\cdot}CO{\cdot} \qquad (85)$$

$$C_6H_5{\cdot}CO{\cdot} + O{:}CH{\cdot}C_6H_5 \longrightarrow C_6H_5{\cdot}CO_2{\cdot}\dot{C}H{\cdot}C_6H_5 \qquad (86)$$

$$2\,C_6H_5{\cdot}CO_2{\cdot}\dot{C}H{\cdot}C_6H_5 \longrightarrow (C_6H_5{\cdot}CO_2{\cdot}\underset{|}{C}H{\cdot}C_6H_5)_2 \qquad (87)$$

(CXIV)

The glycol dibenzoate (CXIV) is also obtained in good yield when *t*-butyl perbenzoate is used instead of di-*t*-butyl peroxide.[80]

In the presence of cuprous ions, benzaldehyde and di-*t*-butyl peroxide (LIV) react[71] to yield *t*-butyl benzoate (CXV) and the corresponding reaction with *t*-butyl perbenzoate[80] yields benzoic anhydride (CXVI).

$$C_6H_5{\cdot}CO_2{\cdot}C(CH_3)_3 \qquad\qquad (C_6H_5{\cdot}CO)_2{\cdot}O$$

(CXV) (CXVI)

Similar results were obtained in the reaction of *n*-butyraldehyde with *t*-butyl perbenzoate and copper ions[80] and also the reaction between benzoyl peroxide and valeraldehyde.[71]

The α-hydrogen atoms of ketones have been shown to be prone to abstraction by free radicals. Kharasch *et al*[104] demonstrated that the decomposition-products of diacetyl peroxide (CXVII) readily abstract the α-hydrogens from ketones to produce the radicals (CXVIII), which then dimerize to form 1,4-diketones (CXIX).

$$(CH_3{\cdot}CO_2)_2 \qquad R{\cdot}R'{\cdot}\overset{\bullet}{C}{\cdot}CO{\cdot}CH{\cdot}R{\cdot}R' \qquad (R{\cdot}R'{\cdot}\underset{|}{C}{\cdot}CO{\cdot}CH{\cdot}R{\cdot}R')_2$$

(CXVII) (CXVIII) (CXIX)

Similar dimeric products are obtained when di-*t*-butyl peroxide (LIV) is decomposed in the presence of ketones.[105] However, when Sosnovsky and Yang[80] treated cyclohexanone with *t*-butyl perbenzoate (X) in the presence of cuprous bromide, mainly starting material was recovered. The small amount of product from the reaction was not identified.

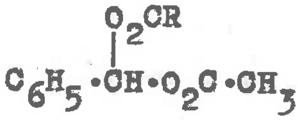
The α-hydrogen atoms of carboxylic acids and their esters are readily abstracted by certain free radicals.[106-108] Hydrogen atoms β- to the carbonyl group are much less reactive. Beckwith has shown[108] that α-hydrogen atoms in the acid-moiety of an ester are abstracted six-times more readily by t-butoxy-radicals than those in the alcohol-moiety. In all cases, dimers are the products.

When Sosnovsky and Yang[80] treated benzyl acetate (CXX) with t-butyl peracetate (XI) they obtained a good yield of the glycol ester (CXXI). This ester resulted from the dimerization of the radical (CXXII)

$$C_6H_5 \cdot CH_2 \cdot O_2C \cdot CH_3 \qquad (C_6H_5 \cdot \underset{|}{C}H \cdot O_2C \cdot CH_3)_2 \qquad C_6H_5 \cdot \dot{C}H \cdot O_2C \cdot CH_3$$

(CXX) (CXXI) (CXXII)

A good yield of benzylidine diacetate (CXXIII; $R=CH_3$) was obtained instead of the dimers when the reaction was repeated in the presence of cuprous bromide. When t-butyl perbenzoate (X) was used, the principal product was benzylidine acetate benzoate (CXXIII; $R=C_6H_5$).



$$C_6H_5\cdot\overset{\overset{O_2CR}{|}}{C}H\cdot O_2C\cdot CH_3$$

(CXXIII)

The cuprous ion-catalysed decomposition of *t*-butyl perbenzoate in the presence of diethyl malonate (CXXIV) and cuprous chloride,[83] gave a poor yield of diethyl *O*-benzoyl tartronate (CXXV; R=$C_6H_5\cdot CO_2$). The main product proved to be diethyl *O*-*t*-butyl tartronate (CXXV; R=$(CH_3)_3CO$).

$CH_2\cdot(CO_2\cdot C_2H_5)_2$

(CXXIV)

$RCH\cdot(CO_2\cdot C_2H_5)_2$

(CXXV)

These workers failed to prepare diethyl *O*-*t*-butyl tartronate (CXXV; R = $(CH_3)_3CO$) by refluxing the benzoyloxy compound (CXXV; R = $C_6H_5\cdot CO_2$) with *t*-butanol (*Cf*. the acylal derivatives obtained from ethers.[78,85,94]).

The reaction between ethyl acetoacetate (CXXVI) *t*-butyl perbenzoate and cuprous chloride[83] gave ethyl α-*t*-butoxy acetoacetate (CXXVII; R=$(CH_3)_3CO$) in 20% yield. A small quantity of the benzoyloxy derivative (CXXVII; R=$C_6H_5CO_2$) was formed but not purified.

$CH_3{\cdot}CO{\cdot}CH_2{\cdot}CO_2{\cdot}CH_2{\cdot}CH_3$ (CXXVI)

$CH_3{\cdot}CO{\cdot}CHR{\cdot}CO_2{\cdot}CH_2{\cdot}CH_3$ (CXXVII)

Although transition-metal salts do not influence reactions between t-butyl perbenzoate and amines,[80] the reaction of peresters with amides is considerably affected by cuprous salts. Berglund and Lawesson[83] showed that peresters were very unstable in amines, even at room temperature, but a smooth reaction occurred between t-butyl perbenzoate, N,N-dimethylformamide (CXXVIII) and cuprous salts to give a fair yield of N-benzoyloxymethyl-N-methylformamide (CXXIX).

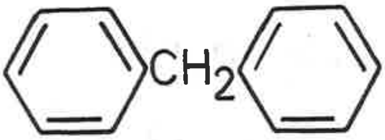
$H{\cdot}CO{\cdot}N{\cdot}(CH_3)_2$ (CXXVIII)

$H{\cdot}CO{\cdot}N{\cdot}CH_3{\cdot}CH_2{\cdot}O_2C{\cdot}Ph$ (CXXIX)

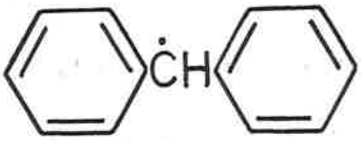
It has long been known that certain free radicals readily abstract activated-hydrogen atoms from hydrocarbons; invariably dimeric products are obtained. Hydrogen-atoms most prone to such abstraction are those α- to an aromatic ring; the benzyl type radical so produced enjoys considerable stabilization by resonance (CXXX). Thus toluene (CXXXI), ethylbenzene (CXXXII), cumene (CXXXIII) and β - and γ-picoline

(CXXXIV and CXXXV) all yielded the expected dimers when treated with t-butoxy-, methyl- and phenyl- radicals.[57, 109-113] No dimerization occurs, however, if cuprous salts are present. When tetralin (CXXXVI) was treated[80] with t-butyl perbenzoate and cuprous bromide, the main product proved to be 1-benzoyloxytetrahydronaphthalene (CXXXVII).

Contrary to this result, Berglund and Lawesson[83] treated diphenylmethane (CXXXVIII) under similar conditions, and only obtained the dimer of the diphenylmethyl-radical (CXXXIX).

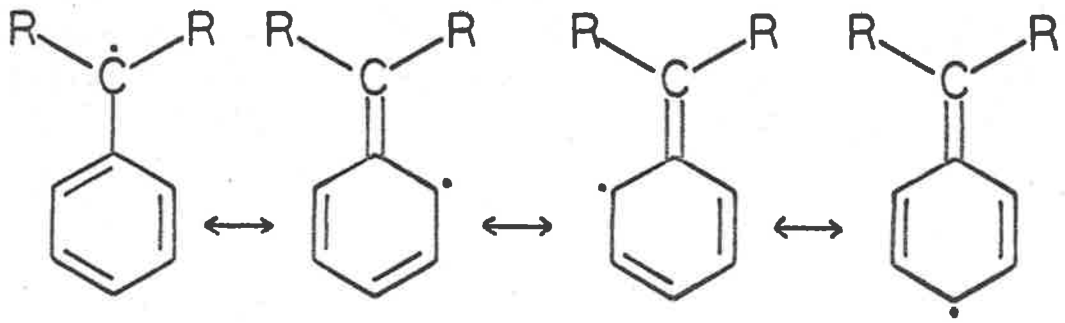


(CXXXVIII)

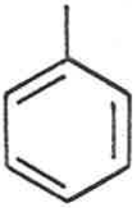


(CXXXIX)

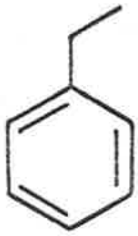
When dicumene (CXL) is pyrolysed in bromobenzene at 225° for 10 hr. in a sealed tube, all the dicumene is decomposed. Kharasch and Fono[71] found that the presence of cuprous bromide, in such a reaction, considerably retarded the dissociation of dicumene into cumyl-radicals (CXLI). Even when the temperature was



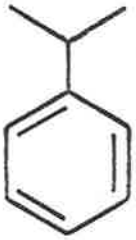
(CXXX)



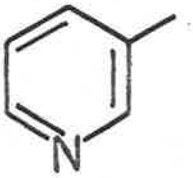
(CXXXI)



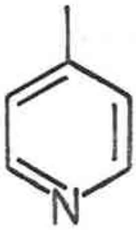
(CXXXII)



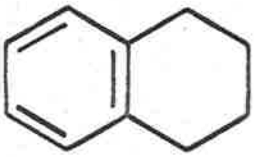
(CXXXIII)



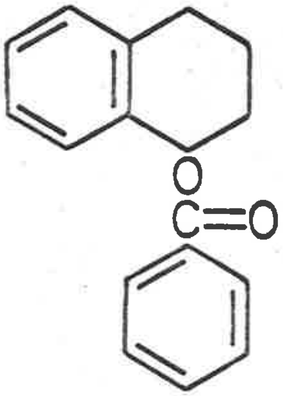
(CXXXIV)



(CXXXV)

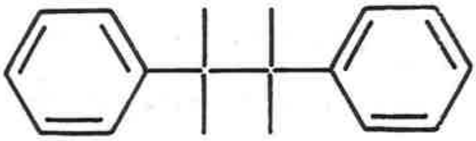


(CXXXVI)

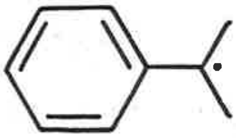


(CXXXVII)

raised to 225° and the pyrolysis time was increased to 24 hr., 37% of unchanged dicumene was still recovered.

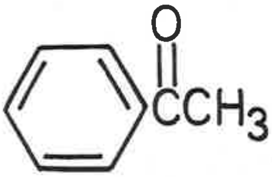


(CXL)

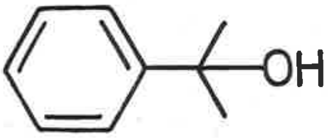


(CXLI)

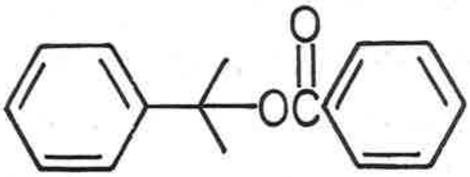
The same workers treated cumene (CXXXIII) with a mixture of benzoyl peroxide (XLIV) and cuprous chloride and isolated acetophenone (CXLII), α-cumyl alcohol (CXLIII), a mixture of isopropylbiphenyls, and a large quantity of α-cumyl benzoate (CXLIV). Repitition of this experiment using <u>t</u>-butyl perbenzoate (X) also yielded α-cumyl benzoate (CXLIV) in 40% yield.



(CXLII)



(CXLIII)



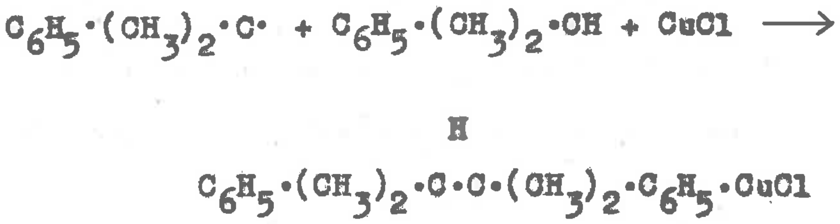
(CXLIV)

Kharasch and Fono[71] attempted to explain the abnormal effect of copper salts upon these reactions. Considering the reaction between benzoyl peroxide (XLIV), cuprous salt and cumene (CXXXIII), they suggested that the initially-formed cumyl-radicals (CXLI) could be reversibly "trapped" on the copper salt. These "trapped" radicals could then attack a new benzoyl peroxide molecule (88 and 89). The induced-decomposition of the peroxide would thus be explained.

$$C_6H_5\cdot(CH_3)_2\cdot C\cdot + Cu^+ \rightleftharpoons C_6H_5\cdot(CH_3)_2\cdot C\cdot Cu^+ \qquad (88)$$

$$C_6H_5\cdot(CH_3)_2\cdot C\cdot Cu^+ + (C_6H_5\cdot CO_2)_2 \longrightarrow C_6H_5\cdot(CH_3)_2\cdot C\cdot + C_6H_5\cdot(CH_3)_2\cdot C\cdot O_2C\cdot Ph + Cu^+ \qquad (89)$$

Alternatively, these workers suggested that free-radicals can form complexes in the presence of cuprous salts. They produced some evidence to show that such a complex (CXLV) was formed between a cumene molecule, cumyl radical and cuprous salt during the catalysed-decomposition of di-*t*-butyl peroxide (LIV) in cumene.



$$C_6H_5\cdot(CH_3)_2\cdot C\cdot + C_6H_5\cdot(CH_3)_2\cdot CH + CuCl \longrightarrow C_6H_5\cdot(CH_3)_2\cdot \overset{H}{C}\cdot C\cdot(CH_3)_2\cdot C_6H_5\cdot CuCl \qquad (90)$$

(CXLV)

Since this hypothesis was published, however, many experimental results have shown that a radical complex such as (CXLV) is unimportant.

Kharasch and Fono[71] also suggested that the acyl radical, derived from benzaldehyde by hydrogen abstraction (85), was reversibly "trapped" on a cuprous ion, and therefore could not add to a benzaldehyde molecule. Instead it attacked the di-t-butyl peroxide (LIV) and yielded t-butyl benzoate (CXV).

$$C_6H_5\cdot CO\cdot + CuCl \longrightarrow C_6H_5\cdot CO\cdot CuCl \qquad (91)$$

$$C_6H_5\cdot CO\cdot CuCl + (CH_3)_3CO\cdot OC(CH_3)_3 \longrightarrow C_6H_5\cdot CO_2\cdot C(CH_3)_3 + (CH_3)_3CO\cdot + CuCl \qquad (92)$$

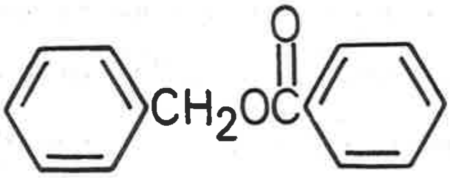
(CXV)

When the experiments for this thesis were initiated, the mechanism of the reactions between peresters and substrates with labile-hydrogen atoms (as in the case of olefin-perester reactions) was still obscure. Several experiments presented in this thesis, therefore, were designed to explore the mechanism of these reactions. However, similar to the olefin-perester reactions, subsequent publications by other workers, notably Kochi, reasonably explained the mechanism of these reactions. Nevertheless we did furnish early evidence for the oxidation and reduction of free-radicals by copper ions in non-polar solvents.[68]

These reactions, which will be discussed in detail in a later section of this thesis, provided evidence for the oxidation of benzyl-radicals with cupric ions and also the reduction of benzoyloxy-radicals with cuprous ions. Thus the decomposition of di-t-butyl peroxide (LIV) in the presence of cupric ions, toluene (CXXXI) and benzoate ions, yielded benzyl benzoate (CXLVI), indicating that the intermediate benzyl-radicals (CXLVII) were being oxidized.

$$C_6H_5{\cdot}CH_2{\cdot} + Cu^{2+} \longrightarrow C_6H_5{\cdot}CH_2^{+} + Cu^{+} \qquad (93)$$

It will be shown in the next section that an intermediate carbonium ion need not be formed in this reaction.



(CXLVI)

(CXLVII)

Likewise, the cuprous-ion catalysed decomposition of benzoyl peroxide (XLIV) in benzene yielded 70% benzoic acid, whereas in the absence of cuprous ions only 22% yield was obtained. We postulated the following sceme:

$$Cu^{+} + (C_6H_5{\cdot}CO_2)_2 \longrightarrow C_6H_5{\cdot}CO_2Cu^{2+} + C_6H_5{\cdot}CO_2{\cdot} \qquad (94)$$

$$C_6H_5{\cdot}CO_2{\cdot} + Cu^{+} \longrightarrow C_6H_5{\cdot}CO_2Cu^{2+} \qquad (95)$$

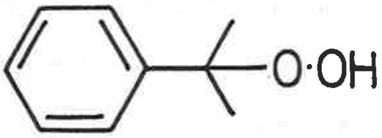
We also suggested that the acyloxylation of ethers and sulphides by peresters, in the presence of copper salts, could proceed by a similar mechanism to that proposed by us for the stereospecific acyloxylation of olefins (43 and 44).

(d) HYDROPEROXIDE REACTIONS

The induced-decomposition of hydrogen peroxide by ferrous ions has already been discussed. Most organic-hydroperoxides are <u>also</u> reduced by ferrous ions through an analogous pathway;[114] alkoxy radicals are thus produced.

$$\mathrm{RO{\cdot}OH} + \mathrm{Fe}^{2+} \longrightarrow \mathrm{RO{\cdot}} + \mathrm{OH}^{-} + \mathrm{Fe}^{3+} \qquad (96)$$

The ferrous-salt induced-decomposition of cumene hydroperoxide (CXLVIII) has been extensively studied. Kinetic results,[115-117] and examination of products derived from the decomposition of this hydroperoxide in the presence[73] and in the absence[40,118] of substrates, has indicated that the hydroperoxide and ferrous ions are consumed according to equation (96) (where R = $C_6H_5{\cdot}C(CH_3)_2$). Likewise, <u>t</u>-butyl hydroperoxide (LI) has been shown[73] to yield <u>t</u>-butoxy-radicals under the same conditions.



(CXLVIII)

Since <u>t</u>-butyl hydroperoxide (LI) has been more extensively studied than other hydroperoxides, the reactions of this compound will receive most attention in the following discussion.

When t-butyl hydroperoxide is decomposed in the presence of copper or cobalt salts, two types of fission can occur within the hydroperoxide:

$$RO{\cdot}OH + M^{n+} \longrightarrow RO\cdot + OH^- + M^{(n+1)^+} \qquad (97)$$

$$RO{\cdot}OH + M^{(n+1)^+} \longrightarrow RO{\cdot}O\cdot + H^+ + M^{n+} \qquad (98)$$

(CXLIX)

The cuprous or cobaltous salts can reduce the hydroperoxide (97). This is analogous to the ferrous ion decomposition of hydroperoxides (96). Alternatively cupric or cobaltic salts may oxidize the hydroperoxide (98) to give alkyl peroxy radicals (CXLIX).

Campbell and Coppinger,[119] and Kharasch and his co-workers,[49] have provided evidence for the existence of these alkyl peroxy radicals (CXLIX). The former group of workers coupled t-butyl peroxy radicals (CL) with some aryl radicals to produce t-butylaryl peroxides; the latter group treated t-butyl peroxy radicals (CL) with olefins, to produce t-butylalkenyl peroxides.

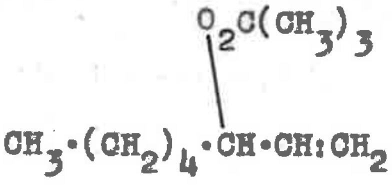
$(CH_3)_3COO\cdot$

(CL)

The isomer distribution is of interest in these latter reactions. The reaction of t-butyl peroxy radicals with oct-1-ene, in the presence of cobalt salts, yielded mainly t-butyl-2-octenyl peroxide (CLI). Very little of the isomeric peroxide (CLII) was isolated. This is a similar distribution of isomers to that found during the copper-ion catalysed-decomposition of benzoyl peroxide (XLIV) in but-1-ene.[38]

$CH_3\cdot(CH_2)_4\cdot CH{:}CH\cdot CH_2\cdot O_2C(CH_3)_3$

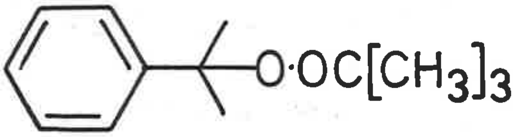
(CLI)



$CH_3\cdot(CH_2)_4\cdot\overset{O_2C(CH_3)_3}{CH}\cdot CH{:}CH_2$

(CLII)

Kharasch and Fono[47,120] studied the copper-salt catalysed-decomposition of t-butyl hydroperoxide (LI) in the presence of cumene (CXXXIII) and isolated t-butyl-α-cumyl peroxide (CLIII).



(CLIII)

These workers[47,120,121] also found that t-butyl peroxy groups would substitute into the α-positions of ketones, ethers and nitriles, the N-methyl groups of N,N-dimethylaniline and the allylic-position of olefins when these substrates were present in the reaction mixture. In all cases, t-butyl peroxy-substituted compounds were the products. Cumene hydroperoxide (CXLVIII) behaved in a similar fashion. The following mechanism was suggested for these reactions.[120]

$$RO{\cdot}OH + M^{+} \longrightarrow RO{\cdot} + M(OH)^{+} \qquad (99)$$

$$RO{\cdot} + R'H \longrightarrow ROH + R'{\cdot} \qquad (100)$$

$$R'{\cdot} + RO{\cdot}OH + M(OH)^{+} \longrightarrow R'O{\cdot}OR + M^{+} + H_2O \qquad (101)$$

Thus, the cuprous- or cobaltous-salt is oxidized during the production of alkoxy radicals (99) and is then reduced to its original valency-state by the oxidation-step (101). A trace of metal-salt will therefore catalyse these reactions to completion.

Kharasch and Fono[120] suggested that the oxidation-step (101) could follow one of two pathways:

(a) Cleavage of the hydroperoxide by cupric- or cobaltic-ions (98) to yield free alkyl peroxy radicals, which could then couple with the substrate radical (102).

$$RO{\cdot}O{\cdot} + R'{\cdot} \longrightarrow RO{\cdot}OR' \qquad (102)$$

(b) Complex-formation between the hydroperoxide and substrate-radical (103), and subsequent oxidation of the complex by cupric- or cobaltic-ions, to yield the products (104).

$$R'{\cdot} + RO{\cdot}OH \longrightarrow R'{\cdot}HO{\cdot}OR \qquad (103)$$

$$R'{\cdot}HO{\cdot}OR + M(OH)^{+} \longrightarrow R'O{\cdot}OR + M^{+} + H_2O \qquad (104)$$

When the copper salt-catalysed-decomposition of hydroperoxides is carried out in the presence of inert solvents, large quantities of molecular oxygen are evolved.[43,120,122] Kharasch _et al_[43] originally suggested that further reaction of the alkyl peroxy radical (CXLIX) with cupric- or cobaltic-ions, could produce oxygen and carbonium ions.

$$RO{\cdot}O{\cdot} + Cu^{2+} \longrightarrow R^{+} + O_2 + Cu^{+} \qquad (105)$$

These workers[120] later repudiated this theory because no acetate-formation occurred when the reaction was conducted in acetic acid. They suggested that, either the interaction of two peroxy-radicals (106), or the reaction between a peroxy radical and hydroperoxide (107), could produce the oxygen.

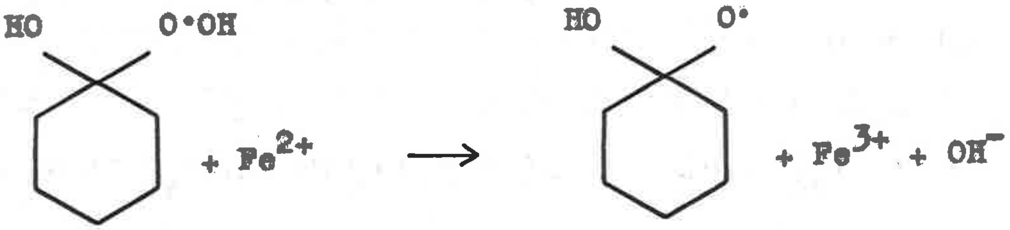
$$2\ RO{\cdot}O{\cdot} \longrightarrow 2\ RO^{\cdot} + O_2 \qquad (106)$$

$$RO{\cdot}O{\cdot} + RO{\cdot}OH \longrightarrow ROH + O_2 + RO^{-} \qquad (107)$$

The oxidation of hydroperoxides by cupric ions to form peroxy-radicals (98) was shown, in the preceding discussion, to provide a possible synthetic route to the formation of peroxy-compounds from hydrogen-donor substrates.

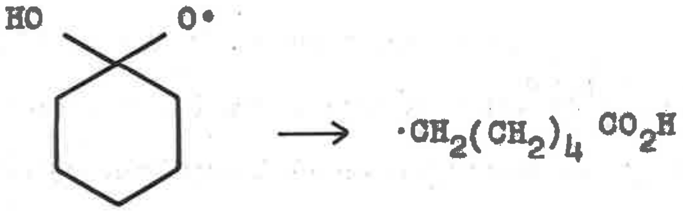
Under certain circumstances, however, this abnormal cleavage of the O-H bond is undesirable. If, in the presence of added anions, the cupric salt could be employed in oxidizing substrate-radicals to cations, the subsequent interaction of the two ionic species would lead to new products. Thus, if the added anion was a carboxylate ion, an unlimited number of esters could be formed, depending upon the nature of the substrate and carboxylic acid. Under these circumstances, the abnormal cleavage of the O-H bond of hydroperoxide by cupric ions would result in a deficiency of cupric ions and the production of unwanted by-products.

This difficulty was overcome by De La Mare _et al_[28] when they used a mixture of ferrous and cupric ions as a catalyst. The ferrous ions cleaved the hydroperoxide in the conventional manner (97) and the cupric ions oxidized the substrate-radical. The following mechanism was suggested for the formation of 5-hexenoic acid (CLV) from 1-hydroxy-1-hydroperoxycyclohexane (CLIV) using a mixture of ferrous sulphate and cupric sulphate.



(108)

(CLIV)



(109)

$$\cdot CH_2\cdot(CH_2)_4\cdot CO_2H + Cu^{2+} \longrightarrow \underset{(CLV)}{CH_2{:}CH\cdot(CH_2)_3\cdot CO_2H} + Cu^{+} + H^{+} \qquad (110)$$

$$Cu^{+} + Fe^{3+} \longrightarrow Cu^{2+} + Fe^{2+} \qquad (111)$$

The oxidation-reduction potentials (in volts) of the systems $Fe^{3+} \longrightarrow Fe^{2+}$ and $Cu^{2+} \longrightarrow Cu^{+}$ are 0.75 and 0.16 respectively. Thus equation (111) should be expected to proceed smoothly.

When the hydroperoxide (CLIV) was treated[123] with ferrous sulphate but no cupric ions, oxidation of the substrate-radical did not occur; dimerization resulted (112).

$$2\cdot CH_2\cdot(CH_2)_4\cdot CO_2H \longrightarrow HO_2C\cdot(CH_2)_{10}\cdot CO_2H \qquad (112)$$

De La Mare *et al*[28] showed that cupric ions were unnecessary to oxidize the substrate-radical if the ferrous salt contained groups with good ligand-transfer properties. Thus ferrous-chloride and - thiocyanate reacted with the hydroperoxide (CLIV) to give the corresponding ω-substituted hexanoic acids (CLVI and CLVII).

$ClCH_2{\cdot}(CH_2)_4{\cdot}CO_2H$ (CLVI)

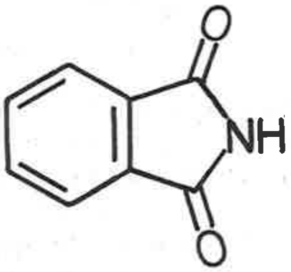
$NCS{\cdot}CH_2{\cdot}(CH_2)_4{\cdot}CO_2H$ (CLVII)

Minisci and his co-workers[124-129] extensively studied this field of hydroperoxide-decomposition. The anions they used included CN^-, Cl^-, $S_2O_3^{2-}$, N_3^- and SCN^-.

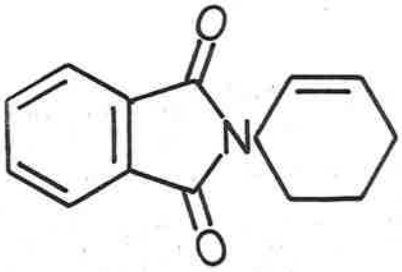
Kharasch and Fono[130] have shown that cupric ions do not cleave hydroperoxides abnormally (98) under certain circumstances. The oxidation of substrate radicals is preferred, in these reactions, and the resultant cuprous ions cleave the hydroperoxide in the conventional manner (97).

Hence a mixture of cyclohexene and benzoic acid reacted with *t*-butyl hydroperoxide (LI) in the presence of cuprous chloride to give a 90% yield of cyclohexenyl benzoate (XII). There was no evidence of abnormal-cleavage of the hydroperoxide (98) by cupric ions, the allylic radicals were preferentially oxidized.

When oct-1-ene was the substrate, the main product proved to be 1-pentylallyl benzoate (XIII). Similarly, a mixture of cyclohexene and phthalimide (CLVIII) reacted with *t*-butyl hydroperoxide (LI) in the presence of cuprous chloride to yield *N*-cyclohexenyl phthalimide (CLIX).



(CLVIII)



(CLIX)

DISCUSSION

The aim of this work was twofold: (a) to attempt to elucidate the mechanism of the metal-ion catalysed reactions of t-butyl peresters with olefins, and other substrates and (b) to carry out a survey of metal-ion catalysed reactions of peroxy compounds with a variety of substrates in the hope of observing transformations of potential synthetic utility. These two aspects of this research project will be discussed separately in the following sections.

(a) MECHANISTIC STUDIES

1. General

The information concerning the copper-ion catalysed benzoyloxylation of olefins and other substrates with t-butyl perbenzoate available to us at the commencement of this investigation has been discussed at length in the preceding section. The salient features to be accommodated in any working hypothesis were as follows:

(i) The decomposition of t-butyl perbenzoate proceeds more rapidly when copper ions are present than during the uncatalysed thermal-reaction. In the absence of a substrate, the catalysed-reaction yields benzoic acid and methyl benzoate.

(ii) The copper-ion catalysed benzoyloxylation of olefins proceeds without positional isomerization of the double bond.

(iii) When the copper-salt catalysed reaction is conducted in the presence of a large excess of a carboxylic acid, it yields the appropriate carboxylate ester.

(iv) The reaction with substrates other than olefins, proceeds at positions most susceptible to attack by _t_-butoxy radicals.

(v) Denney's results[66] of tracer studies showed that the _t_-butoxy radicals, in these reactions, were not true free-radicals.

It appeared that there was no simple hypothesis incorporating all of these experimental observations. The first acceptable mechanism, which was based on analogy with known reactions, was suggested by Kharasch _et al_[58] as in equations (38-42), (where RH = a reactive substrate). However, this mechanism failed to explain the lack of isomerization of the double bond of olefins in these reactions. It also required the presence of free _t_-butoxy radicals.

Probably the most acceptable mechanism available to us, at the commencement of this work, was that conceived by Denney <u>et al</u>.[66] Their suggested concerted-mechanism, involving an intermediate-complex between the substrate molecule, <u>t</u>-butoxy radical, acyloxy radical and cuprous salt (XXX), explained many of the above features. It especially explained the lack of isomerization of the double bonds of olefins, and also did not require the formation of free <u>t</u>-butoxy radicals.

At the start of our investigation, we deemed it necessary to demonstrate that all transient-radicals in these copper-salt catalysed reactions of peroxides, were undergoing oxidation or reduction by the copper ions. Although such steps were well known in other reactions (<u>e.g</u>. Fenton, Sandmeyer and Meerwein reactions) and had been assumed to participate in these peroxide-reactions, there had been no substantial proof that such processes did actually occur. We, therefore, initiated this investigation by showing that free-radicals, formed during peroxide-reactions, could often be oxidized or reduced by copper ions.

When di-<u>t</u>-butyl peroxide (LIV) was decomposed thermally in the presence of toluene (CXXXI), large quantities of bibenzyl (CLX) were obtained. This, obviously, resulted from the dimerization of benzyl radicals (CXLVII), formed by the abstraction of an α-hydrogen atom of toluene by t-butoxy radicals:

$$(CH_3)_3CO\cdot OC(CH_3)_3 \longrightarrow 2(CH_3)_3CO\cdot \tag{84}$$

(LIV)

$$C_6H_5\cdot CH_3 + (CH_3)_3CO\cdot \longrightarrow C_6H_5\cdot CH_2\cdot + (CH_3)_3C\cdot OH \tag{113}$$

(CXXXI) (CXLVII)

$$2\ C_6H_5\cdot CH_2\cdot \longrightarrow C_6H_5\cdot CH_2\cdot CH_2\cdot C_6H_5 \tag{114}$$

(CLX)

When this reaction was repeated in the presence of one molar equivalent of cupric benzoate, the yield of bibenzyl (CLX) was greatly reduced. One of the products proved to be benzyl benzoate (CXLVI), thus providing unequivocal evidence for the oxidation of benzyl radicals through, either, an electron-transfer mechanism (93,115) or a ligand-transfer mechanism (116).

$$C_6H_5\cdot CH_2\cdot + Cu^{2+} \longrightarrow C_6H_5\cdot CH_2^{+} + Cu^{+} \tag{93}$$

$$C_6H_5\cdot CH_2^{+} + C_6H_5\cdot CO_2^{-} \longrightarrow C_6H_5\cdot CH_2\cdot O_2C\cdot C_6H_5 \tag{115}$$

(CXLVI)

$$C_6H_5{\cdot}CH_2{\cdot} + C_6H_5{\cdot}CO_2Cu^{2+} \longrightarrow C_6H_5{\cdot}CH_2{\cdot}O_2C{\cdot}C_6H_5 + Cu^+ \qquad (116)$$

When benzoyl peroxide (XLIV) was decomposed thermally in the absence of metal-salts, it yielded unstable benzoyloxy radicals (XLV), which very rapidly broke down[82,131-133] into phenyl radicals and carbon dioxide (55,117)

$$(C_6H_5{\cdot}CO_2)_2 \longrightarrow \underset{(XLV)}{2\ C_6H_5{\cdot}CO_2} \qquad (55)$$

$$C_6H_5{\cdot}CO_2 \longrightarrow C_6H_5{\cdot} + CO_2 \qquad (117)$$

Thus, our experiments produced a 22% yield of benzoic acid and a 71% yield of carbon dioxide.

