

Experimental Section

General. Melting points were determined on a Kofler hot stage and are uncorrected. Infrared spectra were recorded from samples in KBr pellets with a Perkin-Elmer Model 237 grating infrared spectrophotometer. Nmr spectra were recorded on a Varian Model A-60 spectrometer with CDCl_3 as solvent and tetramethylsilane as internal standard. Mass spectra were recorded on a Hitachi Perkin-Elmer Model RMU-6E mass spectrometer, at 75 V ionizing voltage and 80 μA emission current. The oven was maintained at 185° and the source at 175°. The analyses were performed by Alfred Bernhardt, 433 Mulheim (Ruhr), Germany.

1,1'-Bis(α -deuterio- α -hydroxyethyl)ferrocene was prepared by reduction of 1.0 g of 1,1'-diacetylferrocene (0.0037 mol) and 0.1 g of LiAlD_4 (0.0024 mol) by the standard procedure¹⁰ yielding 0.095 g (94%) of a yellow solid. Recrystallization from hexane yielded a pure compound, mp 70–72° (lit.¹⁰ mp 69–71°).

1,1'-Divinylferrocene was prepared from 1,1'-bis-1-hydroxyethylferrocene (mp 70–72°; lit.¹⁰ 69–71°) by the method of Rausch.¹¹

1,1'-Bis(α -deuteriovinyl)ferrocene was made by the above procedure.

Ethyl *trans*-Ferrocenylacrylate. To a solution of 4.0 g of ethylferrocenylacetate (mp 52.5–4.5°; lit.¹² 50–51°) (0.013 mol) in 50 ml of absolute ethanol was added 1.0 g of NaBH_4 (0.026 mol) in 5 ml of H_2O .^{13,14} The reaction mixture was stirred at 0° for 24 hr, then taken to pH 5 with dilute HCl in EtOH, then stirred 1 hr at room temperature. The ethanol was stripped off at room temperature yielding 2.95 g (78%); washing through a plug of alumina and re-

crystallization from hexane yielded a pure compound, mp 63–64°, 70–70.5°; ν^{KBr} 3080, 1700, 1633, 1105, 1003, and 977 cm^{-1} ; nmr τ 8.67 (t, CH_2), 5.85 (s, C_5H_5), 5.76 (q, CH_2), 4.56 (2t, C_5H_4), and 2.40 and 3.95 (AB doublet, $J = 19$ cps, $\text{CH}=\text{CH}$). The vinyl coupling constant of 19 cps and the ir peak at 977 cm^{-1} indicate a *trans* double bond rather than a *cis*.¹⁵

Anal. Calcd for $\text{C}_{15}\text{H}_{16}\text{FeO}_2$: C, 63.40; H, 5.67. Found: C, 63.53; H, 5.64.

***trans*-Ferrocenylacrylic Acid.** This compound was prepared by saponification of 500 mg of ethyl *trans*-ferrocenylacrylate (0.0018 mol) yielding 350 mg (78%), recrystallized from CH_2Cl_2 -hexane, mp 188–191 dec (lit.¹⁶ 186–187° dec).

Trideuteriomethyl *trans*-Ferrocenylacrylate. To 1.5 ml of CD_3OH in 4 ml of ether was added 50 mg of *trans*-ferrocenylacrylic acid (0.002 mol) and 0.5 ml of $\text{BF}_3 \cdot \text{Et}_2\text{O}$. The solution was refluxed for 24 hr and worked up as before yielding 35 mg (66%), recrystallized from hexane, mp 100–103°.

Methyl *trans*-Ferrocenylacrylate. To 5 ml of CH_3OH was added 150 mg of *trans*-ferrocenylacrylic acid (0.00059 mol) and 1 ml of $\text{BF}_3 \cdot \text{Et}_2\text{O}$. The solution was refluxed for 4 hr and worked up as before yielding 121 mg (77%); recrystallization from hexane gave a pure compound, mp 102–103°; ν^{KBr} 3085, 1700, 1627, 1104, and 975 cm^{-1} ; nmr τ 6.27 (s, CH_2), 5.83 (s, C_5H_5), 5.53 (2t, C_5H_4), and 2.45 and 3.92 (AB doublet, $J = 19$ cps, $\text{CH}=\text{CH}$).

Anal. Calcd for $\text{C}_{14}\text{H}_4\text{FeO}_2$: C, 62.25; H, 5.23. Found: C, 62.54; H, 5.39.

Acknowledgments. We thank Messrs. Laurence R. Dusold and Thomas A. Elwood for recording many of the spectra. D. T. Roberts thanks E. I. du Pont de Nemours and Company, Inc., for a Teaching Fellowship and the American Enka Corporation for a Summer Fellowship.

(15) Two crystal modifications, as seen before in ref 2 and 3.

(16) C. D. Broadhead, J. M. Osgerby, and P. L. Pauson, *J. Chem. Soc.*, 650 (1958).

(10) D. S. Graham, R. V. Lindsey, G. W. Parshal, M. L. Peterson, and J. M. Whitman, *J. Amer. Chem. Soc.*, **79**, 3416 (1957).

(11) M. D. Rausch, personal communication.

(12) K. L. Rinehart, Jr., R. J. Curby, Jr., D. H. Gustafson, K. G. Harrison, R. E. Bozak, and D. E. Bublitz, *J. Amer. Chem. Soc.*, **84**, 3263 (1962).

(13) H. O. House, H. Babad, R. B. Tooth, II, and A. W. Noltes, *J. Org. Chem.*, **27**, 4141 (1962).

(14) W. F. Little and R. Eisenthal, *ibid.*, **26**, 3609 (1961).

Chemistry of Singlet Oxygen. IV.¹ Oxygenations with Hypochlorite-Hydrogen Peroxide^{2a}

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Abstract: Good acceptors for the dye-sensitized photooxygenation can be oxygenated efficiently by metal hypochlorites and hydrogen peroxide to give products identical with those of photooxygenation. Oxygenations of 2,3-dimethyl-2-butene, $\Delta^9,10$ -octalin, 2,5-dimethylfuran, tetraphenylcyclopentadienone, 1,3-cyclohexadiene, and anthracene are described. The reactive intermediate is probably $^1\Delta_g$ molecular oxygen. The yield of singlet oxygen depends on solvent and other factors, for reasons which are not yet understood.

Dye-sensitized photooxygenations of organic compounds have been studied extensively.³ Among the acceptors studied, two types have received particular

(1) Part III: C. S. Foote, S. Wexler, and W. Ando, *Tetrahedron Letters*, 4111 (1965).

