SYNTHETIC APPLICATIONS OF

DISCHARGE-GENERATED SINGLET OXYGEN

by

M. DENNIS OUCHI

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ABSTRACT

The electric discharge method of generating singlet molecular oxygen was demonstrated to be a useful technique for preparative scale oxygenations of suitable organic substrates. Representative examples of known singlet oxygen acceptors were exposed to discharge-generated singlet oxygen while dissolved in organic solvents at -78° or adsorbed onto solid supports at room temperature. Typical oxygenation products were obtained in generally good yields. The various known methods of generating singlet molecular oxygen and the relative advantages and disadvantages of the electric discharge method are discussed.

Adsorption of substrates onto solid surfaces appears to have no effect on the course of the addition of singlet oxygen to the organic moiety. The success of this technique is perhaps due to the increase in the surface area of contact between the substrate and singlet oxygen.

Exploratory oxygenations of 1,4-dienes and epoxides adsorbed onto solid surfaces were all unsuccessful.

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ACKNOWLEDGEMENT

I. INTRODUCTION

A. Oxidation by Molecular Oxygen

Oxygen, because of its key role in terrestial life processes, is the singularly most extensively studied molecule in the fields of chemistry and biochemistry. The accumulation of experimental observations over the past centuries has shown that organic substrates undergo two general types of reactions with molecular oxygen:[1] (1) radical mediated autoxidations and (2) sensitized photooxygenations.

Radical autoxidation reactions require some type of chemical or ultraviolet radiation to initiate the formation of radicals which control the degradative oxidation of a wide variety of organic substances in chain processes. When the concentration of the initial oxidation products, usually peroxides and hydroperoxides, builds up beyond a critical value, the initially slow reaction can rapidly accelerate to combustion rates, yielding simply water, carbon dioxide, and carbon monoxide as final products. Since these are chain processes, the quantum yields are generally much greater than unity and are inversely proportional to the square root of the light intensity.[2]

Sensitized photooxygenation reactions, on the other hand, require the presence of a "sensitizer" (a dye or natural pigment) as well as light and molecular oxygen. The quantum yields are no greater than unity and are independent of the light intensity.[2,3] The sensitizer absorbs low energy light and interacts with molecular oxygen to form an active intermediate which transfers a molecule of "active" oxygen to the acceptor to give the product peroxide. The field of sensitized photooxygenation reactions has been thoroughly reviewed in articles by Bowen,[4] Arbuzov,[5] Gollnick and Schenck,[6] Gollnick,[7] and Foote.[8]

B. History of the Sensitized Photooxygenation Reaction

The dye-sensitized damage or destruction of biological systems by light in the presence of oxygen has been known since 1900.[9] This phenomenon, which is commonly known as "photodynamic action", is attributed to irreversible oxidative degradation of essential cellular components.[10] Straub[11] and Noack[12] suggested that the sensitizing dye perhaps forms intermediate peroxides which transfer oxygen to a substrate and regenerate the original dye.

Ascaridole, a natural peroxide first isolated by Gutig[13] in 1908 from chemopodium oil, was believed to be synthesized in plants from α-terpinene (Eq. 1). Although attempts to autoxidize the diene yielded only polymers,[14]
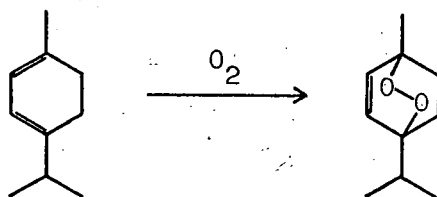
$$\text{Eq. 1}$$

Schenck[15] in 1944 succeeded in photooxygenating it to ascaridole in the presence of various sensitizers in various solvents. He proposed that a similar oxygenation process occurs in vivo under the photosensitizing influence of chlorophyll.

One of the first known "artificial" photoperoxides was synthesized by Moureau and Dufraisse[16] in 1926. They found that dilute solutions of rubrene in various solvents rapidly lost their colour on exposure to light and air. The product, which was later established[17,18] to be the transannular peroxide, decomposed, when heated, to the original hydrocarbon with accompanying luminescence and evolution of oxygen gas (Eq. 2). This unique
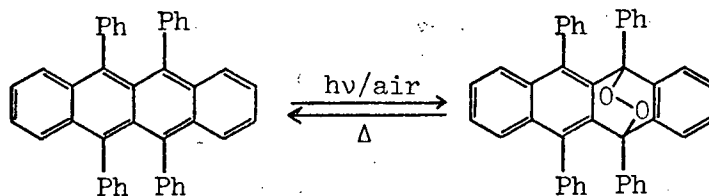
$$\text{Eq. 2}$$

reversible binding of oxygen, which at least superficially parallels the

action of haemoglobin in vivo, initiated a great deal of interest in

photosensitized oxygenation from a biochemical as well as a chemical

point of view.