These results were vastly different when a molar equivalent of cuprous salt was added to the reaction mixture. The yields of the products were practically reversed. Thus, we obtained a 68% yield of benzoic acid and a 26% yield of carbon dioxide. This is most readily explained by the hypothesis that the transient-benzoyloxy radicals were reduced to benzoate ions by the cuprous salt (56). The sceme could, alternatively, be represented by (94 and 95).

There seemed little doubt, therefore, that the basis of all these copper-ion catalysed reactions of peresters, peroxides and hydroperoxides, was one of oxidation or reduction of the transient-radicals by copper-ions. It must be remembered that the above two experiments were not catalysed by the copper salts. In the former case of toluene, the cupric benzoate was acting as a true oxidizing-agent, while the cuprous salt in the later case as a true reducing-agent. Most copper ion-peroxide reactions reported either before or since these preliminary experiments in this laboratory, were catalysed by the copper salt. In such experiments, only a trace of copper salt was required to accomplish all the oxidation and reduction steps. The valency state of the copper-ion, before the start of the reaction, was not critical. It seemed likely at this early stage of our investigation, therefore, that the minute quantity of copper ions, in all these reactions, was oxidized and reduced continuously throughout the reaction, hence only small quantities were required.

2. Olefin Reactions

Having thus established that the basic function of copper-ions was to oxidize or reduce transient-radicals in these peroxide reactions, we then extended the investigation to study the mechanism of the copper salt-catalysed perester-olefin reactions. Up to this stage, the only attempt to explain the non-positional isomerization of the double bonds in these reactions had been carried out by Denney et al.[66] At that time, their complex-transition state (XXX) appeared quite reasonable, but lacked confirmation.

Accordingly, we carried out a series of reactions of olefins with t-butyl perbenzoate, in the presence of copper-ions with two objectives in mind:

(i) to confirm the existing reports that the double bonds of the olefins did not isomerize during these reactions, and

(ii) to obtain more information as to the nature of the mechanism of these stereospecific reactions.

Therefore, we catalytically-decomposed t-butyl perbenzoate in the presence of oct-1-ene and found, in support of the results of Kharasch et al,[59] that the terminal-double bond did, in fact, remain in the terminal-position in the main product, which proved to be 1-pentylallyl benzoate (XIII). However, there was evidence of the presence of a small quantity ($<10\%$) of the isomeric 1-benzoyloxyoct-2-ene (XV).

A larger quantity of rearranged product was obtained during the copper-salt catalysed decomposition of di-t-butyl peroxide (LIV) in the presence of oct-1-ene and acetic acid, but the main product of this reaction again proved to be the isomer with the terminal double bond, viz. 1-pentylallyl acetate (CLXI).

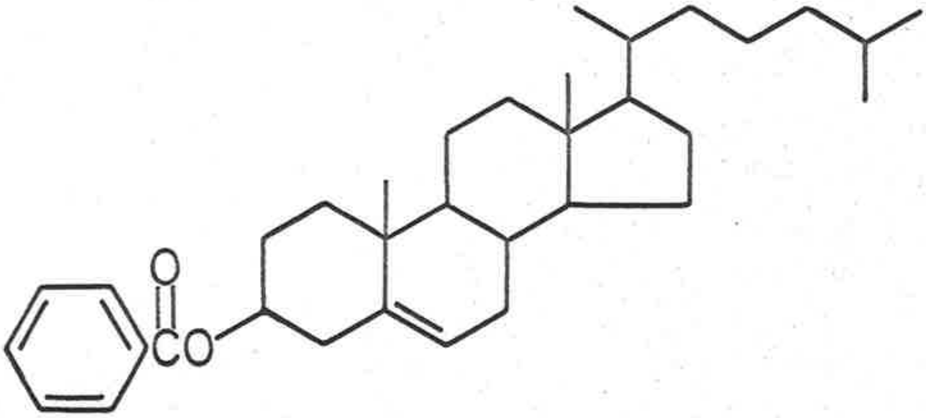
$$CH_3\cdot(CH_2)_4\cdot CH(OAc)\cdot CH{:}CH_2$$

(CLXI)

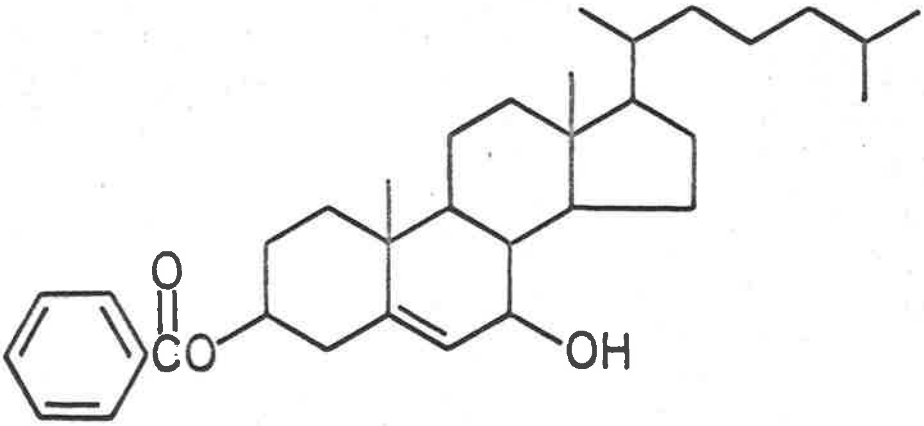
A reaction of allylbenzene (XVIII) and t-butyl perbenzoate in the presence of cuprous salt, confirmed the earlier reports that the double bond remained in the terminal-position even though conjugation with the aromatic ring could be achieved if isomerization did occur. 1-Phenylallyl benzoate (XIX) proved to be the only product isolated. However, a repitition of this experiment using benzene as solvent (no solvent had been used in the first attempt) resulted in the production of a small amount of cinnamyl benzoate (XXIX), but 1-phenylallyl benzoate (XIX) again proved to be the main product.

When t-butyl perbenzoate was decomposed in the presence of excess cholesteryl benzoate (CLXII) and a trace of cuprous salt, poor yields of cholest-5-en-3β, 7β-diol 3-benzoate (CLXIII) and its 7α-isomer (CLXIV) were isolated in approximately equal quantities. It was considered that these disappointing yields were due to excessive dilution of the perester within the solvent (benzene). Accordingly the reaction was repeated using a great excess of t-butyl perbenzoate. Although considerable darkening occurred, and many impure coloured oils were obtained, a 40% yield of both epimers (CLXIII and CLXIV) was isolated. No isomerized products could be isolated. However, a third experiment conducted in these laboratories[134] did yield a trace of the isomeric cholest-4-en-3β,6βdibenzoate (CLXV), in addition to a fair yield of the 7β and 7α epimers. Unlike the previous two experiments, this particular reaction yielded products which had not been hydrolysed during the chromatography. Thus the dibenzoate esters were obtained (CLXVI and CLXVII) instead of the partially hydrolysed products (CLXIII and CLXIV).

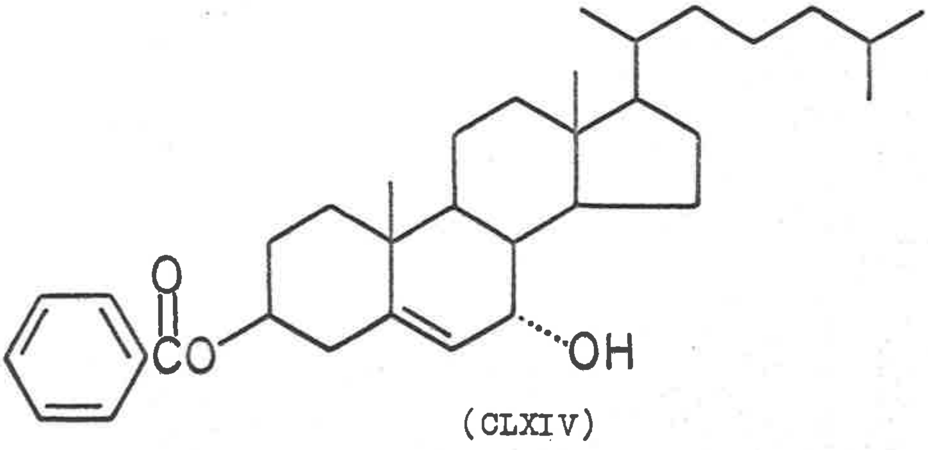
It is of interest that the 7β-epimer (CLXIII) always preceded the 7α-epimer (CLXIV) during chromatography. This is unexpected since the 7β-epimer (CLXIII) is equitorial, while the 7α-epimer (CLXIV) is axial. There is, in fact, some considerable confusion as to the



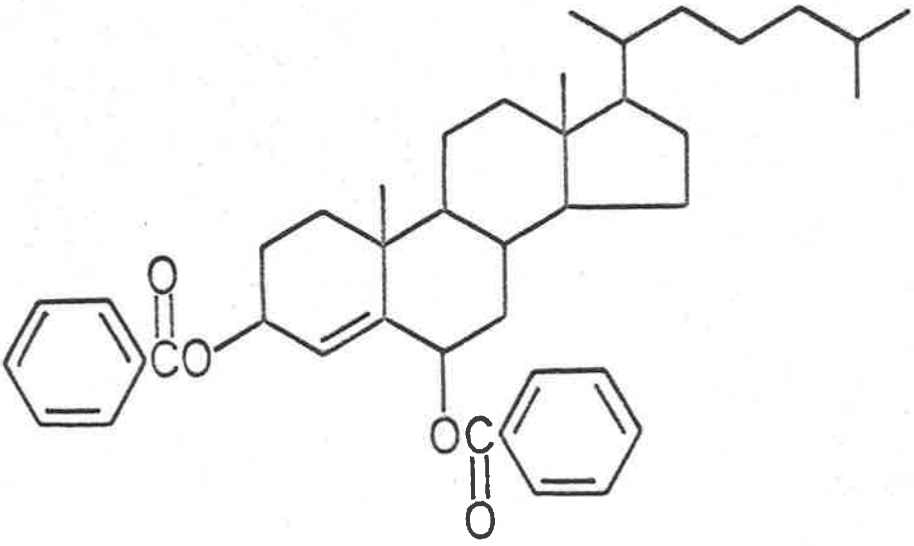
(CLXII)



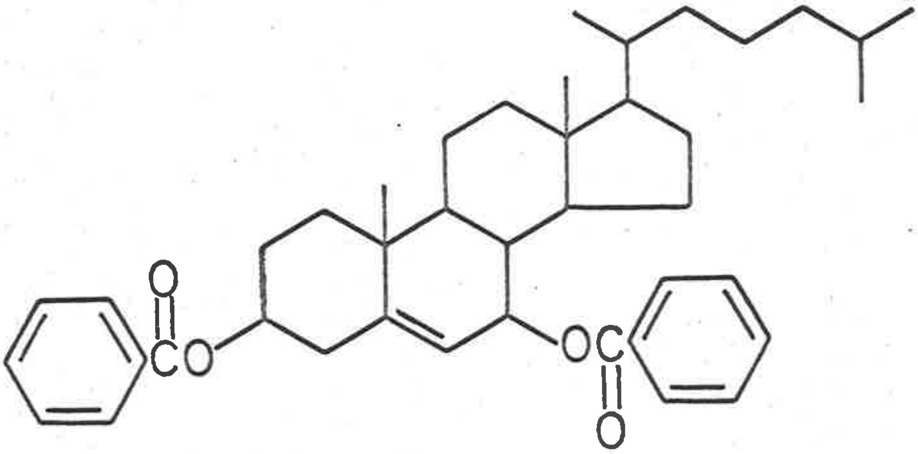
(CLXIII)



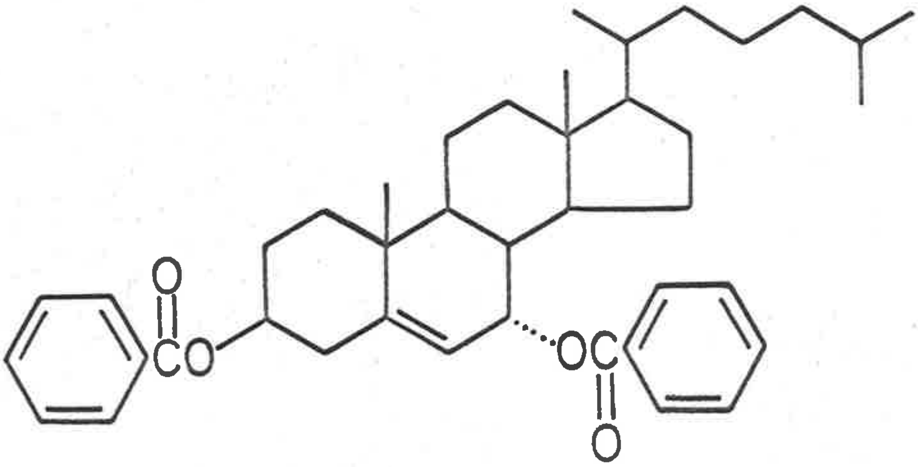
(CLXIV)



(CLXV)



(CLXVI)



(CLXVII)

true configuration of these compounds.[135]

As a result of all these experiments, we reasonably concluded that olefins react with t-butyl perbenzoate in the presence of copper-ions to yield products in which no rearrangement of the double bond had occurred. Accordingly we turned our attention to a study of the mechanism of these specific reactions. It appeared essential to obtain proof for the existence or absence of free t-butoxy radicals in these reactions; the results of Denney et al[66] had shown these radicals to be under some form of restriction during hydrogen-abstraction from the allylic-position of olefins.

When we decomposed t-butyl perbenzoate in the presence of olefins and certain other substrates, under sealed conditions, we obtained acetone and t-butanol in similar ratios regardless of the presence or absence of copper-ions. Thus, when t-butyl perbenzoate was decomposed in the presence of toluene (CXXXI), using cupric benzoate as a catalyst, the ratio of t-butanol to acetone was 4.09 to 1. A repeat of this experiment in the absence of cupric benzoate gave a ratio of t-butanol to acetone of 4.81 to 1. Although these ratios are not consistent with those obtained by Williams et al,[136] it must be pointed out that these figures are not ratios of the weights of the products. They were, in fact, obtained from the G.L.C. curves of these compounds by removing the paper inside these curves and weighing it; they are therefore a comparison of the weights of these curves. The t-butanol-acetone ratios were also similar, regardless of the presence or absence of copper-ions, when cyclohexene was a substrate.

These results, of course, indicate that t-butoxy radicals are, in fact, free. Free t-butoxy radicals undergo two competitive reactions. They can either abstract a labile hydrogen-atom from a substrate-molecule to yield t-butanol (41), or decompose[57] into acetone and methyl radicals as in (36). The relative rates of these competitive reactions depend upon the temperature of the reaction-mixture and also the nature of the substrates present. Since both these variables were constant in the above described competitive reactions, it seems likely that the formation of free t-butoxy radicals was not affected by the presence of copper ions. Had the copper ions restricted the formation of free t-butoxy radicals in some way, the ratio of t-butanol to acetone would have been different to that of the uncatalysed reaction. The presence of free t-butoxy radicals was later confirmed by the rate studies of Walling et al.[137]

The results of these experiments indicated that the transition-state (XXX), suggested by Denney et al,[66] could not be correct, for it required the t-butoxy radicals to be in a complex with the copper-ion and not exist in the free state.

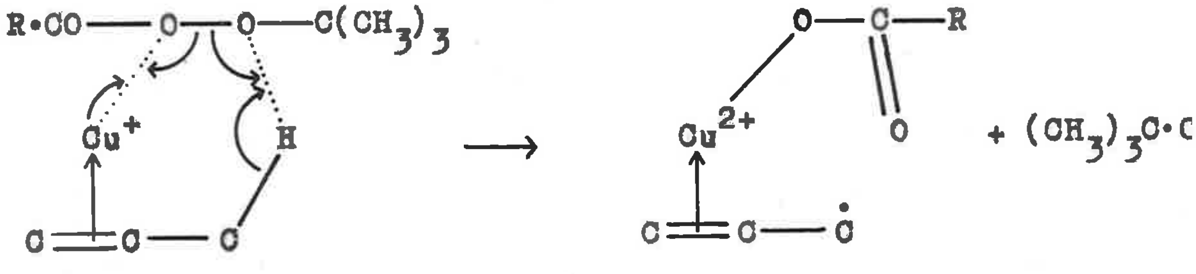
We therefore conceived an alternative hypothesis which was designed to explain (i) the existence of free t-butoxy radicals, (ii) the induced-decomposition of the perester by copper ions, and (iii) the non-isomerization of double bonds during these reactions. We had little doubt that the perester was reduced by cuprous ions as an initial step in all these reactions. Indeed, Kharasch et al[58] had originally suggested that these reactions were initiated by the cuprous-ion reduction of the perester to yield free t-butoxy radicals and the cupric carboxylate as in (38).

Although, in principle, this primary step appeared feasible, it seemed probable that the intimate mechanism involved reduction of the perester by a cuprous-olefin π-complex rather than by an isolated cuprous ion. Since cuprous ions and olefins very readily form π-complexes,[138-] it would seem unusual for the perester-reduction to be accomplished by an uncomplexed-cuprous ion. This is especially important when it is realized that the olefin concentration exceeds that of the cuprous catalyst, often, by several hundred times; a situation which must favour relatively high complex-formation between the olefin and cuprous salt.

The working hypothesis, therefore, initially required that a π-complex be formed between the π-electrons of the double bond and the cuprous salt. We considered that it was this complex which reduced the perester, as in (43), and not a free cuprous-ion as suggested[58] by Kharasch et al (38). The reduction of the perester by the π-complex would result in the formation of free t-butoxy radicals and a complex (XXXIII) between the olefin and cupric carboxylate group (43). There appears to be little evidence concerning the existence of cupric-olefin π-complexes.

Once the cupric carboxylate-olefin π-complex was formed, it seems likely that benzoyloxylation of the allylic-position could occur by the transfer of the carboxylate from the cupric-ion to the allylic-position, as in (44). Such a process, involving one-electron shifts, seemed quite acceptable, for it proceeded through a six-membered ring transition-state. The driving force of this step was two-fold. It consisted of the abstraction of the allylic-hydrogen atom by a *t*-butoxy radical, coupled with the tendency of the cupric ion to attain monovalency and thus be more strongly complexed to the double bond. This mechanism, therefore, requires that the hydrogen-abstraction and benzoyloxylation of the resultant allylic-radical occurs in a concerted manner.

This working hypothesis explained the lack of positional isomerization of the double bond because it was anticipated that a double-bond complexed with copper ions would not be free to migrate. We also considered an alternate working hypothesis, which was basically the same as the first mechanism (43 and 44). This new mechanism took place in a concerted manner, as shown in (118 and 119). This sceme did not account for the formation of acetone in these reactions, however.



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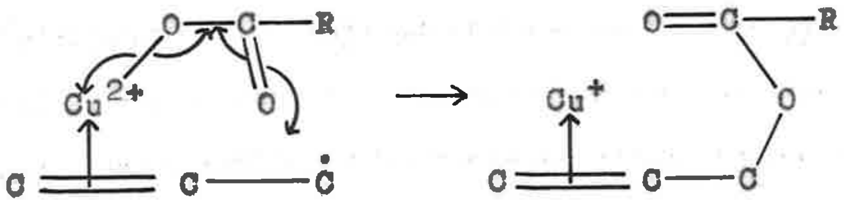
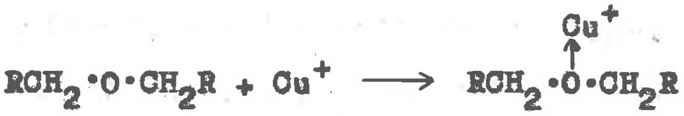

(119)

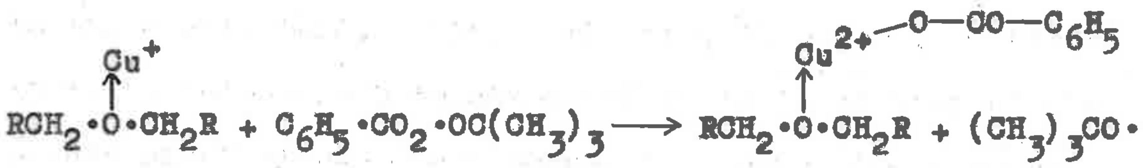
According to these above hypothetical scemes, in the absence of copper ions the conventional uncatalysed-decomposition of *t*-butyl peresters would occur, and the double bonds of the olefins, now being free to isomize, would yield equal quantities of each isomeric product.

There have been very many cases of simple ethers, benzyl ethers, cyclic ethers, thio ethers, benzyl sulphides and alcohols all being acyloxylated in the α-position during cuprous-catalysed perester reactions. It must be emphasized in passing, therefore, that the above hypothesis also readily explains these reactions. Assuming cuprous and cupric ions can form complexes with etherial-oxygens and the oxygen atoms of alcohols, these complexes being analagous to those formed with olefins, the acyloxylation could again proceed by a ligand-transfer mechanism (120-122). Again, the driving force of the oxidation step (122) would be the attainment of monovalency by the cupric ion, which would yield a more stable complex, and the abstraction of the α-hydrogen atom by a t-butoxy radical.



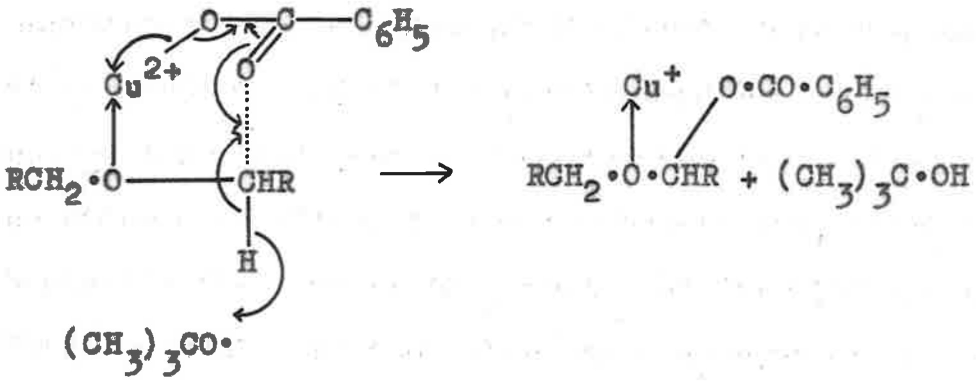
$$\mathrm{RCH_2{\cdot}O{\cdot}CH_2R + Cu^+ \longrightarrow RCH_2{\cdot}\overset{\overset{Cu^+}{\uparrow}}{O}{\cdot}CH_2R}$$

(120)



$$\mathrm{RCH_2{\cdot}\overset{\overset{Cu^+}{\uparrow}}{O}{\cdot}CH_2R + C_6H_5{\cdot}CO_2{\cdot}OC(CH_3)_3 \longrightarrow RCH_2{\cdot}\overset{\overset{Cu^{2+}-O-CO-C_6H_5}{\uparrow}}{O}{\cdot}CH_2R + (CH_3)_3CO\cdot}$$

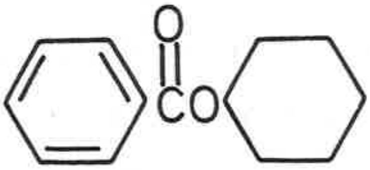
(121)



(122)

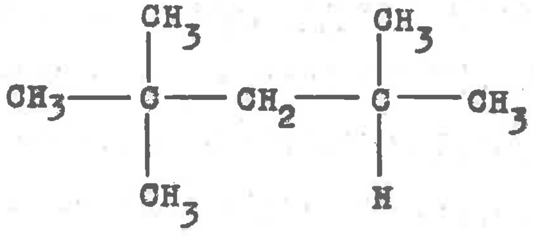
This working hypothesis appeared consistent with all recorded experimental results. It accounted for the existence of free t-butoxy radicals, the induced-decomposition of the perester by copper-ions and the lack of isomerization of the double bonds of olefins. It could also be applied to the acyloxylation of other substrates such as ethers and alcohols. However it required that the allylic-position of olefins must be very activated by cuprous-ions towards hydrogen-abstraction by t-butoxy radicals. If this was not so, then there appeared to be no valid reason why many of the t-butoxy radicals would not abstract allylic-hydrogen atoms from uncomplexed olefins. If this happened, the allylic-radical (XVII) so produced should yield large quantities of isomerized products. Therefore, a series of competitive reactions between olefinic and non-olefinic substrates was attempted to prove that, in the presence of cuprous ions, the olefinic-substrate was a much more reactive species than in the absence of cuprous ions.

When an equimolar mixture of cyclohexene and cyclohexane was treated with t-butyl perbenzoate in the presence of cuprous chloride, all the ester products proved to be cyclohexenyl benzoate (XII). This was very encouraging for it appeared that the alkene was indeed very much more reactive than the alkane. This reaction, when repeated in the absence of catalyst, yielded substantial quantities of cyclohexyl benzoate (CLXVIII). It appeared, therefore, that the olefin was much less reactive in the absence of copper ions.



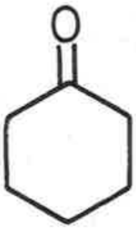
(CLXVIII)

A similar competitive reaction between cyclohexene and 2,2,4-trimethylpentane (CLXIX) was less clear-cut. The products from the catalysed reaction again were shown to be 100% unsaturated. However, in the absence of cuprous chloride, the products proved to be at least 95% unsaturated. This unreactivity of iso-octane, even in the absence of catalyst, is not surprising, however, for Brook[142] has found that the C-H groups of n-alkanes are 50% more reactive towards abstraction by t-butoxy radicals than those of iso-octane (CLXIX). He attributes this unreactivity to steric hindrance.



(CLXIX)

A third competitive reaction between cyclohexene and cyclohexanone (CLXX) indicated that the olefin was ten-times more reactive than the ketone in the presence of cuprous chloride than in its absence. In the absence of catalyst the ketone and the olefin were both of equal reactivity; the addition of cuprous salt, therefore, appeared to greatly activate the olefin. The results of this last experiment were based upon hydrogenation figures only; no attempt was made to identify any of the reaction products.



(CLXX)

These competitive reactions appeared to indicate that olefins were considerably activated towards attack by free <u>t</u>-butoxy-radicals when cuprous salts were present, and it was thought that the most probable way a cuprous salt could achieve this would be through a π-complex with the olefin. That the cuprous salt has this effect upon the allylic-position of olefins is probably true, however De La Mare *et al*[28] have shown that alkyl-radicals, which undergo electron-transfer oxidation with cupric sulphate to form transient-carbonium ions, often eliminate a proton to yield olefinic products (123).

$$R.CH_2.CH_2\cdot \xrightarrow{Cu^{2+}} R.CH_2.CH_2^+ \longrightarrow R.CH{:}CH_2 + H^+ \qquad (123)$$

Beckwith and Acott[143] have also shown that when

2-methyl-2-hexanyl hydroperoxide (CLXXI) is warmed with ferrous hydroxide and cupric acetate, large quantities of 2-methylhex-5-en-2-ol (CLXXII) are formed; there is also evidence for the formation of the isomeric 2-methylhex-4-en-2-ol (CLXXIII) in small quantities. The following mechanism was suggested:

$$CH_3\cdot CH_2\cdot CH_2\cdot CH_2\cdot CMe_2\cdot O\cdot OH \xrightarrow{Fe^{2+}} CH_3\cdot CH_2\cdot CH_2\cdot CH_2\cdot CMe_2\cdot O\cdot \qquad (124)$$

(CLXXI)

$$CH_3\cdot CH_2\cdot CH_2\cdot CH_2\cdot CMe_2\cdot O\cdot \longrightarrow CH_3\cdot \dot{C}H\cdot CH_2\cdot CH_2\cdot CMe_2\cdot OH \qquad (124a)$$

$$CH_3\cdot \dot{C}H\cdot CH_2\cdot CH_2\cdot CMe_2\cdot OH \xrightarrow{Cu^{2+}} CH_3\cdot \overset{+}{C}H\cdot CH_2\cdot CH_2\cdot CMe_2\cdot OH \qquad (125)$$

$$2\ CH_3\cdot \overset{+}{C}H\cdot CH_2\cdot CH_2\cdot CMe_2\cdot OH \longrightarrow CH_2{:}CH\cdot CH_2\cdot CH_2\cdot CMe_2\cdot OH$$

(CLXXII)

$$+\ CH_3\cdot CH{:}CH\cdot CH_2\cdot CMe_2\cdot OH \qquad (126)$$

(CLXXIII)

The above results of De La Mare *et al*[28] and Beckwith and Acott[143] suggest that the competitive reactions, previously described, do not now appear so conclusive. Thus, it is possible that, in the case of the cyclohexanone-cyclohexene experiment, considerable quantities of unsaturated products were derived from the non-olefinic substrate when the reactions were conducted in the presence of cuprous ions. Thus the hydrogenation figures could be much higher than would normally be expected. It must be concluded, therefore, that while these competitive reactions support the theory that the allylic-position of olefins is much more susceptible to attack by t-butoxy radicals when the olefinic double-bond is complexed with a cuprous ion, the results must be treated with caution.

Subsequent to the completion of our competitive reactions, Kochi[32,69] found that non-terminal double bonds of olefins are, in fact, readily isomerized into the terminal-positions during the reaction of the olefins with t-butyl peresters and copper ions. The results of experiments with non-terminal olefins, carried out by us at the same time, confirmed the results of Kochi.

$$CH_3{\cdot}CH_2{\cdot}CH_2{\cdot}CH_2{\cdot}CH_2{\cdot}CH{:}CH{\cdot}CH_2$$

(CLXXIV)

When oct-2-ene (CLXXIV) was treated with t-butyl perbenzoate and cuprous chloride, the main product proved to be 1-pentylallyl benzoate (XIII) with a small amount of oct-2-enyl benzoate (XV). Other unidentified products from the reaction could have resulted from the acyloxylation of the 4-position of the oct-2-ene. The results were similar when *t*-butyl perbenzoate reacted with β-methylstyrene (XXVIII) in the presence of cuprous chloride. Although the yield of ester products was not good (35-40%), the main isomer proved to be 3-benzoyloxy-3-phenylprop-1-ene (XIX). Only a small quantity of cinnamyl benzoate (XXIX) was formed. This result was in direct contrast to that originally reported by Denney *et al*[66] who also treated β-methylstyrene (XXVIII) with a perester and cuprous-salt and found that no isomerization had occurred, the entire product being cinnamyl benzoate (XXIX). These workers recently repudiated this report,[144] however, and suggested that side reactions, possibly involving radical-addition to the olefin, were occurring.

Walling and Zavitsas[137] recently repeated the reaction of t-butyl peresters with β-methylstyrene (XXVIII) and confirmed our observation that the main ester-product contains a terminal double-bond. However, they found that 100% isomerization had occurred; cinnamyl benzoate (XXIX) was completely absent in the products.[*]

Kochi[32,69] catalytically-decomposed *t*-butyl peresters in the presence of but-1-ene (XXXIV) and also but-2-ene (XXXV) and obtained the same isomer distribution in each case. The 3-acyloxybut-1-ene isomer (XXXVI) comprised 90% of the ester-products. This worker was forced to conclude that *free* allyl radicals were, in fact, the intermediate-species in these reactions. He declared that the existence of these allyl radicals (XXXIX) in the free-state could then account for the isomerized-products from the but-2-ene reaction, since the butenyl radicals (XXXIX) are stabilized by resonance. Kochi proposed an intermediate transition-state (XLIII) to explain the predominance of the terminal double-bond in the products.

This mechanism of Kochi, which has been thoroughly discussed in the preceding section, accords very well with all experimental results. However, this mechanism is not faultless, one weakness being its failure to utilize a cuprous-olefin π-complex in the

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[*] The description of the reaction product (after hydrogenation) in the experimental section of this paper is presumed to be erroneous.

initial reduction-step. For reasons previously given, this seems very likely to occur. Kochi had suggested that the initial reduction of the perester took place with an uncomplexed-cuprous ion.

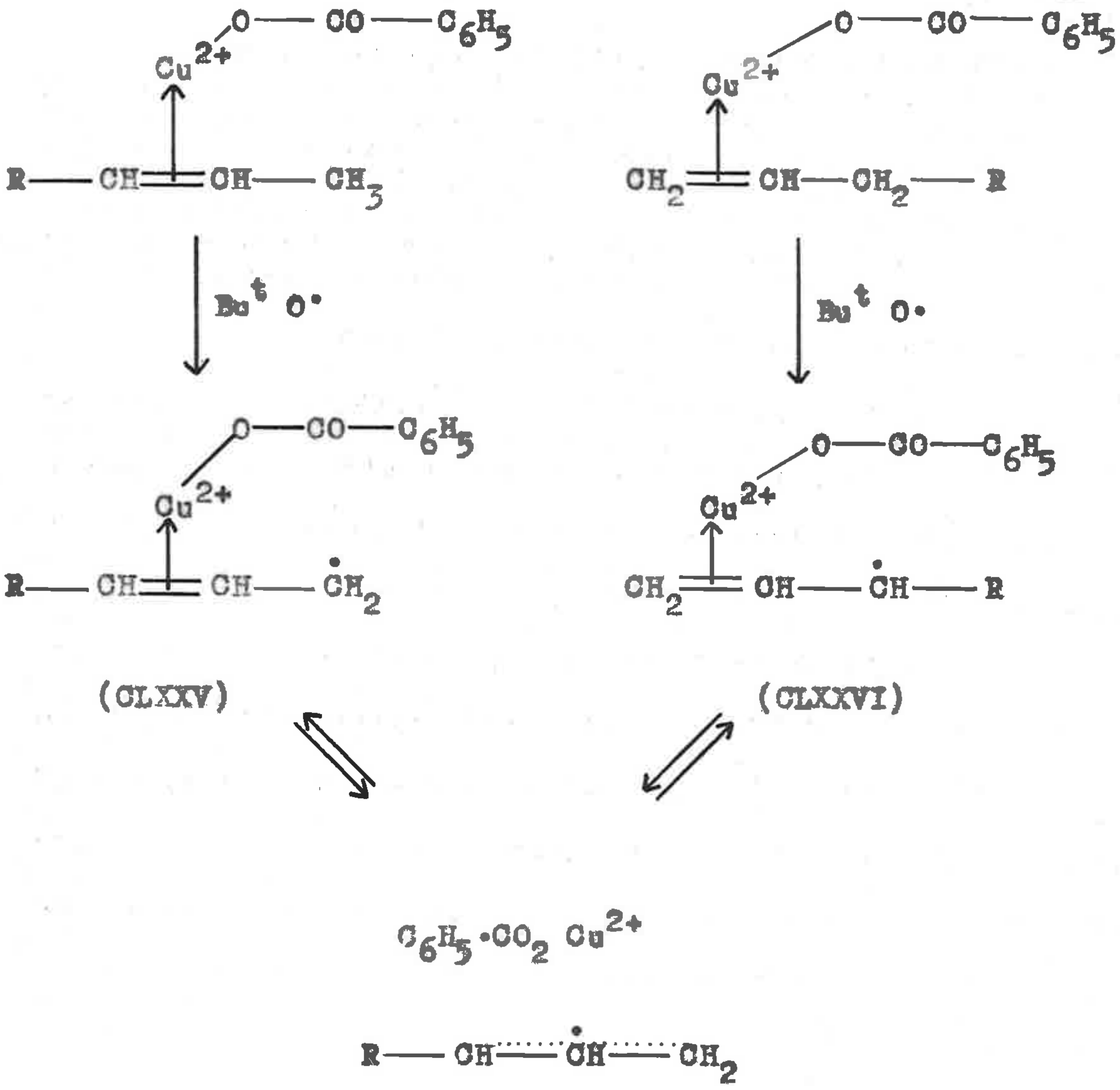
A modification of our original working-hypothesis can quite readily explain the lack of positional-isomerization of terminal double bonds and also the movement of non-terminal double bonds to the terminal-position during these reactions.