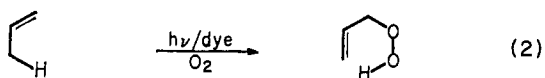
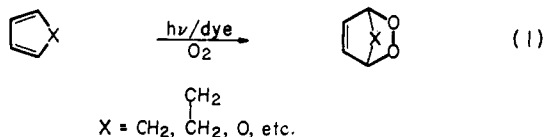
(2) (a) Supported by National Science Foundation Grants No. G-25086, GP-3358, and GP-5835, and by a grant from the Upjohn Company; taken in part from S. Wexler, Ph.D. Thesis, UCLA, 1966; (b) Alfred P. Sloan Research Fellow, 1965–1967.

(3) For leading references, see: (a) G. O. Schenck, *Angew. Chem.*, **69**, 579 (1957); (b) K. Gollnick and G. O. Schenck, *Pure Appl. Chem.*, **9**, 507 (1964); (c) E. J. Bowen, *Advan. Photochem.*, **1**, 23 (1963); (d) A. Nickon, N. Schwartz, J. B. DiGiorgio, and D. A. Widdowson, *J. Org. Chem.*, **30**, 1711 (1965); (e) Yu. A. Arbuzov, *Russ. Chem. Rev.*, **34**, 558 (1965); (f) K. Gollnick and G. O. Schenck in "1,4-Cycloaddition

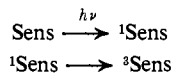
attention. Conjugated dienoids (cyclic and a few other *s-cis* dienes, polycyclic aromatics, and some heterocycles) undergo addition of oxygen to give (at least as the primary products) 1,4-*endo*-peroxides, in a reaction analogous to Diels-Alder addition (reaction 1). Many olefins with allylic hydrogens produce allylic hydroperoxides with an attendant specific shift of the double bond to the allylic position (reaction 2), in a reaction analogous to the "ene" reaction.⁴

Reactions," J. Hamer, Ed., Academic Press Inc., New York, N. Y., 1967, p 255.

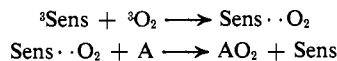
(4) K. Alder and H. von Brachel, *Ann.*, **651**, 1411 (1962), and earlier papers.



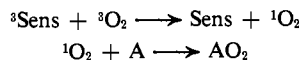
Several mechanisms have been suggested for the dye-sensitized photooxygenations, but only two are consistent with the kinetic evidence which has been presented.³ Both mechanisms require the intermediacy of the sensitizer (Sens) in its triplet state.



The first mechanism postulates the reaction of ³Sens with oxygen to give a complex of sensitizer and oxygen (Sens · O₂), which transfers oxygen to the acceptor (A) to produce the product (AO₂).³ This mechanism was originally suggested by Schönberg,⁵ and was widely accepted until recently.³



Another mechanism (originally suggested by Kautsky⁶) involves energy transfer from ³Sens to oxygen to give singlet molecular oxygen (¹O₂), which reacts with acceptor to form the product peroxide.



Singlet oxygen can be produced by radiofrequency discharge in gaseous oxygen⁷ and by the reaction of positive-halogen compounds with hydrogen peroxide⁷ among other processes.⁸

Both the ¹Σ_g⁺ and ¹Δ_g states of oxygen are usually produced, and have been identified by their characteristic (although somewhat complex) emission;⁷ in addition, the ¹Δ_g state gives a characteristic esr absorption in the vapor phase.⁹

The two metastable singlets differ in the electronic configuration of their degenerate highest occupied (antibonding) orbitals. The ¹Δ_g state (22 kcal) has both electrons in one orbital, and the other vacant; the ¹Σ_g⁺ (37 kcal) has one electron in each orbital.¹⁰

State	Energy (kcal) rel to ground state	Configuration of highest occupied orbitals
¹ Σ _g ⁺	37	↑ ↓
¹ Δ _g	22	↑↓ —
³ Σ _g ⁻	Ground state	↑ ↑

(5) A. Schönberg, *Ann.*, **518**, 299 (1935).

(6) H. Kautsky, *Biochem. Z.*, **291**, 271 (1937), and earlier papers.

(7) See J. S. Arnold, R. J. Browne, and E. A. Ogryzlo, *Photochem. Photobiol.*, **4**, 963 (1965), and references therein.

(8) E. McKeown and W. A. Waters, *Nature*, **203**, 1063 (1963); *J. Chem. Soc., Sect. B*, 1040 (1966), and H. H. Wasserman and J. R. Scheffer, *J. Amer. Chem. Soc.*, **89**, 3073 (1967), describe other sources of singlet oxygen.

(9) A. M. Falick, B. H. Mahan, and R. J. Myers, *J. Chem. Phys.*, **42**, 1837 (1965).

(10) G. Herzberg, "Molecular Spectra and Molecular Structure. I. Spectra of Diatomic Molecules," 2nd ed, D. Van Nostrand Co., New York, N. Y., 1950, p 560.

Oxygen in the ¹Δ_g state is produced in at least 10% yield in the reaction of chlorine with H₂O₂.¹¹ This state of oxygen (which resembles ethylene electronically) might be expected to react in two-electron, concerted processes. The ¹Σ_g⁺ state should resemble the ground state, and would be expected to undergo radical-like reactions. The ¹Δ_g state is extremely long-lived (it is known to survive more than 10⁸ collisions in the vapor).¹² The ¹Σ_g⁺ state is shorter lived, and is rapidly quenched by water vapor.^{7,13}

We previously reported in preliminary form that an oxidizing species (probably ¹Δ_g oxygen) produced in the reaction of sodium hypochlorite and hydrogen peroxide oxygenates many compounds to give products identical with those of the dye-sensitized photooxygenation.¹⁴ Similar observations were made by Corey and Taylor, using singlet oxygen produced by radiofrequency discharge in gaseous oxygen.¹⁵ Since these reports, several investigators have described oxygenations using these methods or similar ones.^{8,12b,16} In this paper, the chemical oxygenation of a number of organic substrates which yield a single product on photooxygenation is described from a mainly preparative standpoint, with attention to the effect of certain reaction variables on product yield. A series of papers in preparation will present detailed comparisons of the photooxygenation and hypochlorite-hydrogen peroxide oxygenation in regard to stereoselectivity, substrate reactivity, substituent effects, and mechanism.