Since these initial observations, photosensitized oxygenation of a

variety of organic substrates has been extensively investigated for both

synthetic and mechanistic purposes.[4-8]

C. Mechanism of the Sensitized Photooxygenation Reaction

The earliest mechanistic studies were by Gaffron[19-22] starting in

1926. In the direct photooxygenation (i.e. the substrate also acts as the

sensitizer) of rubrene, he showed that two molecules of rubrene are re-

quired for the formation of one molecule of stable endoperoxide (Eq. 3).

$$2Ru + O_2 \xrightarrow{h\nu} RuO_2 + Ru \qquad\qquad Eq. 3$$
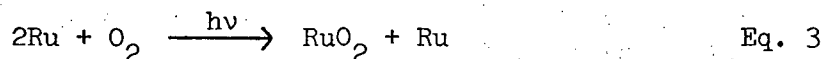
He postulated an acceptor-activation mechanism in which the important

step was the formation of an activated double molecule of rubrene (Eq. 4-6).

$$Ru \xrightarrow{h\nu} Ru^* \qquad\qquad Eq. 4$$

$$Ru^* + Ru \longrightarrow (Ru)_2^* \qquad\qquad Eq. 5$$

$$(Ru)_2^* + O_2 \longrightarrow RuO_2 + Ru \qquad\qquad Eq. 6$$
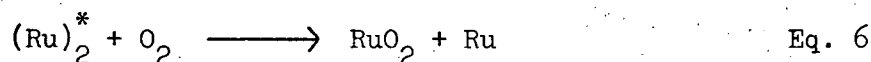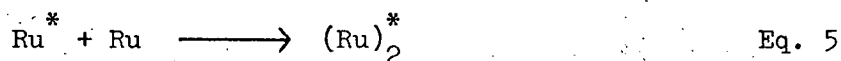
Although Gaffron's mechanism adequately explained the direct photo-

oxygenation of rubrene, it could not be extended on a general basis to

indirect (dye-sensitized) photooxygenation reactions. Because the absorp-

tion bands of many substrates are at shorter wavelengths than those of the

dyes used, the excited dye molecules do not have sufficient energy to

electronically excite the acceptor molecules.

Schönberg[23] in 1935 postulated instead that the excited sensitizer

(either the substrate or added dye) reacts with triplet oxygen to form a sensitizer-oxygen complex. This "moloxide" then transfers the oxygen molecule to the substrate to give the product peroxide and regenerate the sensitizer. This mechanism was strongly advocated by Schenck,[24-28] who is probably the main contributor to the field of photosensitized oxygenations.

An alternate mechanism was proposed by Kautsky[29-33] in 1931. He assumed that the interaction of excited sensitizer with triplet oxygen results not in the formation of a sensitizer-oxygen complex but rather in physical transfer of energy from the sensitizer to oxygen to give singlet oxygen and the deactivated sensitizer. Singlet oxygen then reacts with the acceptor to give the product peroxide. Kautsky elegantly demonstrated the validity of his mechanism by showing that, when substrate and sensitizer were adsorbed onto physically separate grains of silica gel and the system exposed to light in the presence of oxygen, the substrate was efficiently oxygenated. Evidently some gaseous intermediate, presumably singlet oxygen, was able to diffuse across the space separating sensitizer and substrate.

Both the energy-transfer mechanism and the complex-formation mechanism are consistent with the kinetic studies which have been carried out.[4,24,34,35] The only significant difference lies in the nature of the active oxygenating intermediate: a sensitizer-oxygen complex or singlet molecular oxygen (Eq. 7-10).

$$S \xrightarrow{h\nu} {}^1S \qquad \text{Excitation} \qquad \text{Eq. 7}$$

$$ {}^1S \longrightarrow {}^3S \qquad \text{Intersystem Crossing} \qquad \text{Eq. 8}$$

$$ {}^3S + {}^3O_2 \longrightarrow S\text{-}O_2 \qquad \text{Complex Formation} \qquad \text{Eq. 9a}$$

$$S\text{-}O_2 + A \longrightarrow S + AO_2 \qquad \text{Termination} \qquad \text{Eq. 10a}$$

$$ {}^3S + {}^3O_2 \longrightarrow S + {}^1O_2 \qquad \text{Energy Transfer} \qquad \text{Eq. 9b}$$

$$ {}^1O_2 + A \longrightarrow AO_2 \qquad \text{Termination} \qquad \text{Eq. 10b}$$
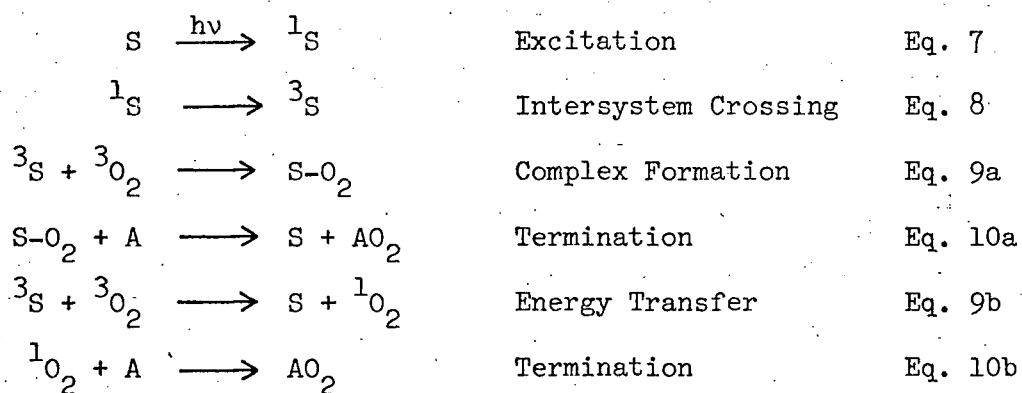
Although most workers preferred to believe in the sensitizer-oxygen complex, the controversy remained unresolved until more thorough investigations of the physical and chemical properties of singlet molecular oxygen were carried out.