It seems reasonable to assume that entropy factors will be much the same in these two possible modes of reaction, and if this is so, the reaction having the transition-complex of lower-energy will predominate. The energy of any given transition-state would be greatly influenced by the stability of the copper ion-olefin π-complex.

It is emphasized that the stability of cuprous-olefin π-complexes is very dependent upon steric factors, and it has been shown[145,146] that the stability of these complexes is considerably reduced when the double bond is non-terminal or sterically hindered by substituent groups. This has also been clearly demonstrate with silver(1)-olefin π-complexes.[147]

It is not unreasonable, therefore, that the transition-state depicted in the working hypothesis, as in (44), for a non-terminal olefin would be of higher energy than that for a terminal-olefin.

The working hypothesis has been slightly modified, therefore, to include, as intermediates, cupric carboxylate-allylic radical π-complexes (CLXXV and CLXXVI). We suggest that these transition-states are different in energy content, the former (CLXXV) having the higher energy by reason of its less stable copper-complex. These radical complexes would be free to interconvert and the terminal-complex (CLXXVI) would thus be the principal isomer. The sceme could be represented as follows.



(CLXXV)

(CLXXVI)

This hypothesis is based entirely upon the relative stabilities of π-complexes between the olefin and the copper ion. One would predict that a given double-bond should migrate to a new position if, in that new position, the π-complex was more stable. This, in fact, means that the double-bond would isomerize if, by doing so, it occupied a less substituted position, but if it was already in the position of least possible substitution, no isomerization would occur. Hence terminal double-bonds are fixed, whereas the non-terminal double-bonds isomerize by as much as 90%.

It must also be remembered that the stability of the resultant product has no bearing upon the driving-force in these reactions. Indeed, it is generally accepted that the main product from all these reactions *e.g.* the 3-acyloxyalk-1-ene, is the thermodynamically least favoured isomer.

This is especially obvious in the case of allylbenzene (XVIII) and β-methylstyrene (XXVIII). The driving-force which moves non-terminal double bonds into the terminal positions is so great that it readily removes double-bonds from conjugation with aromatic rings, as in β-methylstyrene (XXVIII). On the other hand, terminal double-bonds are prevented from shifting into non-terminal conjugated positions, as in allylbenzene (XVIII). The thermodynamically less-stable isomer[75] was the main product in both cases. During pure homolytic reactions involving free phenylvinylmethyl radicals (CLXXVIIa) at least 75% of the products contained double bonds in conjugation with the aromatic ring[148,149] and there was one report[150] of this figure being near to

100%. The phenylvinylmethyl radical (CLXXVIIa) is a resonance hybrid of the cinnamyl radical (CLXXVIIb) and undoubtedly the cinnamyl contribution would greatly exceed the phenylvinylmethyl contribution due to the conjugation of the olefinic double-bond with the aromatic nucleus.

$$C_6H_5\cdot\dot{C}H\cdot CH{:}CH_2 \quad \longleftrightarrow \quad C_6H_5\cdot CH{:}CH\cdot CH_2\cdot$$

(CLXXVIIa) (CLXXVIIb)

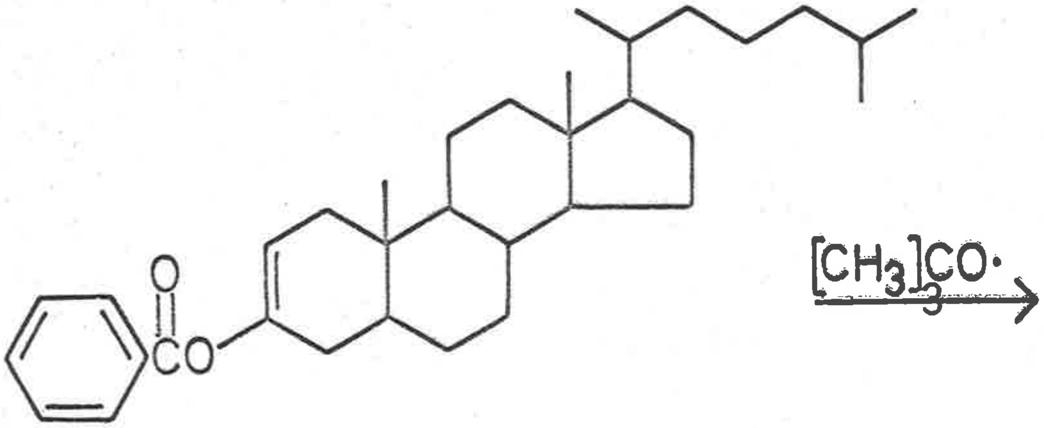
The working hypothesis would certainly predict the observed shift of the double bond of β-methylstyrene to the terminal-position; the double bond, when adjacent to the phenyl ring, would be in a very unfavourable position indeed for complex-formation with a copper ion. The working-hypothesis would also predict that the double bond of a cycloalkene would isomerize if, by doing so, the conditions would be more favourable for complex-formation with a copper ion.

Indeed, experiments have shown that any double-bond, which is sterically hindered by a substituent group, will readily migrate to a less-hindered position, even though this less-hindered position is not a terminal one. Furthermore, once this less-hindered position is attained, it is prevented from further isomerization. A steroid reaction clearly demonstrated these observations.

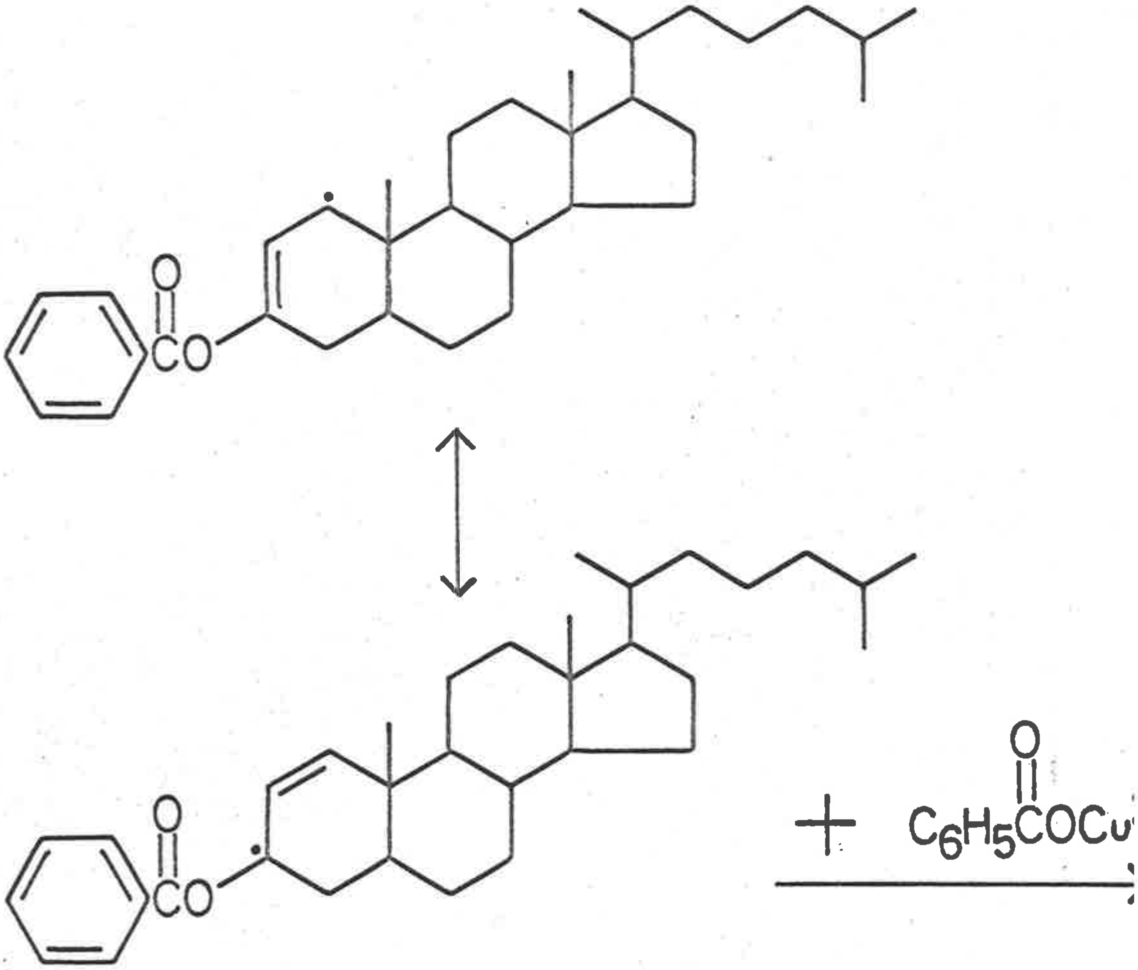
When t-butyl perbenzoate was decomposed in the presence of 3-benzoyloxycholest-2-ene (CLXXVIII) and a trace of cuprous salt, the main product preved to be cholest-1-en-3-one (CLXXX). The most likely route to this product would involve the abstraction of a hydrogen-atom from the 1-position by a t-butoxy radical, followed by oxidation of the 3-position in the resultant allylic radical (CLXXIX).

A similar reaction between 3-ethoxycholest-2-ene (CLXXXI), t-butyl perbenzoate and cuprous ions failed to yield any identifiable products. Impure coloured oils were obtained, which often exhibited more than one carbonyl absorption in the infrared. Quite possibly the α-position of the ethoxy-group had entered into the reaction. The important result from this reaction, as with the previous enol-benzoate reaction, was the apparent isomerization of the double-bond away from the ethoxy group.

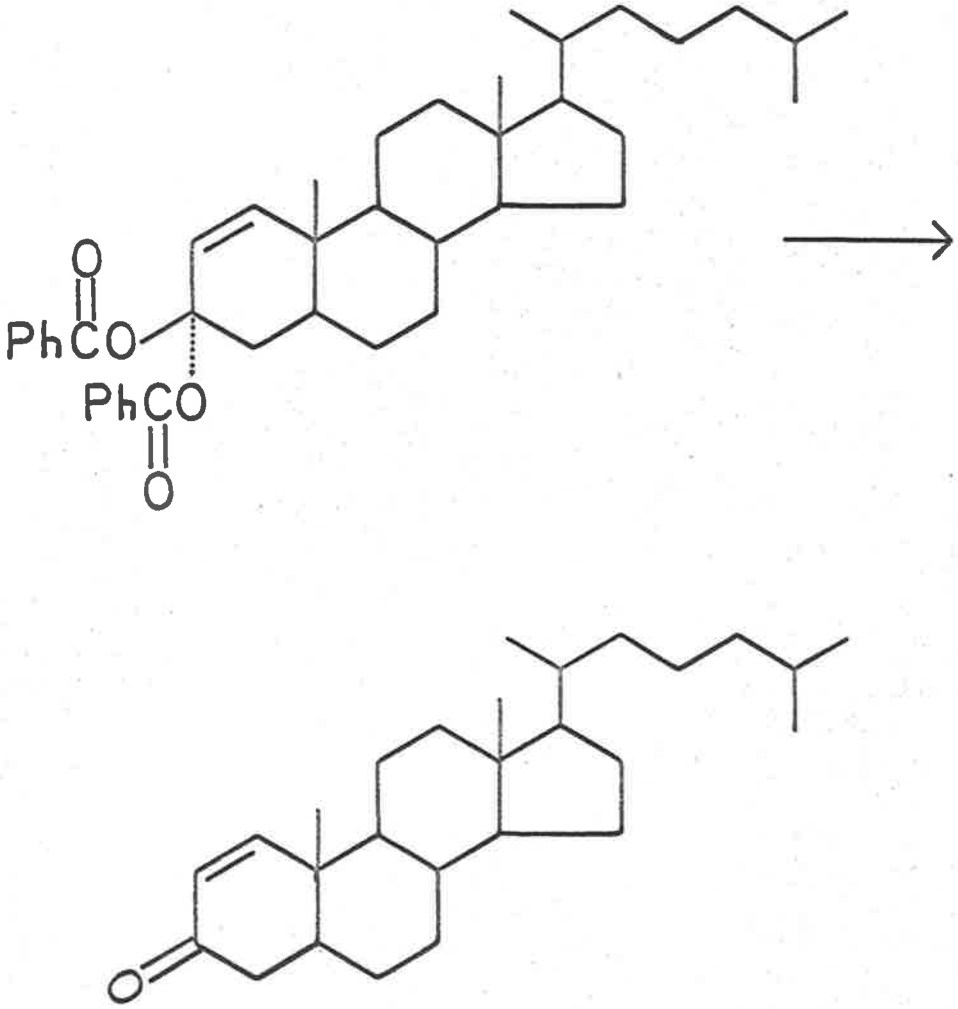
This observation is based purely upon infrared data, as reported by Rosenkrantz and Gut,[151] who found



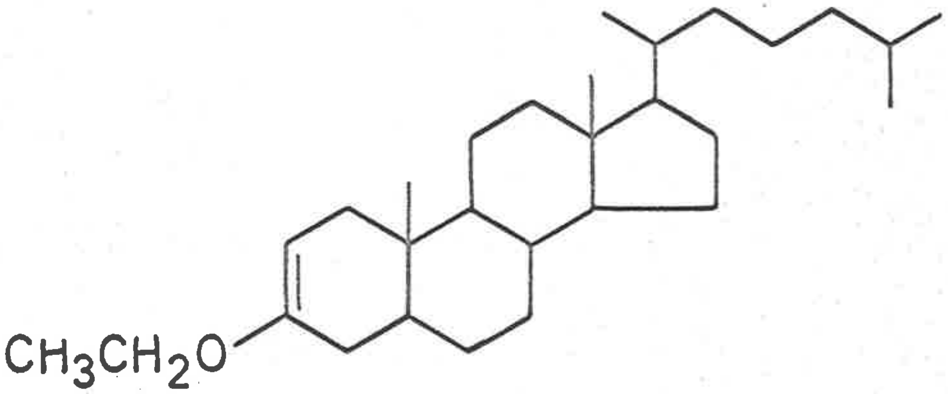
(CLXXVIII)



(CLXXIX)



(CLXXX)



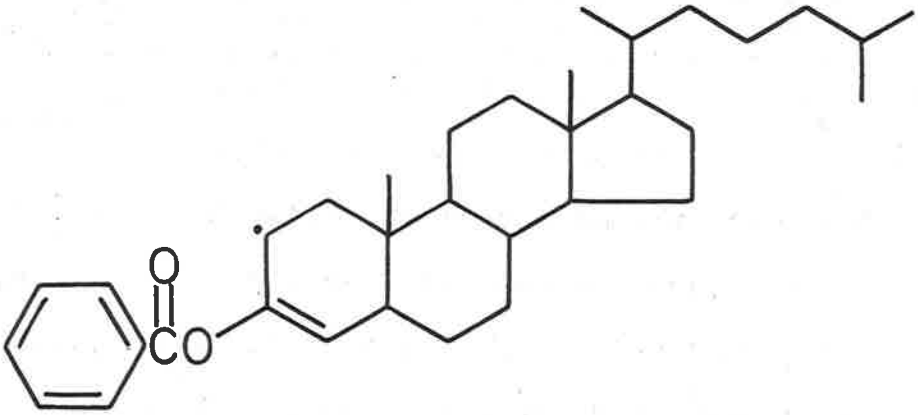
(CLXXXI)

that all enol-ethers exhibit an abnormally strong C=C stretching frequency at approximately 1670 cm.$^{-1}$ It is significant that most of the oils obtained from the chromatography of the crude-material from this reaction, completely failed to exhibit this characteristic absorption. Spectral evidence did show, however, that an ether group was still present in most of these products.

It would not be justified to base too much emphasis on these two isolated experiments, but it does support the theory that double bonds try to attain the least-hindered position for complex formation.

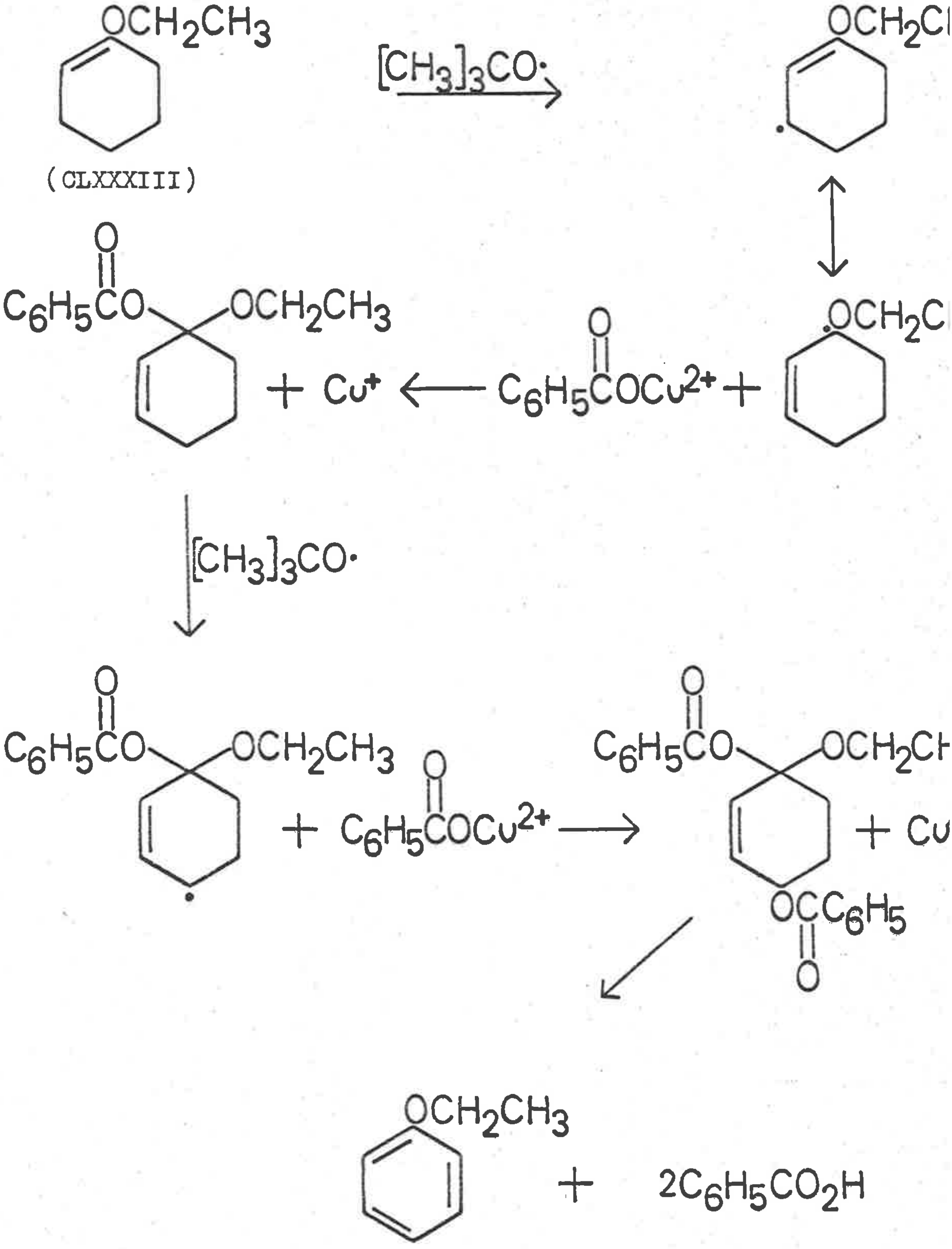
It is interesting that the 4-position of the enol-benzoate (CLXXVIII) did not react to any appreciable extent. However it is significant that if hydrogen-abstraction had occurred in this position, the double-bond would <u>not</u> have been placed into a better position for complex-formation with copper ions by the resonance hybrid contribution (CLXXXII).

The isomerization of the double-bond of the enol-benzoate (CLXXVIII) into the 1-position, could also be attributed to the stability of the resultant radical (CLXXIX). It appears likely that free-radicals containing oxygen-atoms at the free-valency sites are more stable than the normal unsubstituted carbon-radicals. There are many cases of ethers dimerizing at the α-positions when treated with t-butoxy radicals.



(CLXXXII)

A reaction between 1-ethoxycyclohex-1-ene (CLXXXIII), t-butyl perbenzoate and copper ions gave mainly aromatic products, of which only one, phenetol (CLXXXIV), was identified. After distillation of all the volatile products, including phenetol, the crude residue gave strong infra red absorption in the aromatic region. Hydrolysis of this crude material yielded alcohols which were also aromatic; they were not identified. The following sceme (p. 119) may account for the formation of phenetol and, possibly, the

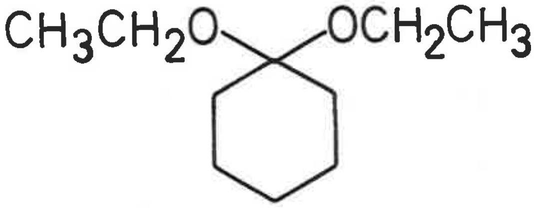


(CLXXXIII)

(CLXXXIV)

unidentified aromatic products. As in the case of the steroid enol-ester (CLXXVIII) reaction, the copper ions are shown not complexed to the olefinic double-bonds for the sake of simplicity.

Two other products were identified from this reaction, both were non-aromatic. They were shown to be cyclohexanone (CLXX), presumably resulting from hydrolysis of the enol ether (CLXXXIII) and cyclohexanone diethylacetal (CLXXXV), the origin of which is obscure.



(CLXXXV)

The results of all these reactions certainly supports the theory that a double bond will migrate, not necessarily to attain a terminal-position, but to gain a position which is most favourable for complex-formation with the copper ions. Only one experiment is known which has not supported this hypothesis. The previously described reaction of cholesteryl benzoate (CLXII) with t-butyl perbenzoate in the presence of cuprous ions yielded the 7-substituted products (CLXIII and CLXIV), where the double-bond had not migrated.

The position of this double bond (in the 5- position) is not a good one for complex-formation. Had it moved into the 6-position, the chances of complex-formation would have been greatly enhanced.

A very favourable feature about the working hypothesis is the contiguous nature of all the reacting species, a feature which is perhaps lacking in the Kochi mechanism. The reduction of the perester by an olefin-cuprous ion π-complex would result in the free t-butoxy radical being adjacent to, and thereby abstracting, the allylic-hydrogen atom from the olefin which was in the most favourable condition to be oxidized (complexed to a cupric carboxylate). This readily accounts for the extensive oxidation of nearly every substrate-radical by a mere trace of oxidizing agent. The Kochi mechanism requires that the free allylic radicals be formed before coming in contact with the cupric carboxylate. Under these circumstances, therefore, it would not be unreasonable to expect many of these allylic radicals never to come in contact with a cupric-ion, the stationary concentration of which is very low. There has never been evidence to suggest that free allylic radicals are present which, being unable to meet a cupric ion, react in other ways. Examination of the unreacted starting material at the completion of a reaction has always failed to show double-bond isomerization during the reaction.

The reactions of β-methylstyrene (XXVIII) and allylbenzene (XVIII) have never given reproducible yields of products. Whereas Kharasch et al[58] obtained entirely 3-phenyl-3-benzoyloxyprop-1-ene (XIX) in their reaction of allylbenzene with t-butyl perbenzoate and copper ions, Walling et al[137] obtained 30% of the cinnamyl isomer (XXIX). The results of the allylbenzene-experiments in this laboratory were also inconsistent, the cinnamyl isomer (XXIX) being present when the experiment was conducted in the presence of a solvent, but in the absence of solvent no cinnamyl isomer was found.

Similarly, Walling et al[137] obtained the terminal double-bonded product entirely when β-methylstyrene was the substrate, whereas our results indicated the presence of a mixture of isomers, the one with the terminal double-bond predominating.

These discrepancies in the isomer-distribution of these reactions could possibly be explained if it is realized that the main product of these reactions, 3-phenyl-3-acyloxyprop-1-ene (XIX), is not the thermodynamically most-stable isomer.[75] This isomer could be expected to isomerize slowly into the more stable cinnamyl isomer (XXIX) upon prolonged heating. Indeed Walling _et al_[137] have shown that such isomerization does extensively occur during G.L.C. analysis. The reaction conditions as described by Kharasch _et al_[58] involved the heating of the reaction at 90° for a _maximum_ of four hours, whereas the conditions used by Walling _et al_[137] required heating at 70° for no less than 35 hours. The prolonged heating during this latter experiment could possibly lead to partial isomerization of the product.

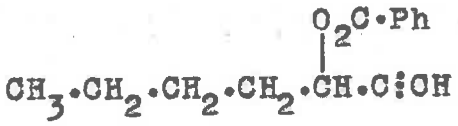
It is possible, too, that at increased dilution with a solvent, the chances of specific acyloxylation would be reduced. Our observation that allylbenzene reacts in a less stereospecific manner when diluted by a solvent, is in support of the working hypothesis, for cuprous ion-olefin complex formation would surely be less favoured under these conditions. Likewise, diluted conditions would lessen the chances of reduction of the perester by a cuprous-olefin π-complex; it is conceivable, therefore, that a thermal, uncatalysed, decomposition of the perester could play a more conspicuous role in the reaction with the resultant formation of a mixture of isomers.

The acyloxylation of the 3-position of alkynes has been successfully attempted. When t-butyl perbenzoate was decomposed in the presence of hept-1-yne (CLXXXVI) and cuprous chloride, a quantitative yield of 3-benzoyloxyhept-1-yne (CLXXXVII) was obtained. Only a trace of isomerized-product was isolated. The mechanism suggested by us for the specific-benzoyloxylation of terminal-olefins would also apply very readily to this experiment. It is well known that addition and substitution complexes are readily formed between cuprous ions and alkynes.[152-154] The former type of complex, which is analogous to the cuprous ion-olefin π-complexes has been shown[154] to be the most predominant.

The radical intermediate from the hept-1-yne reaction, viz. ethynylbutylmethyl radical (CLXXXVIII), would be in resonance with a less-stable allene contribution (CLXXXIX). There was no spectral evidence for the presence of allene groups in the products.

$CH_3{\cdot}CH_2{\cdot}CH_2{\cdot}CH_2{\cdot}CH_2{\cdot}C{\equiv}CH$

(CLXXXVI)



$$CH_3{\cdot}CH_2{\cdot}CH_2{\cdot}CH_2{\cdot}\overset{O_2C{\cdot}Ph}{\overset{|}{C}H}{\cdot}C{\equiv}CH$$

(CLXXXVII)

$$CH_3{\cdot}CH_2{\cdot}CH_2{\cdot}CH_2{\cdot}\dot{C}H{\cdot}C\vdots CH \longleftrightarrow CH_3{\cdot}CH_2{\cdot}CH_2{\cdot}CH_2{\cdot}CH{:}C{:}CH{\cdot}$$

(CLXXXVIII) (CLXXXIX)

It is well known that dimerization often occurs when terminal alkynes are treated with cuprous and cupric salts,[155] presumably by the following sceme:

$$RC\vdots C^- + Cu^{2+} \longrightarrow RC\vdots C{\cdot} + Cu^+ \tag{127}$$

$$2\ RC\vdots C{\cdot} \longrightarrow RC\vdots C{\cdot}C\vdots CR \tag{128}$$

It was considered possible, therefore, that a trace of cuprous salt could similarly cause dimerization in our reaction, by the following sceme:

$$RC\vdots C^- + Cu^{2+} \longrightarrow RC\vdots C{\cdot} + Cu^+ \tag{127}$$

$$RCO_2{\cdot}OC(CH_3)_3 + Cu^+ \longrightarrow RCO_2^- + (CH_3)_3CO{\cdot} + Cu^{2+} \tag{129}$$

(followed by equation (128))

Careful ultraviolet spectroscopy of the products failed to reveal any conjugated diyne group, however.

There has been no previously reported case involving a cuprous-catalysed perester reaction with an alkyne and it would indeed be interesting to treat an alkyne, possessing a non-terminal triple bond, with *t*-butyl perbenzoate in the presence of copper ions. Allene formation could perhaps be more favoured in this case, since the terminal-position would then contain double-bond character due to the resonance of the radical (CXC).

$$R\,CH_2{\cdot}C{\vdots}C{\cdot}CH_2{\cdot} \longleftrightarrow R\,CH_2{\cdot}\dot{C}{:}C{:}CH_2$$

(CXC)

3. Perester Reactions with Non-olefinic substrates

Up to the time when the reaction with hept-1-yne had been completed, nearly all our investigation of catalysed-perester reactions had been devoted to a study of the mechanism of olefin-acyloxylations and the isomerism involved therein. At this stage, the investigation was concentrated upon the catalysed-perester reactions of substrates other than olefins. The situation is different with these substrates than in the case of olefins. Because there is an absence of double bonds, the formation of complexes between the substrate-molecule, or radical, and copper-ion is not likely (except the possible formation of a complex between an etherial-oxygen and copper-ion (120-122)). This, of course, greatly reduces the chances of intermediate cyclic-transition states, lessens the chances of ligand-transfer mechanisms operating and, conversely, increases the possibility of transient-carbonium ions.

The factors which determine whether or not a given free-radical will be reduced or oxidized by a metal-ion, and the extent of such a process, has been discussed in the preceding section. The importance of substituent-groups adjacent to the free-valency site was emphasized; groups with electron-attracting capabilities decreased the availability of the odd-electron at the free-valency site and thus lessened the chances of oxidation. The situation was reversed with electron-donating groups. It was also emphasized that the stability of the ions, which would result from these oxidation or reduction reactions, was also important.

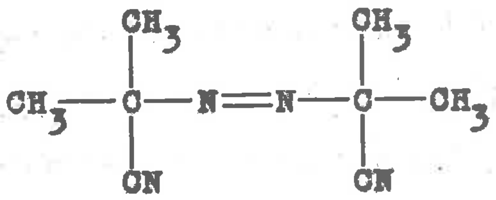
The results of our reactions with substrates other than olefins have shown that the stability of the carbonium-ion, resulting from the oxidation of the substrate-radical, is very important, and so also is the availability of the odd-electron at the free-valency site. It was found that this latter aspect was not only dependent upon the electronic effects of substituent groups, but, as will be shown, is closely related to the stability of the radical.

An important consideration, which determines the extent to which a given substrate-molecule will be oxidized in these reactions, is the dissociation energy of its C-H bonds. This is closely related to the stability of the radical formed by such a dissociation and is also affected by the electronic-effects of substituent groups. It is obvious, therefore, that the extent of oxidation of substrate-molecules and the radicals resulting from them, is dependent upon several, very closely related, principles.

Perhaps the greatest reason for certain molecules not to undergo facile-oxidation, in these perester-reactions, is the detrimental effect of certain substituent groups adjacent to the free-valency site. The results of Merz and Waters[9] had previously indicated this when they oxidized many substrates under the Fenton conditions. They found that electron-attracting groups tended to remove the odd-electron from the free-valency site and so lessen the possibility of it being removed by an oxidizing-agent.

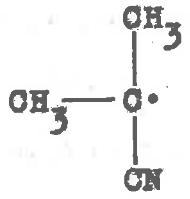
This effect was observed in this laboratory when t-butyl perbenzoate was decomposed in the presence of diethyl malonate (CXXIV) and cuprous chloride. The oxidation product, diethyl O-benzoyl tartronate (CXXV; $R=C_6H_5\cdot CO_2$) was obtained in poor yield. Berglund and Lawesson[83] also performed this reaction at the same time, and they too obtained a very poor yield of diethyl O-benzoyl tartronate. Their report that diethyl O-t-butyl tartronate (CXXV; $R=(CH_3)_3CO$) was also a reaction product, was not observed by us. The low yield of ester-products from these reactions cannot be accounted for by assuming that the free t-butoxy radicals had failed to abstract the hydrogens from the diethylmalonate molecule. Indeed, Beckwith[108] has shown that the α-position on the acid-moiety of an ester is quite prone to abstraction by t-butoxy radicals. It is apparent that the electron-withdrawing effect of the two carboxyl groups removed the unpaired-electron from the scene of oxidation. For a similar reason, the reaction of ethyl acetoacetate (CXXVI) with t-butyl peracetate (XI) and copper ions, as described by Berglund and Lawesson,[83] also failed to yield much oxidation product. The main product was a 20% yield of the t-butoxy-derivative (CXXVII; $R=(CH_3)_3CO$).

When we decomposed azobisisobutyronitrile (CXCI) in the presence of excess cupric benzoate, using butan-2-one as a solvent, there was little evidence that the 2-cyanopropyl radicals (CXCII) had been oxidized. It was also observed that these radicals had not dimerized to any extent. It is therefore possible that the radicals (CXCII) abstracted hydrogen-atoms from the solvent to yield isobutyronitrile (CXCIII).



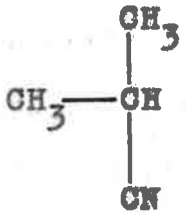
$CH_3-C(CH_3)(CN)-N=N-C(CH_3)(CN)-CH_3$

(CXCI)



$CH_3-\dot{C}(CH_3)(CN)$

(CXCII)



$CH_3-CH(CH_3)(CN)$

(CXCIII)

This is a further example of an electron-attracting substituent hindering these oxidation reactions.

The unpaired-electron of a free-radical can be displaced from the free-valency site by other causes.

When a radical is greatly stabilized by resonance, the odd-electron is very delocalized. In such cases, oxidation of the radical is not efficient, and this is attributed to the non-availability of the odd-electron at the free-valency site. This was especially seen during the oxidation of benzyl-type radicals which gave very poor yields of oxidation products and sometimes did not oxidize at all.

In several reactions between toluene (CXXXI), di-*t*-butyl peroxide (LIV) and mole-equivalents of cupric benzoate, the yield of the expected oxidation product, benzyl benzoate (CXLVI), was always less than 10%. The addition of large quantities of benzoic acid to the reaction-mixture failed to increase this yield. This product was presumably formed by the following oxidation-reaction.

$$C_6H_5{\cdot}CH_3 + (CH_3)_3CO{\cdot} \longrightarrow C_6H_5{\cdot}CH_2{\cdot} + (CH_3)_3C{\cdot}OH \qquad (113)$$

$$C_6H_5{\cdot}CH_2{\cdot} + Cu^{2+}O_2C{\cdot}C_6H_5 \longrightarrow C_6H_5{\cdot}CH_2{\cdot}O_2C{\cdot}C_6H_5 + Cu^{+} \qquad (116)$$

Alternatively, the oxidation could have proceeded through a benzyl carbonium ion as in (93) and

(115). When cupric acetate was used instead of cupric benzoate an equally poor yield of the oxidation-product, benzyl acetate (CXX), was obtained.