Results

Oxygenation of 2,3-Dimethyl-2-butene. Photooxygenation of 2,3-dimethyl-2-butene (tetramethylethylene (I), hereafter referred to as TME) has been reported to produce 3-hydroperoxy-2,3-dimethyl-1-butene (II).¹⁷ The reaction was repeated with rose bengal as sensitizer, in methanol. The properties of the product (isolated by distillation) are in good agreement with those reported, and the infrared and nmr spectra support the assigned¹⁷ structure. Reduction of II with a wide variety of reducing agents produces 3-hydroxy-2,3-dimethyl-1-butene (III). When the crude photooxygenation mixture is reduced, no volatile products other than III can be detected by gas chromatography. The amount of product formed (measured gas chromatographically, using an internal standard) is in excellent agreement with that calculated from the oxygen uptake, which is quantitative when the reaction is carried to completion.

The oxygenation of TME with hypochlorite-hydrogen peroxide takes a very similar course. A methanolic solution of TME containing excess hydrogen peroxide was oxidized by adding dilute aqueous sodium hypochlorite. Somewhat more than 1 equiv of hypochlorite/ equiv of olefin was used (the reasons for this are discussed

(11) R. J. Browne and E. A. Ogryzlo, *Can. J. Chem.*, **43**, 2915 (1965).

(12) (a) R. M. Badger, A. C. Wright, and R. F. Whitlock, *J. Chem. Phys.*, **43**, 4345 (1965); (b) A. M. Winer and K. D. Bayes, *J. Phys. Chem.*, **70**, 302 (1966); (c) A. Vallance-Jones and A. W. Harrison, *J. Atmospheric Terrestrial Phys.*, **13**, 45 (1958).

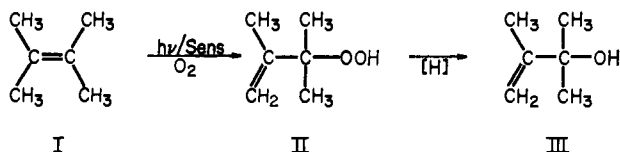
(13) L. W. Bader and E. A. Ogryzlo, *Discussions Faraday Soc.*, **37**, 46 (1964).

(14) C. S. Foote and S. Wexler, *J. Amer. Chem. Soc.*, **86**, 3879 (1964).

(15) E. J. Corey and W. C. Taylor, *ibid.*, **86**, 3881 (1964).

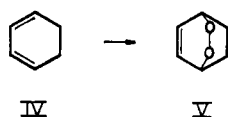
(16) (a) J. A. Marshall and A. R. Hochstetler, *J. Org. Chem.*, **31**, 1020 (1966); (b) T. Wilson, *J. Amer. Chem. Soc.*, **88**, 2898 (1966); (c) H. H. Wasserman and M. B. Floyd, *Tetrahedron Suppl.*, **7**, 441 (1966).

(17) G. O. Schenck and K.-H. Schulte-Elte, *Ann.*, **618**, 185 (1958).



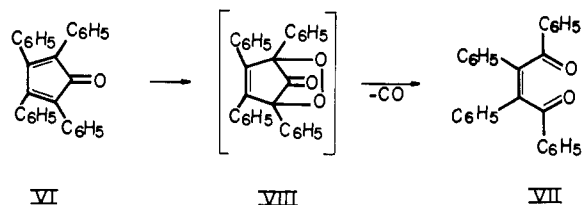
in a subsequent section). After extraction with ether and removal of the solvent, the product was distilled *in vacuo* to give a 63% yield of the peroxide II, identical with the product of photooxygenation. Gas chromatographic analysis of crude oxygenation mixtures, after reduction, showed that, in addition to III, no other volatile products were present (except under conditions discussed in a subsequent section).

Oxygenation of 1,3-Cyclohexadiene. Photooxygenation of 1,3-cyclohexadiene (IV) is reported to yield 5,6-dioxabicyclo[2.2.2]octene-2 ("norascaridol" (V)) in 21% yield.¹⁸ The photooxygenation was repeated and produced a 35% yield of impure V; the nmr and infrared spectra support the previously assigned structure. Isolation of completely pure V was not attempted as the compound appears to undergo ready polymerization.



Oxygenation of 1,3-cyclohexadiene in methanol with hypochlorite-hydrogen peroxide also produced V, identical with the product of photooxygenation. The yield was 20% after distillation.

Oxygenation of Tetraphenylcyclopentadienone. Tetraphenylcyclopentadienone (VI) is reported to give *cis*-dibenzoylstilbene (VII) in 65% yield on photooxygenation.¹⁹ This reaction is believed to proceed by loss of carbon monoxide from an initial 1,4-*endo*-peroxide (VIII). Oxygenation with hypochlorite-hydrogen peroxide was carried out in dioxane (subsequently found to be a very poor solvent for the reaction). The reaction was followed by loss of the intense color of tetraphenylcyclopentadienone. A 50-fold excess of hypochlorite was required to cause nearly complete loss of color. The yield of pure VII was 50% (after recrystallization).



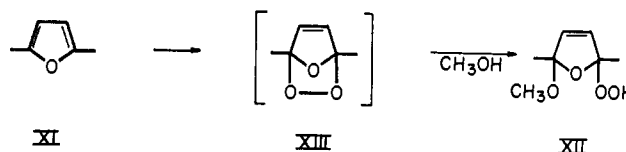
Oxygenation of Anthracene. Anthracene (IX) was photooxygenated in chloroform (because of low solubility in methanol) using methylene blue as sensitizer. The product had physical and chemical properties in accord with the reported structure (X).²⁰

Hypochlorite-hydrogen peroxide oxygenation of anthracene was carried out in dioxane. Although a 20-

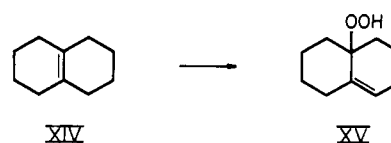
fold excess of hypochlorite was used, only a small fraction of the anthracene reacted. The peroxide X was separated from unreacted anthracene by fractional crystallization, in low yield. Subsequent investigations (reported below) showed that the yield of singlet oxygen is very low in dioxane; however, solubility considerations precluded the use of other, more favorable, solvents. McKeown and Waters have recently described a two-phase system using the aqueous phase reaction of bromine with alkaline hydrogen peroxide to oxidize anthracene derivatives in chlorobenzene, with improved results.⁸



Oxygenation of 2,5-Dimethylfuran. The photooxygenation of 2,5-dimethylfuran (XI) in methanol gives high yields of 2-methoxy-5-hydroperoxy-2,5-dimethyl-dihydrofuran (XII).²¹ The reaction apparently proceeds *via* solvolytic ring opening of an initially formed *endo*-peroxide XIII. Oxygenation of this excellent acceptor with hypochlorite-hydrogen peroxide in methanol proceeds very smoothly to give an excellent yield of XII.