D. Theoretical Description of Singlet Molecular Oxygen[36,37]

The three lowest energy electronic states of molecular oxygen ($^3\Sigma_g^-$, $^1\Delta_g$, and $^1\Sigma_g^+$) all arise from the same electronic configuration. They differ only in the way two of the sixteen electrons occupy the pair of degenerate antibonding orbitals. The arrangement of the two electrons in the set of "real" orbitals π_x^* and π_y^* is shown pictorially with circles and arrows below:[37]

$$
\begin{array}{ccc}
 & \pi_x^* & \pi_y^* \\
^1\Sigma_g^+ & \bigcirc & (\uparrow\downarrow) \\
^1\Delta_g & (\uparrow\downarrow) & \bigcirc \\
 & (\uparrow) & (\downarrow) \\
^3\Sigma_g^- & (\uparrow) & (\uparrow)
\end{array}
$$
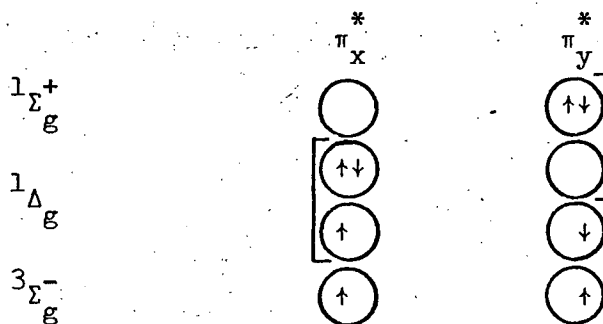
The ground state $^3\Sigma_g^-$ has the two electrons with spins parallel (triplet state) but opposite orbital angular momentum (Σ state). This state is responsible for the diradical behavior and paramagnetic properties of molecular oxygen.

The next two electronic states, which are 22.5 kcal and 37.5 kcal above the ground state, both have the two electrons with spins paired (singlet states). In the lower singlet state, both electrons have their orbital angular momenta in the same direction. This state is therefore a doubly degenerate Δ state (orbital angular momentum quantum number is ±2). The upper singlet state, like the ground state, has zero orbital angular

momentum (Σ state).

Any perturbation which destroys the cylindrical symmetry of the molecule (e.g. the approach of a second molecule) results in the mixing of the $^1\Sigma_g^+$ state with one of the $^1\Delta_g$ components (the upper one in the diagram). Since this perturbation always stabilizes the $^1\Delta_g$ component at the expense of the $^1\Sigma_g^+$ state, this $^1\Delta_g$ component becomes the most energetically favorable state for concerted addition reactions.[36] The other component has its electrons in separate orbitals and should react as a "diradical" similar to the ground state. The $^1\Sigma_g^+$ state, having both electrons in the same orbital, would not be expected to undergo one-electron free-radical reactions. In fact, it probably displays a repulsive interaction with all approaching molecules.[37]

E. Discovery of Singlet Molecular Oxygen

The visible red emission produced in the decomposition reaction of hydrogen peroxide with hypochlorite salts or alkaline bromine or chlorine was first noted by Mallet[38] in 1927. The significance of this observation was not appreciated for the next several decades, even though it was mentioned occasionally in the literature.[39-41] In 1960, Seliger's report[42] that the spectrum of this emission consisted of a narrow band centred at 6348 $\overset{o}{A}$ focused new attention on this chemiluminescence phenomenon. Khan and Kasha[43] later observed a second band at 7032 $\overset{o}{A}$ in addition to one at 6334 $\overset{o}{A}$. The 1567 cm^{-1} spacing between these two bands closely corresponded to the ground state lowest vibrational spacing of molecular oxygen (1556 cm^{-1}), thus implicating the involvement of molecular oxygen in the emission. They tentatively assigned the two peaks to the (0,0) and (0,1) bands of the oxygen $^1\Sigma_g^+ \rightarrow {}^3\Sigma_g^-$ transitions shifted by solvation.

Meanwhile, Ogryzlo and coworkers[44] were studying the emission spectrum of gaseous oxygen subjected to electric discharge. Mass spectrometric,[45]

calorimetric,[46] and spectroscopic[47] studies of this system had shown that

the oxygen gas stream contained about 10% $O_2(^1\Delta_g)$ and about 0.1% $O_2(^1\Sigma_g^+)$.