It must be emphasized that benzyl radicals (CXLVII) are very stable and, as a result, are generated in large quantities by the action of _t_-butoxy radicals on toluene (CXXXI). This is, of course, closely connected with the dissociation energy of the benzylic C-H bond of toluene, which is very low[156] (77.5 Kcal./Mole.). This was clearly seen when di-_t_-butyl peroxide (LIV) was thermally-decomposed in the presence of toluene (CXXXI) with no catalyst present; a near quantitative yield of bibenzyl (CLX) was obtained.

It was quite unexpected, therefore, that, after having obtained an extremely poor yield of benzyl benzoate (CXLVI) from the copper-salt catalysed reaction, the yield of bibenzyl (CLX) was also very poor. Apparently the added copper-catalyst had markedly hindered the formation of benzyl radicals (CXLVII).

An examination[134] of the volatile products, from one of these reactions, using G.L.C. apparatus has indicated a much higher _t_-butanol-acetone ratio than would be expected. The only explanation for the low production of benzyl radicals (CXLVII) and the high production of t-butanol is the reduction of t-butoxy radicals to the t-butoxide anion by cuprous ions as in (130), followed by protonation (131).

$$(CH_3)_3CO\cdot + Cu^+ \longrightarrow (CH_3)_3CO^- + Cu^{2+} \qquad (130)$$

$$(CH_3)_3CO^- + H^+ \longrightarrow (CH_3)_3C\cdot OH \qquad (131)$$

It seems likely that, as soon as a cupric ion is reduced to a cuprous ion during the oxidation of benzyl radicals, it is rapidly oxidized back to the cupric-ion by the sceme above. Alternatively, induced-decomposition of the peroxide could occur:

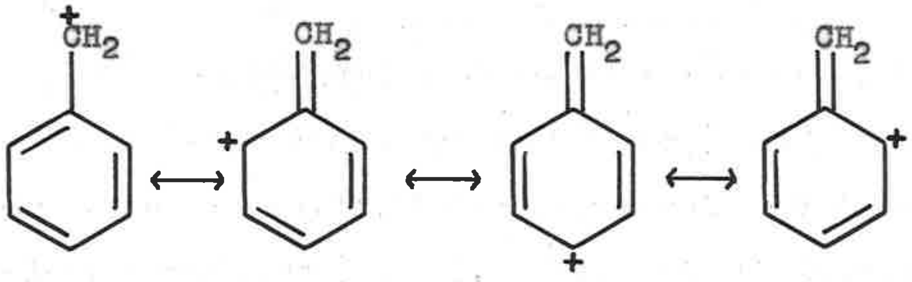
$$(CH_3)_3CO\cdot OC(CH_3)_3 + Cu^+ \longrightarrow (CH_3)_3CO^- + (CH_3)_3CO\cdot + Cu^{2+} \qquad (132)$$

The first two attempts at this reaction involved the use of cupric benzoate which contained water of crystallization. In both cases benzyl alcohol was produced in comparable quantities to the benzyl benzoate. A third attempt at this reaction utilized cupric benzoate which had been subject to azeotropic distillation with toluene prior to use; in this way much water of crystallization had been removed. It is interesting that this third experiment failed to produce any benzyl alcohol. This, surely, is good evidence for the formation of intermediate benzyl carbonium ions by an electron-transfer mechanism as in (93) followed by (133).

$$C_6H_5{\cdot}CH_2^+ + H_2O \longrightarrow C_6H_5{\cdot}CH_2{\cdot}OH + H^+ \qquad (133)$$

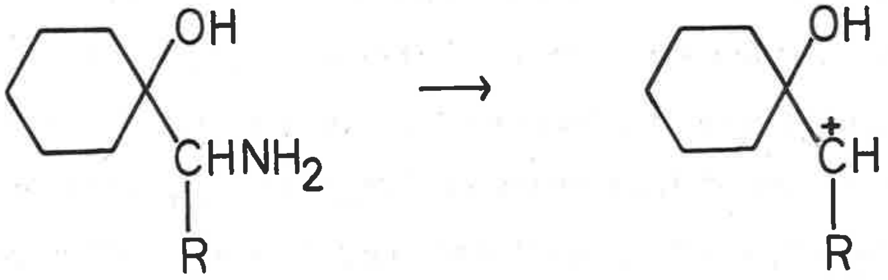
Since the oxidation product, benzyl benzoate (CXLVI), and the dimer, bibenzyl (CLX), were formed in approximately equal quantities in all these reactions, it appears that benzyl radicals (CXLVII) are not very prone to oxidation by cupric salts. The extensive delocalization of the unpaired-electron would readily account for this observation. The results of De La Mare _et al_[28] clearly indicated that the removal of the unpaired-electron by the oxidizing agent from the _free-valency site_ is essential for these oxidations to proceed successfully, a situation which is not greatly favoured with benzyl radicals.

This hypothesis seems even more plausible when it is realized that benzyl carbonium ions are considerably more stable than related alkyl carbonium ions, due, presumably, to stabilization by resonance (CXCIV).



(CXCIV)

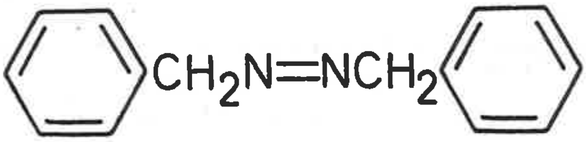
Thus, the reactivity of benzyl halides is attributed to a tendency to form these resonance stabilized ionic species. Similarly, during Tiffeneau-Demjanov ring expansion reactions,[157] the substitution of R by a phenyl group (CXCV) is very detrimental to ring expansion, due to the increased stability of the resultant carbonium ion (CXCVI).



(CXCV) (CXCVI)

It will be shown later that a radical is usually more prone to oxidation when the resultant carbonium ion is a very stable one. Therefore, the fact that benzyl radicals are not readily oxidized, even though the benzyl carbonium ion is so stable, supports the theory that the delocalization of the unpaired-electron within the aromatic nucleus seriously affects the removal of that unpaired-electron by the oxidizing agent.

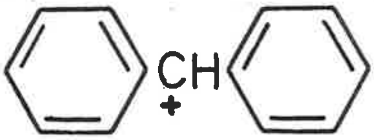
A by-product from these toluene reactions is worth mentioning. An unidentified compound, m.p. 180-180.5° was obtained in small quantities. When dissolved in organic solvents, it gave a faint blue-fluorescence and its ultraviolet absorption spectrum was identical to that of bibenzyl (CLX). It analysed for $C_{28}H_{26}$, and contained no functional groups. This compound is probably a tetramer of benzyl radicals (CXLVII). It is interesting that there have been two separate reports of a compound of this description having been isolated during the pyrolysis of α, α'-azotoluene (CXCVII).



(CXCVII)

In 1950, Bickel et al[158] heated a solution of α, α'-azotoluene (CXCVII) in decalin and obtained crystals m.p. 177.5-178.5° which analysed for $C_{28}H_{26}$. Some Russian workers[159] later heated α,α'-azotoluene (CXCVII) in a sealed-tube and obtained crystals m.p. 179.5-180.5° which also analysed for $C_{28}H_{26}$. It is probable that all these reports concern the same compound.

Certain reactions, carried out by other workers, have also confirmed the hypothesis that radicals, which are stabilized by resonance, are not easily oxidized. Berglund and Lawesson[83] showed that diphenylmethyl radicals (CXXXIX) completely failed to undergo oxidation with cupric salts and yet the diphenylmethyl carbonium ion (CXCVIII) would be considerably more stable than a benzyl carbonium ion (CXCIV). The cation (CXCVIII) could be represented by many more resonance structures than the cation (CXCIV); in addition, it is not a primary, but a secondary carbonium ion.



(CXCVIII)

The unpaired-electron of the diphenylmethyl radical (CXXXIX) would be so delocalized that its removal from the free-valency site by the oxidizing reagent would be very unlikely.

Similar results were obtained in the previously described olefin reactions whenever the unpaired-electron of the allylic radical was extensively delocalized. Thus the yields of oxidation products from the allylbenzene and β-methylstyrene reactions were very much lower than those from the unsubstituted alkene reactions. The unpaired-electron of the phenylvinylmethyl radical (CLXXVIIa) is expected to be well distributed over the aromatic nucleus, and so the removal of this electron during oxidation would not be easy.

Another experiment further emphasized the preceding theory. When 1,1,3-triphenylprop-1-ene (CXCIX) was treated with t-butyl perbenzoate in the presence of cuprous bromide, the only product isolated was shown to be a dimer, m.p. 209-211 (decomp.). Although this dimer was not positively identified it seems likely that it was 1,1,3,4,6,6-hexaphenylhexa-2,4-diene (CC). This assumption is based on our previous observations that double bonds will always isomerize into positions less sterically hindered for complex formation with copper ions. Likewise, the ultraviolet absorption spectrum of this dimer resembled that of styrene.

$PhCH \cdot CH{:}CPh_2$ (CXCIX)

$Ph_2CH \cdot CH{:}PhCH \cdot PhCH{:}CH \cdot Ph_2CH$ (CC)

The results of Kharasch and Fono[71] are not consistent with the preceding results, for they found that cumyl radicals (CXLI) were, in fact, quite readily oxidized by cupric ions. Thus the catalysed decomposition of *t*-butyl perbenzoate in the presence of cumene gave a 40% yield of α-cumyl benzoate (CXLIV). However, the combined inductive effect of the two methyl groups would probably facilitate electron-removal (oxidation) at the free-valency site.

The many examples, in the literature, of benzyl ethers,[90,91] simple ethers,[79] and benzyl alcohol[78] undergoing facile-oxidation, is not consistent with the preceding results. The combined electronic effects of the phenyl-ring and the oxygen-atom would be expected to render the free-valency site void of the unpaired-electron. However Merz and Waters[9] have shown that oxygen atoms adjacent to the free-valency site do not hinder these oxidations when the Fenton conditions are employed.

Indeed, it is possible that the inductive effect of the oxygen-atom, in the radicals derived from benzyl ethers, would reduce the delocalization of the unpaired-electron on the aromatic nucleus. Hence the chances for the removal of this unpaired-electron from the free-valency site by an oxidizing-agent would be enhanced. In addition, it would be expected that these radicals would not be as stable as would be expected in systems which were completely stabilized by resonance.

This latter point has been proven several times. Whereas the radicals derived from simple ethers undergo complete dimerization[78] as in (62), the radicals from benzyl ethers readily decompose as well as dimerize,[87-89] as in (63). Why the radicals derived from benzyl ethers should be so less stable than those from simple ethers is not clear. Nevertheless it is apparent that the etherial-oxygen atom has a detrimental effect upon the stability of these radicals, possibly due, in part, to the removal of the unpaired-electron from the resonance in the aromatic ring. The ready-availability of the unpaired-electron, derived from benzyl alcohol, for oxidation could be explained in similar terms.

It has been seen that the substituent groups of a substrate greatly influence the pathway and extent of oxidation of that substrate by cupric ions. Another important factor which determines how readily, or by what route, a given substrate-molecule will be oxidized, is the stability of the transient-radicals and cations. If a molecule is to be oxidized, in these reactions, it is essential that the dissociation energy of the C-H bond in question must be reasonably low, otherwise hydrogen-abstraction by t-butoxy radicals would not be favoured. As cited earlier, the dissociation energy will only be low enough for this to happen if the resultant radical is reasonably stable. A stable radical could be obtained at a site adjacent to a secondary or, preferably, a tertiary carbon atom. Alternatively the dissociation energy would be lowered if the resultant radical was stabilized by resonance.

It is reasonable to assume that long-chain alkanes would be relatively inert to attack by t-butoxy radicals, whereas alkyl benzenes, or carbonyl compounds would be prone to such attack.

Assuming that the conditions are ideal for radical-formation, and assuming, also, that there are no substituent groups which could remove the unpaired-electron from the free-valency site, then the conditions would appear favourable for oxidation to occur. However, another factor is still to be considered; the stability of the resultant carbonium ion. Obviously, oxidation of a radical would not be favoured if, as a result, a less-stable transient-species is obtained. It is also apparent that, if the conditions were favourable for an oxidation to proceed by a ligand-transfer mechanism, then the above-mentioned factor would be unimportant, for such a mechanism does not require the intermediate formation of a carbonium ion. Thus Kochi and Rust[37] found that radicals, which could not accommodate a positive charge and thus fail to be oxidized by an electron-transfer mechanism, were readily oxidized by a ligand-transfer process.

Aldehydes are perhaps more readily oxidized in these reactions than any of the substrates studied and, for the reasons stated above, this is not unexpected. The conditions are favourable for the abstraction of the aldehydic hydrogen-atom by a t-butoxy-radical, for the dissociation energy of the C–H bond is low and the resultant acyl-radical is stabilized[160] by resonance (CCI).

$$R - \dot{C} = O \longleftrightarrow R - \overset{-}{C} = \overset{+}{O}\cdot \qquad\qquad R - \overset{+}{C} = O$$

(CCI) (CCII)

Likewise, the acyl carbonium ion (CCII), which would be formed upon oxidation of this acyl radical (CCI), is an extremely stable one. It takes part in Friedel-Crafts acylations and is even stable in sulphuric acid solution.[161] Therefore, the conditions are very favourable for aldehydes to be oxidized in these reactions.

This was clearly seen when _t_-butyl perbenzoate was decomposed in the presence of benzaldehyde and a trace of copper salt. Benzoic anhydride (CXVI) and _t_-butyl benzoate (CXV) were both isolated, the former in 45% yield. This yield is disappointing when it is realized that a similar experiment by Sosnovsky and Yang[80] gave benzoic anhydride in 70% yield. However their reaction temperature was considerably higher than ours, and therefore, the _t_-butanol formed during the reaction, would be expected to reside in the condenser and not take part in the reaction. The formation of _t_-butyl benzoate (CXV) in our reaction could have resulted from the action of _t_-butanol upon the anhydride (134).

$$(C_6H_5\cdot CO)_2\cdot O + (CH_3)_3C\cdot OH \longrightarrow C_6H_5\cdot CO_2\cdot C(CH_3)_3 + C_6H_5\cdot CO_2H \qquad (134)$$

The mechanism of the reaction can be represented as follows:

$$C_6H_5\cdot CO_2\cdot OC(CH_3)_3 + Cu^+ \longrightarrow C_6H_5\cdot CO_2^- + (CH_3)_3CO\cdot + Cu^{2+} \qquad (38)$$

$$C_6H_5\cdot CHO + (CH_3)_3CO\cdot \longrightarrow C_6H_5\cdot\dot{C}O + (CH_3)_3C\cdot OH \qquad (85)$$

$$C_6H_5\dot{C}O + Cu^{2+} \longrightarrow C_6H_5\cdot\overset{+}{C}O + Cu^+ \qquad (135)$$

$$C_6H_5\cdot\overset{+}{C}O + C_6H_5\cdot CO_2^- \longrightarrow (C_6H_5\cdot CO)_2\cdot O \qquad (136)$$

followed (in part) by equation (134).

Although the conditions for the oxidation of aldehydes are very favourable, the reverse is true for the oxidation of the α-position of the alcohol-moiety of an ester. If the α-hydrogen is removed by a *t*-butoxy radical, the resultant radical does not only fail to undergo stabilization by resonance, but the oxidation of such a radical would not yield a particularly stable carbonium ion.

When di-*t*-butyl peroxide (LIV) was decomposed in the presence of ethyl benzoate (CCIII), acetic acid and excess cupric chloride, 80% of the ester was recovered unchanged. Examination of the products showed that only a small amount (13% of the total products) of acetoxylation had taken place in the α-position. The oxidation could be represented as follows:

$$C_6H_5\cdot CO_2\cdot CH_2\cdot CH_3 + (CH_3)_3CO\cdot \longrightarrow C_6H_5\cdot CO_2\cdot \dot{C}H\cdot CH_3 \qquad (137)$$

(CCIII)

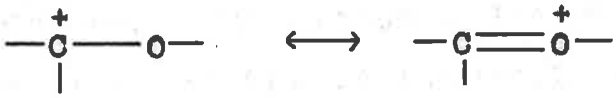
$$C_6H_5\cdot CO_2\cdot \dot{C}H\cdot CH_3 + Cu^{2+} \longrightarrow C_6H_5\cdot CO_2\cdot \overset{+}{C}H\cdot CH_3 \qquad (138)$$

$$C_6H_5\cdot CO_2\cdot \overset{+}{C}H\cdot CH_3 + CH_3\cdot CO_2^- \longrightarrow C_6H_5\cdot CO_2\cdot CH(OAc)\cdot CH_3 \qquad (139)$$

Alternatively, a ligand-transfer mechanism could operate:

$$C_6H_5\cdot CO_2\cdot \dot{C}H\cdot CH_3 + CH_3\cdot CO_2Cu^{2+} \longrightarrow C_6H_5\cdot CO_2\cdot CH(OAc)\cdot CH_3 + Cu^+ \qquad (140)$$

For reasons not yet understood, the radicals derived from ethers, by abstraction of an α-hydrogen atom, are relatively stable. The carbonium ion, formed by removal of the unpaired-electron from these radicals, is also reasonably stable; it can be represented by the following resonance structure:



$$-\overset{+}{\underset{|}{C}}-O- \longleftrightarrow -\underset{|}{C}=\overset{+}{O}-$$

(CCIV)

Therefore, it is reasonable to expect that ethers would be easily oxidized by cupric ions in the presence of _t_-butoxy radicals, and this, of course, has been demonstrated by many workers. Thus the cuprous-catalysed reduction of _t_-butyl peresters in the presence of simple ethers, thio ethers, and benzyl ethers, have invariably yielded acylals or the acetals derived from them. As described earlier (120-122), the situation appears to be very favourable for ethers to be oxidized by a ligand-transfer process, through a similar mechanism to that described for the acyloxylation of olefins.

Since the conditions are very favourable for aldehydes to be oxidized in these reactions, it was thought likely that the formyl-hydrogen atom of formamide and formate esters would be quite prone to abstraction by _t_-butoxy-radicals, and that the resultant radicals would also be readily oxidized. It is therefore remarkable that the reactions of these compounds with free-radical reagents has been sadly neglected.

There appears to be only one instance where formamide (CCV) has been directly involved in a radical-reaction. When Elad[162] irradiated formamide (CCV) in the presence of the esters of some unsaturated acids, the C-H bond was homolytically fissioned and the resultant carbamoyl radicals (CCVI) added across the double bonds of the esters.

$H{\cdot}CO{\cdot}NH_2$ (CCV) $\qquad$ ${\cdot}CO{\cdot}NH_2$ (CCVI)

Similar to aldehydic-hydrogen atoms, we have found that the formyl hydrogen-atom of formamide (CCV), is readily abstracted by _t_-butoxy-radicals. Here the similarity ends, however, for the carbamoyl radical (CCVI), unlike the acyl radical (CCI), does not, apparently, yield very stable carbonium ions upon oxidation with cupric salts.

When _t_-butyl perbenzoate was decomposed in the presence of excess formamide (CCV) and a trace of cuprous chloride, the only product proved to be _t_-butyl allophanate (CCVII) in a fair yield.

$$(CH_3)_3C{\cdot}O_2C{\cdot}NH{\cdot}CO{\cdot}NH_2$$

(CCVII)

It had been expected that carbamoyl radicals

(CCVI) would be produced by the action of *t*-butoxy radicals upon formamide (CCV), and it was also considered probable that these transient radicals (CCVI) would be oxidized, by cupric ions to the carbonium ions (CCVIII). Subsequent combination of these cations (CCVIII) with benzoate anions could then yield the mixed anhydride (CCIX), and we anticipated that the reaction of this anhydride (CCIX) with *t*-butanol would give either *t*-butyl benzoate (CXV) or *t*-butyl carbamate (CCX). The sceme could be represented as follows:

$$C_6H_5\cdot CO_2\cdot OC(CH_3)_3 + Cu^{+} \longrightarrow C_6H_5\cdot CO_2^{-} + (CH_3)_3CO\cdot + Cu^{2+} \qquad (38)$$

$$\underset{\text{(CCV)}}{H\cdot CO\cdot NH_2} + (CH_3)_3CO\cdot \longrightarrow \underset{\text{(CCVI)}}{\cdot CO\cdot NH_2} + (CH_3)_3C\cdot OH \qquad (141)$$

$$\cdot CO\cdot NH_2 + Cu^{2+} \longrightarrow \underset{\text{(CCVIII)}}{\overset{+}{C}O\cdot NH_2} + Cu^{+} \qquad (142)$$

$$\overset{+}{C}O\cdot NH_2 + C_6H_5\cdot CO_2^{-} \longrightarrow \underset{\text{(CCIX)}}{C_6H_5\cdot CO\cdot O\cdot CO\cdot NH_2} \qquad (143)$$

$$C_6H_5{\cdot}CO{\cdot}O{\cdot}CO{\cdot}NH_2 + (CH_3)_3C{\cdot}OH \longrightarrow C_6H_5{\cdot}CO_2{\cdot}C(CH_3)_3 + HO_2C{\cdot}NH_2$$

(CXV) (144)

$$\searrow$$

$$(CH_3)_3C{\cdot}O_2C{\cdot}NH_2 + C_6H_5{\cdot}CO_2H$$

(CCX) (145)

Neither *t*-butyl benzoate (CXV) nor *t*-butyl carbamate (CCX) was obtained. A reaction, which would compete with the above sceme, can be envisaged if the carbonium ion (CCVIII) is not a stable species. If combination of the carbonium ion (CCVIII) with a benzoate ion did not occur rapidly, as in (143), the carbonium ion (CCVIII) could, conceivably, lose a proton to form *iso*cyanic acid (CCXI).

$$\overset{+}{C}O{\cdot}NH_2 \longrightarrow O{:}C{:}NH \qquad (146)$$

(CCVIII) (CCXI)

It is likely, therefore, that both *t*-butyl carbamate (CCX) and *iso*cyanic acid (CCXI) are being f ,
and that the subsequent reaction between the *t*-butyl carbamate and *iso*cyanic acid would yield the observed product, *t*-butyl allophanate (CCVII).

$$(CH_3)_3C{\cdot}O_2C{\cdot}NH_2 + H{\cdot}N{:}C{:}O \longrightarrow (CH_3)_3C{\cdot}O_2C{\cdot}NH{\cdot}CO{\cdot}NH_2 \qquad (147)$$

The reaction of alkyl carbamates with cyanic acid is known to yield alkyl allophanates.[163] It is also well accepted that alkyl *iso*cyanates react with amines to yield substituted ureas (148).

$$RNH_2 + R'NCO \longrightarrow RNH{\cdot}CO{\cdot}NHR' \qquad (148)$$

Alternatively, the action of the carbonium ions (CCVIII) upon *t*-butyl carbamate (CCX) could yield the product (CCVII).

$$(CH_3)_3C{\cdot}O_2C{\cdot}NH_2 + \overset{+}{C}O{\cdot}NH_2 \longrightarrow (CH_3)_3C{\cdot}O_2C{\cdot}NH{\cdot}CO{\cdot}NH_2 + H^+ \qquad (149)$$

Since no *t*-butyl carbamate was isolated from the reaction, it would appear that equation (146) took place at a much greater rate than equation (143); this, of course, indicates that the carbamoyl carbonium ion (CCVIII) is not a very stable species. Further evidence for the formation of *iso*cyanic acid was the presence of a white, polymeric substance in the products, which could not be dissolved in any organic solvent. It is well known that cyanic acid is unstable above 0°

and readily polymerizes. The t-butyl allophanate (CCVII) decomposed at its melting point to yield large quantities of ammonia and a white insoluble residue which is assumed to be cyanuric acid.

It is interesting to compare the result of this reaction with a similar reaction conducted by Berglund and Lawesson[83] where N,N-dimethylformamide (CXXVIII) was treated with t-butyl perbenzoate in the presence of cuprous salt to yield N-benzoyloxymethyl-N-methylformamide (CXXIX). It is significant that this compound (CXXIX) was also obtained by Bamford and White[164] during the uncatalysed-decomposition of benzoyl peroxide (XLIV) in the presence of N,N-dimethylformamide (CXXVIII).

Obviously, the C-H bond dissociation energy of the N-methyl groups is considerably less than the bond dissociation energy of the formyl hydrogen-atom. It is also apparent that the formyl hydrogen-atom will only be abstracted by t-butoxy radicals when there is no competition from other C-H units. It can be reasonably concluded, therefore, that the formyl hydrogen-atom of formamide and substituted formamides is less reactive than the active hydrogen of aldehydes. This can be attributed to the lower stability of carbamoyl radicals (CCVI) as compared with acyl radicals (CCI).

Formate esters behave in a similar fashion to formamide and substituted formamides. The abstraction of the formyl-hydrogens by *t*-butoxy-radicals, competes with the removal of α-hydrogens from the alcohol moiety of the ester. Due to the low reactivity of the α-hydrogens of the alcohol moiety of esters (previously discussed) the formyl-hydrogen abstraction by *t*-butoxy radicals competes favourably when formate esters are the substrates.

Thus Urry and Huyser[165] treated methyl formate (CCXII) with di-*t*-butyl peroxide (LIV) in the presence of ethylene and found that the formyl-hydrogen atom was exclusively abstracted to yield methyl carbonoyl radicals (CCXIII) which then formed adducts with the olefin. The results were more complex when ethyl formate (CCXIV) was used, however. There was evidence for the production of both ethyl carbonoyl radicals (CCXV) and 1-formyloxyethyl radicals (CCXVI).

$H{\cdot}CO_2{\cdot}CH_3$	${\cdot}CO_2{\cdot}CH_3$	$H{\cdot}CO_2CH_2CH_3$	${\cdot}CO_2{\cdot}CH_2CH_3$
(CCXII)	(CCXIII)	(CCXIV)	(CCXV)

$H{\cdot}CO_2{\cdot}\dot{C}H{\cdot}CH_3$

(CCXVI)

When t-butyl perbenzoate was decomposed in the presence of n-butyl formate (CCXVII) and a trace of cuprous salt, the main product proved to be n-butyl-n-butyrate (CCXVIII) together with an 8% yield of n-butyl benzoate (CCXXIII).

$$H{\cdot}CO_2{\cdot}(CH_2)_3{\cdot}CH_3 \qquad CH_3{\cdot}(CH_2)_2{\cdot}CO_2{\cdot}(CH_2)_3{\cdot}CH_3$$

(CCXVII) (CCXVIII)

We had expected t-butyl-n-butyl carbonate (CCXIX) to be the main product, but it was not found.

$$(CH_3)_3{\cdot}CO{\cdot}CO_2{\cdot}(CH_2)_3{\cdot}CH_3$$

(CCXIX)

It was thought that this carbonate ester (CCXIX) could be formed from n-butyl formate (CCXVII) by abstraction of the formyl hydrogen atom to yield n-butyl carbonoyl radicals (CCXX). Oxidation of these radicals (CCXX) was then envisaged to yield the carbonium ion (CCXXI), which could then combine with a benzoate anion to give the anhydride (CCXXII). t-Butyl-n-butyl carbonate (CCXIX) could then have resulted from the action of t-butanol upon this anhydride (CCXXII). The sceme can be represented as follows:

$$C_6H_5\cdot CO_2\cdot OC(CH_3)_3 + Cu^{+} \longrightarrow C_6H_5\cdot CO_2^{-} + (CH_3)_3CO\cdot + Cu^{2+} \qquad (38)$$

$$H\cdot CO_2\cdot (CH_2)_3\cdot CH_3 + (CH_3)_3CO\cdot \longrightarrow \cdot CO_2\cdot (CH_2)_3\cdot CH_3 + (CH_3)_3C\cdot OH \qquad (150)$$

(CCXVII) (CCXX)

$$\cdot CO_2\cdot (CH_2)_3\cdot CH_3 + Cu^{2+} \longrightarrow \overset{+}{C}O_2\cdot (CH_2)_3\cdot CH_3 + Cu^{+} \qquad (151)$$

(CCXXI)

$$\overset{+}{C}O_2\cdot (CH_2)_3\cdot CH_3 + C_6H_5\cdot CO_2^{-} \longrightarrow C_6H_5\cdot CO\cdot O\cdot CO\cdot O\cdot (CH_2)_3\cdot CH_3 \qquad (152)$$

(CCXXII)

$$C_6H_5\cdot CO\cdot O\cdot CO\cdot O\cdot (CH_2)_3\cdot CH_3 + (CH_3)_3C\cdot OH \longrightarrow (CH_3)_3CO\cdot CO_2\cdot (CH_2)_3\cdot CH_3 + C_6H_5\cdot CO_2H \qquad (153)$$

(CCXIX)

The reason for the production of n-butyl benzoate

(CCXXIII) and *n*-butyl-*n*-butyrate (CCXVIII) is not clearly understood. It is apparent, from the results of this experiment and others conducted in this laboratory,[134] that the formyl-hydrogen atom of formate esters is reasonably active towards attack by *t*-butoxy-radicals and that the alkyl carbonoyl radicals, formed by such an attack, are very unstable and decompose into more stable components.

The results also suggest that the *n*-butyl carbonoyl radicals (CCXX) are not being oxidized, but are decomposing into *n*-butyl radicals (CCXXIV), as in (154), and *n*-butoxy radicals (CCXXV), as in (155), by the loss of carbon dioxide and carbon monoxide respectively.

$$\underset{\text{(CCXX)}}{CH_3\cdot(CH_2)_2\cdot CH_2\cdot O_2C\cdot} \longrightarrow \underset{\text{(CCXXIV)}}{CH_3\cdot(CH_2)_2\cdot CH_2\cdot} + CO_2 \qquad (154)$$

$$\underset{\text{(CCXX)}}{CH_3\cdot(CH_2)_2\cdot CH_2\cdot O_2C\cdot} \longrightarrow \underset{\text{(CCXXV)}}{CH_3\cdot(CH_2)_2\cdot CH_2\cdot O\cdot} + CO \qquad (155)$$

Although decarboxylation of these radicals (154) has been observed by another worker,[166] there appears to be no report of decarbonylation (155) occurring. The *n*-butyl benzoate undoubtedly results from the combination of a benzoate ion with a *n*-butyl carbonium ion (CCXXVI), the latter being the oxidation product of the n-butyl radical (CCXXIV).

$$CH_3\cdot(CH_2)_2\cdot CH_2\cdot + Cu^{2+} \longrightarrow CH_3\cdot(CH_2)_2\cdot CH_2^{+} + Cu^{+} \qquad (156)$$

(CCXXIV) (CCXXVI)

$$CH_3\cdot(CH_2)_2\cdot CH_2^{+} + C_6H_5\cdot CO_2^{-} \longrightarrow C_6H_5\cdot CO_2\cdot CH_2\cdot(CH_2)_2\cdot CH_3$$

(CCXXIII) (157)

The formation of the n-butyl-n-butyrate can only be accounted for by the presence of n-butanol or n-butoxy-radicals in the reaction mixture, and, unless the n-butanol resulted from the hydrolysis of the starting material during the reaction, these intermediates could only be formed by decarbonylation (155) of the n-butyl carbonoyl radicals (CCXX). The n-butyl-n-butyrate could be formed, either from n-butoxy radicals as in (157 and 158) or through the intermediate formation of n-butanol as in (159-161).

$$CH_3\cdot(CH_2)_2\cdot CH_2\cdot O\cdot + Cu^{+} \longrightarrow CH_3\cdot(CH_2)_2\cdot CH_2\cdot O^{-} + Cu^{2+}$$

(157)

$$CH_3\cdot(CH_2)_2\cdot CH_2\cdot O^- + CH_3\cdot(CH_2)_2\cdot\overset{+}{C}O \longrightarrow$$

(CCXXVII)

$$CH_3\cdot(CH_2)_2\cdot CH_2\cdot O_2C\cdot CH_2\cdot CH_2\cdot CH_3 \qquad (158)$$

(CCXVIII)

$$CH_3\cdot(CH_2)_2\cdot CH_2\cdot O\cdot + RH \longrightarrow CH_3\cdot(CH_2)_2\cdot CH_2\cdot OH + R\cdot \qquad (159)$$

$$CH_3\cdot(CH_2)_2\cdot\overset{+}{C}O + C_6H_5\cdot CO_2^- \longrightarrow CH_3\cdot(CH_2)_2\cdot CO\cdot O\cdot CO\cdot C_6H_5$$

(CCXXVII) (160)

$$CH_3\cdot(CH_2)_2\cdot CO\cdot O\cdot CO\cdot C_6H_5 + CH_3\cdot(CH_2)_2\cdot CH_2\cdot OH \longrightarrow$$

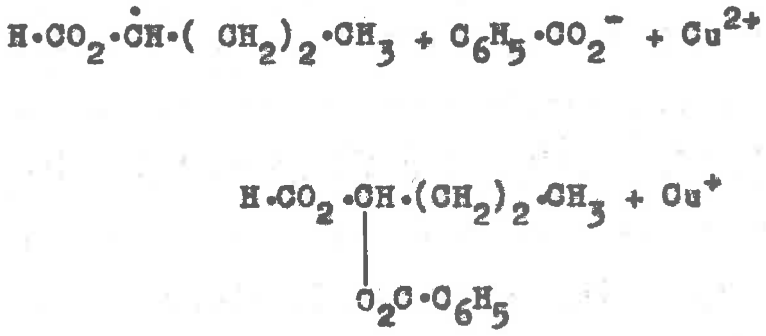
$$CH_3\cdot(CH_2)_2\cdot CH_2\cdot O_2C\cdot CH_2\cdot CH_2\cdot CH_3 + C_6H_5\cdot CO_2H$$

(CCXVIII) (161)

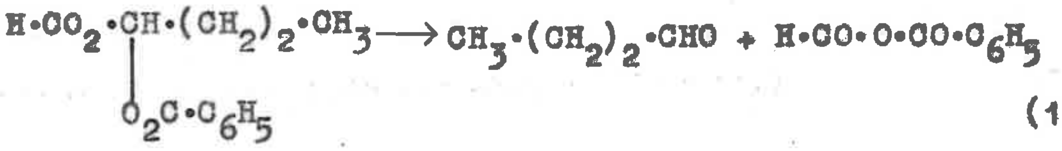
(where RH is any hydrogen-donor molecule.)