Oxygenation of $\Delta^{9,10}$ -Octalin.²² The photooxygenation of $\Delta^{9,10}$ -octalin (XIV) is reported to produce 10-hydroperoxy- $\Delta^{1,9}$ -octalin (XV).¹⁷ Repetition of the photooxygenation yielded a product with melting point similar to that reported; the infrared and nmr spectra are in agreement with the previously assigned structure. Oxygenation of XIV with hypochlorite-hydrogen peroxide also yielded XV, identified by melting point and infrared spectrum.



Effect of Reaction Variables on Yield. In none of the oxygenations described above was any attempt made to optimize product yields. In order to establish the synthetic utility of the reaction, one of the acceptors was subjected to more detailed study. TME was chosen because it is very reactive; in addition, the oxygenation product II can be quantitatively reduced to the alcohol III which can be determined accurately by gas chromatography. In these studies, a known small amount of hypochlorite was added to a solution of excess TME and excess H_2O_2 . The amounts were chosen so that the change in TME or H_2O_2 concentration during the course of the reaction was small. The amount of product formed was measured by gas chro-

(18) G. O. Schenck and W. Willmund, reported by R. Criegee in Houben-Weyl, "Methoden der organischen Chemie," Vol. VIII, 4th ed, E. Müller Ed., Georg Thieme Verlag, Stuttgart, 1952, p 16.

(19) (a) C. F. Wilcox, Jr., and M. P. Stevens, *J. Amer. Chem. Soc.*, **84**, 1258 (1962); (b) G. O. Schenck, *Z. Elektrochem.*, **56**, 855 (1952).

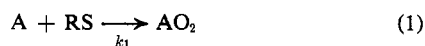
(20) C. Dufraisse and M. Gérard, *Bull. Soc. Chim. France*, **4**, 2052 (1937).

(21) C. S. Foote, M. T. Wuesthoff, S. Wexler, I. G. Burstain, R. Denny, G. O. Schenck, and K.-H. Schulte-Elte, *Tetrahedron*, **23**, 2583 (1967).

(22) These reactions were carried out by Miss Elaine Holstein, whose assistance is gratefully acknowledged.

matography of the reduced reaction mixture after addition of an internal standard, using a calibrated flame-ionization detector.

Acceptor Concentration. Kinetic studies of the photooxygenation have shown that the reactive species (RS, either singlet oxygen or sensitizer-oxygen complex) may either react with acceptor (A) to give peroxide (AO₂, reaction 1) or decay to ground-state oxygen (reaction 2).^{3b,c} In this scheme, singlet oxygen and a sensitizer-oxygen complex are kinetically equivalent.



Application of steady-state kinetics to the reaction gives the result^{3a,b,23}

$$\Phi_{AO_2} = \Phi_{RS} \frac{k_1[A]}{k_1[A] + k_2}$$

where Φ_{AO_2} is the quantum yield of product formation and Φ_{RS} is the quantum yield of formation of reactive species, which does not depend on acceptor. The fraction of RS which gives product is

$$\frac{[A]}{\beta + [A]}$$

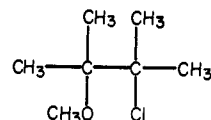
where $\beta = k_2/k_1$; β is the concentration of A at which half of RS is trapped to give product. Kinetic studies show that the reactive species in the hypochlorite-hydrogen peroxide oxygenation has behavior identical with that of the photooxygenation intermediate, and that in both reactions, β is approximately 0.003 M for TME.^{3b,24} Thus at TME concentrations over 0.1 M, more than 95% of the reactive species is trapped, and the yield of oxidation product provides a good measure of the yield of the reactive species. Tetramethylethylene is one of the most reactive olefins studied; most compounds are less reactive, and correspondingly less efficient at trapping the reactive species.^{3b,24,25} The studies reported below were all carried out at TME concentrations above 0.1 M. The maximum yield of III under any conditions so far studied was about 80%, based on hypochlorite. This yield was obtained by adding 1.5 M aqueous sodium hypochlorite to a methanol solution containing 0.18 M hydrogen peroxide, 0.012 M NaOH, and 0.21 M TME at -20° . The amount of product formed was proportional to the amount of hypochlorite added, and did not depend on the concentration of hypochlorite added. The yield was constant between -50 and 0° , but dropped to 40% at 30° .

Effect of pH. In the absence of added NaOH (except for that introduced with the sodium hypochlorite), the product yield dropped to about 70%. If the pH was below 7, almost no III was formed, and the major product was the methoxychloro adduct XVI (which is the main product of reaction of hypochlorite with TME in methanol in the absence of H₂O₂). All of the following experiments were carried out without added NaOH, except for that introduced with the hypochlorite.

(23) R. Livingston and V. Subba Rao, *J. Phys. Chem.*, **63**, 794 (1959), and references therein cited.

(24) R. Higgins, C. S. Foote, and H. Cheng, *Advances in Chemistry Series*, American Chemical Society, Washington, D. C., in press.

(25) K. R. Kopecky and H. Reich, *Can. J. Chem.*, **43**, 2265 (1965).



XVI

Effect of Solvent. The solvent chosen was found to have a drastic effect on product yield for reasons which are not yet understood. Methanol (pure, aqueous, or saturated with sodium chloride), ethanol, and 1:1 (v/v) methanol-*t*-butyl alcohol as solvent gave comparable high yields of III (over 60%). In isopropyl alcohol, the yield dropped to 40%. In pure *t*-butyl alcohol, 50% aqueous *t*-butyl alcohol, tetrahydrofuran, dioxane, and acetonitrile, yields were below 10%. No new products were formed; the only apparent effect was a marked increase in oxygen evolution from the solution.

Other Effects. Considerable difficulty in reproducing yields at high and low peroxide concentrations was observed, and drastically lowered yields were often observed below 0.05 M or above 0.3 M H₂O₂. Part of this effect seems to be associated with the rate of addition of the hypochlorite (rapid addition decreases yields) and may involve local depletion of reactants, but further study is necessary.