The spectrum consisted of not only the two known sharp bands at 7600 Å

and 8600 Å from the (0,0) and (0,1) transitions in the $^1\Sigma_g^+ \rightarrow {}^3\Sigma_g^-$ system,

but also the same two diffuse bands observed by Khan and Kasha. Ogryzlo

reinvestigated the hydrogen peroxide-hypochlorite system and observed an

additional extemely weak band at 7600 Å corresponding to the $^1\Sigma_g^+ \rightarrow {}^3\Sigma_g^-$

emission. Since the 6340 Å and 7030 Å bands obviously could not belong to

the $^1\Sigma_g^+ \rightarrow {}^3\Sigma_g^-$ system, Ogryzlo assigned them to unique one-photon double-

molecule transitions previously postulated by Ellis and Kneser[48] in their

interpretation of the liquid oxygen absorption spectrum. Two excited $(^1\Delta_g)$

oxygen molecules in a collisional complex undergo simultaneous deactivation

with the energies of both molecules released in a single photon (Eq. 11).

$$2(^1\Delta_g) \longrightarrow 2(^3\Sigma_g^-) + h\nu \qquad \text{Eq. 11}$$
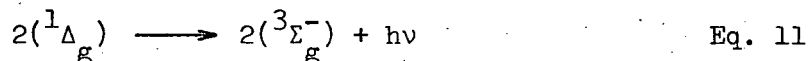
This assignment has since been corroborated by the observation that the

intensities of these two bands depends on the square of the $O_2(^1\Delta_g)$ con-

centration.[49-51] Thus, Ogryzlo's interpretation of the emission spectra

of oxygen in the hydrogen peroxide-hypochlorite and electric discharge

systems had revealed that excited singlet oxygen could be conveniently

generated in both systems.

F. Identification of the Active Intermediate in the Sensitized

Photooxygenation Reaction

Organic chemists were prompt to utilize the two methods of generating

singlet molecular oxygen to clarify the mechanism of the dye-sensitized

photooxygenation reaction.

Foote[52] in 1964 demonstrated that singlet oxygen produced in the

hypochlorite-hydrogen peroxide system reacts with a wide variety of sub-
strates to give products identical to those of the sensitized photooxygen-
ation reaction. In addition to synthesizing typical photoproducts in
synthetically useful yields, he subsequently compared product distributions
and stereoselectivity, relative reactivities of acceptors, and the ratio
of the decay rate to the reaction rate of the intermediate for the two
reactions.[53-55] All comparisons were shown to be identical within exper-
imental error.

Meanwhile, Corey and Taylor[56] also effected the oxygenation of several
typical photooxygenation substrates using radiofrequency discharge-gener-
ated singlet oxygen. Although the system at this time was relatively
inefficient (low yields and inconveniently long reaction times) and the
number of successfully oxygenated substrates very limited, the results at
least served to illustrate that the same products arise from photooxygen-
ation and discharge-generated singlet oxygen.

Foote's and Corey's work provided overwhelming, though only circum-
stantial evidence in favor of Kautsky's energy-transfer mechanism for the
sensitized photooxygenation reaction.

More direct evidence was provided by Kautsky's original experiments[29-32]
which demonstrated that the intermediate must be gaseous in order to
bridge the space between physically separated substrate and sensitizer.
These experiments have recently been refined by two groups of workers,[57,58]
but the results are essentially the same as Kautsky's.

Perhaps the most direct and compelling evidence in favor of the
involvement of singlet oxygen in the sensitized photooxygenation reaction
was the detection by physical methods of $O_2(^1\Delta_g)$ generated by gas-phase
photosensitization with aromatic hydrocarbons. Falick[59] was the first to
observe the characteristic four-line electron paramagnetic resonance

spectrum of $O_2(^1\Delta_g)$ due to the orbital magnetic moment of the electrons in gaseous oxygen subjected to an electric discharge. Kearns[60] and Wasserman[61] simultaneously reported the observation of this characteristic spectrum in gaseous mixtures of naphthalene or naphthalene derivatives and oxygen subjected to ultraviolet irradiation. The formation of singlet $(^1\Delta_g)$ oxygen by this process was found to be highly efficient ($\Phi \approx 0.5$).[60] Although these experiments were restricted to the gas-phase, they provided strong support for the energy-transfer mechanism in the sensitized photo-oxygenation reaction in solution.

Finally, after decades of dormancy, Kautsky's singlet oxygen mechanism is receiving the recognition it deserves from workers in the field of the senitized photooxygenation reaction.

Theoretically, both singlet states of oxygen may be generated if the triplet energy of the sensitizer is sufficiently high ($E_t > 38$ kcal).[62] However, $O_2(^1\Sigma_g^+)$ is so quickly relaxed by collisions to $O_2(^1\Delta_g)$ that it is not likely to have a chance to react. On the other hand, $O_2(^1\Delta_g)$ has a lifetime long enough to be consistent with that of the active intermediate.[55,37] Many effective sensitizers have triplet energies significantly lower than 38 kcal and can therefore generate only $O_2(^1\Delta_g)$. In addition, the chemistry of the intermediate is identical to that of $O_2(^1\Delta_g)$ generated by electric discharge and decomposition of hydrogen peroxide. There appears to be little doubt that the active intermediate is $O_2(^1\Delta_g)$ and not $O_2(^1\Sigma_g^+)$.