With regard to the great ability of alkoxyl radicals to abstract hydrogen atoms from substrate molecules,[167,168] the route involving n-butanol as an intermediate (159-161) is more acceptable. The intermediate acyl carbonium ion (CCXXVII) could be formed by two pathways in which either 1-formyloxybutyl radicals (CCXXVIII), or n-butoxy radicals (CCXXV), could be the transient-radicals. The sceme could be represented as follows:

$$H{\cdot}CO_2{\cdot}CH_2{\cdot}(CH_2)_2{\cdot}CH_3 + (CH_3)_3CO{\cdot} \longrightarrow \underset{\text{(CCXXVIII)}}{H{\cdot}CO_2{\cdot}\dot{C}H{\cdot}(CH_2)_2{\cdot}CH_3} + (CH_3)_3C{\cdot}OH \qquad (162)$$



$$H{\cdot}CO_2{\cdot}\dot{C}H{\cdot}(CH_2)_2{\cdot}CH_3 + C_6H_5{\cdot}CO_2^{-} + Cu^{2+} \longrightarrow H{\cdot}CO_2{\cdot}\underset{O_2C{\cdot}C_6H_5}{\underset{|}{C}H}{\cdot}(CH_2)_2{\cdot}CH_3 + Cu^{+} \qquad (163)$$



$$H{\cdot}CO_2{\cdot}\underset{O_2C{\cdot}C_6H_5}{\underset{|}{C}H}{\cdot}(CH_2)_2{\cdot}CH_3 \longrightarrow CH_3{\cdot}(CH_2)_2{\cdot}CHO + H{\cdot}CO{\cdot}O{\cdot}CO{\cdot}C_6H_5 \qquad (164)$$

$$CH_3{\cdot}(CH_2)_2{\cdot}CHO + (CH_3)_3CO{\cdot} \longrightarrow CH_3{\cdot}(CH_2)_2\dot{C}O + (CH_3)_3C{\cdot}OH \qquad (165)$$

$$CH_3\cdot(CH_2)_2\cdot\dot{C}O + Cu^{2+} \longrightarrow CH_3\cdot(CH_2)_2\cdot\overset{+}{C}O \qquad (166)$$

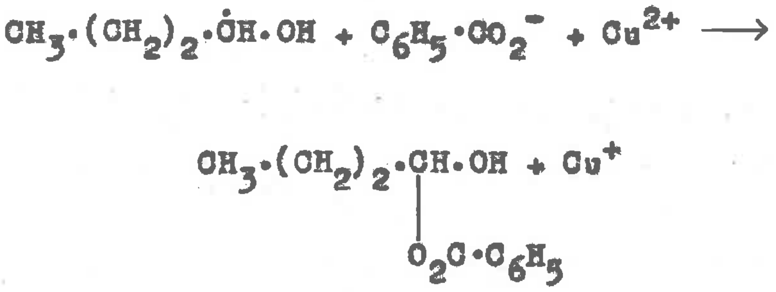
(CCXXVII)

$$CH_3\cdot(CH_2)_2\cdot CH_2\cdot O\cdot + (CH_3)_3CO\cdot \longrightarrow CH_3\cdot(CH_2)_2\cdot CHO + (CH_3)_3C\cdot OH \qquad (167)$$

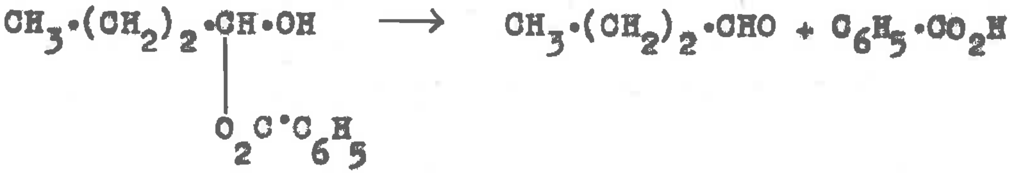
followed by equations (165) and (166).

It is also possible to predict the formation of this acyl carbonium ion by the following sceme:

$$CH_3\cdot(CH_2)_2\cdot CH_2\cdot OH + (CH_3)_3CO\cdot \longrightarrow CH_3\cdot(CH_2)_2\cdot\dot{C}H\cdot OH + (CH_3)_3C\cdot OH \qquad (168)$$



$$CH_3\cdot(CH_2)_2\cdot\dot{C}H\cdot OH + C_6H_5\cdot CO_2^- + Cu^{2+} \longrightarrow CH_3\cdot(CH_2)_2\cdot\underset{\displaystyle O_2C\cdot C_6H_5}{\underset{|}{C}}H\cdot OH + Cu^+ \qquad (169)$$



$$CH_3\cdot(CH_2)_2\cdot\underset{\displaystyle O_2C\cdot C_6H_5}{\underset{|}{C}}H\cdot OH \longrightarrow CH_3\cdot(CH_2)_2\cdot CHO + C_6H_5\cdot CO_2H \qquad (170)$$

followed by equations (165) and (166).

This latter route is not favoured, however, for it requires copious amounts of n-butanol.

It is probable that considerably more decarboxylation (154) occurred than the results indicate, and that the resultant n-butyl radicals (CCXXIV) were oxidized to but-1-ene by the following mechanism:

$$CH_3\cdot(CH_2)_2\cdot CH_2\cdot + Cu^{2+} \longrightarrow CH_3\cdot(CH_2)_2\cdot CH_2^{+} + Cu^{+} \qquad (156)$$

$$CH_3\cdot(CH_2)_2\cdot CH_2^{+} \longrightarrow CH_3\cdot CH_2\cdot CH{:}CH_2 + H^{+} \qquad (171)$$

De La Mare et al[28] have found that the oxidation of primary-alkyl radicals with cupric sulphate often leads to olefinic products. Although no attempt was made to isolate olefinic products from the n-butyl formate reaction, a related reaction performed in these laboratories[134] between n-pentyl formate (CCXXIX), t-butyl perbenzoate and cuprous ions yielded large quantities of pent-1-ene (LXIV) and pent-2-ene (CCXXX), the former isomer being the predominant product.

$H{\cdot}CO_2{\cdot}CHMe{\cdot}(CH_2)_2{\cdot}CH_3$ $CH_3{\cdot}CH_2{\cdot}CH{:}CH{\cdot}CH_3$

(CCXXIX) (CCXXX)

There was no evidence for the decarbonylation of the intermediate radical (CCXXXI) occurring, as in (155). However, decarboxylation (154) of this radical (CCXXXI) would probably be more favoured than that for the n-butyl carbonoyl radical (CCXX), since the resultant s-pentyl radical (CCXXXII) would be more stable than the n-butyl radical (CCXXIV), it being a secondary, and not a primary radical.

${\cdot}CO_2{\cdot}CHMe{\cdot}(CH_2)_2{\cdot}CH_3$ ${\cdot}CHMe{\cdot}(CH_2)_2{\cdot}CH_3$

(CCXXXI) (CCXXXII)

Also obtained from this reaction was s-pentyl benzoate (CCXXXIII) in low yield, presumably resulting from the combination of benzoate ions and s-pentyl carbonium ions (CCXXXIV).

$C_6H_5{\cdot}CO_2{\cdot}CHMe{\cdot}(CH_2)_2{\cdot}CH_3$ $\overset{+}{C}HMe{\cdot}(CH_2)_2{\cdot}CH_3$

(CCXXXIII) (CCXXXIV)

Another formate ester reaction performed in these laboratories[134] gave similar results. When t-butyl formate (CCXXXV) was treated with t-butyl perbenzoate and copper ions, there was considerable olefin-formation with the production of isobutylene (CCXXXVI).

$H \cdot CO_2 \cdot C \cdot (CH_3)_3$ (CCXXXV)

$CH_2 : C \cdot (CH_3)_2$ (CCXXXVI)

$CO_2 \cdot C \cdot (CH_3)_3$ (CCXXXVII)

Again, there was no indication of decarbonylation as in (155), decarboxylation of the intermediate-radical (CCXXXVII) had been the main route of decomposition. An interesting product, isolated in small yield, proved to be di-t-butyl carbonate (CCXXXVIII). This was probably formed by the route suggested for the formation of t-butyl-n-butyl carbonate (CCXIX) from n-butyl formate (CCXVII) (150-153) which, needless to say, was not found.

$$(CH_3)_3CO \cdot CO_2 \cdot C(CH_3)_3$$

(CCXXXVIII)

These formate-ester reactions, the reaction of formamide, and the earlier reactions with benzaldehyde and ethyl benzoate, all demonstrate the importance of the stability of transient-species in these oxidation-reactions. The results indicate that only stable-radicals will be readily oxidized, and then only those in which the unpaired-electron is not too delocalized by resonance. If the substrate-radical, which would result from hydrogen-abstraction by _t_-butoxy-radicals, was not stable, it would either be formed in very small quantities (as in the ethyl benzoate-reaction) or rapidly decompose into more stable radicals (as was shown in the formate ester reactions). It is clear, therefore, that substrates would not be greatly oxidized if the initial radicals were unstable.

The stability of the carbonium ion, resulting from the oxidation of the substrate-radical, has also been shown to be important in determining the ease by which a substrate-molecule will be oxidized. Oxidation would proceed more readily if the resultant-carbonium ion was more stable than the substrate-radical and, conversely, oxidation would be hindered if the carbonium-ion was less stable than the radical. As in the case of unstable radicals, unstable carbonium ions would rapidly decompose to attain stability. This was shown in the formamide reaction.

4. Catalysed Hydroperoxide Reactions

The acyloxylation of active-substrates, including olefins, by cuprous-catalysed perester-reactions have proved, in many cases, to have excellent synthetic application. The reaction conditions are mild, the reactants are inexpensive, the yield of products are often very good and the by-products are often gaseous or very volatile, which simplifies the isolation of products. The one big draw-back of these perester-reactions is the limitation on the nature of the acyloxy group. *t*-Butyl perbenzoate (X) and *t*-butyl peracetate (XI) are the only *t*-butyl peresters which are readily available commercially, and this, of course, limits the scope of these reactions to the formation of benzoyloxy- and acetoxy-derivatives.

This limitation can be overcome, however, by one of two methods.

(1) The decomposition of di-*t*-butyl peroxide (LIV) in the presence of a trace of copper salt, the substrate requiring to be acyloxylated and the free-acid containing the required anion. By this method the substrate-radical could be oxidized to a carbonium ion by cupric ions, and the interaction of this cation

with the anion of the acid would give the required ester. Obviously the nature of this ester could be dictated by the identity of the acid added. This type of reaction has not been seriously studied, and little is known about the reaction between the peroxide (LIV) and cuprous ions. From the results of Kharasch and Fono[71] and also the results of some experiments described in this thesis, it appears very likely that the role of cuprous ions is to reduce the peroxide as in (132). Although this reduction-step appears never to have been considered before, it does explain why:

(i) The decomposition of the di-t-butyl peroxide is greatly accelerated in the presence of copper ions.

(ii) Our observation of abnormally large quantities of t-butanol from these reactions.

(iii) The Kharasch and Fono[71] observation that the reaction between di-t-butyl peroxide and benzaldehyde in the presence of a trace of cuprous chloride gives a quantitative yield of t-butyl benzoate (CXV). We suggest this product possibly results from the combination of a t-butoxide ion with an acyl carbonium ion (172) or, more likely, the attack of t-butanol upon the acyl carbonium ion (173). The acyl-carbonium ion would be formed from benzaldehyde as shown in (85) and (135).

$$(CH_3)_3 \cdot CO^- + C_6H_5 \cdot \overset{+}{CO} \longrightarrow (CH_3)_3C \cdot O_2C \cdot C_6H_5 \qquad (172)$$

$$(CH_3)_3C \cdot OH + C_6H_5 \cdot \overset{+}{CO} \longrightarrow (CH_3)_3C \cdot O_2C \cdot C_6H_5 + H^+ \qquad (173)$$

(iv) The cuprous salt appears to act as a true-catalyst and, therefore, is not required in large amounts. This can only be explained if a reduction-reaction is occurring concurrent with the oxidation of the substrate-radical.

The use of olefins as substrates in these reactions was shown by us to give a mixture of isomeric products. Although the isomer with the terminal-double bond predominated, the reaction was less stereospecific than the corresponding perester reaction. This reaction between oct-1-ene, di-t-butyl peroxide, benzoic acid and cuprous ions has already been discussed.

(2) The decomposition of t-butyl hydroperoxide (LI) in the presence of a mixed-catalyst containing ferrous and cupric ions, the substrate requiring to be acyloxylated and a free-acid containing the required anion. The use of the ferrous ions to promote O-O fission of the hydroperoxide, the role of the cupric ions to oxidize the substrate-radical, and the subsequent conversion of the

two metal catalysts back to their original valency-states has been discussed at length in a preceding section.

Although the above two methods can both yield unlimited numbers of esters, the second type of reaction, viz. hydroperoxide reactions is preferred to the first type, viz. di-t-butyl peroxide reactions, due to the considerably milder reaction-conditions and shorter reaction-time. Thus the ferrous ion-catalysed decomposition of t-butyl hydroperoxide (LI) occurs smoothly at 70°, whereas a temperature in excess of 100° would be required for the di-t-butyl peroxide reaction. The hydroperoxide reactions have been extensively studied in this work.

It appears very likely that catalysed-hydroperoxide reactions with olefins, unlike the corresponding perester reactions, are not very stereospecific. During the cupric-ferrous ion-catalysed decomposition of t-butyl hydroperoxide (LI) in the presence of oct-1-ene and acetic acid, a mixture of isomeric acetoxyoctenes (CLXI and CCXXXIX) was obtained. As in the perester reactions, the isomer with the terminal-double bond was the principal product, but its predominance over the non-terminal double bonded isomer had been greatly reduced.

$CH_3{\cdot}(CH_2)_4{\cdot}CHOAc{\cdot}CH{:}CH_2$ (CLXI)

$CH_3{\cdot}(CH_2)_4{\cdot}CH{:}CH{\cdot}CH_2{\cdot}OAc$ (CCXXXIX)

When Walling et al[137] decomposed t-butyl hydroperoxide with cuprous chloride in the presence of β-methylstyrene (XXVIII) and acetic acid, they obtained almost equal quantities of the two isomeric acetoxy products (CCXL and CCXLI). This is in direct contrast to their and our results when this reaction was performed with t-butyl peresters; the isomer with the terminal-double bond was then the main product. These two workers[137] also obtained equal quantities of isomeric products when allylbenzene (XVIII) was the substrate. This again is in direct contrast with the results from perester reactions.

$C_6H_5{\cdot}CHOAc{\cdot}CH{:}CH_2$ (CCXL)

$C_6H_5{\cdot}CH{:}CH{\cdot}CH_2OAc$ (CCXLI)

The results of Kharasch et al[130] have shown, however, that oct-1-ene and t-butyl hydroperoxide react, in the presence of cuprous chloride, with benzoic acid to yield specifically 3-benzoyloxyoct-1-ene (XIII) and no isomeric 1-benzoyloxyoct-2-ene (XV). This result is based upon infrared data only, and it must therefore be treated with caution.

It is not clearly understood why these hydroperoxide reactions are less specific than their perester counterparts. When we apply our working hypothesis for the stereospecific acyloxylation of olefins (previously discussed), the situation is, admittedly, slightly different than in the corresponding perester reactions. In the case of peresters, the initial step was the reduction of the perester by a cuprous-olefin π-complex to yield a cupric carboxylate-allylic radical π-complex (CLXXV and CLXXVI); the corresponding reduction of a hydroperoxide would also yield a cupric-allylic radical π-complex, but there would be a reasonable chance that the anion associated with this cupric complex would not be a carboxylate anion but, in fact, a hydroxide anion (derived from the hydroperoxide as in (97)).

Admittedly, within a very short time, this hydroxide ion could be replaced by a carboxylate anion, the situation then being the same as for the perester reactions. In our experiment with oct-1-ene, however, the acetic acid was appreciably diluted in the starting material, and was certainly not present in excess. In such a situation it is possible that certain cupric-allyl radical π-complexes could fail to make contact with a carboxylate group before oxidation took place at the allylic position. Such an oxidation in the absence of a carboxylate group could not proceed by a ligand-transfer mechanism. The chances of an electron-transfer oxidation occurring would thus be enhanced and the resultant _free_-carbonium ion could lead to a mixture of isomeric products.

It is probable that, once the allylic radical-cupric complex (CLXXV and CLXXVI) was formed, there would be great driving-force for oxidation to proceed, since the cupric-complex could be converted to the more stable cuprous-complex. Therefore, the electron-transfer oxidation would occur very rapidly unless a carboxylate-group was readily available for a ligand-transfer mechanism to operate. The less-specific acyloxylation, in these hydroperoxide reactions, could thus be attributed to the dilution of the carboxylate anions in the starting material; a ligand-transfer acyloxylation being favoured by an excess of the carboxylic acid. The experimental results have shown that the double bond is still partially retained in the terminal-position of the olefinic products, indicating that the conventional ligand-transfer mechanism is still operating to a considerable extent.

In the preceding discussion there has been little mention of the role of ferrous ions in these reactions. However, this was adequately dealt with in a preceding section of this thesis. It was shown that ferrous ions were required to reduce the hydroperoxide (96) to yield alkoxy-radicals and hydroxide ions. The cupric ions were only required to oxidize the substrate-radicals to cations as in (93), or to acyloxy derivatives by a ligand-transfer mechanism, as in (42). It was also shown that the two metallic salts could be returned to their original valency-states by a mutual oxidation-reduction sequence (111). In the absence of ferrous ions it was considered likely that cupric ions would attack the hydroperoxide abnormally (98) to yield alkylperoxy radicals (CXLIX). This is essentially an oxidation-reaction where the cupric ion is reduced to cuprous.

This abnormal fission of the hydroperoxide is certainly undesirable, for it would cause a deficiency of cupric ions which are necessary for the oxidation of the substrate-radical. The presence of ferrous ions was therefore considered essential to preserve the cupric ions and to promote conventional O-O fission of the hydroperoxide.

It now appears likely, however, that, under certain circumstances, ferrous ions are not required. It is possible that, if the energy required to oxidize a transient-radical by a cupric ion is much lower than that required to oxidize the hydroperoxide and so cause abnormal fission (98), then ferrous ions are not required.

Substrates which form readily oxidizable-radicals could therefore be oxidized in these hydroperoxide reactions without the presence of ferrous ions. The cupric ion would preferentially oxidize the substrate radical than the hydroperoxide in such circumstances. The cuprous ions, resulting from this oxidation, could then reduce the hydroperoxide in the conventional manner as in (97), a process which was originally reserved for the ferrous ions. In this way the cupric ions could be regenerated.

Substrates which could be oxidized in this way would include olefins, aldehydes and ethers, all of which have shown, repeatedly, their susceptibility to oxidation during catalysed-perester reactions. This was clearly demonstrated when Kharasch and Fono[130] decomposed t-butyl hydroperoxide in the presence of cyclohexene and benzoic acid, using cuprous chloride as the only catalyst. They obtained cyclohexenyl benzoate (XII) in over 90% yield. Likewise, when phthalimide (CLVIII) was used as an acid instead of benzoic acid, N-cyclohexenyl phthalimide (CLIX) was obtained. The reaction using oct-1-ene and benzoic acid was reported by these workers[130] to give 3-benzoyloxyoct-1-ene (XIII) in a yield comparable to that from the related perester reactions; again no ferrous ions were present.

In all the hydroperoxide reactions carried out in this laboratory, it is unlikely that the ferrous salt, in this case ferrocene, was required, since most of the substrates were olefins and, therefore, very prone to oxidation. Indeed, it is doubtful that the ferrocene even took part in the reaction, for in every case it was recovered unchanged.

When De La Mare *et al*[28] decomposed certain cyclic hydroperoxides with ferrous ions, they found that the resultant primary alkyl-radicals could easily be oxidized by cupric sulphate. Our experience has also shown that alkyl-radicals are very prone to oxidation by cupric salts, as was shown in the several reactions involving formate esters, previously discussed. In view of this, and the preceding discussion, it is unlikely that the ferrous catalyst was needed in these reactions of De La Mare *et al*. Unfortunately they did not attempt any reactions using solely a copper-salt as the catalyst.

The situation is entirely reversed when the transient-radicals are not so prone to oxidation by cupric ions. If the ferrous ions were not used in these reactions, a considerable quantity of cupric ions would be reduced to cuprous ions during the abnormal cleavage of the hydroperoxide (98), and the substrate-radicals would be left without an oxidizing agent.

This was observed when Kharasch and Fono[130] decomposed *t*-butyl hydroperoxide in the presence of cumene (CXXXIII) and benzoic acid, using only cuprous chloride as the catalyst. In all attempts, these workers obtained mainly α-cumyl-*t*-butyl peroxide (CLIII). The expected product from the oxidation of α-cumyl radicals (CXLI) was α-cumyl benzoate (CXLIV). This product was obtained in 40% yield during the corresponding reaction of cumene (CXXXIII) with *t*-butyl perbenzoate and cuprous ions.[71] This expected product (CXLIV), from the hydroperoxide reaction, was only obtained in very poor yield, however.

It was mentioned in an earlier section of this thesis that radicals, such as cumyl radicals (CXLI), where the unpaired-electron was very delocalized, are not very prone to oxidation. The results of the above experiment between cumene, *t*-butyl hydroperoxide and copper ions, surely indicate, therefore, that the unreacted hydroperoxide molecules are competing very successfully for cupric ions at the expense of the α-cumyl radicals (CXLI). This was further emphasized when these workers[130] added extra copper-salt to the reaction mixture. They found that the yield of α-cumyl benzoate (CXLIV) decreased while that of the α-cumyl-*t*-butyl peroxide (CLIII) increased. This product could only have resulted by the following sceme:

$$(CH_3)_3CO{\cdot}OH + Cu^{+} \longrightarrow (CH_3)_3CO{\cdot} + OH^{-} + Cu^{2+} \qquad (174)$$

$$C_6H_5{\cdot}CHMe_2 + (CH_3)_3CO{\cdot} \longrightarrow C_6H_5{\cdot}\dot{C}Me_2 + (CH_3)_3C{\cdot}OH \qquad (175)$$

$$(CH_3)_3CO{\cdot}OH + Cu^{2+} \longrightarrow (CH_3)_3CO{\cdot}O{\cdot} + H^{+} + Cu^{2+} \qquad (176)$$

$$C_6H_5{\cdot}\dot{C}Me_2 + (CH_3)_3CO{\cdot}O{\cdot} \longrightarrow C_6H_5{\cdot}CMe_2{\cdot}O{\cdot}OC(CH_3)_3 \qquad (177)$$

(CLIII)

The previously discussed reactions of Walling and Zavitsas[137] involving β-methylstyrene (XXVIII) and allylbenzene (XVIII) with t-butyl hydroperoxide, acetic acid and cuprous chloride was accomplished without the use of ferrous salt. The yield of acetoxy products was poor, however, and these workers also mentioned the formation of many unidentified products. It was suggested, in an earlier section, that the allylic-radicals derived from β-methylstyrene (XXVIII) and allylbenzene (XVIII) by hydrogen abstraction would not be prone to extensive oxidation. It seems likely, therefore, that these reactions conducted by Walling et al[137] could have given improved yields of products if a catalytic amount of ferrous ion had been added to the reaction mixture.

The observation that ferrocene is possibly an unsuccessful catalyst in the reactions conducted in this laboratory, suggests that all the hydroperoxide reactions attempted by us were catalysed purely by copper ions. For reasons just explained, this did not affect the course of the olefin reactions. However the absence of ferrous ions undoubtedly influenced the reaction between diethyl malonate (CXXIV) and benzoic acid, for the radical derived from diethyl malonate

(CCXLII) by hydrogen-abstraction, is very unresponsive to oxidation by cupric ions. This, therefore, agrees with the results of this reaction where no diethyl O-benzoyl tartronate (CXXV; $R=C_6H_5\cdot CO_2$) was found. The reaction yielded a complex-mixture of coloured oils, most of which were too high boiling to be distilled even under very high vacuum.

$$\cdot CH\cdot (CO_2Et)$$

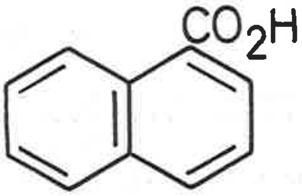
(CCXLII)

(b) SYNTHETIC STUDIES

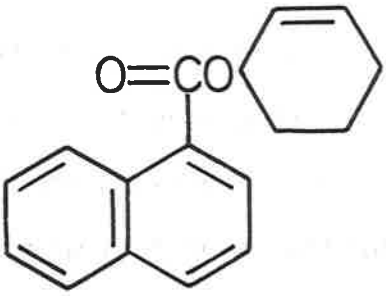
The use of the catalysed-perester reactions and also the catalysed-hydroperoxide reactions as a synthetic tool is extensive. It is obvious that the hydroperoxide-reactions are more important than the perester-reactions in this respect, for the acyloxylation of substrates is not limited to acetate and benzoate groups only, but can be extended to any acyloxy group depending upon the carboxylic acid used.

The experiments conducted in this laboratory have clearly demonstrated the versatility of these hydroperoxide-reactions. When t-butyl hydroperoxide was decomposed in the presence of cyclohexene, benzoic acid and catalyst, a good yield of 2-cyclohexen-1-yl benzoate (XII) was obtained. This yield of product was well less than that obtained by Kharasch and Fono.[130]

A repeat of the above experiment using 1-naphthoic acid (CCXLIII), instead of benzoic acid, gave a very good yield of cyclohex-2-en-1-yl 1-naphthoate (CCXLIV). This ester decomposed appreciably at its boiling point, 164°/0.35 m.m.



(CCXLIII)



(CCXLIV)

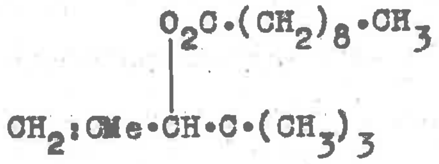
These reactions were not confined to simple substrates and simple acids. When *t*-butyl hydroperoxide was decomposed in the presence of di-isobutylene (CCXLV), decanoic acid (CCXLVI), and a catalyst, the ester products from this reaction comprised mainly of 2,2,4-trimethylpent-4-ene-2-yl decanoate (CCXLVII).

$[(CH_3)_2\cdot C{:}CH\cdot C\cdot (CH_3)_3 \qquad CH_2{:}CMe\cdot CH_2\cdot C\cdot (CH_3)_3]$

(CCXLV)

$CH_3\cdot (CH_2)_8\cdot CO_2H$

(CCXLVI)



$$\begin{array}{l} \quad\quad\quad\quad\;\; O_2C\cdot (CH_2)_8\cdot CH_3 \\ \quad\quad\quad\quad\;\; | \\ CH_2{:}CMe\cdot CH\cdot C\cdot (CH_3)_3 \end{array}$$

(CCXLVII)

Even though the analysis of this product (CCXLVII) was correct, there must be some doubt as to its purity, because it could only be partially hydrogenated, indicating that it may, in fact, be a mixture of isomers. Further, when the "hydrogenated" ester was hydrolysed and the resultant alcohols were oxidized there was obtained 2,4,4-trimethylpentanoic acid (CCXLVIII) and 2,2,4-trimethylpentan-3-one (CCXLIX). Therefore, it appears that the product (CCXLVII) of the reaction contained small amounts of 2,2,4-trimethylpent-2-ene-1-yl decanoate (CCL). This is understandable in view of the previous observations that these hydroperoxide reactions are less stereospecific than the corresponding perester-reactions. It must be remembered, too, that the starting material, diisobutylene (CCXLV), is essentially a mixture of 2,2,4-trimethylpent-3-ene and 2,2,4-trimethylpent-4-ene as shown in (CCXLV). Indeed G.L.C. analysis showed the presence of small quantity of a third isomer.

$(CH_3)_3\cdot C\cdot CH_2\cdot CHMe\cdot CO_2H$

(CCXLVIII)

$(CH_3)_3\cdot C\cdot CO\cdot CH\cdot (CH_3)_2$

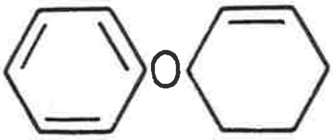
(CCXLIX)

$CH_3\cdot (CH_2)_8\cdot CO_2\cdot CH_2\cdot CMe{:}CH\cdot C(CH_3)_3$

(CCL)

This di-isobutylene reaction gave a mixture of isomeric decanoates, but, nevertheless, it does demonstrate the remarkable scope and synthetic utility of these hydroperoxide reactions. Indeed, it seems likely that any carboxylic acid could be used successfully in these reactions as long as the substrate-molecule, requiring to be oxidized, had a hydrogen-atom which was prone to abstraction, and that the resultant free-radical had an unpaired-electron which was available for removal by an oxidizing agent.

There appears to be no reason why the acids used in these reactions cannot be extended to include dicarboxylic acids, sulphonic acids or even compounds with acidic hydrogen atoms such as imides or phenols. However, an attempt in this laboratory to prepare cyclohex-2-en-1-yl phenyl ether (CCLI) from cyclohexene and phenol, by this method, failed. Only polymeric material was obtained.



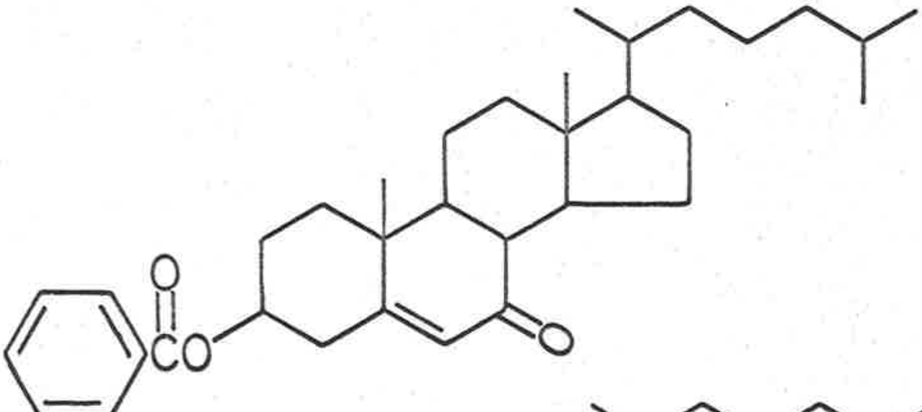
(CCLI)

Although these hydroperoxide reactions can be very successfully applied to the acyloxylation of various substrates in one single step, it does appear that their usefulness is limited in the acyloxylation of olefins. Unlike the perester-olefin reactions, these hydroperoxide-reactions give a mixture of isomeric products which, for most synthetic purposes, is undesirable. In the olefin acyloxylations, therefore, the reactions of the peresters would be of more synthetic importance, and it has been shown on many occasions that very good yields of 3-acyloxyalk-1-enes can be obtained in a one-step synthesis direct from the parent-alkene. It is unfortunate that the acyloxy groups are limited to acetate and benzoate groups only.

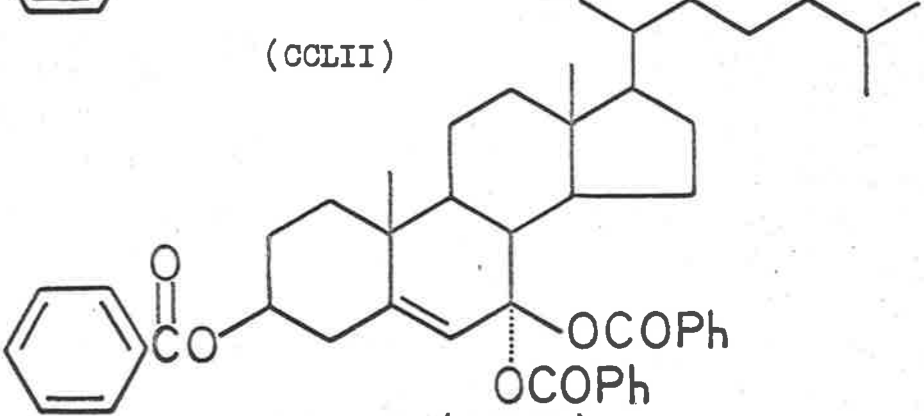
As was shown earlier, the acyloxylation of cholestenes and their derivatives can be very successfully accomplished with peresters and copper salts. Thus, when *t*-butyl perbenzoate was catalytically decomposed in the presence of cholesteryl benzoate (CLXII), a 40% yield cholest-5-en-3β,7β-dibenzoate (CLXVI) and its 7α-epimer (CLXVII) was obtained. During chromatography of these products, the 7-position was hydrolysed to give the 7-hydroxy derivatives (CLXIII and CLXIV). The success of these catalysed perester-olefin reactions in the steroid field could be of significant value to synthetic problems. As was shown in the case of 3-benzoyloxycholest-2-ene (CLXXVIII) and 3-ethoxycholest-2-ene (CLXXXI), however, the double bond does migrate within the steroid nucleus under certain circumstances. The production of equal quantities of the 7β and 7α derivatives, in the cholesteryl benzoate reaction, is unique, and can only be explained if the cuprous ion complex with the π-electrons of the double bond took place above and below the plane of the ring in equal amounts.

We attempted to repeat the above experiment of cholesteryl benzoate with *t*-butyl hydroperoxide, benzoic acid and a catalyst, in the hope that the less stereospecific nature of olefin reactions with *t*-butyl hydroperoxide was not extended into the steroid field. It appears, however, that the reactions with steroids are also less specific. The only product identified from this reaction proved to be 7-ketocholesteryl benzoate (CCLII) in poor yield. This product probably resulted from the decomposition of 7,7-dibenzoyloxycholesteryl benzoate (CCLIII); it is not unexpected that an allylic-position could be disubstituted in these reactions. All the other products of this reaction were coloured oils, but were, nevertheless, benzoate esters, as shown by infrared absorption. Repeated chromatography failed to purify these compounds. It is not inconceivable that a mixture of 6α, 6β, 7α, 7β benzoyloxy derivatives had been formed, due to the isomerization of the double bond. Clear cut separation of these products by chromatography would be very difficult.

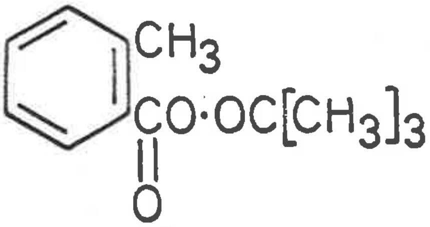
During the study of the synthetic applications of these copper-ion catalysed peroxy reactions, an attempt was made to prepare phthalide (CCLIV) from _t_-butyl per-_o_-toluate (CCLV) by intramolecular-acyloxylation. When _t_-butyl per-_o_-toluate was decomposed at 80° in benzene using cuprous chloride as a catalyst, no phthalide was obtained. The two products isolated were methyl _o_-toluate (CCLVI) in 29% yield, and the dimethyl ester of 1,2-di-(2-carboxyphenyl)-ethane (CCLVII) in 3% yield.



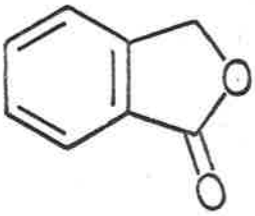
(CCLII)



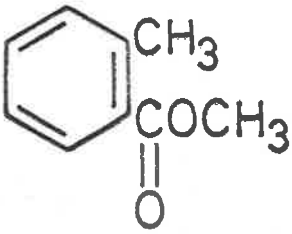
(CCLIII)



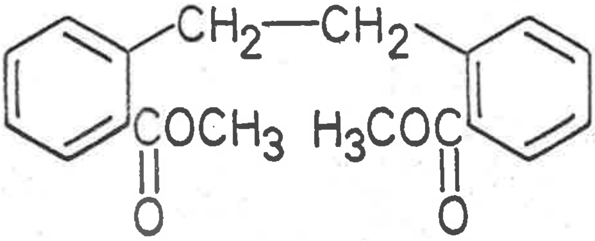
(CCLV)



(CCLIV)

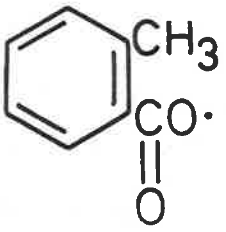


(CCLVI)

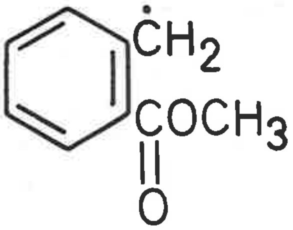


(CCLVII)

Apparently the former product (CCLVI) had resulted from the combination of methyl-radicals (formed by the decomposition of t-butoxy-radicals as in (36)) with 2-methylbenzoyloxy-radicals (CCLVIII) (from the decomposition of the perester (CCLV)). The abstraction of a benzylic-hydrogen atom from the methyl-o-toluate by a t-butoxy-radical would give the radical (CCLIX), the dimerization of which would yield the other product of this reaction (CCLVII).