Oxygen Evolution. Oxygen is produced by the reaction between sodium hypochlorite and hydrogen peroxide. In the absence of an acceptor, the yield of oxygen is nearly stoichiometric to the amount of hypochlorite added, if hydrogen peroxide is in excess. Some difficulty was encountered in obtaining completely reproducible measurements of oxygen evolution, probably because of some reaction of hypochlorite with solvent; in addition, blank values varied somewhat from solvent to solvent. However, in a variety of solvents and with a variety of acceptors, the sum of the amount of oxygen evolved and the amount of product formed is equal to the amount of hypochlorite added. Under conditions where product yield is high, the amount of oxygen evolved is low, and *vice versa*. Oxygen evolution can thus be used to follow the course of the oxygenation. The amount of oxygen evolved during the course of the addition of a known amount of hypochlorite is measured and subtracted from the theoretical evolution calculated from blank experiments; the difference corresponds to the amount of acceptor oxidized. If oxidation is less than complete, additional reagent is added.

Discussion

Synthetic Utility of Chemical Oxygenation. The results of the studies reported above show that the hypochlorite-hydrogen peroxide reaction can produce synthetically useful yields of oxygenation products under certain conditions. In order to trap a useful fraction of the reactive intermediate, the substrate must be present in a concentration not much less than its $\beta(k_2/k_1)$ value. Values of β for chemical oxygenation can be calculated from relative reactivity data,²⁴ and are listed in Table I for several typical substrates.

In general, in chemical oxygenation,²⁴ as in photooxygenation,^{3b,25} reactivity decreases in the series:

Table I. Values of $\beta(k_2/k_1)$ for Various Substrates^a

Substrate	β, M	Substrate	β, M
	0.001		(0.14)
	0.0030		0.55
	0.003		13
	0.01		70

^a Calculated from data in ref 24, based on an average value of β for chemical and photochemical oxygenation of 0.14 M for 2-methyl-2-pentene. Values given are for oxygenation with H_2O_2 - $NaOCl$, but are identical within experimental error with the values for photosensitized oxygenation.

tetraalkylated > trialkylated > dialkylated olefins, and compounds with double bonds in a six-membered ring are less reactive than acyclic compounds. This reactivity variation implies that tetra- and trialkylated acyclic olefins, furans, etc. can be oxygenated practically, but difficulty in obtaining sufficient conversion is obtained with methylcyclohexene derivatives.¹ In addition, substituted anthracenes,²³ (but not anthracene itself), cyclohexadienes, and cyclopentadienes are reactive enough to be good acceptors.

For the less reactive acceptors, or those which are limited to low concentrations by solubility, large excesses of hypochlorite may be required to obtain appreciable conversion. Side reactions (probably free radical in nature) also compete with the oxygenation when unreactive acceptors are used; the side reactions can be at least partially suppressed by the use of free-radical inhibitors such as 2,6-di-*t*-butylphenol.¹ As reagents, aqueous sodium hypochlorite or solutions of calcium hypochlorite (which is less basic) are equally suitable; a wide variety of other positive-halogen sources can also be used.²⁶

As solvents, so far only methanol, ethanol, and methanol-*t*-butyl alcohol have been found to be very practical. Of these, 1:1 (v/v) methanol-*t*-butyl alcohol offers solubility advantages when aqueous hypochlorite is used. Further investigation of the solvent effect, particularly with other reagents, is under way.²⁶ One method of avoiding the solubility and solvent limitations described above is the two-phase system described by McKeown and Waters, in which the acceptor is dissolved in chlorobenzene and the hypochlorite-hydrogen peroxide reaction carried out in an aqueous layer; a large excess of reagents is required to effect appreciable conversions with this method.⁸

Nature of the Oxidizing Species. On the basis of quenching experiments, Rosenberg and Humphries have suggested that both the dye-photosensitized and hypochlorite-peroxide oxygenations may involve the intermediacy of vibrationally excited ground-state (triplet) oxygen, rather than singlet oxygen.²⁷ However, the following arguments strongly favor the intermediacy of singlet oxygen. (1) Singlet ($^1\Delta_g$) oxygen is known to be produced by the reaction of chlorine and

H_2O_2 in a yield of at least 10%;¹¹ high yields (up to 80%) of the oxidizing species are observed in the chemical oxygenation. (2) Energy transfer from triplet sensitizer to triplet oxygen to give singlet oxygen and singlet sensitizer is a spin-allowed process, and could therefore be very efficient (as is the production of the excited species in the photoreaction^{3b} and the reaction of oxygen with triplet sensitizers).³ (3) Kinetically and stereochemically, the reactive intermediates in the photooxygenation and the chemical oxygenation behave identically, and would appear to be the same.^{1,24} Thus arguments applying to one reaction should apply also to the other. (4) The observed chemistry in both reactions seems to be a concerted or nearly concerted cycloaddition of oxygen to acceptors.^{1,3} Vibrationally excited triplet oxygen should resemble a free radical in its reactions, as should $^1\Sigma_g^+$ oxygen. The presence of free-radical inhibitors does not inhibit the formation of oxygenated products.¹ Molecular oxygen in the $^1\Delta_g$ stage, in contrast, has both electrons paired in the same orbital, and should be capable of concerted two-electron reactions. The chemistry would be predicted to be that of a reactive dienophile, as observed.²⁸ (5) A minimum lifetime can be calculated for the reactive species by simple considerations.²⁹ The most reactive substrate yet studied is 1,3-diphenylisobenzofuran,^{16b} which has a $\beta(k_2/k_1)$ value which can be calculated to be $10^{-4} M$ from the published data.^{3b,16b,24} The rate constant (k_1) for reaction of the reactive species with acceptors cannot exceed the diffusion-controlled rate, about $10^{10} M^{-1} sec^{-1}$. Therefore, the decay rate (k_2) of the reactive species must be no larger than $10^6 sec^{-1}$ in solution. In fact, since most Diels-Alder reactions have a large negative entropy of activation, the maximum reaction rate is probably less than diffusion controlled, and the decay rate is therefore probably less than $10^6 sec^{-1}$.³⁰ Since collision rates in solution are of the order of $10^{13} sec^{-1}$,³¹ the reactive species must survive roughly 10^7 solvent collisions. Vibrationally excited oxygen in the gas phase requires about 10^8 collisions with small molecules per vibrational quantum for deactivation;^{27,32} however, the quenching efficiency of methanol should be greater than this. Thus it seems very unlikely that vibrationally excited oxygen is the reactive species. Similarly, $^1\Sigma_g^+$ oxygen is rapidly quenched by collisions with water (and thus presumably also with methanol).^{7,13} On the other hand, $^1\Delta_g$ oxygen survives more than 10^8 collisions in the vapor, and thus has a lifetime long enough to be consistent with the lifetime of the intermediate.¹² Thus from both the chemical and the longevity criteria, the reactive species would seem to be $^1\Delta_g O_2$. Gaffron showed that in at least one case photooxidation could be effected with light of insufficient energy to produce $^1\Sigma_g^+ O_2$.³³ Curiously,

(28) Very recent results suggest that O_2 ($^1\Sigma_g^+$) does indeed behave as a free radical: D. R. Kearns, R. A. Hollins, A. U. Khan, R. W. Chambers, and P. Radlick, *J. Amer. Chem. Soc.*, **89**, 5455 (1967); D. R. Kearns, R. A. Hollins, A. U. Khan, and P. Radlick, *ibid.*, **89**, 5457 (1967); we are grateful to Professor Kearns for a prepublication copy of his manuscripts.