II. CHEMICAL REACTIVITY OF SINGLET OXYGEN

Singlet molecular oxygen is known to be a highly selective reagent which undergoes no reaction at all with most organic compounds. Of those substrates found to be reactive, two types have received particularly thorough study:[4-7,54,55] (1) Conjugated 1,3-dienes give 1,4-endoperoxides as initial products which often undergo subsequent rearrangement and (2) olefins containing an allylic hydrogen give α,β-unsaturated hydroperoxides in which the double bond has migrated to the allylic position. A third and more recently studied reaction of singlet oxygen is the direct 1,2-cycloaddition to an olefin to give carbonyl fragments via a dioxetane intermediate.

A. 1,4-Cycloaddition (Diels-Alder Reaction)

Singlet oxygen adds directly to the 1,4-positions of most conjugated 1,3-dienes, including cyclic and s-cis-dienes, heterocycles (furans, pyrroles, thiophenes, oxazoles,etc.), and polycyclic aromatics, to give 1,4-endoperoxides as initial products(Eq. 12). Molecular orbital and state
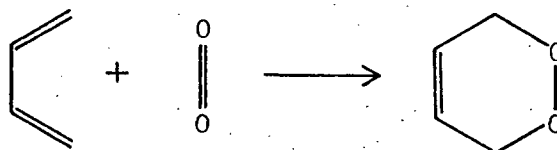
correlations clearly predict that the concerted 1,4-cycloaddition of singlet oxygen to s-cis-dienes is thermally allowed in a manner analagous to the Diels-Alder reaction of olefins.[36] The initial addition products often undergo facile rearrangement and/or reaction with solvent to give more stable products. Representative examples of the 1,4-cycloaddition reaction of singlet oxygen with 1,3-dienes are as follows (Eq. 13-16):

α-Terpinene:[15]
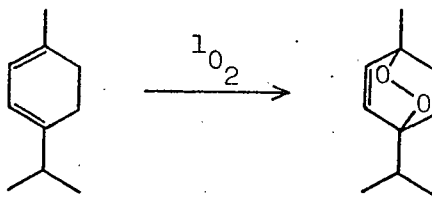
Eq. 13

Tetraphenylcyclopentadienone:[55a,62]
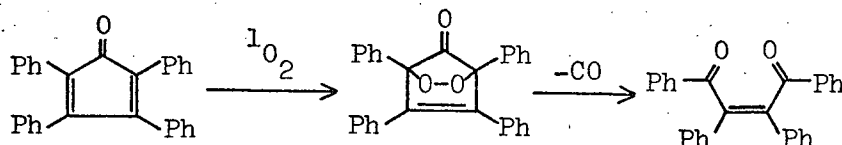
Eq. 14

1,3-Diphenylisobenzofuran:[63,64]
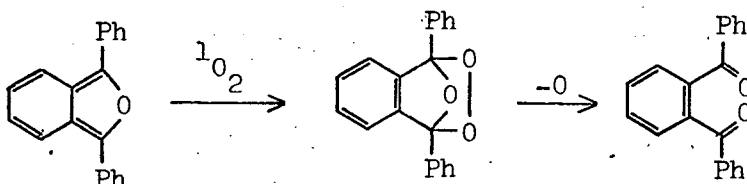
Eq. 15

9,10-Diphenylanthracene:[65,66]
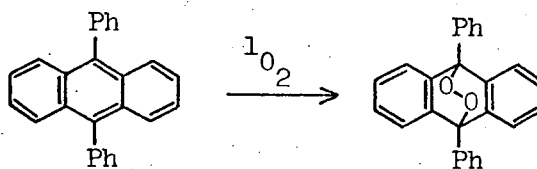
Eq. 16

B. 1,3-Cycloaddition (Ene-Type Reaction)

Singlet oxygen reacts with olefins which contain an allylic hydrogen to give α,β-unsaturated hydroperoxides in which the double bond has shifted to the allylic position of the original olefin (Eq. 17). This reaction of
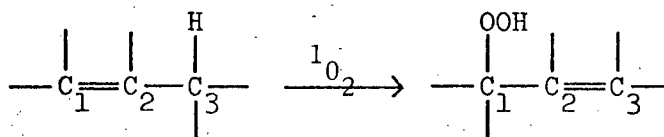
Eq. 17

singlet oxygen is analagous to the well-known ene-reaction of olefins.[67]

Most of the experimental evidence favors a concerted mechanism involv-
ing a cyclic six-membered transition state.[7,55b] Invariably the double
bond is shifted to the allylic position, thereby ruling out any mechanism
involving hydrogen abstraction as the first step to form an allylic radical,
which would give a mixture of two hydroperoxides (Eq. 18)..