(CCLVIII)



(CCLIX)

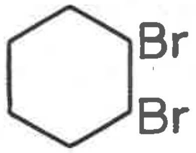
It seemed obvious that the temperature of this reaction had been too high, and thus many of the t-butoxy radicals had decomposed into acetone and methyl radicals (36). This reaction was therefore repeated at a much lower temperature and, as expected, the products (CCLVI and CCLVII) were not obtained. Instead, a small yield of the desired product, phthalide (CCLIV), was isolated, indicating that a limited amount of intramolecular acyloxylation had occurred.

The poor yield of this product (CCLIV) is not unexpected, however, in view of our earlier observations that benzylic-type radicals are not readily oxidized under these reaction conditions. There also appears to be no synthetic use for this type of reaction since the preparation of the starting perester is a lengthy process.

It is well known[169-173] that cupric halides readily halogenate substrate-molecules. The thermal decomposition of cupric bromide has been shown[174] to yield cuprous bromide and bromine atoms

$$CuBr_2 \longrightarrow CuBr + Br\cdot \qquad (178)$$

It was therefore considered possible that the decomposition of cupric bromide in the presence of olefins could yield allylic bromides. This did not materialize, however. When a mixture of cyclohexene and anhydrous cupric bromide was heated at 80° for 30 hours, the only product isolated was 1,2-dibromocyclohexane (CCLX). Hydrogen bromide was evolved during the reaction.



(CCLX)

When this reaction was repeated using oct-2-ene (CLXXIV) as an olefin, three products were identified. They were shown to be octan-2-one (CCLXI), 2-bromo-octane (CCLXII) and 2,3-dibromo-octane (CCLXIII). No unsaturated products were found and, again, hydrogen bromide was evolved. The bromo-products could be formed by the addition of bromine-radicals and also hydrogen bromide to the double bond. The octan-2-one must have been formed during work-up by the autoxidation of a reaction product.

$CH_3\cdot(CH_2)_4\cdot SH_2\cdot CO\cdot CH_3$

(CCLXI)

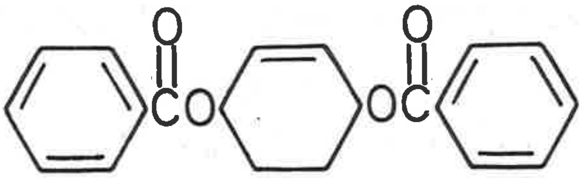
$CH_3\cdot(CH_2)_4\cdot CH_2\cdot CHBr\cdot CH_3$

(CCLXII)

$CH_3\cdot(CH_2)_4\cdot CHBr\cdot CHBr\cdot CH_3$

(CCLXIII)

An interesting by-product from the reaction between cyclohexene, iso-octane, *t*-butyl perbenzoate and cuprous ions has proved to be *cis*-cyclohex-2-en-1,4-diol dibenzoate (CCLXIV). Although obtained in small quantities, the yield of this compound could have been improved if 1 mole equivalent of perester had been used. Whereas the synthesis of this product was accomplished in one-step from the parent olefin, its synthesis by any other method would indeed be difficult and involve several steps.



(CCLXIV)

EXPERIMENTAL

(a) GENERAL

Analyses were performed by the Australian Microanalytical Service, Melbourne. Infrared absorption spectra were determined with a Perkin-Elmer Infracord, model 137. Ultraviolet absorption spectra were determined with an Optica CF4 spectrophotometer. Vapour-phase chromatography was carried out using a Griffin and George vapour-phase chromatographic apparatus; the columns used were dependent upon the type of compound being separated. Columns, packed with "Celite" (40-80 mesh B.S.S.) bearing a stationary phase of "Apiezon L" or "Silicone 30" (1:4 w/w) were the most used.

Paper chromatography of mono-carboxylic acids was carried out on Whatman No. 1 paper by descending chromatography using the system 1.5N ammonia-butanol (1:1) as described by Reid and Lederer.[175] Bromocresol purple was used for the detection of the spots. Unless stated to the contrary, the identity of the acid-products from all the forthcoming reactions and hydrolyses were confirmed by comparison with authentic specimens, using paper-chromatography.

Two types of alumina were used for adsorption chromatography. Type A: Spence-alumina (type U.G.1) was washed in dilute hydrochloric acid and then thoroughly with distilled water. It was then dried at 180° for 24 hours and, if necessary, deactivated with distilled water (up to 8% w/w). Type B: B.D.H. chromatographic-alumina was continuously stirred in pure ethyl acetate for four days and then thoroughly washed with copious amounts of hot distilled-water. It was then dried at 110° for 48 hours and, if necessary, deactivated with distilled water (2% w/w).

All melting points were determined in capillaries and are uncorrected. Wherever possible, the identity of all crystalline reaction products was confirmed by the melting points and mixed melting points with authentic specimens.

Unless otherwise stated, the identity of all reaction products was confirmed by comparing the infrared absorption spectra with those of authentic compounds.

W-7 Raney nickel was prepared by the method described by Billica and Adkins.[176] The catalyst was stored under absolute ethanol at 5°.

Hydrogenations which were conducted above 1 atmosphere, were carried out in the Parr Hydrogenation Apparatus, model B-3C; and also the Baskerville and Lindsay Hydrogenation Apparatus.

(b) PREPARATION OF STARTING MATERIALS

Prior to use, all starting materials, whether synthesised or available commercially, were either distilled or fractionated to constant boiling-point or recrystallized to constant melting-point. The following compounds, which were used as starting materials, were available commercially.

Toluene, b.p. 110°.

Di-t-butyl peroxide, not purified.

Benzoyl peroxide, m.p. 106° (decomp.), purified by the method of Vogel.[177]

Oct-1-ene, b.p. 122°, n_D^{22} 1.4076 (Lit.,[178] b.p. 121.3°, n_D^{20} 1.4088).

t-Butyl perbenzoate, b.p. 87°/0.85 mm., $n_D^{25.5}$ 1.4984 (Lit.,[52] b.p. 75-77°/2 mm., n_D^{20} 1.5007).

Cyclohexene, b.p. 83°.

Cyclohexane, b.p. 81°.

2,2,4-Trimethylpentane, b.p. 99-100° (*Lit.*,[179] b.p. 99.3°)

Cyclohexanone, b.p. 154°.

Oct-2-ene, b.p. 124°, n_D^{22} 1.4128 (*Lit.*,[180] b.p. 125°, n_D^{20} 1.4146).

Diethyl malonate, b.p. 94°/18 mm., n_D^{18} 1.4144 (*Lit.*,[181] b.p. 88°/13 mm.).

t-Butyl hydroperoxide, not purified but dried over $MgSO_4$.

Benzaldehyde, b.p. 67-68°/15 mm.

Formamide, b.p.112°/18 mm., n_D^{22} 1.4473 (*Lit.*,[182] b.p. 105-106°/11 mm.).

n-Butyl formate, b.p. 106-107° (*Lit.*,[183] b.p. 106.5°).

1-Naphthoic acid, m.p. 160-161°, R_F 0.65.

Di-isobutylene, b.p. 102-103°.

n-Decanoic acid, m.p. 30-31°, R_F 0.82.

Phenol, b.p. 85°/22 mm.

Ferrocene, m.p. 171.5-172.5 (*Lit.*,[184] m.p. 172.5-173°).

The following compounds were prepared as required:

Cuprous chloride was prepared by bubbling sulphur dioxide into an aqueous solution of equi-molar quantities of cupric sulphate and sodium chloride. The resultant precipitate of white cuprous chloride was filtered by suction and quickly washed with dilute sulphurous acid. The cuprous salt was washed further with glacial acetic acid, ethanol and finally ether. It was then dried at 80° for ½ hour and stored in a desiccator under vacuum.

Cupric bromide was prepared according to Watt *et al*[185] using cupric acetate and an excess of acetyl bromide. The cupric bromide was obtained as a black amorphous powder, and was stored under vacuum in a desiccator.

Cupric benzoate was prepared by the method of Ephraim and Pfister[186] from cupric sulphate and sodium benzoate in aqueous-solution. When anhydrous cupric benzoate was required, the hydrated compound was suspended in an excess of pure toluene and the toluene-water azeotrope was slowly distilled. The mixture was stirred continuously throughout.

3-Phenylprop-1-ene was prepared from phenylmagnesium bromide and allyl bromide in 75% yield by the method of Hershberg.[187] Immediately before use it was fractionated through a 20 cm. column packed with glass helices, b.p. 156-157°, n_D^{24} 1.5102 (*Lit.*,[188] b.p. 156-157°), ν *max*.(film) 1680 cm.$^{-1}$, 870 cm.$^{-1}$ A previous attempt to prepare allylbenzene by a Friedel Crafts reaction between benzene, allyl alcohol and aluminium chloride was unsuccessful. An unidentified liquid (b.p. 130-

140°/0.85 mm.) was obtained. Infrared examination showed it to contain no olefinic double bond and a sodium fusion test indicated the presence of chlorine.

Cholest-5-en-3-yl benzoate. Cholesterol (13.0 g., 0.03 mole) was dissolved in pyridine (13 ml.) and benzoyl chloride (7.8 g., 0.05 mole) was added dropwise with shaking. After the addition, the mixture was warmed at 80° for ½ hr. and then water was added dropwise to destroy the unreacted benzoyl chloride. The mixture was then added to a large excess of water and filtered. Cholesteryl benzoate (13.3 g., 80%) crystallized from ethanol-benzene (1:1 V/V) in plates, m.p. 146-148° (lit.,[189] m.p. 146.6°), ν max. (Nujol) 1715 cm.$^{-1}$, 1275 cm.$^{-1}$, 1115 cm.$^{-1}$, and 720 cm.$^{-1}$).

1-Phenylpropan-1-ol. Ethylmagnesium bromide was prepared from dry magnesium turnings (17.5 g., 0.72 mole) and ethyl bromide (75 g., 0.70 mole) in anhydrous ether (240 ml.) by the conventional method. Benzaldehyde (100 g., 0.94 mole), which had been washed in 20% aqueous sodium carbonate, dried and distilled under nitrogen; and anhydrous ether (100 ml.) was then added dropwise to the etherial solution of the Grignard reagent so as to promote gentle refluxing. The flask was cooled in ice during this addition. After the addition, the mixture was heated on a water-bath for 1 hour. The reaction mixture was then poured, with rapid stirring, into a 1-litre beaker containing crushed ice (400 g.) and a solution of ammonium chloride (100 g.) in water (200 ml.)

The ether layer was separated and dried with anhydrous potassium carbonate. The ether was then evaporated to yield crude 1-phenylpropan-1-ol (80 g., 85%). Fractionation in vacuo gave the pure compound, b.p. 108-110°/16 mm., n_D^{22} 1.5182 (lit.,[190] b.p. 103°/14 mm., n_D^{20} 1.5257), $\nu_{max.}$ (film) 3450 cm.$^{-1}$, 1045 cm.$^{-1}$, 1015 cm.$^{-1}$, and 980 cm.$^{-1}$.

1-Phenylprop-1-ene was prepared from 1-phenylpropan-1-ol by dehydration with tetra-n-propyl pyrophosphate. This dehydrating agent was prepared from phosphorous pentoxide and n-butanol as described by Mukaijama and Hata.[191] 1-Phenylpropan-1-ol (66 g., 0.45 mole) was added to tetra-n-propyl pyrophosphate (100 g., 0.30 mole) and the mixture was heated at 90° with constant stirring for 3 hours. When cool, the mixture was shaken with ether (200 ml.). The ether layer was then dried and the ether was evaporated to yield crude 1-phenylprop-1-ene. The crude product was fractionated twice through a 20 cm.

column packed with glass helices to give pure 1-phenylprop-1-ene (29.0 g., 50%), b.p. 84°/27 mm. (lit.,[192] b.p. 74°/13 mm.), n_D^{20} 1.5485 (lit.,[193] n_D^{20} 1.5492), γ max. (film) 1650 cm.$^{-1}$, 965 cm.$^{-1}$, 735 cm.$^{-1}$, and 695 cm.$^{-1}$.

Cholestan-3β-ol was prepared by hydrogenation of cholesterol at 200 atmospheres with W-7 Raney nickel at 90°. Ethanol was used as a solvent and the yield was almost quantitative. Cholestan-3β-ol crystallized from ethanol in white plates, m.p. 142-143°, $[\alpha]_D^{25}$ + 22° (chloroform) (lit.,[194] m.p. 142°, $[\alpha]_D^{25}$ + 23°).

Cholestan-3-one was prepared from cholestan-3β-ol in 80% yield using chromic acid as the oxidizing agent. The procedure was the same as that described by Bruce.[195] Cholestan-3-one crystallized from methanol as needles m.p. 129-129.5°, $[\alpha]_D^{20}$ + 42° (chloroform) (lit.,[196] m.p. 128.8-129.8°, $[\alpha]_D$ + 42.7°), γ max. (nujol) 1725 cm.$^{-1}$.

Cholest-2-en-3-yl benzoate was prepared from cholestan-3-one in 64% yield by the action of benzoyl chloride. The conditions were identical to those described by Ruzicka and Fischer.[197] Cholest-2-en-3-yl benzoate was obtained as colourless-needles from acetone m.p. 127-128° (lit.,[197] m.p. 127-128°) (Found: C, 82.98;

H, 10.22. Calc. for $C_{34}H_{50}O_2$: C, 83.21; H, 10.27%), $[\alpha]_D^{20}$ + 49° (chloroform), max. (chloroform) 1725 cm.$^{-1}$, 1275 cm.$^{-1}$, and 1125 cm.$^{-1}$.

3,3-Diethoxycholestane was prepared from cholest-3-one and ethyl orthoformate in 75% yield by the procedure described by Serini and Koster.[198] 3,3-Diethoxycholestane crystallized from pyridine-ethanol as colourless crystals m.p. 66-68° (*lit.*,[198] m.p. 68-69.5°).

3-Ethoxycholest-2-ene was prepared in 70% yield from 3,3-diethoxycholestane by the action of boiling xylene, as described by Serini and Koster.[198] 3-Ethoxycholest-2-ene was obtained as colourless crystals from pyridine-ethanol m.p. 86-87° (*lit.*,[198] m.p. 87-88°), ν max. (chloroform) 1670 cm.$^{-1}$, 1470 cm.$^{-1}$, 1445 cm.$^{-1}$, 1375 cm.$^{-1}$, 1180 cm.$^{-1}$, and 1120 cm.$^{-1}$. The intense band at 1670 cm.$^{-1}$ agrees with the report of Rosenkrantz and Gut[151] that the presence of an (-O-C=CH-) group enhances the intensity of the C=C stretching frequency.

1,1-Diethoxycyclohexane. A mixture of cyclohexanone (98 g., 1 mole) and ethyl orthoformate, b.p. 146° (140 g., 0.95 mole), in absolute ethanol (250 ml.), was cautiously heated under reflux to 75°. A trace of hydrochloric acid was used as a catalyst. The reaction-mixture was maintained at 75° for 4 hours. When cooled, the mixture was added to an excess of distilled water, and the organic layer was separated and dried. Distillation __in vacuo__ yielded the crude 1,1-diethoxycyclohexane, which was then fractionated through a 20 cm. column packed with glass helices to yield the pure compound (37 g., 23%), b.p. 84-87°/22 mm., n_D^{20} 1.4372 (__lit.__,[199] b.p. 75-76°/13 mm., $n_D^{17.5}$ 1.4452), ν __max.__ (film) 1160 $cm.^{-1}$, 1120 $cm.^{-1}$, 1090 $cm.^{-1}$, 1060 $cm.^{-1}$, and 965 $cm.^{-1}$.

__1-Ethoxycyclohex-1-ene.__ 1,1-Diethoxycyclohexane (37 g., 0.20 mole) was mixed with redistilled quinoline (2 g.) and __p__-toluenesulphonic acid (0.5 g.). The mixture was refluxed for ½ hour and then very slowly distilled. The crude 1-ethoxycyclohex-1-ene was fractionated to give the pure product (21.5 g., 84%), b.p. 160° (__lit.__,[200] b.p. 74-76°/14 mm.), ν __max.__ (film) 1670 $cm.^{-1}$, 1370 $cm.^{-1}$, 1190 $cm.^{-1}$, 1115 $cm.^{-1}$, 1090 $cm.^{-1}$, 1060 $cm.^{-1}$, 965 $cm.^{-1}$, and 780 $cm.^{-1}$.

__Hept-1-yne__ (c.f. Vogel[201]). Sodamide was prepared from sodium and liquid-ammonia in the usual manner. Acetylene was then slowly bubbled into the sodamide-liquid ammonia mixture during 3 hours, while the temperature was maintained at -35°. The reaction mixture was continuously stirred throughout. After 3 hours the black solution was cooled to -50° and redistilled n-pentyl bromide (152 g., 1 mole) was then added dropwise (1.5 hr.) with constant stirring. During this addition acetylene was slowly bubbled into the solution.

When the addition of n-pentyl bromide was complete, the acetylene supply was discontinued and the reaction mixture was stirred at -35° for a further 15 hours. Ammonium chloride (12 g.) was then cautiously added and the liquid-ammonia was evaporated. Crushed ice (100 g.), and distilled water (400 ml.), were then added and the mixture was steam-distilled. The crude hept-1-yne was separated from the water, dried, and fractionated through a 20 cm. column packed with glass helices. Pure hept-1-yne (46 g., 48%) had b.p. 99-100°, n_D^{22} 1.4076 (lit.,[188] b.p. 99.8°, n_D^{20} 1.4088); ν max. (film) 3300 cm.$^{-1}$, 2920 cm.$^{-1}$, 2100 cm.$^{-1}$ and 1450 cm.$^{-1}$.

α,α'-Hydrazobisisobutyronitrile was prepared from hydrazine sulphate, potassium cyanide and acetone, as described by Thiele and Heuser.[202] The compound crystallized from ether m.p. 92-93° (*lit.*,[202] m.p. 92-93°).

α, α'-Azobisisobutyronitrile was prepared from α,α'-hydrazobisisobutyronitrile in 95% yield by the action of bromine, as described by Bickle and Waters.[203] The compound was crystallized from ethyl acetate below 50°, m.p. 102-103° (*lit.*,[203] m.p. 102°).

1,1,3-Triphenylpropan-1-ol was prepared by a Grignard reaction between ethyl 2-phenylpropionate and bromobenzene. The tertiary alcohol was not isolated, but was dehydrated *in situ* with 40% sulphuric acid to yield *1,1,3-triphenylprop-1-ene* b.p. 170-172°/0.3 mm. (*lit.*,[204] b.p. 222°/10 mm.), ν *max*. (film) 1600 cm.$^{-1}$, 1070 cm.$^{-1}$, 1030 cm.$^{-1}$, 760 cm.$^{-1}$, and 695 cm.$^{-1}$.

o-Toluoyl chloride. (c.f. Davies and Perkin[205]). *o*-Toluic acid (50 g., 0.37 mole), and thionyl chloride (60 g., 0.50 mole), were heated under reflux for 2 hours. Fractionation *in vacuo* of the crude reaction mixture yielded *o*-toluoyl chloride (48 g., 90%), b.p. 94°/10 mm. n_D^{18} 1.5570 (lit.,[205] b.p. 213°/760 mm.) .

t-Butyl per-o-toluate was prepared in 67% yield from *o*-toluoyl chloride and *t*-butyl hydroperoxide under identical conditions to those used by Blomquist *et al*[55] for the preparation of related peresters. t-Butyl per-o-toluate, when purified by vacuum-distillation under nitrogen, had b.p. 83°/0.45 mm., n_D^{18} 1.5032, ν max. (film) 1760 cm.$^{-1}$, 1230 cm.$^{-1}$, 1185 cm.$^{-1}$, 1040 cm.$^{-1}$, 1025 cm.$^{-1}$, and 735 cm.$^{-1}$. A correct analysis was not obtained. (Found: C, 68.07; H, 7.76. $C_{12}H_{16}O_3$ requires: C, 69.21; H, 7.74%).

(c) PREPARATION OF REFERENCE COMPOUNDS

All reference compounds were purified by distillation, fractionation or recrystallization before use. The following, which were used as reference compounds, were available commercially.

Bibenzyl, m.p. 52° (crystals from ethanol).
Benzoic acid, m.p. 121-122°, R_F 0.42.
Benzyl alcohol, b.p. 205°.
Octanoic acid, (not purified), R_F 0.75.
n-Propylbenzene, b.p. 66-68°/15 mm.
t-Butanol, b.p. 82-83°.
Cyclohexanol, b.p. 161°.
Cyclohexanone, b.p. 154-155°.
Phenyl ethyl ether, b.p. 169-170° (lit.,[206] b.p. 169.9°).
Tetramethylsuccinonitrile, m.p. 169°.

Benzoic anhydride, m.p. 41-42° (lathes from benzene-light petroleum)(lit.,[207] m.p. 42°).

n-Butyl benzoate, b.p. 100°/0.85 mm.

t-Butyl benzoate, b.p. 58°/0.2 mm., n_D^{18} 1.4933 (lit.,[168] b.p. 58-60°/0.2 mm., n_D^{25} 1.4890).

1-Naphthoic acid, m.p. 160-161°. R_F 0.65.

n-Decanoic acid, m.p. 30-31°. R_F 0.82.

o-Toluic acid, m.p. 107-108°. R_F 0.49.

Phthalan-1-one, m.p. 73-74° (plates from water) (lit.,[208] m.p. 72-73°).

Butyric acid, (not purified), R_F 0.32.

The following reference compounds were prepared:

Benzyl benzoate was prepared by heating a mixture of benzoic acid (30 g., 0.25 mole), benzyl alcohol (108 g., 1 mole), and concentrated sulphuric acid (1 ml.) at 120° for 6 hours. The crude benzyl benzoate was fractionated to yield the pure compound (32 g., 60%), b.p. 96°/0.2 mm., n_D^{21} 1.5686, ν max. (film) 1715 cm.$^{-1}$, 1275 cm.$^{-1}$, 1110 cm.$^{-1}$, and 715 cm.$^{-1}$.

Benzyl acetate was prepared from acetic acid (15 g., 0.25 mole), and benzyl alcohol (108 g., 1 mole), by the same method as above. The product (13.1 g., 35%)

was fractionated in vacuo b.p. 112/22 mm., n_D^{20} 1.5246, ν max. (film) 1740 cm.$^{-1}$, 1390 cm.$^{-1}$, 1375 cm.$^{-1}$, 1230 cm.$^{-1}$, 1025 cm.$^{-1}$, 750 cm.$^{-1}$, and 695 cm.$^{-1}$.

Octan-3-ol was prepared from pentylmagnesium bromide and propionaldehyde by a similar method to that described by Naves.[209] When purified by distillation in vacuo, it had b.p. 75°/18 mm., n_D^{20} 1.4270 (lit.,[209] b.p. 53-54°/2.4 mm., n_D^{20} 1.4273).

Octan-3-one. Octan-3-ol was dissolved in excess pure acetone, and a solution of chromium trioxide (12 g.) dissolved in 50% sulphuric acid (35 ml.) was added dropwise with cooling. When the oxidation was complete (red colour), the products were extracted with ether. The ether extract was shaken with 20% aqueous sodium carbonate, washed with distilled water, and then dried. The ether was evaporated to yield octan-3-one b.p. 74°/25 mm., n_D^{25} 1.4160 (lit.,[210] b.p. 76-77°/30 mm., n_D^{20} 1.4153), 2,4-dinitrophenylhydrazone (needles from methanol) m.p. 62-63°.

1-Phenylpropan-1-ol. The preparation of this compound was described in the preceding section.

Ethyl phenyl ketone was prepared from 1-phenylpropan-1-ol by chromic acid oxidation. The conditions were identical to those previously described for the oxidation of octan-3-ol. Ethyl phenyl ketone was obtained as a sweet smelling liquid b.p. 100°/18 mm., 2,4-ditrophenylhydrazone m.p. 191-192° (lit.,[211] m.p. 193-194°).

2-Phenylpropionic acid. Cinnamyl alcohol was dissolved in excess ethanol and hydrogenated at 100 atmospheres at room temperature with W-7 Raney nickel. The catalyst was removed and the ethanol evaporated to yield crude 3-phenylpropan-1-ol. This alcohol was not purified, but was oxidized with chromic acid by an identical procedure to that described above for the oxidation of octan-3-ol. The ether solution of the oxidation product was shaken with 20% aqueous-sodium carbonate. The aqueous layer was then acidified with dilute sulphuric acid and extracted with ether. The ether solution was dried and the ether was evaporated to yield 2-phenylpropionic acid, which crystallized from petroleum ether m.p. 47-48°, R_F 0.56.

Cholest-5-en-7-one-3-yl benzoate. Cholesteryl benzoate (10 g., 0.02 mole) was dissolved in a minimum of benzene. An excess of glacial acetic acid was then added and, during constant stirring, aqueous sodium dichromate (6 g.) was added at such a rate that the temperature did not rise above 65°. After the addition, the temperature was maintained at 65° for an additional 2 hours. When cooled, the mixture was added to a large excess of cold distilled-water with rapid stirring. The benzene layer was then removed and washed with 20% aqueous sodium carbonate. It was then dried, and the benzene was evaporated to leave crude cholest-5-en-7-one-3-yl benzoate (4.1 g., 40%). The steroid was crystallized from ethanol to give colourless needles m.p. 159-161°, $[\alpha]_D^{20}$ -52° (chloroform) (*lit.*,[212] m.p. 159°, $[\alpha]_D$ -54°), ν *max.* (chloroform) 1720 cm.$^{-1}$, 1675 cm.$^{-1}$, 1280 cm.$^{-1}$, and 1120 cm.$^{-1}$.

Cholest-5-en-3 .7 -diol 3-benzoate and cholest-5-en-3 .7 -diol 3-benzoate were prepared by the reduction of cholest-5-en-7-one-3-yl benzoate with sodium borohydride as follows. The ketonic ester was dissolved in toluene and one mole-equivalent of sodium borohydride was added slowly. Methanol was then added until the solution became clear. After standing at 0° for two days, dilute acetic acid was added dropwise to destroy the sodium-borohydride complex. The solvents were then removed *in vacuo* and the residue was thoroughly washed with distilled water and dried in a desiccator over sodium hydroxide pellets. This residue was then chromatographed on acid-washed alumina to yield cholest-5-en-3β,7β-diol 3-benzoate in 40% yield, m.p. 192-193° (needles from ethanol), $[\alpha]_D^{20}$ + 13° (lit.,[213] m.p. 192°, $[\alpha]_D^{21}$ + 13.8°). A trace amount of cholest-5-en-3β,7α-diol 3 benzoate was also obtained from the chromatography m.p. 173-174°, $[\alpha]_D^{20}$ - 49° (lit.,[214*] m.p. 165-167°, $[\alpha]_D^{21}$ - 50°).

Dihydroresorcinol was prepared in 85% yield by the catalytic-reduction of resorcinol with W-7 Raney nickel in alkaline solution, according to the procedure described by Thompson.[216] Dihydroresorcinol, when crystallized from benzene, had m.p. 104-105° (lit.,[216] m.p. 103-104°), ν max. (nujol) 2900 cm.$^{-1}$, 1270 cm.$^{-1}$, 1225 cm.$^{-1}$, 1190 cm.$^{-1}$, 1140 cm.$^{-1}$, and 825 cm.$^{-1}$.

3-Ethoxycyclohex-2-en-1-one was prepared in 60% yield from the reaction between dihydroresorcinol, ethyl orthoformate, ethanol, and sulphuric acid, as described by Meek et al.[217] The pure compound had b.p. 115°/9 mm.

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[*] This compound was reported as the 7β-epimer in this publication. The configuration at the 7-position has since been reversed. (Cf. Fieser and Fieser[215]).

(lit.,[217] b.p. 104-108°/4 mm.).

Cyclohex-2-en-1-one was prepared in 60% yield by the method of Gannon and House[218] using 3-ethoxy-cyclohex-2-en-1-one and lithium aluminium hydride. Cyclohex-2-en-1-one, obtained by fractionation *in vacuo*, had b.p. 64-66°/17 mm., (lit.,[218] b.p. 56-57.5°/10 mm.), $\nu_{max.}$(film) 1695 cm.$^{-1}$, and 1070 cm.$^{-1}$, 2,4-dinitrophenylhydrazone m.p. 167.5-168°, (lit.,[219,220] m.p. 162-163.5°).

Cyclohex-2-en-1-ol was prepared in 65% yield by the reduction of cyclohex-2-en-1-one with lithium aluminium hydride, as described by Mousseron *et al.*[221] Cyclohex-2-en-1-ol, obtained by factionation *in vacuo*, had b.p. 68-69°/15 mm., phenylurethane m.p. 105-106° (benzene-light petroleum).

2-Bromocholestan-3-one. (Cf. Heath-Brown *et al.*[222]) To a solution of cholestan-3-one (10 g., 0.03 mole) in glacial acetic acid (250 ml.), was added a 50% solution of hydrogen bromide in acetic acid (1 ml.). With constant stirring, a solution of bromine (4.1 g.) in acetic acid (25 ml.) was added dropwise. After standing of the reaction mixture for several hours, the product began to crystallize. It was then filtered and recrystallized from ethanol-acetone m.p. 170-171° (*lit.*,[223,224] m.p. 170-170.5°), $[\alpha]_D^{20}$ + 39° (chloroform).

Cholest-1-en-3-one was obtained in almost quantitative yield when 2-bromocholestan-3-one was boiled in 2,4-dimethylpyridine according to the method of Inhoffen *et al.*[225] Cholest-1-en-3-one was purified by chromatography on acid-washed alumina m.p. 99-99.5° (needles from acetone) (*lit.*,[226] m.p. 98-100°), $[\alpha]_D^{25}$ + 61.0° (chloroform) (*lit.*,[226] $[\alpha]_D^{23}$ + 57.5°), ν *max.* (chloroform) 1675 cm.$^{-1}$.

Heptan-3-ol was prepared from butylmagnesium bromide and propionaldehyde in 48% yield by the method described by Dillon and Lucas.[227] It was purified by distillation *in vacuo* b.p. 66°/22 mm., n_D^{22} 1.4204 (*lit.*,[227] b.p. 152.7-154°/745 mm., n_D^{20} 1.4201).

Heptan-3-one was prepared by chromic acid oxidation of heptan-3-ol by the same method as used for the oxidation of octan-3-ol above. Heptan-3-one, when purified by distillation *in vacuo*, had b.p. 60°/22 mm., n_D^{22} 1.4140 (*lit.*,[228] b.p. 146.5-147°/765 mm., n_D^{20} 1.4088), 2,4-dinitrophenylhydrazone m.p. 82-83° (*lit.*,[211] m.p. 80-81°).

t-Butyl allophanate. (*Cf.* Davis and Blanchard.[229]) *t*-Butanol (100 *ml.*) was added to a solution of potassium cyanate (35 g.) in water (60 *ml.*). During rapid stirring, concentrated hydrochloric acid (25 *ml.*) was added dropwise. After the addition, the reaction mixture was stirred for an additional 2 hours. The products were extracted with an excess of ether. The ether-solution was then dried and evaporated to dryness. The crude residue was recrystallized from benzene-ethanol to yield pure *t*-butyl allophanate (1.5 g., 5%), m.p. 175-176° (*decomp.*) (*lit.*,[230] m.p. 190°), ν *max.* (nujol) 3450 cm.$^{-1}$, 3300 cm.$^{-1}$, 1715 cm.$^{-1}$, 1695 cm.$^{-1}$, 1595 cm.$^{-1}$, 1245 cm.$^{-1}$, 1155 cm.$^{-1}$, 850 cm.$^{-1}$, and 785 cm.$^{-1}$.

n-Butyl n-butyrate was prepared in 51% yield from *n*-butanol and chromic acid, as described by Robertson.[231] The product was carefully fractionated twice *in vacuo* through a 20 cm. column packed with glass helices b.p. 69°/18 mm. (*lit.*,[232] b.p. 69-70°/20 mm.) n_D^{20} 1.4084 (*lit.*,[183] n_D^{20} 1.4064), ν *max.* (film) 1740 cm.$^{-1}$, and 1180 cm.$^{-1}$.

2,2,4-Trimethylpentan-3-one was prepared from di-isopropyl ketone and methyl iodide as described by Beckwith,[233] 2,4-dinitrophenylhydrazone m.p. 163-164°

(*lit.*,[234] m.p. 163-164°).

2,4,4-Trimethylpentanoic acid was prepared by the method described by Beckwith.[233]

Benzyl o-toluate was obtained in poor yield by heating a mixture of *o*-toluic acid and excess benzyl alcohol at 120° for 8 hours in the presence of a trace-amount of concentrated sulphuric acid. The benzyl *o*-toluate was distilled *in vacuo* b.p. 118°/0.6 mm., n_D^{23} 1.5648, ν *max.* (film) 1710 cm.$^{-1}$, 1445 cm.$^{-1}$, 1270 cm.$^{-1}$, 1250 cm.$^{-1}$, 1090 cm.$^{-1}$, 1070 cm.$^{-1}$, 1030 cm.$^{-1}$, 780 cm.$^{-1}$ and 695 cm.$^{-1}$.

Methyl-o-toluate was obtained in poor yield by refluxing a mixture of *o*-toluic acid and excess methanol for 12 hours in the presence of a trace-amount of concentrated sulphuric acid. The methyl *o*-toluate was distilled *in vacuo* b.p. 102°/20 mm. n_D^{19} 1.5194, ν *max.* (film) 1720 cm.$^{-1}$, 1435 cm.$^{-1}$, 1295 cm.$^{-1}$, 1255 cm.$^{-1}$, 1140 cm.$^{-1}$, 1080 cm.$^{-1}$, and 740 cm.$^{-1}$.

The *dimethyl ester of 1,2-di-(2-carboxyphenyl)-ethane* was prepared in poor yield by heating a mixture of di-*t*-butyl peroxide and excess methyl *o*-toluate at 110° for 100 hours. Chromatography, on acid-washed alumina, afforded the pure compound, which was crystallized from ethanol m.p. 102.5-103° (*lit.*,[235] m.p. 103°).

Octan-2-one was prepared from commercially-available octan-2-ol by the usual chromic acid oxidation procedure previously described. Octan-2-one was obtained as a sweet smelling liquid b.p. 74-78°/22 mm., n_D^{19} 1.4152 (*lit.*,[236] b.p. 59-60°/11 mm., n_D^{20} 1.4151), 2,4-dinitrophenylhydrazone m.p. 56-58° (needles from petroleum ether).