(29) G. O. Schenck and E. Koch, *Z. Elektrochem.*, **64**, 170 (1960).

(30) The enthalpy of activation is near zero with reactive acceptors.²⁹ However, no determination of absolute rates has been made.

(31) J. E. Leffler and E. Grunwald, "Rates and Equilibria of Organic Reactions," John Wiley and Sons, Inc., New York, N. Y., 1963.

(32) (a) N. Basco and R. G. W. Norrish, *Discussions Faraday Soc.*, **33**, 99 (1962); (b) H. Knotzel and L. Knotzel, *Ann. Physik*, **2**, 383 (1948).

(33) H. Gaffron, *Biochem. Z.*, **287**, 130 (1936).

(26) C. S. Foote and J. Barnett, unpublished results.

(27) J. L. Rosenberg and F. S. Humphries, *Photochem. Photobiol.*, **4**, 1185 (1965).

this experiment was used as evidence against the intermediacy of *any* form of singlet oxygen, although Kautsky pointed out that ample energy was available to excite the $^1\Delta_g$ state.⁶

Evidence against the intermediacy of a sensitizer-oxygen complex has already been presented,^{1,3,4} and will be supplemented in subsequent papers.^{2,4}

Experimental Section³⁵

Materials. H_2O_2 was J. T. Baker reagent grade 30% solution. NaOCl was General Chemical reagent grade ("5%") or Purex 14 (up to 17%). $Ca(OCl)_2$ solutions were prepared from J. T. Baker reagent grade solid (30–35% "active Cl") mixed with approximately twice its weight of water and filtered. All peroxide and hypochlorite solutions were standardized frequently by reaction with KI solution and titration of I_2 formed with thiosulfate.³⁶

Photosensitized Oxygenations. A water-cooled immersion irradiation apparatus similar to the one described by Gollnick and Schenck was used.³⁷ O_2 was recirculated by a diaphragm pump (Cole-Palmer Dyna-Vac Model 3). The solutions were irradiated with a Sylvania "Sungun" Type DWY 625-W tungsten-iodine lamp; oxygen uptake was measured by a gas buret. The maximum rate of oxygen uptake in this apparatus was about 200 cc/min, which corresponds to about 1.5×10^{-4} mol/sec.

Hypochlorite-Hydrogen Peroxide Oxygenations. In all runs, the acceptor was dissolved in the solvent, the solutions were chilled, and H_2O_2 was added. The amount of H_2O_2 in the solution was always in excess of the amount of hypochlorite to be added. Hypochlorite was added dropwise to the vigorously stirred solution.

The volume of O_2 evolved from the solution was measured with a gas buret in several experiments. Blank experiments with no olefin present showed that, in methanol, somewhat less than the theoretical amount of O_2 was evolved, presumably because some of the NaOCl was consumed by reaction with methanol. The volumes were therefore always corrected for this consumption, which limits the accuracy of the calculations, since it is not entirely reproducible.

Control experiments showed that under the reaction conditions used, neither H_2O_2 nor the products remaining in solution after reaction of NaOCl and H_2O_2 cause significant oxidation of olefins; in addition, reaction of hypochlorite with olefin is negligible when H_2O_2 is present in excess.

In the absence of H_2O_2 , however, or at pH below 7, hypochlorite reacts with olefins. In the case of tetramethylethylene, the product is apparently the methoxy chloro adduct XVI. The compound was isolated gas chromatographically and had ir bands (CCl_4) at 3.40, 6.85, 7.30, 7.37, 8.65, 9.00, 9.40, 11.25, and 14.1 μ ; in the nmr, there were sharp singlets at τ 8.70, 8.47, and 6.78, relative areas 2:2:1. The compound was not further characterized.

Photooxygenation of 2,3-Dimethyl-2-butene.¹⁷ A solution of 2.72 g (32.3 mmol) of TME (I) (Columbia Organic Chemicals) and 30 mg of rose bengal in 250 ml of CH_3OH was irradiated in the immersion apparatus; 776 cc (32 mmol) of O_2 was absorbed in 3.75 min. The solution was decolorized and most of the solvent removed by distillation (Vigreux) at atmospheric pressure. The residue, approximately 20 ml, was distilled (6-in. concentric-tube column) to give 2.02 g (17.4 mmol, 54%) of hydroperoxide II, bp 53–55° (12 mm) (lit.¹⁷ bp 55° (12 mm)). The ir spectrum (neat) had principal bands at 2.83, 6.04, 6.86, 7.25, 7.32, 7.68, 8.27, 8.51, 8.69, 9.83, 11.04, and 11.94 μ . The nmr spectrum (CCl_4) had peaks at τ 1.62 (broad, OOH), 5.08 (multiplet, CH_2), 8.22 (doublet, $CH_3C=C$), and 8.70 (singlet, CH_3CO); excluding the hydroperoxyl proton, the peaks were in the ratio 2:3:6.

Hypochlorite-Hydrogen Peroxide Oxygenation of 2,3-Dimethyl-2-butene. A solution of 5.05 g (60 mmol) I in 300 ml of methanol

was chilled to 10° and 19.2 ml of 9.36 M (180 mmol) H_2O_2 was added. To this solution 145.5 ml (150 mmol) of 1.03 M NaOCl solution was added dropwise with continual cooling and stirring during 90 min. The reaction mixture was diluted with water and extracted with ether. The dried ether extracts were concentrated (Vigreux) at atmospheric pressure, and the residue was distilled. The fraction with bp 51–54° (9 mm) was 4.43 g (38.3 mmol, 64%) of hydroperoxide II, with nmr and ir spectra identical with those of the photoproduct and $n^{24,5}_D$ 1.4408 (lit.¹⁷ n^{20}_D 1.4428).