Eq. 18
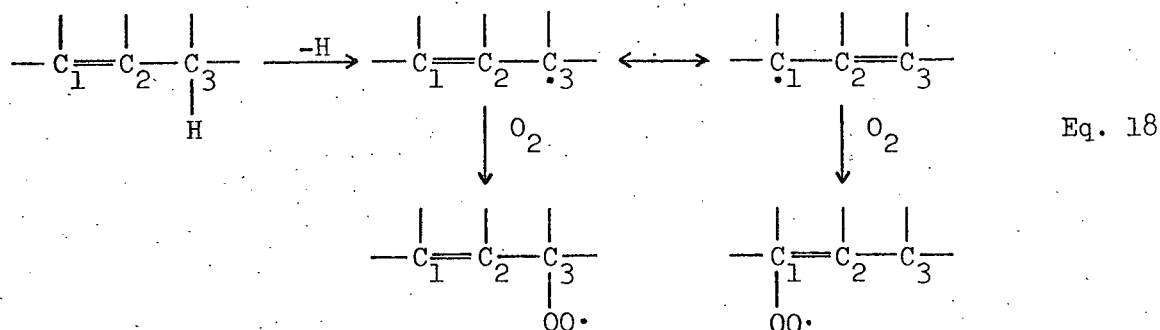
The migrating hydrogen has been shown to be abstracted from the same
side of the double bond to which the oxygen becomes attached.[68,69] Photo-
sensitized oxygenations of cholesterols deuterated at the 7α- and 7β-posi-
tions showed almost exclusive migration of the 7α-hydrogen (Eq. 19).

Eq. 19
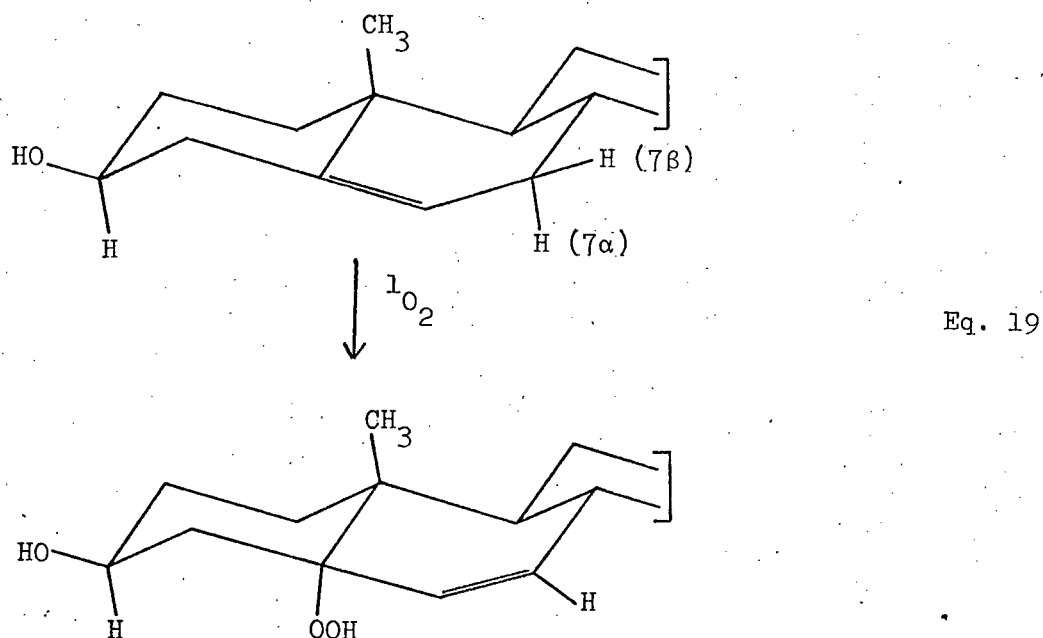
Since the β-methyl group at C_{10} sterically hinders β-attack by oxygen, the

oxygen attack on the double bond must be _cis_ to the migrating hydrogen.

This stereoselective hydrogen abstraction can be rationalized by a two

step mechanism in which the oxygen first attacks the double bond to give a

diradical or ionic intermediate which then stereoselectively abstracts an

allylic hydrogen atom or proton.[7] However, the absence of any definite

Markovnikov directing effect with nonsterically hindered unsymmetric double

bonds provides strong evidence against any ionic or diradical intermediate.

[55b] For example, 2-methyl-2-butene gives almost equal amounts of secon-

dary and tertiary alcohols after reduction (Eq. 20). Ionic or radical
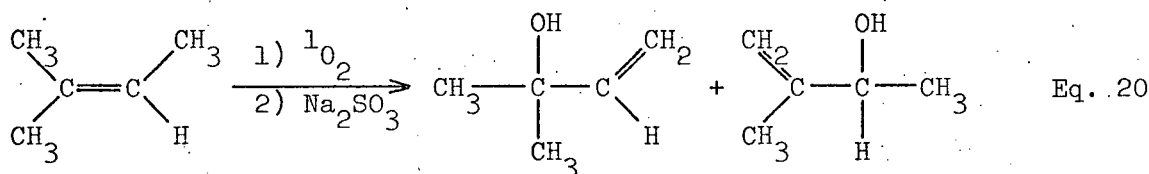
intermediates would also be expected to exhibit a noticeable substituent