1,2-Dibromocyclohexane was prepared in 90% yield by the method of Snyder and Brooks,[237] using cyclohexene and bromine dissolved in carbon tetrachloride at -5°. The product was distilled *in vacuo* b.p. 104°/18 mm. (*lit.*,[237] b.p. 99-103°/16 mm.), ν *max.*(film) 1445 cm.$^{-1}$, 1430 cm.$^{-1}$, 1180 cm.$^{-1}$, 1005 cm.$^{-1}$, 905 cm.$^{-1}$, and 865 cm.$^{-1}$.

2-Bromo-octane was prepared in 80% yield by the reaction between dry hydrogen bromide and octan-2-ol as described by Hughes and Shapiro.[238] The bromo-compound, b.p. 85°/24 mm. (*lit.*,[238] b.p. 79°/17 mm.), n_D^{23} 1.4480, had ν *max.* (film) 1450 cm.$^{-1}$, and 1370 cm.$^{-1}$

1,2-Dibromo-octane was prepared from oct-1-ene and bromine at -12° as described by Wilkinson.[239] The compound was fractionated in vacuo b.p. 123°/18 mm., n_D^{22} 1.4953 (lit.,[239] b.p. 118.5°/15 mm., n_D^{20} 1.4970), ν max. (film) 1460 cm.$^{-1}$, 1430 cm.$^{-1}$, and 1145 cm.$^{-1}$.

2,3-Dibromo-octane was prepared by an identical method to that described above, using oct-2-ene and bromine at -12°. The product was fractionated in vacuo b.p. 134°/28 mm., ν max. (film) 1460 cm.$^{-1}$, 1380 cm.$^{-1}$, and 1165 cm.$^{-1}$.

(d) COPPER-SALT CATALYSED REACTIONS OF PEROXY COMPOUNDS

All the following reactions were conducted in an atmosphere of dry, oxygen-free nitrogen. They were constantly stirred throughout.

Reaction between benzyl radicals and cupric benzoate I

A mixture of toluene (300 ml.), di-t-butyl peroxide (50.0 g., 0.34 mole), cupric benzoate (170 g., 0.55 mole) and benzoic acid (60 g., 0.50 mole) was heated at 110° for 108 hours.

When the dark reaction mixture was cooled, it was filtered, and the residue was washed several times with toluene. The washings were combined with the mother-liquor and the resultant solution was extracted with 20% aqueous sodium carbonate.

The organic layer was dried and unreacted toluene was evaporated. The residue was then fractionated in vacuo to yield:

(a) benzyl alcohol (4.13 g.), b.p. 50-52°/0.25 mm., n_D^{20} 1.5393, 3,5-dinitrobenzoate m.p. and mixed m.p. 112-113°.

(b) bibenzyl (8.59 g., 14%), b.p. 70-80°/0.2 mm., m.p. and mixed m.p. 52-53°.

(c) benzyl benzoate (5.33 g., 4%), b.p. 96-102°/ 0.2 mm., n_D^{21} 1.5685.

The above experiment was repeated using cupric acetate (106 g., 0.86 mole) and acetic acid (29.0 g., 0.48 mole) instead of cupric benzoate and benzoic acid. Benzyl acetate (4.71 g., 5%) was obtained b.p. 108°/ 25 mm., n_D^{20} 1.5246.

Reaction between benzyl radicals and cupric benzoate II

A mixture of toluene (300 ml.) and cupric benzoate (100 g., 0.32 mole) was heated at 110° while di-t-butyl peroxide (50 g., 0.34 mole) was added dropwise.

After the addition (2 hours) the mixture was continuously stirred at 110° for 50 hours. When the dark-brown reaction mixture was cooled, it was filtered, and the residue was washed several times with toluene. The washings were combined with the mother-liquor and the resultant solution was extracted with 20% aqueous sodium carbonate.

The organic layer was dried, and unreacted toluene was evaporated. The residue was then distilled *in vacuo* to yield:

(a) benzyl alcohol (8.05 g.) b.p. 50-60°/0.25 mm., n_D^{20} 1.5392, 3,5-dinitrobenzoate m.p. and mixed m.p. 112-113°.

(b) bibenzyl (4.80 g., 8%) b.p. 70-80°/0.2 mm., m.p. and mixed m.p. 52-53°.

(c) benzyl benzoate (8.55 g., 6%), b.p. 96-102°/ 0.2 mm., n_D^{21} 1.5683.

The residue (6.2 g.) from the distillation, was chromatographed on acid-washed alumina to yield:

(a) unidentified compound (0.85 g.) (needles from ethanol), m.p. 180-180.5° (Found: C, 92.84; H, 7.20; M.W. 357. $C_{28}H_{26}$ requires C, 92.77; H, 7.23%;

M.W. 362.5), infrared absorption failed to show the presence of any functional groups; ultraviolet absorption was similar to that of authentic bibenzyl.

(b) unidentified esters (3.5 g.), ν max. (film) 1715 cm.$^{-1}$, and 1270 cm.$^{-1}$.

When the above experiment was repeated using anhydrous cupric benzoate, the yields of bibenzyl and benzyl benzoate were reproduceable; however, no benzyl alcohol could be detected by vapour-phase chromatography.

Thermal decomposition of benzoyl peroxide

Benzoyl peroxide (20 g., 0.08 mole) was heated at 80° in benzene (100 ml.) for 20 hours. Carbon dioxide, which formed during the decomposition, was absorbed in a preweighed soda-lime/calcium chloride tube.

When cool, the colourless solution was extracted with 20% aqueous sodium carbonate. After acidification with dilute sulphuric acid, the aqueous layer was extracted with ether (100 ml.). The ether solution was then dried and the ether evaporated to yield benzoic acid (4.41 g., 22%), m.p. and mixed m.p. 121-122°.

The soda-lime/calcium chloride tube was reweighed immediately after the decomposition was complete. The increase in weight of this tube was 5.13 g. ≡ 71% yield of carbon dioxide.

The preceding experiment was repeated in the presence of cuprous bromide (30 g., 0.20 mole) to yield benzoic acid (13.65 g., 68%) and carbon dioxide (26% yield).

Reaction between oct-1-ene, t-butyl perbenzoate and cuprous chloride.

A mixture of oct-1-ene (25 g., 0.23 mole) and cuprous chloride (0.5 g., 0.005 mole) was maintained at 75° while t-butyl perbenzoate (20 g., 0.10 mole) was added dropwise, with constant stirring, at such a rate that the temperature did not rise above 75°. The reaction was exothermic.

After the addition (3 hours), the mixture was continuously stirred at 75° for an additional 30 hours. When the green reaction mixture was cooled, ether (100 ml.) was added, and the resultant solution was extracted with 20% aqueous sodium carbonate. After acidification with dilute sulphuric acid, the aqueous layer was extracted with ether (50 ml.). The ether solution was then dried and evaporated to yield benzoic acid (4.24 g., 33%), m.p. and mixed m.p. 121-122°.

The organic layer, remaining after extraction with sodium carbonate, was dried. Ether and unchanged oct-1-ene were evaporated. The residue (16.88 g.) was hydrogenated with 5% palladium on carbon at 1 atmosphere and the hydrogenated products were then hydrolysed with boiling 40% aqueous potassium hydroxide for 12 hours.

An aliquot (4.2 g.) of the resultant alcohols (7.44 g.) was dissolved in pure acetone and chromic acid solution was added dropwise with cooling. At the completion of the oxidation (red colour), the mixture was extracted with ether (30 ml.). The ether extract was then shaken with 20% aqueous sodium carbonate. After acidification with dilute sulphuric acid, the aqueous layer was extracted with ether (15 ml.). The ether layer was then dried and evaporated to yield octanoic acid (0.25 g.).

The organic layer, remaining after extraction with sodium carbonate, was dried. The ether was distilled to yield octan-3-one (3.25 g.) 2,4-dinitrophenylhydrazone (needles from methanol) m.p. and mixed m.p. 62-63°.

Reaction between oct-1-ene, di-*t*-butyl peroxide, acetic acid and cupric benzoate

A mixture of oct-1-ene (30.75 g., 0.29 mole), acetic acid (32.0 g., 0.53 mole) and cupric benzoate (0.25 g., 0.001 mole) was heated at 90° while di-*t*-butyl peroxide (15.0 g., 0.10 mole) was added dropwise with constant stirring.

After the addition (1 hour) the mixture was continuously stirred at 90° until all the peroxide had decomposed (tested with starch-potassium iodide solution). When the reaction mixture was cooled, it was extracted with 20% aqueous sodium carbonate.

The organic layer was dried and the unreacted oct-1-ene was evaporated. The residue (11.92 g.) was hydrogenated over palladium on carbon (5%) at one atmosphere, using ethanol as a solvent. The ethanol was then evaporated and the residue (10.2 g.) was hydrolysed with boiling 30% aqueous potassium hydroxide to yield a mixture of alcohols (7.0 g.).

G.L.C. analysis of this mixture showed octan-3-ol to be the main component. By comparison with standard mixtures of octan-3-ol and octan-1-ol, it was estimated that the mixture of alcohols was composed of 75-80% octan-3-ol and 20-25% octan-1-ol.

Reaction between allylbenzene, *t*-butyl perbenzoate and cuprous chloride I.

A mixture of allylbenzene (40.0 g., 0.34 mole) and cuprous chloride (0.2 g., 0.002 mole) was heated at 80° while *t*-butyl perbenzoate (16.50 g., 0.09 mole) was added dropwise with constant stirring at such a rate that the temperature did not rise above 80°. The reaction was exothermic.

After the addition (3 hours) the mixture was continuously stirred at 80° for an additional 20 hours. When the dark-green reaction mixture was cooled, it was extracted with 20% aqueous sodium carbonate. After acidification with dilute sulphuric acid, the aqueous layer was extracted with ether (50 ml.). The ether solution was then dried and evaporated to yield benzoic acid (1.84 g., 18%), m.p. and mixed m.p. 121-122°.

The organic layer (51.26 g.) remaining after extraction with sodium carbonate was dried. An aliquot of this residue was hydrogenated with 5% palladium on carbon at 1 atmosphere. The resultant saturated compounds were then hydrolysed with 20% aqueous potassium hydroxide. Neutral components from the hydrolysis were extracted, dried and then fractionated to yield:

(a) *n*-propylbenzene, b.p. 66-68°/15 mm., n_D^{20} 1.4928.

(b) 1-phenylpropan-1-ol, b.p. 106-110°/15 mm., n_D^{20} 1.5211, *p*-nitrobenzoate m.p. and mixed m.p. 59-60°.

(c) unidentified compound (trace) shown by gas-phase chromatography to be neither ethylphenylcarbinol nor 3-phenylpropan-1-ol. 3-Phenylpropan-1-ol could not be detected by G.L.C. in any of the products.

Reaction between allylbenzene, *t*-butyl perbenzoate and cuprous chloride II

A mixture of allylbenzene (18 g., 0.15 mole) and cuprous chloride (0.02 g., 0.0002 mole) in benzene (50 *ml*.), was heated at 80° while *t*-butyl perbenzoate (18 g., 0.09 mole) was added dropwise with constant stirring at such a rate that the temperature did not rise above 80°.

After the addition (2 hours), the mixture was continuously stirred at 80° for an additional 20 hours. When the green-reaction mixture was cooled, it was extracted with 20% aqueous sodium carbonate. After acidification with dilute sulphuric acid, the aqueous layer was extracted with ether (50 ml.). The ether solution was then dried and evaporated to yield benzoic acid (3.37 g., 30%), m.p. and mixed m.p. 121-122°.

The organic layer remaining after extraction with sodium carbonate, was dried and the benzene was evaporated. An aliquot (16.2 g.) of the residue (25.71 g.) was then hydrogenated with 5% palladium on carbon at 1 atmosphere. The resultant saturated compounds were then hydrolysed with 20% aqueous potassium hydroxide. Neutral components from the hydrolysis were extracted, dried, and fractionated to yield:

(a) n-propylbenzene (6.0 g.) b.p. 66-68°/15 mm., n_D^{20} 1.4928.

(b) liquid, (1.99 g.), b.p. 215-225°.

(c) liquid, (1.58 g.), b.p. 225-235°.

Products (b) and (c) were each dissolved in pure acetone and oxidized with chromic acid at room temperature. The oxidation products were extracted with ether and the resultant solutions were shaken with 20% aqueous sodium carbonate. After acidification with dilute sulphuric acid, the aqueous layers were extracted with ether. The ether solutions were then dried and the ether distilled. Liquid (b) yielded 2-phenylpropionic acid (0.11 g.) (prisms from petroleum ether) m.p. and mixed m.p. 47-48°. Liquid (c) also yielded 2-phenylpropionic acid (0.79g.).

The neutral layers of the sodium carbonate extractions were dried and the ether was evaporated. Liquid (b) yielded ethyl phenyl ketone (1.42 g.), 2,4-dinitrophenylhydrazone m.p. and mixed m.p. 191-192°. Liquid (c) also yielded ethyl phenyl ketone (0.48 g.).

The total yield of esters from the reaction was 45%. The above oxidation results indicate that 1-phenylallyl benzoate comprised approximately 70% of the total ester products, cinnamyl benzoate comprising the remaining 30%.

The presence of both 1-phenylpropan-1-ol and 3-phenylpropan-1-ol in liquids (b) and (c) was confirmed by G.L.C. analysis.

Reaction between cholesteryl benzoate, *t*-butyl perbenzoate and cupric benzoate I

A mixture of cholesteryl benzoate (13.0 g., 0.03 mole) and cupric benzoate (0.3 g., 0.001 mole) was maintained at 80° in butan-2-one (130 ml.) while t-butyl perbenzoate (5.14 g., 0.03 mole) was added dropwise with constant stirring.

After the addition (1 hour) the mixture was continuously stirred at 80° for an additional 20 hours. When the reaction mixture was cooled, unchanged cholesteryl benzoate (7.59 g.) crystallized and was collected by filtration. The butan-2-one was then distilled from the mother-liquor.

The residue was then dissolved in benzene (150 ml.), and extracted with 20% aqueous sodium carbonate. After acidification with dilute sulphuric acid, the aqueous layer was extracted with ether (50 ml.). The ether solution was then dried and evaporated to yield benzoic acid (2.21 g., 68%), m.p. and mixed m.p. 121-122°.

The organic layer, remaining after extraction with sodium carbonate, was dried and the benzene was distilled. A dark-red residue (5.94 g.) remained. Chromatography of this residue on acid-washed alumina yielded:

(a) Cholesteryl benzoate (1.20 g.) m.p. and mixed m.p. 146-148°.

(b) Cholest-5-ene-3β,7β-diol 3-benzoate (0.32 g., 3%), (needles from ethanol) m.p. and mixed m.p. 192-193°, $[\alpha]_D^{20}$ + 13° (chloroform) (Found: C, 80.90; H, 9.68. Calc. for $C_{34}H_{51}O_3$: C, 80.58; H, 9.95%).

(c) Cholest-5-ene-3β,7α-diol 3-benzoate (0.93 g., 7%) (needles from ethanol) m.p. and mixed m.p. 173-174°, $[\alpha]_D^{20}$ -49° (chloroform) (Found: C, 80.66; H, 10.06. Calc. for $C_{34}H_{51}O_3$: C, 80.58; H, 9.95%).

Reaction between cholesteryl benzoate, t-butyl perbenzoate and cupric benzoate II.

A mixture of cholesteryl benzoate (9.53 g., 0.02 mole) and cupric benzoate (1.00 g., 0.003 mole) was maintained at 80° in benzene (50 ml.) while t-butyl perbenzoate (30 g., 0.15 mole) was added dropwise with constant stirring.

After the addition (2 hours), the mixture was continuously stirred at 80° for an additional 20 hours. When the reaction mixture was cooled, it was extracted with 20% aqueous sodium carbonate. After acidification with dilute sulphuric acid, the aqueous layer was extracted with ether (100 ml.). The ether solution was then dried and evaporated to yield benzoic acid

(7.47 g., 40%), m.p. and mixed m.p. 121-122°.

The organic layer remaining after extraction with sodium carbonate was dried and the benzene was distilled. A dark residue (22.80 g.) remained. An aliquot (6 g.) of this residue was chromatographed on acid-washed alumina to yield:

(a) cholesteryl benzoate (0.51 g.), m.p. and mixed m.p. 146-147°, $[\alpha]_D^{20}$ - 8° (chloroform).

(b) cholest-5-ene-3β,7β-diol 3 benzoate (1.10 g.) (needles from ethanol) m.p. and mixed m.p. 192-193°, $[\alpha]_D^{20}$ + 13° (chloroform).

(c) cholest-5-ene-3β,7α-diol 3-benzoate (1.04 g.) (needles from ethanol) m.p. and mixed m.p. 173-174°, $[\alpha]_D^{20}$ - 49° (chloroform).

The overall yields of each product, (b and c), were 40%.

Estimation of t-butanol and acetone ratios

A mixture of toluene (20.0 g., 0.22 mole), cupric benzoate (0.5 g., 0.002 mole) and *t*-butyl perbenzoate (4.0 g., 0.02 mole) was sealed in a Carius tube and continuously shaken at 125° for 3 hours. The tube was cooled in a bath of solid carbon dioxide and ethanol before unsealing. All volatile products were then distilled in a closed system. Examination of these volatile products by gas-phase chromatography indicated a t-butanol to acetone ratio of 4.09 to 1.

The experiment was repeated in the absence of cupric benzoate. The volatile products consisted of a t-butanol to acetone ratio of 4.81 to 1.

When the experiments above were repeated using cyclohexene (10 g., 0.12 mole) as a substrate instead of toluene, the t-butanol-acetone ratios were again closely related, regardless of the presence or absence of copper salts.

Reaction between cyclohexene, cyclohexane, t-butyl perbenzoate and cuprous chloride

A mixture of cyclohexene (84 g., 1 mole), cyclohexane (84 g., 1 mole), and cuprous chloride (0.2 g., 0.002 mole) was maintained at 85° while t-butyl perbenzoate (50 g., 0.26 mole) was added dropwise with constant stirring.

After the addition (4 hours) the mixture was continuously stirred at 85° for an additional 28 hours. When the green reaction mixture was cooled, ether (100 ml.)

was added and the resultant solution was extracted with 20% aqueous sodium carbonate. After acidification with dilute sulphuric acid, the aqueous layer was extracted with ether (100 ml.). The ether solution was then dried and evaporated to yield benzoic acid (6.09 g., 19%), m.p. and mixed m.p. 121-122°.

The organic layer remaining after extraction with sodium carbonate was dried. Ether and unchanged cyclohexene and cyclohexane were distilled. Distillation *in vacuo* of the dark-yellow residue yielded cyclohex-2-en-1-yl benzoate (33.39 g., 63%), b.p. 110-115°/0.5 mm. Quantitative hydrogenation of an aliquot of this product with 5% palladium on carbon at 1 atmosphere, showed it to be 100% unsaturated.

Reaction between cyclohexene, cyclohexane and *t*-butyl perbenzoate

A mixture of cyclohexane (84 g., 1 mole), and cyclohexene (84 g., 1 mole) was maintained at 85° while *t*-butyl perbenzoate (50 g., 0.26 mole) was added dropwise with constant stirring.

After the addition (1 hour), the mixture was continuously stirred at 85° for an additional 190 hours. When the reaction mixture was cooled, ether (100 ml.) was added, and the resultant solution was extracted with 20% aqueous sodium carbonate. After acidification with dilute sulphuric acid, the aqueous layer was extracted with ether (100 ml.). The ether solution was then dried and evaporated to yield benzoic acid (5.93 g., 19%), m.p. and mixed m.p. 121-122°.

The organic layer remaining after extraction with sodium carbonate was dried. Ether and unchanged cyclohexane and cyclohexene were evaporated. Distillation *in vacuo* of the dark residue yielded a mixture of esters (32.67 g., 60%) b.p. 90-120°/0.55 mm., ν max. (film) 1750 cm.$^{-1}$, and 1705 cm.$^{-1}$. An aliquot of this residue was hydrogenated at atmospheric pressure and room temperature with 5% palladium on carbon. The ester mixture proved to be 75-80% unsaturated, indicating that cyclohex-2-en-1-yl benzoate comprised 75-80% of the ester products. The hydrogenated products were shown to consist entirely of cyclohexyl benzoate (identical infrared absorption spectrum to that of the authentic compound.)

Upon hydrogenation with Adam's catalyst at atmospheric pressure, the ester products were completely hydrogenated, including the aromatic ring of the benzoate group.

Reaction between 2,2,4-trimethylpentane, cyclohexene, t-butyl perbenzoate and cuprous chloride.

A mixture of 2,2,4-trimethylpentane (95 g., 0.83 mole), cyclohexene (69 g., 0.83 mole) and cuprous chloride (0.21 g., 0.002 mole) was heated at 85° while *t*-butyl perbenzoate (41 g., 0.21 mole) was added dropwise with constant stirring.

After the addition (4 hours), the mixture was continuously stirred at 85° for an additional 25 hours. When the dark-green reaction mixture was cooled, ether (100 *ml*.) was added and the resultant solution was extracted with 20% aqueous sodium carbonate. After acidification with dilute sulphuric acid, the aqueous layer was extracted with ether (100 *ml*.). The ether solution was then dried and evaporated to yield benzoic acid (2.98 g., 11%); m.p. and mixed m.p. 121-122°.

The organic layer remaining after extraction with sodium carbonate was dried. Ether and unchanged isooctane and cyclohexene were evaporated. Distillation *in vacuo* of the residue yielded cyclohex-2-en-1-yl benzoate (20.29 g., 46%) b.p. 105-110°/0.3 mm.

The residue remaining (4.85 g.) was chromatographed on acid-washed alumina. The chromatography yielded:

(a) cyclohex-2-en-1-yl benzoate (1.37 g.). Total yield of this ester from the reaction = 50%.

(b) <u>cis-cyclohex-2-en-1,4-diol dibenzoate</u> (0.99 g.), (colourless needles from ethanol) m.p. 97-98.5° (Found: C, 74.42; H, 5.87; Mol.Wt. by Rast 336. $C_{20}H_{18}O_4$ requires C, 74.52; H, 5.63% Mol.Wt., 322), ν max. (chloroform) 1705 cm.$^{-1}$, 1265 cm.$^{-1}$, 1115 cm.$^{-1}$, and 930 cm.$^{-1}$. Hydrogenation of this diester with 5% palladium on carbon at 1 atmosphere yielded *cis*-cyclohexane-1,4-diol dibenzoate (colourless lathes from light-petroleum) m.p. 112.5-114°, (*lit.*,[240] m.p. 112.5-114°).

(c) Unidentified oils, all having ν max. (film) 1710 cm.$^{-1}$, and 1265 cm.$^{-1}$. Quantitative hydrogenation of these oils with 5% palladium on carbon indicated 80% unsaturation.

Reaction between 2,2,4-trimethylpentane, cyclohexene and t-butyl perbenzoate.

A mixture of 2,2,4-trimethylpentane (114 g., 1.0 mole) and cyclohexene (82 g., 1.0 mole) was heated at 85° while *t*-butyl perbenzoate (50 g., 0.26 mole) was added dropwise with constant stirring.

After the addition (1 hour), the mixture was continuously stirred at 85° for an additional 190 hours. During this time the mixture became pale yellow. When the reaction mixture was cooled, ether (100 ml.) was added and the resultant solution was extracted with 20% aqueous sodium carbonate. After acidification with dilute sulphuric acid, the aqueous layer was extracted with ether (100 ml.). The ether solution was then dried and evaporated to yield benzoic acid (4.13 g., 13%) m.p. and mixed m.p. 121-122°.

The organic layer remaining after extraction with sodium carbonate was dried. Ether and unchanged iso-octane and cyclohexene were distilled. Distillation *in vacuo* of the residue yielded:

(a) cyclohex-2-en-1-one (8.5 g.), b.p. 66-67°/17 mm. (Found: C, 52.19; H, 4.30. Calc. for C_6H_8O: C, 52.12; H, 4.74%), 2,4-dinitrophenylhydrazone m.p. and mixed m.p. 167.5-168° (needles from methanol).

(b) cyclohex-2-en-1-yl benzoate (13.75 g., 26%), b.p. 105°/0.3 mm. (Found: C, 76.73; H, 6.90. Calc. for $C_{13}H_{14}O_2$: C, 77.20; H, 6.98%), n_D^{19} 1.5397.

When distillate (b) was hydrogenated at 1 atmosphere with 5% palladium on carbon, 1 mole equivalent of hydrogen was absorbed. Hydrolysis of the resultant saturated ester with 20% aqueous potassium hydroxide yielded cyclohexanol and benzoic acid m.p. and mixed m.p. 121-122°.

Quantitative hydrogenation of the dark residue (15 g.) from the distillation with 5% palladium on carbon showed 70% unsaturation.

Reaction between 2,2,4-trimethylpentane, t-butyl perbenzoate and cuprous chloride

A mixture of 2,2,4-trimethylpentane (100 g., 0.88 mole) and cuprous chloride (0.2 g., 0.002 mole) was heated at 100° while *t*-butyl perbenzoate (30 g., 0.15 mole) was added dropwise with constant stirring.

After the addition (2 hours), the mixture was continuously stirred at 100° for an additional 24 hours. When the reaction mixture was cooled ether (100 *ml*.) was added and the resultant solution was extracted with 20% aqueous sodium carbonate. After acidification with dilute sulphuric acid, the aqueous layer was extracted with ether (100 *ml*.). The ether solution was then dried and evaporated to yield benzoic acid (14.12 g., 74%), m.p. and mixed m.p. 121-122°.

The organic layer remaining after extraction with sodium carbonate was dried. Ether and unchanged isooctane were distilled. The residue (6.73 g.) had ν max. (film) at 1710 cm.$^{-1}$, and 1260 cm.$^{-1}$.

Reaction between cyclohexanone, cyclohexene, t-butyl perbenzoate and copper salts.

A mixture of cyclohexanone (24 g., 0.24 mole), cyclohexene (20 g., 0.24 mole), cuprous chloride (0.25 g., 0.002 mole) and cupric bromide (0.25 g., 0.001 mole) was heated at 75° while t-butyl perbenzoate (28 g., 0.14 mole) was added dropwise with constant stirring at such a rate that the temperature did not rise above 75°. The reaction was exothermic.

After the addition (5 hours), the mixture was continuously stirred at 75° for 30 hours. When the green-reaction mixture was cooled, ether (50 ml.) was added and the resultant solution was extracted with 20% aqueous sodium carbonate. After acidification with dilute sulphuric acid, the aqueous layer was extracted with ether (100 ml.). The ether solution was then dried and evaporated to yield benzoic acid (5.02 g., 28%), m.p. and mixed m.p. 121-122°.

The organic layer remaining after extraction with sodium carbonate was dried. Ether and unchanged cyclohexanone and cyclohexene were distilled. The residue (22.00 g.) was dissolved in ethanol and an excess of sodium borohydride was added slowly at 0°. The resultant mixture was left overnight at 0°. Addition of dilute acetic acid decomposed the sodium borohydride complex. The solution was then basified with aqueous sodium carbonate and extracted with ether.

The organic layer was dried and the ether was distilled. The residue was then hydrolysed in boiling 40% aqueous potassium hydroxide for 10 hours. When cool, ethyl acetate was added to the hydrolysed mixture. The aqueous layer was acidified with dilute sulphuric acid and extracted with ether to yield benzoic acid (10.19 g.), m.p. and mixed m.p. 121-122°. The neutral layer of the hydrolysis extraction was dried, and the ethyl acetate evaporated, to leave a mixture of alcohols, ν max. (film) 3450 cm.$^{-1}$. These alcohols were distilled *in vacuo* to yield:

(a) cyclohex-2-en-1-ol (6.38 g.), b.p. 76-78°/22 mm. Quantitative hydrogenation of distillate (a) with 5% palladium on carbon at 1 atmosphere indicated 100% unsaturation.

(b) Mixture of alcohols (1.25 g.), b.p. 100-136°/ 22 mm., ν max. (film) 3450 cm.$^{-1}$. Quantitative hydrogenation of this mixture with 5% palladium on carbon at 1 atmosphere indicated 71% unsaturation.

(c) Residue (1.56 g.), quantitative hydrogenation with 5% palladium on carbon at 1 atmosphere indicated 70% unsaturation.

It was estimated that 8.37 g. of unsaturated products were obtained from the hydrolysis, whereas 0.83 g. of saturated products were obtained.

Reaction between cyclohexanone, cyclohexene and *t*-butyl perbenzoate

A mixture of cyclohexanone (24 g., 0.24 mole) and cyclohexene (20 g., 0.24 mole) was maintained at 80° while *t*-butyl perbenzoate (28 g., 0.14 mole) was added dropwise with constant stirring.

After the addition (2 hours), the mixture was continuously stirred at 80° for 190 hours. When the reaction mixture was cooled, ether (50 ml.) was added, and the resultant solution was extracted with 20% aqueous sodium carbonate. After acidification with dilute sulphuric acid, the aqueous layer was extracted with ether (100 ml.). The ether solution was then dried and evaporated to yield benzoic acid (6.98 g., 39%) m.p. and mixed m.p. 121-122°.

The organic layer remaining after extraction with sodium carbonate was dried. Ether and unchanged cyclohexanone and cyclohexene were evaporated. The residue (27.42 g.) was dissolved in ethanol and an excess of sodium borohydride was added slowly at 0°. The resultant mixture was left overnight at 0°. Addition of dilute acetic acid decomposed the sodium borohydride complex. The solution was then basified with aqueous sodium carbonate and extracted with ether.

The organic layer was dried and the ether evaporated. The residue was then hydrolysed in boiling 40% aqueous potassium hydroxide for 10 hours. When cool, ethyl acetate was added to the hydrolysed mixture. The aqueous layer was acidified with dilute sulphuric acid and extracted with ether, to yield benzoic acid (6.35 g.), m.p. and mixed m.p. 121-122°. The neutral layer of the hydrolysis extraction was dried and the ethyl acetate evaporated to leave a mixture of alcohols, ν <u>max.</u> (film) 3450 cm.$^{-1}$. These alcohols were distilled <u>in vacuo</u> to yield:

(a) cyclohex-2-en-1-ol (3.79g.), b.p. 84-88°/35 mm. Quantitative hydrogenation of distillate (a) with 5%

palladium on carbon at 1 atmosphere indicated 95% unsaturation.

(b) Mixture of alcohols (2.46 g.), b.p. 120-130°/ 22 mm., ν max. (film) 3450 cm.$^{-1}$. Quantitative hydrogenation of distillate (b) with 5% palladium on carbon at 1 atmosphere indicated 55% unsaturation.

(c) Residue (10.31 g.). Quantitative hydrogenation with 5% palladium on carbon at 1 atmosphere indicated 30% unsaturation.

It was estimated that 8.23 g. of unsaturated products were obtained from the hydrolysis, whereas 8.22 g. of saturated products were obtained.

Reaction between oct-2-ene, t-butyl perbenzoate and cuprous chloride.

A mixture of oct-2-ene (50 g., 0.45 mole) and cuprous chloride (0.5 g., 0.005 mole) was maintained at 65° while t-butyl perbenzoate (30 g., 0.15 mole) was added dropwise, with constant stirring, at such a rate that the temperature did not rise above 70°. The reaction was exothermic.

After the addition (5 hours), the mixture was continuously stirred at 65° for an additional 40 hours. When the green reaction mixture was cooled, ether (100 ml.)

was added, and the resultant solution was extracted with 20% aqueous sodium carbonate. After acidification with dilute sulphuric acid, the aqueous layer was extracted with ether (50 ml.). The ether solution was then dried and evaporated to yield benzoic acid (4.57 g., 24%) m.p. and mixed m.p. 121-122°.

The organic layer remaining after extraction with sodium carbonate was dried. Ether and unchanged oct-2-ene were distilled. The residue (24.68 g.) was hydrogenated with W-7 Raney nickel at 60° and 100 atmospheres. The hydrogenated products were then hydrolysed with boiling 50% aqueous potassium hydroxide for 12 hours.

An aliquot (2.90 g.) of the resultant alcohols (10.9 g.) was dissolved in pure acetone (30 ml.) and a mixture of chromium trioxide (12 g.) dissolved in 50% sulphuric acid (35 ml.) was added dropwise with cooling. When the oxidation was complete (red colour), the mixture was extracted with ether (20 ml.). The ether extract was then shaken with 20% aqueous sodium carbonate. After acidification with dilute sulphuric acid, the aqueous layer was extracted with ether (15 ml.). The ether layer was then dried and evaporated to yield octanoic acid (0.11 g.).

The organic layer remaining after extraction with sodium carbonate was dried. The ether was distilled to yield octan-3-one (1.87 g.), 2,4-dinitrophenylhydrazone (needles from methanol) m.p. and mixed m.p. 62-63°. Considerable difficulty was experienced in purifying this 2,4-dinitrophenylhydrazone.

Reaction between 1-phenylprop-1-ene, t-butyl perbenzoate and cuprous chloride.

A mixture of 1-phenylprop-1-ene (29.0 g., 0.25 mole) and cuprous chloride (0.5 g., 0.005 mole) was heated at 75° while t-butyl perbenzoate (28.5 g., 0.15 mole) was added dropwise, with constant stirring, at such a rate that the temperature did not rise above 75°. The reaction was exothermic.

After the addition (3 hours), the mixture was continuously stirred at 75° for an additional 20 hours. When the green reaction mixture was cooled, ether (100 ml.) was added and the resultant solution was extracted with 20% aqueous sodium carbonate. After acidification with dilute sulphuric acid, the aqueous layer was extracted with ether (50 ml.). The ether solution was then dried and evaporated to yield benzoic acid (9.48 g., 52%), m.p. and mixed m.p. 121-122°.

The organic layer of the sodium carbonate extraction was dried and the ether evaporated. Distillation *in vacuo* of the residue yielded:

(a) unchanged β-methylstyrene (9.80 g.), b.p. 70°/ 20 mm. The residue (15.2 g.) gave ν max. (chloroform) 1710 cm.$^{-1}$, 1270 cm.$^{-1}$, 1115 cm.$^{-1}$ and 965 cm.$^{-1}$.

An aliquot of the residue was dissolved in ethanol and hydrogenated over W-7 Raney nickel at 100 atmospheres at 70°. The hydrogenation products were then hydrolysed in boiling 20% ethanolic potassium hydroxide for 12 hours. The acidic product of the hydrolysis proved to be benzoic acid, m.p. and mixed m.p. 121-122°. The neutral product of the hydrolysis was a mixture of alcohols (0.84 g.) ν max. (film) 3450 cm.$^{-1}$.

This mixture was dissolved in pure acetone and oxidized with chromic acid at room temperature. The oxidation products were extracted with ether and the ether solution was shaken with 20% aqueous sodium carbonate. After acidification with dilute sulphuric acid, the aqueous layer was extracted with ether. The ether solution was then dried and the ether evaporated to yield 2-phenylpropionic acid (0.22 g.).

The organic layer, remaining after extraction with sodium carbonate, was dried and the ether was evaporated to yield ethyl phenyl ketone (0.45 g.), 2,4-dinitrophenylhydrazone m.p. and mixed m.p. 190-191°.