Reduction of Hydroperoxide II. A solution from photooxygenation of 7.1 g (0.085 mol) of TME (O_2 uptake 1660 cc, 0.074 mol) was reduced by the addition of excess sodium borohydride. The crude product was purified by vpc to give alcohol III, with ir (CCl_4) bands at 2.75, 2.86, 3.24, 6.10, 6.92, 7.30, 7.37, 7.63, 8.62, 10.42, 10.70, and 11.10 μ . The nmr spectrum had bands at τ 8.70 (singlet, 6 H), 8.22 (singlet, 3 H), 6.35 (singlet, 1 H), 5.32 (singlet, 1 H), and 5.05 (singlet, 1 H); mass spectrum (*m/e* of molecular ion), calcd for $C_8H_{12}O$: 100.08881; found: 100.08881.

Photosensitized Oxygenation of 1,3-Cyclohexadiene.¹⁸ A solution of 3.206 g of cyclohexadiene IV (Aldrich, 40 mmol) and 30 mg of rose bengal in 250 ml of methanol was irradiated; 913 cc of oxygen (40 mmol) was absorbed in 8 min. The irradiated solution was evaporated below room temperature and the resulting 4.00 g of syrup taken up in ether. A reddish precipitate was filtered off and the yellow ethereal solution dried. After removal of solvent, 3.47 g of semisolid material was obtained. A portion (0.528 g) of this semisolid was distilled (bulb to bulb at 1 μ) yielding 0.226 g of liquid containing waxy solid. Both phases were investigated by nmr and ir and found to be identical in spectral characteristics. The yield of peroxide V was 35%. No attempt was made to obtain pure crystalline material. The principal ir bands (CCl_4) were 7.28, 8.25, 8.60, 9.50, 10.40, 10.80, 13.80, and 14.60 μ . The nmr spectrum (CCl_4) was at τ 3.43 (overlapping doublets), 5.47 (broad), and 8.26 (multiplet) in the ratio 1:1:2, assigned to vinylic, bridgehead, and methylene protons, respectively.

Hypochlorite-Hydrogen Peroxide Oxygenation of 1,3-Cyclohexadiene. A solution of 3.21 g (40 mmol) of IV in 250 ml of methanol was chilled to -5° and treated with 25.6 cc (240 mmol) of 9.36 M H_2O_2 , followed by 168 ml (150 mmol) of 0.89 M NaOCl solution at -5 to -10°. Evolved O_2 amounted to 2640 cc at 23° (109 mmol). The reaction mixture was diluted with water and extracted with ether. The solvent was removed from the dried ether extracts on a rotary evaporator and the residue (1.18 g) purified by bulb-to-bulb distillation at $\sim 1 \mu$. The product, *endo*-peroxide V, weighed 0.88 g (7.85 mmol, 19.6%) and had nmr and ir spectra identical with that produced by photooxygenation.

Oxygenation of Tetraphenylcyclopentadienone with Hypochlorite-Hydrogen Peroxide. Tetraphenylcyclopentadienone³⁷ (VI) (mp 219–220°), 0.17 g (0.44 mmol), was dissolved in 125 ml of dioxane, cooled in ice water, and treated with 5.0 ml of 8.8 M H_2O_2 (44 mmol). To this solution 32.8 ml of 0.67 M NaOCl solution (22 mmol) was added dropwise with stirring. Only a small amount of color remained. The solution was extracted with benzene and the solvent evaporated. The resulting crystals were recrystallized from ethanol and yielded 0.085 g of *cis*-dibenzoylstilbene (VII) (0.22 mmol, 50%), mp 215.9–216.3° (lit.¹⁹ 215–216°). The ir spectrum (in $CHCl_3$) was in good agreement with that reported¹⁹ (a Nujol mull spectrum).

Photooxygenation of Anthracene. Anthracene (Eastman, blue-violet fluorescence), 0.535 g (3 mmol), and 50 mg of methylene blue were dissolved in 250 ml of freshly prepared, purified³⁸ $CHCl_3$ and irradiated. The lamp was operated at 60 V to remove any small amount of uv light and to keep the solution temperature low. In 10 min, 58 cc (2.4 mmol) of O_2 was absorbed, and the rate of absorption had decreased appreciably. The solution was filtered through silica gel to remove the dye. The colorless solution was evaporated to dryness and the residue recrystallized from purified $CHCl_3$. The first crop of crystals (needles, mp 139–143°, 0.19 g, 0.91 mmol, 30% yield) was almost pure anthracene peroxide (X) (lit.²⁰ mp 120° dec).

Anal. Calcd for $C_{14}H_{10}O_2$: C, 79.98; H, 4.79. Found: C, 79.89; H, 4.71.

The principal ir bands (Nujol mull) were at 7.57, 7.75, 8.12, 8.33, 8.56 m, 8.71, 9.00, 9.86, 10.10, 10.25, 10.55, 11.14, 11.26, 11.42, 11.51 m, 11.63 m, 11.82, 12.12 m, 12.25, 12.42 m, 13.02 s,

(37) E. C. Horning, Ed., "Organic Syntheses," Coll. Vol. III, John Wiley and Sons, Inc., New York, N. Y., 1955, p 806.

(38) L. F. Fieser, "Experiments in Organic Chemistry," D. C. Heath and Co., Boston, Mass., 1957, p 283.

(34) C. S. Foote and S. Wexler, *J. Amer. Chem. Soc.*, **86**, 3880 (1964).

(35) Infrared (ir) spectra were recorded on a Perkin-Elmer Model 137 spectrophotometer. Nuclear magnetic resonance (nmr) spectra were recorded on a Varian A-60 spectrometer. Molecular weights were determined on a Mechrolab vapor pressure osmometer using benzene as the solvent and benzil as the standard. Melting points were determined on a Fisher-Johns melting block and are corrected except where otherwise indicated. Gas chromatography was carried out on a Perkin-Elmer Model 800, a Varian Aerograph HI-FI III (flame ionization), or an Aerograph A90-P (thermal conductivity) instrument. Elemental analyses were performed by Miss H. King (UCLA), and methoxyl determinations were done by Elek Laboratories, Los Angeles, Calif.

(36) I. M. Kolthoff and R. Belcher, "Volumetric Analysis," Vol. 3, Interscience Publishers, Inc., New York, N. Y., 1957, p 283.

and 13.42 μ . All the above bands are weak except those marked m (medium) and s (strong). The nmr spectrum (CDCl_3) had bands at τ 2.64 (multiplet) and 3.98 (singlet, bridgehead protons) in the ratio 4:1.