effect on product distribution. However, the photosensitized or chemical

oxygenation of trimethylstyrene gave the same product distribution with a

variety of _meta_ and _para_ substituents (Y) on the phenyl ring[55b] (Eq. 21).
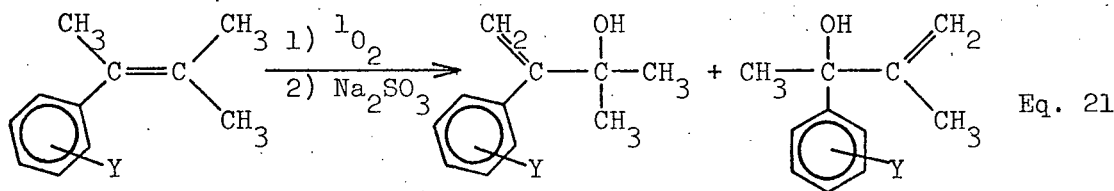
Polar solvents would be expected to stabilize ionic intermediates, but no

solvent effect was observed on the ratio of the decay rate to the reaction

rate of the intermediate. The stereoselectivity of the reaction and the

lack of a Markovnikov-type directing effect, substituent effect, or solvent

effect are consistent with a concerted cycloaddition of singlet oxygen to

the olefin exactly analagous to the mechanism of the ene-reaction of

olefins[55b] (Eq. 22).

$$\text{(structure)} \xrightarrow{^{1}O_2} \text{(structure)} \longrightarrow \text{(structure)} \qquad \text{Eq. 22}$$
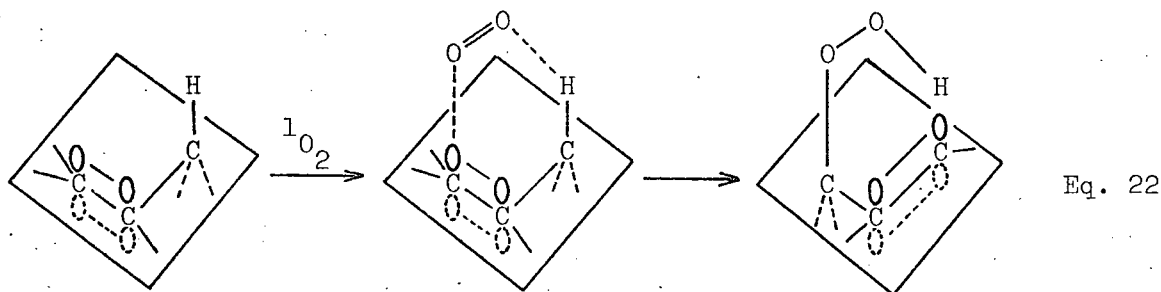
Fenical and coworkers[70] have recently reported evidence against this concerted mechanism. Photooxygenation of tetramethylethylene and 1,2-dimethylcyclohexene in the presence of sodium azide gave azido-alcohols as the major products after reduction (Eq. 23 and 24). The normal oxygenation

$$\begin{array}{c}\text{CH}_3 \quad\quad \text{CH}_3 \\ \text{C}=\text{C} \\ \text{CH}_3 \quad\quad \text{CH}_3\end{array} \xrightarrow[\text{2) Na}_2\text{SO}_3]{\text{1) }^{1}\text{O}_2\text{-N}_3^-} \begin{array}{c}\text{CH}_3 \;\; \text{CH}_3 \\ \text{CH}_3-\overset{|}{\underset{|}{\text{C}}}-\overset{|}{\underset{|}{\text{C}}}-\text{CH}_3 \\ \text{N}_3 \quad \text{OH}\end{array} + \begin{array}{c}\text{CH}_2 \quad\quad \text{OH}\\ \text{C}-\overset{|}{\underset{|}{\text{C}}}-\text{CH}_3 \\ \text{CH}_3 \quad \text{CH}_3 \end{array} \qquad \text{Eq. 23}$$

$$\text{(structure with CH}_3\text{)} \xrightarrow[\text{2) Na}_2\text{SO}_3]{\text{1) }^{1}\text{O}_2\text{-N}_3^-} \text{(structure with CH}_3, \text{N}_3, \text{OH, CH}_3\text{)} \qquad \text{Eq. 24}$$
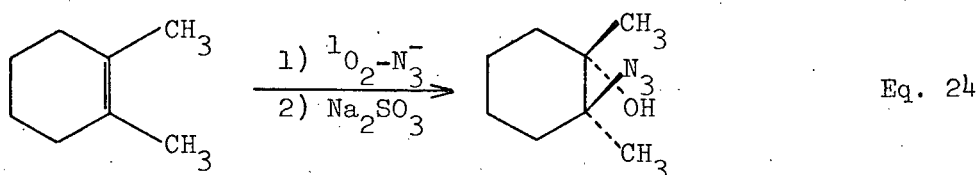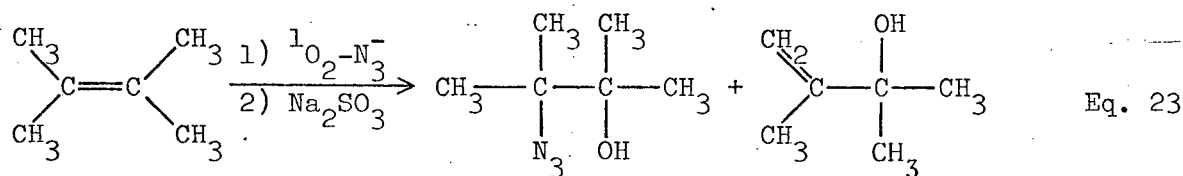
products of these acceptors were found to be unreactive towards azide ion. Since the formation of the azido-compounds is consistent only with a reaction path which involves an intermediate susceptible to nucleophilic attack by azide ion, they ruled out the concerted ene-type mechanism as a possible route to allylic hydroperoxides.