Reaction between cholest-2-en-3-yl benzoate, *t*-butyl perbenzoate, cuprous chloride and cupric bromide.

A mixture of cholest-2-en-3-yl benzoate (20.0 g., 0.04 mole) , cuprous chloride (0.4 g., 0.004 mole) and cupric bromide (0.58 g., 0.003 mole) was maintained at 80° in benzene (75 *ml*.) while *t*-butyl perbenzoate (5.7 g., 0.03 mole) was added dropwise with constant stirring.

After the addition (1 hour), the mixture was continuously stirred at 80° for an additional 20 hours. When the reaction mixture was cool, it was extracted with 20% aqueous sodium carbonate. After acidification with dilute sulphuric acid, the aqueous layer was extracted with ether (50 *ml*.). The ether solution was then dried and evaporated to yield benzoic acid (2.21 g., 62%) m.p. and mixed m.p. 121-122°.

The organic layer, remaining after extraction with sodium carbonate was dried and the benzene was evaporated. The dark residue was dissolved in a minimum of hot acetone and the resultant solution was cooled slowly. Cholest-2-en-3-yl benzoate (6.33 g.,) m.p. and mixed m.p. 127-128°, soon separated and was filtered. The acetone was distilled from the filtrate and an aliquot (4.61 g.) of the residue (15.55 g.) was chromatographed on acid-washed alumina to yield:

(a) cholest-2-en-3-yl benzoate (1.55 g.) m.p. and mixed m.p. 126-127°.

(b) cholest-1-en-3-one (2.08 g.) m.p. and mixed m.p. 99-99.5° (needles from acetone), $[\alpha]_D^{25}$ + 61.0° (chloroform) (Found: C, 84.42; H, 11.46. Calc. for $C_{27}H_{44}O$: C, 84.31; H, 11.53%).

(c) unidentified red oils (1.0 g.).

(d) unidentified crystals (trace) (needles from ethanol) m.p. 161.5-162.5°, $[\alpha]_D^{20}$ + 1.5° (approximate) (chloroform), ν <u>max</u>. (chloroform) 1725 cm.$^{-1}$, and 1275 cm.$^{-1}$.

<u>Reaction between 3-ethoxycholest-2-ene, *t*-butyl perbenzoate and cuprous chloride</u>.

A mixture of 3-ethoxycholest-2-ene (3.90 g., 0.01 mole) and cuprous chloride (0.20 g., 0.002 mole) was heated at 75° in benzene (20 *ml*.) while *t*-butyl perbenzoate (7.2 g., 0.03 mole) was added dropwise with constant stirring.

After the addition (1 hour), the mixture was continuously stirred at 75° for an additional 20 hours. When the reaction mixture was cooled, it was extracted with 20% aqueous sodium carbonate. After acidification with dilute sulphuric acid, the aqueous layer was extracted with ether (50 ml.). The ether solution was then dried and evaporated to yield benzoic acid (2.53 g., 56%) m.p. and mixed m.p. 121-122°.

The organic layer, remaining after extraction with sodium carbonate, was dried and the benzene was evaporated. The residue (5.77 g.) was chromatographed on acid-washed alumina to yield:

(a) cholestan-3-one (trace) m.p. and mixed m.p. 129-129.5°.

(b) unidentified crystals (0.05 g.), nodules from methanol, m.p. 103.5-105.5, ν max. (chloroform) 1715 cm.$^{-1}$, and 1670 cm.$^{-1}$.

(c) unidentified crystals (0.2 g.) (blades from methanol) m.p. 97.5-98°, ν max. (chloroform) 1665 cm.$^{-1}$.

(d) dark-red oils which could not be purified upon repeated chromatography. Most of these oils absorbed strongly at 1720 cm.$^{-1}$, and 1275 cm.$^{-1}$ and several gave double carbonyl absorption at 1720 cm.$^{-1}$, and

1690 cm.$^{-1}$, as well as 1275 cm.$^{-1}$. In certain cases the infrared absorption indicated aromatization even in the absence of benzoyloxy groups.

A similar reaction between cholest-4-en-3-one, *t*-butyl perbenzoate and cuprous chloride, also failed to yield any products which could be identified.

Reaction between 1-ethoxycyclohex-1-ene, *t*-butyl perbenzoate and cuprous chloride.

A mixture of 1-ethoxycyclohex-1-ene (65 g., 0.52 mole) and cuprous chloride (1.0 g., 0.01 mole) was heated at 75° while *t*-butyl perbenzoate (60.0 g., 0.31 mole) was added dropwise with constant stirring at such a rate that the temperature of the reaction was maintained at 75°. The reaction was highly exothermic and during the addition the reaction mixture changed from blue to green.

After the addition (5 hours), the mixture was continuously stirred at 75° for a further 20 hours. When the green reaction mixture was cooled, ether (150 *ml.*) was added and the resultant solution was extracted with 20% aqueous sodium carbonate. After acidification with dilute sulphuric acid, the aqueous layer was extracted with ether (200 *ml.*). The ether solution was then dried and evaporated to yield benzoic acid (18.57 g., 46%) m.p. and mixed m.p. 121-122°.

The organic layer, remaining after extraction with sodium carbonate, was dried and the ether was evaporated. The residue was fractionated in vacuo through a 20 cm. column. Seven fractions were obtained (see table) and examination of each fraction by G.L.C. analysis showed that most of them contained more than one compound. These compounds had retention times identical to those of cyclohexanone (a), 1-ethoxycyclohex-1-ene (b), phenyl ethyl ether (c) and 1,1-diethoxycyclohexane (d).

Standard mixtures of each of these compounds were prepared and compared with the gas-phase chromatograms of the fractions 1-7. Approximate quantities of the compounds in each fraction were thus obtained (see table).

Cyclohexanone-2,4-dinitrophenylhydrazone was prepared from fraction 1, m.p. and mixed m.p. 161-162°.

Ultraviolet absorption of fraction 5 was identical to that of authentic phenetol.

Infrared absorption of fraction 7 was identical to that of authentic cyclohexanone diethyl acetal,

Frac. No.	Wt. of Fraction (g.)	Wt. of (a) (g.)	Wt. of (b) (g.)	Wt. of (c) (g.)	Wt. of (d) (g.)
1	2.20	0.77	1.43	-	-
2	6.63	0.33	5.97	0.33	-
3	6.66	-	5.96	1.33	-
4	1.71	-	1.11	0.60	-
5	2.01	-	0.70	1.31	-
6	3.38	-	-	1.69	1.69
7	4.24	-	-	-	4.24

n_D^{20} 1.4370 (Found: C, 69.72; H, 11.77; O, 18.94. Calc. for $C_{10}H_{20}O_2$: C, 69.72; H, 11.70; O, 18.58%).

The residue (25.37 g.), which remained after the fractionation, was chromatographed on acid-washed alumina, but only coloured-impure oils were obtained. In many cases these oils gave ν max. (film) 1720 cm.$^{-1}$.

Reaction between hept-1-yne, t-butyl perbenzoate and cuprous chloride

A mixture of hept-1-yne (25 g., 0.26 mole) and cuprous chloride (0.2 g., 0.002 mole) was maintained at 75° while t-butyl perbenzoate (25 g., 0.13 mole) was added dropwise at such a rate that the temperature did not rise above 80°. The copper salt was readily soluble in cold hept-1-yne to give a green solution. As soon as the first few drops of perester were added, the reaction mixture changed rapidly to deep purple. As the perester addition proceeded, the colour gradually changed to the original green.

After the addition (3 hours), the mixture was continuously stirred at 75° for an additional 22 hours. When the green reaction mixture was cooled, ether (100 ml.) was added, and the resultant solution was extracted with 20% aqueous sodium carbonate. After acidification with dilute sulphuric acid, the aqueous layer was extracted with ether (100 ml.). The ether solution was then dried and evaporated to yield benzoic acid (5.21 g., 33%), m.p. and mixed m.p. 121-122°.

The organic layer remaining after extraction with sodium carbonate was dried. Ether and unchanged hept-1-yne were distilled. An aliquot (6.59 g.) of the residue (18.0 g.) was chromatographed on acid-washed alumina to yield:

(a) Unidentified ester (0.2 g.), ν max. (film) 1710 cm.$^{-1}$, and 1265 cm.$^{-1}$; weak absorption occurred at 2200 cm.$^{-1}$, the ester did not show absorption at 2100 cm.$^{-1}$ and 3300 cm.$^{-1}$.

(b) Hept-1-yn-3-yl benzoate (2.50 g.), b.p. 101°/0.15 mm., $n_D^{19.5}$ 1.5068 (Found: C, 77.66; H, 7.74. $C_{14}H_{16}O_2$ requires: C, 77.75; H, 7.46%), ν max. (film) 1710 cm.$^{-1}$, and 1265 cm.$^{-1}$; medium absorption was observed at 3300 cm.$^{-1}$, and weak absorption occurred at 2100 cm.$^{-1}$, the ester did not show absorption at 2200 cm.$^{-1}$.

(c) Unidentified alcohol (3.5 g.), resulting from the hydrolysis of esters during chromatography. This alcohol showed ν max. (film) 3300 cm.$^{-1}$.

The crude residue used for the chromatography gave an identical infrared absorption spectra to that of fraction (b). An aliquot (1.0 g.) of fraction (b) was dissolved in ethanol (5 ml.) and hydrogenated with 5% palladium on carbon at 1 atmosphere. The resultant saturated ester was then hydrolysed in boiling 20% ethanolic potassium hydroxide for 5 hours. The hydrolysis yielded:

(i) heptan-3-ol, b.p. 70-71°/22 mm., n_D^{20} 1.4226.
(ii) benzoic acid, m.p. and mixed m.p. 121-122°.

The total yield of hept-1-yn-3-yl benzoate from the reaction was 17.20 g., 61%.

The heptan-3-ol was oxidized with chromic acid to yield heptan-3-one, 2,4-dinitrophenylhydrazone m.p.

and mixed m.p. 82-83°.

Reaction between diethyl malonate, t-butyl perbenzoate and cuprous chloride.

A mixture of diethyl malonate (200 g., 1.25 mole) and cuprous chloride (1.0 g., 0.01 mole) was maintained at 70° while *t*-butyl perbenzoate (35 g., 0.18 mole) was added dropwise so that the temperature did not rise above 70°.

After the addition (5 hours), the mixture was continuously stirred at 70° for a further 30 hours. When the green reaction mixture was cooled, ether (100 *ml.*) was added, and the resultant solution was extracted with 20% aqueous sodium carbonate. After acidification with dilute sulphuric acid, the aqueous layer was extracted with ether (100 *ml.*). The ether solution was then dried and evaporated to yield benzoic acid (14.80 g., 66%) m.p. and mixed m.p. 121-122°.

The organic layer, remaining after extraction with sodium carbonate, was dried. Ether and unchanged diethylmalonate were evaporated. An attempt to distil the crude residue (20.88 g.) under high vacuum resulted in the partial decomposition of the products (benzoic acid produced). Chromatography of the residue on silica yielded reasonably pure diethyl O-benzoyl tartronate. No diethyl O-t-butyl tartronate could be found. The diethyl O-benzoyl tartronate gave ν max. (film) 1750 cm.$^{-1}$, 1740 cm.$^{-1}$, 1275 cm.$^{-1}$, 1155 cm.$^{-1}$, 1060 cm.$^{-1}$, 1025 cm.$^{-1}$, and 965 cm.$^{-1}$. It was not further investigated.

Reaction between α,α'-azobisisobutyronitrile and cupric benzoate.

A mixture of α,α'-azobisisobutyronitrile (8.3 g., 0.05 mole) and cupric benzoate (50.0 g., 0.16 mole) was refluxed for 18 hours in butan-2-one (300 ml.). When the reaction mixture was cool, the insoluble copper-salts were filtered (37.32 g.). All volatile material was then evaporated from the filtrate to yield a residue (17.0 g.). An aliquot (10.0 g.) of this residue was chromatographed on acid-washed alumina to yield:

(a) tetramethylsuccinonitrile (0.2 g.) m.p. and mixed m.p. 168-169° (plates from aqueous methanol).

(b) unidentified compound (0.4 g.) m.p. 163-164°, ν max. (chloroform) 1675 cm.$^{-1}$, 1500 cm.$^{-1}$, 1475 cm.$^{-1}$, and 1280 cm.$^{-1}$.

When the chromatography column was eluted with highly polar solvents, benzoic acid (8.29 g.) was obtained.

The insoluble copper-salts from the reaction (37.32 g.) were steam-distilled from 40% sulphuric acid to yield benzoic acid (27.02 g.).

Reaction between 1,1,3-triphenylprop-1-ene, *t*-butyl perbenzoate and cuprous bromide.

A mixture of 1,1,3-triphenylprop-1-ene (36.28 g., 0.14 mole) and cuprous bromide (0.1 g., 0.001 mole) was maintained at 80° while *t*-butyl perbenzoate (15.5 g., 0.08 mole) was added dropwise with constant stirring.

After the addition (1.5 hour) , the mixture was continuously stirred at 80° for an additional 20 hours. When the reaction mixture was cooled, ether was added and the resultant solution was extracted with 20% aqueous sodium carbonate. After acidification with dilute sulphuric acid, the aqueous layer was extracted with ether (100 ml.). T he ether solution was then dried and evaporated to yield benzoic acid (6.33 g., 65%), m.p. and mixed m.p. 121-122°.

The organic layer from the sodium carbonate extraction was dried and the ether evaporated. An aliquot (7.09 g.) of the residue (40.59 g.) was dissolved in glacial acetic acid (50 ml.) and a mixture of 6-9%

ozone in oxygen was passed into the solution until ozone was present in the issuing gases.

The resultant ozonolysis products were then decomposed by the careful addition of 30% hydrogen peroxide, followed by gentle refluxing for several hours. The resultant solution was extracted with 20% aqueous sodium carbonate and the organic layer was treated with 2,4-dinitrophenylhydrazine reagent to yield benzophenone 2,4-dinitrophenylhydrazone (1.33 g.), m.p. and mixed m.p. 136-137°.

An aliquot (30.54 g.) of the residue from the first sodium carbonate extraction was distilled in vacuo to yield a mixture of compounds (11.38 g.) b.p. 170-174°/ 0.3 mm. The infrared absorption of this mixture closely resembled that of 1,1,3-triphenylprop-1-ene. The mixture was highly fluorescent, however.

Extensive decomposition occurred during the above distillation and the residue was very dark. However, upon cooling, crystals were deposited (plates from benzene-petroleum ether) m.p. 209-211° (decomp.). The infrared absorption spectra was very similar to that of 1,1,3-triphenylprop-1-ene (Found: C, 93.72; H, 6.12; M.W. 490. $C_{42}H_{34}$ requires C, 93.64; H, 6.36%; M.W. 538).

Reaction between benzaldehyde, t-butyl perbenzoate and cuprous chloride.

A mixture of pure benzaldehyde (130 g., 0.82 mole) and cuprous chloride (1.0 g., 0.01 mole) was heated at 70° while t-butyl perbenzoate (25.0 g., 0.13 mole) was added dropwise at such a rate that the temperature of the reaction was maintained at 70°. The reaction was highly exothermic. The reaction mixture attained a deep blue colour when the perester was being added. If the perester addition was temporarily suspended, the reaction mixture rapidly became deep green.

After the addition (4 hours), the mixture was continuously stirred at 70° for a further 20 hours. When the green reaction mixture was cooled, ether (150 ml.) was added and the resultant solution was extracted with 20% aqueous sodium carbonate. After acidification with dilute sulphuric acid, the aqueous layer was extracted with ether (100 ml.). The solution was then dried and the ether evaporated to yield benzoic acid (11.62 g., 73%) m.p. and mixed m.p. 121-122°.

The organic layer remaining after extraction with sodium carbonate was dried and the ether was evaporated under nitrogen. Distillation *in vacuo* of the residue under nitrogen yielded:

(a) t-butyl benzoate (1.95 g., 8%), b.p. 44°/0.2 mm., n_D^{18} 1.4930.

(b) benzoic anhydride (13.22 g., 45%), b.p. 138-142°/0.22 mm., (lathes from benzene-light petroleum) m.p. and mixed m.p. 41-42°.

(c) dark red residue (1.21 g.) not examined.

Reaction between ethyl benzoate, di-t-butyl peroxide, acetic acid and cupric chloride.

A mixture of ethyl benzoate (21.70 g., 0.14 mole), di-t-butyl peroxide (10.1 g., 0.07 mole) and acetic acid (10 g., 0.17 mole) was heated at 90° in the presence of cupric chloride (30 g., 0.23 mole) for five days with constant stirring. Benzene (100 ml.) was used as a solvent.

When the reaction mixture was cooled, the copper salts were removed by filtration and the filtrate was then dried. The benzene was evaporated, and an aliquot (25 g.) of the residue (33.50 g.) was hydrolysed in boiling 20% ethanolic potassium hydroxide for 6 hours. All gaseous products from the hydrolysis were caught in a trap containing solid carbon dioxide. The hydrolysis yielded benzoic acid (9.04 g.) and acetaldehyde (0.18 g.)

2,4-dinitrophenylhydrazone m.p. and mixed m.p. 162-163°.

An aliquot (5.82 g.) of the original (non-hydrolysed) product was distilled to yield unchanged ethyl benzoate (4.61 g.).

Reaction between formamide, t-butyl perbenzoate and cuprous chloride.

A mixture of formamide (100 g., 2.22 mole) and cuprous chloride (1.0 g., 0.01 mole) was heated at 75° while t-butyl perbenzoate (25 g., 0.13 mole) was added dropwise, with constant stirring, at such a rate that the temperature of the reaction was maintained at 75°. The reaction was highly exothermic. The initial mixture of formamide and cuprous chloride was deep purple. After some perester had been added, however, the solution became deep green.

After the addition (4 hours), the mixture was continuously stirred at 75° for an additional 20 hours. When the green reaction mixture was cool, ether (150 ml.) was added and the resultant solution was extracted with 20% aqueous sodium carbonate. After acidification with dilute sulphuric acid, the aqueous layer was extracted with ether (150 ml.). The ether solution was then dried and evaporated to yield benzoic acid (16.29 g., 100%) m.p. and mixed m.p. 121-122° and formic acid (13 g.).

The organic layer remaining after extraction with sodium carbonate was dried and the ether was distilled. The residue (3.72 g.) comprosed mainly <u>t</u>-butyl allophanate (needles from benzene-ethanol) m.p. and mixed m.p. 175-176° (<u>decomp</u>.) (Found: C, 45.03; H, 7.53; N, 17.49. Calc. for $C_6H_{12}N_2O_3$: C, 44.99; H, 7.55; N, 17.49%).

<u>Reaction between n-butyl formate, t-butyl perbenzoate and cuprous chloride</u>.

A mixture of <u>n</u>-butyl formate (100 g., 1.0 mole) and cuprous chloride (1.0 g., 0.01 mole) was heated at 70° while <u>t</u>-butyl perbenzoate (25.0 g., 0.13 mole) was added dropwise, with constant stirring, at such a rate that the temperature of the reaction was maintained at 70°. The reaction was highly exothermic. Carbon dioxide, formed during the reaction, was absorbed in a pre-weighed soda-lime/calcium chloride tube.

After the addition (4 hours), the mixture was continuously stirred at 70° for an additional 20 hours. When the green reaction mixture was cooled, ether (100 <u>ml</u>.)

was added and the resultant solution was extracted with 20% aqueous sodium carbonate. After acidification with dilute sulphuric acid, the aqueous layer was extracted with ether (100 ml.). The ether solution was then dried and evaporated to yield benzoic acid (14.54 g., 91%) m.p. and mixed m.p. 121-122°.

The organic layer, remaining after extraction with sodium carbonate, was dried and the ether was evaporated. Distillation of the residue yielded:

(a) unreacted n-butyl formate.

(b) n-butyl-n-butyrate (4.13 g.), b.p. 61°/13 mm. (Found: C, 66.76; H, 11.16; O, 22.0. Calc. for $C_8H_{16}O_2$: C, 66.63; H, 11.18, O, 22.19%), n_D^{18} 1.4087, n-butyric acid was obtained upon alkaline hydrolysis (R_F 0.32).

(c) n-butyl benzoate (1.79 g., 8%), b.p. 96°/0.6 mm., n_D^{21} 1.4971.

The dark residue (2.5 g.) from the distillation was not examined.

The soda-lime/calcium chloride tube increased in weight by 0.54 g. (10% yield of carbon dioxide).

Reaction between oct-1-ene, *t*-butyl hydroperoxide, acetic acid, ferrous and cupric ions.

A mixture of oct-1-ene (140 g., 1.20 mole), acetic acid (17.0 g., 0.28 mole), cupric bromide (0.62 g., 0.003 mole) and ferrocene (0.55 g., 0.003 mole) was maintained at 70° while *t*-butyl hydroperoxide (25.0 g., 0.28 mole) was added dropwise, with constant stirring, at such a rate that the temperature of the reaction mixture did not rise above 70°. The reaction was exothermic. During the perester addition, the reaction mixture changed from pale yellow to dark green.

After the addition (4 hours), the mixture was continuously stirred at 70° for a further 30 hours. When the green reaction mixture was cooled, ether (100 *ml*.) was added and the resultant solution was extracted with 20% aqueous sodium carbonate. After acidification with dilute sulphuric acid, the aqueous layer was extracted with ether (150 *ml*.). The ether solution was then dried and evaporated to yield acetic acid (1.1 g.).

The organic layer, remaining after extraction with sodium carbonate, was dried and the ether and unreacted oct-1-ene was evaporated. Distillation *in vacuo* of the dark residue yielded:

(a) a mixture of esters (15.04 g.), b.p. 80-85°/ 17 mm., ν *max.* (film) 1740 cm.$^{-1}$, and 1260 cm.$^{-1}$.

(b) a mixture of esters (2.57 g.), b.p. 90-95°/ 17 mm., ν *max.* (film) 1740 cm.$^{-1}$, and 1260 cm.$^{-1}$.

The dark residue (7.72 g.) from the distillation had ν *max.* (film) 1740 cm.$^{-1}$, and 1260 cm.$^{-1}$.

An aliquot of ester mixture (a) was hydrogenated at atmospheric pressure over 5% palladium on carbon. The resultant saturated esters were then hydrolysed with 20% ethanolic potassium hydroxide for 12 hours. The alcohols (1.97 g.) from the hydrolysis were dissolved in pure acetone, and chromic acid solution was added dropwise with cooling. The oxidation products were extracted with ether, and the ether solution was shaken with 20% aqueous sodium carbonate. After acidification with dilute sulphuric acid, the aqueous layer was extracted with ether. The ether solution was dried and evaporated to yield octanoic acid (0.14 g.).

The neutral layer of the sodium carbonate extraction was dried and the ether was evaporated to yield octan-3-one (1.19g.) 2,4-dinitrophenylhydrazone m.p. and mixed m.p. 61-62°.

An aliquot of ester mixture (b) was similarly hydrogenated and hydrolysed. The resultant alcohols (1.60 g.) were oxidized to yield octanoic acid (0.88 g.) and octan-3-one (0.49 g.).

Hence the yield of 1-acetoxyoct-2-ene from the reaction was 3.2 g. (7%), and the yield of 3-acetoxyoct-1-ene was 14.5 g. (31%).

Reaction between cyclohexene, *t*-butyl hydroperoxide, benzoic acid, ferrous and cupric ions.

A mixture of cyclohexene (122 g., 1.49 mole), benzoic acid (68 g., 0.56 mole), cupric bromide (1.24 g., 0.006 mole) and ferrocene (1.09 g., 0.006 mole) was heated at 65° while *t*-butyl hydroperoxide (50.0 g., 0.56 mole) was added dropwise, with constant stirring, at such a rate that the temperature of the reaction mixture did not rise above 70°. During the addition, the reaction mixture changed from pale yellow to dark green and it was exothermic.

After the addition (4 hours), the mixture was continuously stirred at 65° for a further 30 hours. When the green reaction mixture was cooled, ether (150 *ml*.) was added and the resultant solution was extracted with 20% aqueous sodium carbonate. After acidification with dilute sulphuric acid, the aqueous layer was extracted with ether (150 ml.). The ether solution was then dried and evaporated to yield benzoic acid (28.01 g.) m.p. and mixed m.p. 121-122°.

The organic layer, remaining after extraction with sodium carbonate, was dried and the ether and unreacted cyclohexene were evaporated. Distillation *in vacuo* of the dark residue yielded cyclohex-2-en-1-yl benzoate (53.55 g.), b.p. 92-95°/0.15 mm. The residue, a viscous, black, tar (11.37 g.) was chromatographed on neutral alumina to yield:

(a) cyclohex-2-en-1-yl benzoate (1.88 g.)

(b) *cis*-cyclohex-2-en-1,4-diol dibenzoate (1.05 g.) (rods from ethanol) m.p. 97-98.5°.

The total yield of cyclohex-2-en-1-yl benzoate was 55.23 g. (49%).

Reaction between cyclohexene, *t*-butyl hydroperoxide, 1-naphthoic acid, ferrous ions and cupric ions.

A mixture of cyclohexene (240 g., 2.93 mole), 1-naphthoic acid (48.0 g., 0.28 mole), cupric bromide (0.62 g., 0.003 mole) and ferrocene (0.55 g., 0.003 mole) was heated at 75° while *t*-butyl hydroperoxide (25 g., 0.28 mole) was added dropwise, with constant stirring, at such a rate that the temperature of the reaction mixture did not exceed 75°. During the addition, the reaction mixture changed from pale yellow to dark green and heat was evolved.

After the addition (4 hours), the mixture was continuously stirred at 75° for a further 30 hours. When the green reaction mixture was cooled, ether (100 _ml._) was added and the resultant solution was extracted with 20% aqueous sodium carbonate. After acidification with dilute sulphuric acid, the aqueous layer was extracted with ether (150 _ml._). The ether solution was then dried and evaporated to yield 1-naphthoic acid (19.57 g.) m.p. and mixed m.p. 160-161°.

The organic layer, remaining after extraction with sodium carbonate, was dried and the ether and unreacted cyclohexene were evaporated. Distillation _in vacuo_ of the dark residue (51.66 g.) yielded _cyclohex-2-en-1-yl 1-naphthoate_ (40.40 g., 58%), b.p. 164°/0.35 mm., n_D^{20} 1.6052 (Found: C, 80.64; H, 6.22. $C_{17}H_{16}O_2$ requires: C, 80.92; H, 6.39%), ν _max._ (film) 1710 cm.$^{-1}$, 1285 cm.$^{-1}$, 1250 cm.$^{-1}$, 1190 cm.$^{-1}$, and 1135 cm.$^{-1}$., λ _max._ (ethanol) 2340 Å, and 2980 Å. The ester decomposed appreciably at its boiling point, 1-naphthoic acid was a decomposition product.

The ester was hydrogenated at 1 atmosphere using 5% palladium on carbon and ethanol as the solvent. The resultant saturated ester was hydrolysed with 20% ethanolic potassium hydroxide to yield 1-naphthoic acid (m.p. and mixed m.p. 160-161°) and cyclohexanol, b.p. 158-160°.

Reaction between di-isobutylene, *t*-butyl hydroperoxide, *n*-decanoic acid, ferrous and cupric ions.

A mixture of di-isobutylene (200 g., 1.79 mole), *n*-decanoic acid (48.0 g., 0.27 mole), cupric bromide (0.62 g., 0.003 mole) and ferrocene (0.55 g., 0.003 mole) was heated at 75° while *t*-butyl hydroperoxide (25.0 g., 0.28 mole) was added dropwise, with constant stirring, at such a rate that the temperature of the reaction mixture did not rise above 75°. The reaction was exothermic, and during the addition the reaction mixture changed from pale yellow to dark green.

After the addition (4 hours), the mixture was continuously stirred at 75° for a further 30 hours. When the green reaction mixture was cooled, ether (150 *ml*.)

was added and the resultant solution was extracted with 20% aqueous sodium carbonate. After acidification with dilute sulphuric acid, the aqueous layer was extracted with ether (150 *ml.*). The ether solution was then dried and evaporated to yield *n*-decanoic acid (34.11 g.).

The organic layer, remaining after extraction with sodium carbonate, was dried and the ether and unreacted di-isobutylene were distilled. Distillation *in vacuo* of the dark residue (34.37 g.) yielded *2,2,4-trimethylpent-4-en-3-yl decanoate* (24.45 g., 31%) b.p. 104°/0.1 mm., n_D^{18} 1.4478 (Found: C, 76.75; H, 11.96. $C_{18}H_{34}O_2$ requires C, 76.54; H, 12.13%), ν *max.* (film) 1740 cm.$^{-1}$, 1245 cm.$^{-1}$, 1130 cm.$^{-1}$, 909 cm.$^{-1}$.

This ester was hydrogenated at 100 atmospheres with W-7 Raney nickel to yield a mixture of esters, b.p. 104°/0.1 mm., n_D^{20} 1.4411 (Found: C, 76.43; H, 12.60. $C_{18}H_{36}O_2$ requires: C, 75.99; H, 12.76%). Weak infra-red absorption at 1640 cm.$^{-1}$, and 905 cm.$^{-1}$, indicated that the hydrogenation had not gone to completion. Subsequent attempts also failed to completely hydrogenate this ester.

The partially hydrogenated mixture of esters (0.5 g.) was hydrolysed with boiling 20% ethanolic potassium hydroxide for 12 hours. The acid product from the hydrolysis proved to be n-decanoic acid.

The neutral products of the hydrolysis gave ν max. (film) 3500 cm.$^{-1}$. They were dissolved in pure acetone and chromic acid solution was added dropwise with cooling. The oxidation products were extracted with ether and the resultant solution was shaken with 20% aqueous sodium carbonate. After acidification with dilute sulphuric acid, the aqueous layer was extracted with ether. The ether solution was dried and evaporated to yield 2,4,4-trimethylpentanoic acid (trace). Small quantities of other acids were also observed by paper chromatography; all had R_F values lower than that of 2,4,4-trimethylpentanoic acid.

The organic layer of the sodium carbonate extraction was dried and the ether was evaporated to yield 2,2,4-trimethylpentan-3-one (0.2 g.); 2,4-dinitrophenylhydrazone m.p. and mixed m.p. 163-164°. Difficulty was experienced in purifying this derivative due to small amounts of impurities.

Reaction between cholesteryl benzoate, benzoic acid, t-butyl hydroperoxide, cupric and ferrous ions.

A mixture of cholesteryl benzoate (10 g., 0.02 mole), benzoic acid (20.20 g., 0.17 mole), cupric bromide

(0.62 g., 0.003 mole) and ferrocene (0.55 g., 0.003 mole) was heated at 75° in benzene (70 ml.) while t-butyl hydroperoxide (15.0 g., 0.17 mole) was added dropwise with constant stirring at such a rate that the temperature of the reaction mixture did not rise above 75°.

After the addition (1 hour), the mixture was continuously stirred at 75° for an additional 20 hours. When the reaction mixture was cooled, it was extracted with 20% aqueous sodium carbonate. After acidification with dilute sulphuric acid, the aqueous layer was extracted with ether (100 ml.). The ether solution was then dried and evaporated to yield benzoic acid (17.29 g.) m.p. and mixed m.p. 121-122°.

The organic layer, which remained after the sodium carbonate extraction, was dried, and the benzene was evaporated. An aliquot (2.63 g.) of the residue (13.47 g.) was chromatographed on silica gel to yield cholest-5-en-3β-ol-7-one 3-benzoate (0.3 g.) m.p. and mixed m.p. 158-159°.

No other compound was identified from the chromatography, only impure coloured oils were obtained which could not be induced to crystallize.

Reaction between t-butyl per-o-toluate and cuprous chloride I:

A mixture of cuprous chloride (0.4 g., 0.004 mole) in benzene (40 ml.) was heated at 85° while t-butyl per-o-toluate (17.0 g., 0.08 mole) was added dropwise with constant stirring at such a rate that the temperature did not rise above 85°.

After the addition (2 hours), the mixture was continuously stirred at 85° for an additional 26 hours. When the green reaction mixture was cooled, ether (100 ml.) was added and the resultant solution was extracted with 5% aqueous sodium hydrogen carbonate. After acidification with dilute sulphuric acid, the aqueous layer was extracted with ether (50 ml.). The ether solution was then dried and evaporated to yield o-toluic acid (2.63 g., 24%) m.p. and mixed m.p. 107-108°.

The organic layer of the sodium hydrogen carbonate extraction, was dried and the ether and benzene were evaporated. Distillation in vacuo of the residue yielded:

(a) methyl-o-toluate (3.52 g., 29%), b.p. 58-59°/ 0.4 mm. (Found: C, 72.12; H, 6.75; O, 21.2. Calc. for $C_9H_{10}O_2$: C, 71.98; H, 6.71; O, 21.31%), $n_D^{19.0}$ 1.5196.

(b) unchanged *t*-butyl per-*o*-toluate (2.03 g.), b.p. 87°/0.45 mm.

(c) residue (2.97 g.).

This residue was chromatographed on acid-washed alumina to yield:

(a) dimethyl ester of 1,2-di-(2-carboxyphenyl)-ethane (0.36 g., 3%) (crystals from ethanol) m.p. and mixed m.p. 102.5-103° (Found; C, 72.04; H, 6.18. Calc. for $C_{18}H_{18}O_4$: C, 72.46; H, 6.08%).

(b) unidentified red-oil (0.15 g.).

Only 30% recovery was obtained from the column.

Reaction between t-butyl per-o-toluate and cuprous chloride II.

A mixture of cuprous chloride (0.4 g., 0.004 mole) in benzene (25 ml.) was heated at 50° while *t*-butyl per-*o*-toluate (10.96 g., 0.05 mole) was added dropwise at such a rate that the temperature did not rise above 50°.

After the addition (2 hours), the mixture was continuously stirred for 120 hours. During this time the temperature was slowly raised from 50° to 65°. When the green reaction mixture was cooled, ether (25 ml.)

Reaction between oct-2-ene and cupric bromide.

A mixture of oct-2-ene (37.83 g., 0.34 mole) and anhydrous cupric bromide (30.00 g., 0.13 mole) was heated at the boiling point of oct-2-ene for 90 hours. During the early stages of the reaction the black cupric bromide suddenly turned to white. The change was complete within a few seconds. Hydrogen bromide was evolved during the reaction. At the completion of the reaction, the solution was again black.

When cooled, the reaction mixture was filtered; a dark green residue and a black solution resulted. Fractionation of the black solution yielded:

(a) unchanged oct-2-ene, b.p. 124-125°.

(b) octan-2-one (1.21 g.), b.p. 74-78°/22 mm., 2,4-dinitrophenylhydrazone (needles from petroleum ether) m.p. and mixed m.p. 56-58°, mixed m.p. with octan-3-one-2,4-dinitrophenylhydrazone produced a large depression.

(c) 2-bromo-octane (4.39 g.), b.p. 80°/22 mm.

(d) 2,3-dibromo-octane (5.08 g.), b.p. 130-140°/28 mm., 238-240/760 mm. (Found: C, 35.32; H, 5.68; Br, 59.0. Calc. for $C_8H_{16}Br_2$: C, 35.32; H, 5.93; Br, 58.75%).

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