Oxygenation of Anthracene with Hypochlorite-Hydrogen Peroxide. Anthracene, 0.535 g (3 mmol), was dissolved in 100 ml of *p*-dioxane and treated with 6.4 ml (60 mmol) of 9.38 *M* H_2O_2 at 10–15°. Over a period of 30 min, 79.5 ml of 0.32 *M* (50 mequiv) $\text{Ca}(\text{OCl})_2$ solution was added at 5–10°, with vigorous stirring. The O_2 evolved was roughly 1350 cc (55 mmol). The reaction mixture was diluted with water and extracted with chloroform. The dried chloroform extracts were evaporated. The residue (0.535 g) was taken up in hot chloroform and successive crops of crystals were separated by filtration. The first crops were mainly anthracene. The third and fourth crops (0.5 g) were combined and extracted with carbon tetrachloride. The undissolved residue, 32 mg (5.1%), of yellowish powder, had ir and nmr spectra identical with that of anthracene peroxide (X) produced by photooxygenation.

Hypochlorite-Hydrogen Peroxide Oxygenation of 2,5-Dimethylfuran. A solution of 3.01 g (0.031 mol) 2,5-dimethylfuran in 250 ml of methanol was chilled to 5° and 3.0 ml of 9.75 *M* H_2O_2 (0.0292 mol) added. The solution was stirred and 21 ml of 0.67 *M* NaOCl solution (0.0141 mol) was added dropwise in 10 min. The reaction mixture was evaporated under reduced pressure and below 0° to about 20 ml, and ice was added. The mixture was extracted with three 30-ml portions of cold ether. The residue after evaporation of the ether was recrystallized from ether to give 1.89 g (0.0118 mol) of the methoxyhydroperoxide XII (84% yield based on NaOCl used), mp 75–77°. The nmr and ir spectra were identical with those of the product of photooxygenation, mp 75–76°. ²¹

Photooxygenation of $\Delta^{9,10}$ -Octalin. ²² A solution of 1.0 g of $\Delta^{9,10}$ -octalin³⁹ (7.3 mmol) and 45 mg of rose bengal in CH_3OH was irradiated. Within 5 min, 162 cc (7.2 mmol) of O_2 had been taken up, and the reaction became very slow. The solvent was removed, and the product taken up in ether, washed with water, and dried. The product was recrystallized from hexane to give crystals, mp 55–58° (lit.¹⁷ mp 60°). The ir spectrum had principal bands at 2.72, 2.85, 3.35, 3.45, 6.90, 7.83, 8.43, 8.52, 8.71, 10.00, 10.49, 11.09, 11.69, and 11.85 μ .

Hypochlorite-Hydrogen Peroxide Oxygenation of $\Delta^{9,10}$ -Octalin. To a stirred solution of 1.0 g of $\Delta^{9,10}$ -octalin (7.3 mmol) and 2.4 ml of 30% aqueous H_2O_2 (22.2 mmol) in 45 ml of ethanol at 10° was added 20.8 ml of 0.89 *M* NaOCl (18.5 mmol) during 1 hr. At the end of this time, an additional 22.2 mmol of H_2O_2 and then 18.5 mmol of NaOCl were added. The solution was extracted with ether, the ether was dried and evaporated, and the product was recrystallized from hexane to give 0.069 g (6%) of the hydroperoxide, mp 54–57°, with infrared spectrum identical with that of the photooxygenation product. Substantial work-up and crystallization losses were encountered, and the actual product yield was much higher. A second oxidation with 2-propanol as solvent gave a 12% yield of peroxide, with work-up losses again being substantial.

Quantitative Analysis of Oxygenation Products. A. Photooxygenation. A weighed quantity of TME was dissolved in the solvent; an aliquot of a stock solution of rose bengal was added and the solution diluted to a known volume. After irradiation, the hydroperoxide was reduced with a tenfold excess of trimethyl phosphite.⁴⁰

(39) R. A. Benkeser and E. M. Kaiser, *J. Org. Chem.*, **29**, 955 (1964).

(40) D. B. Denny, W. F. Goodyear, and B. Goldstein, *J. Amer. Chem. Soc.*, **82**, 1393 (1960); M. S. Kharasch, R. A. Mosher, and I. S. Bengelsdorf, *J. Org. Chem.*, **25**, 1000 (1960). Yields determined by oxygen absorption agree well with product yields measured by this technique, but are less accurate.

The solution was left overnight and analyzed directly with a flame-ionization gas chromatograph using isoamyl alcohol, dioxane, or *n*-decane as internal standard. The detector was calibrated by injection of solutions containing weighed amounts of the internal standard and the pure product alcohol.

B. Chemical Oxygenation. A weighed quantity of TME was dissolved in the solvent and an aliquot of 30% H_2O_2 added; the solution was then diluted to the desired volume and transferred to a three-necked flask equipped with a magnetic stirrer, a septum, and, if required, a gas buret. The flask was immersed in a bath at the required temperature and allowed to reach equilibrium. Aqueous hypochlorite was then added with an all-glass syringe through a capillary reaching below the surface. The solution was then reduced, using enough excess reductant to consume any remaining H_2O_2 , and analyzed in the same manner as with the photooxygenation experiments. In some cases, sodium borohydride was used as the reductant; in these cases, a small amount of the saturated alcohol (2,3-dimethyl-2-butanol) was also produced, apparently by hydroboration of the olefin. Control experiments showed that this alcohol could be produced (in low yield) by the addition of borohydride to solutions containing only olefin and hydrogen peroxide.

Dependence of Product on NaOCl. To a 0.39 *M* solution of TME in methanol at –20° containing 0.18 *M* H_2O_2 were added various amounts of NaOCl solution. The yield of product is summarized in Table II.

Table II

Amount of NaOCl added, mmol	Concn of NaOCl added, <i>M</i>	Yield of product based on NaOCl, %
1.13	1.51	64
1.51	1.51	69
3.02	1.51	70
4.53	1.51	64
6.04	1.51	65
1.51	0.30	69

Solvent Effect. To 100 ml of the chosen solvent containing H_2O_2 and ca. 0.15 *M* tetramethylethylene was added a measured amount of 1 *M* NaOCl. Yields of product determined by the usual technique are shown in Table III.

Table III

Solvent	Temp, °C	$[\text{H}_2\text{O}_2]$, <i>M</i>	Product yield, %
Methanol	–20	0.18	61
Methanol	25	0.18	40
Ethanol	–20	0.18	69
Isopropyl alcohol	–20	0.18	38.4
<i>t</i> -Butyl alcohol	25	0.18	7.5
Methanol- <i>t</i> -butyl alcohol 1:1 (v/v)	25	0.18	35
Tetrahydrofuran	25	0.45	5.5
Dioxane	25	0.45	2.3
Acetonitrile	25	0.45	1
Methanol	3	0.50	28
Methanol	3	0.90	4.6