However, an alternate explanation of their results does not rule out the concerted mechanism (Eq. 25). If the allylic hydroperoxide is formed by a concerted cycloaddition mechanism (path a), while a species which is susceptible to nucleophilic attack is also formed in rapid equilibrium with the reactants, attack of this species by azide ion could give the azido-

hydroperoxide (path b). Two possible structures of the intermediate [I]

are a dioxetane or an ionic perepoxide. The product distribution would

$$
\begin{array}{c}
\text{CH}_3 \quad\quad \text{CH}_3 \\
\text{C}{=}\text{C} \\
\text{CH}_3 \quad\quad \text{CH}_3
\end{array}
\xrightarrow[\text{path (a)}]{^1\text{O}_2}
\begin{array}{c}
\text{CH}_2 \quad\quad \text{OOH} \\
\text{C}{-}\text{C}{-}\text{CH}_3 \\
\text{CH}_3 \quad\quad \text{CH}_3
\end{array}
$$

$$
\underset{^1\text{O}_2}{\overset{\text{path (b)}}{\underset{\text{(fast)}}{\rightleftarrows}}}
\quad [I] \xrightarrow{\text{N}_3^-}
\begin{array}{c}
\text{N}_3 \quad\quad \text{CH}_3 \\
\text{CH}_3{-}\text{C}{-}\text{C}{-}\text{CH}_3 \\
\text{CH}_3 \quad\quad \text{OOH}
\end{array}
$$

Eq. 25
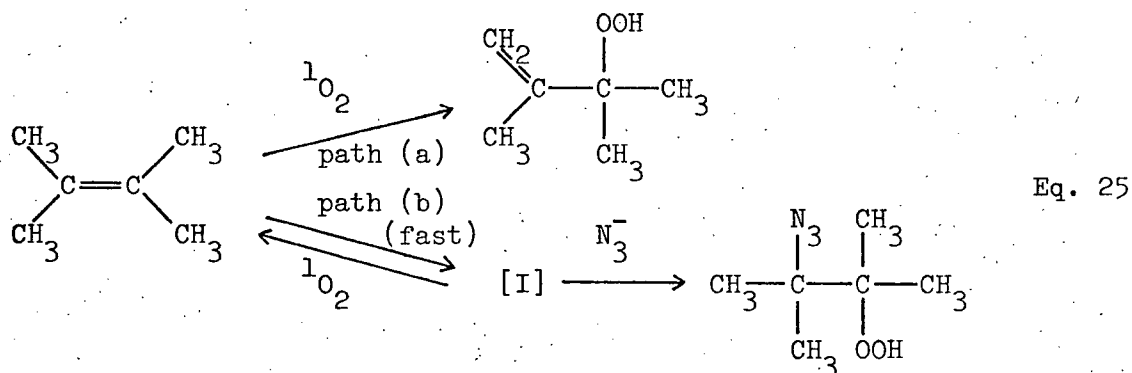
depend on the relative rates of the two pathways. In view of this alter-

nate explanation for the formation of azido-hydroperoxides and the evidence

previously discussed, the concerted ene-type mechanism still appears to be

the most likely path for the formation of allylic hydroperoxides.

The rate of the ene-type reaction is markedly increased by alkyl

substituents. For example, 2,3-dimethylbutene is the most reactive ene-

type acceptor known, whereas 2-methyl-2-butene and 2-butene are progres-

sively less reactive.[55b] This observed enhancement of rate by electron

donating alkyl substituents is consistent with the electrophilic nature of

singlet oxygen.

The ene-type reaction is not restricted to simple olefins. Model

compounds of carotenoids react with singlet oxygen to give unusual allenic

alcohols in low yields in addition to the typical addition products (Eq.

26).[71,72] These allenic products, which are remarkably similar in structure

to fucoxanthin and other carotenoids, may be visualized as resulting from

an ene-type reaction on the cyclic double bond.

Eq. 26
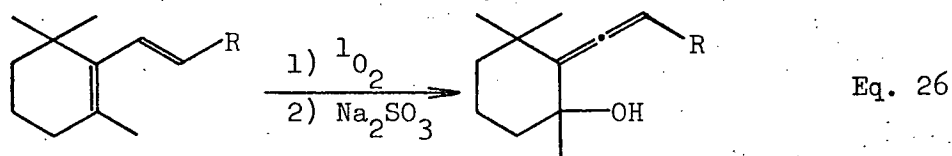
C. 1,2-Cycloaddition

Many electron rich olefins undergo a third mode of reaction with singlet oxygen: direct 1,2-cycloaddition to form unstable 1,2-peroxides (dioxetanes) which thermally fragment to carbonyl compounds[7,73-75] (Eq. 27).

$$\text{Eq. 27}$$
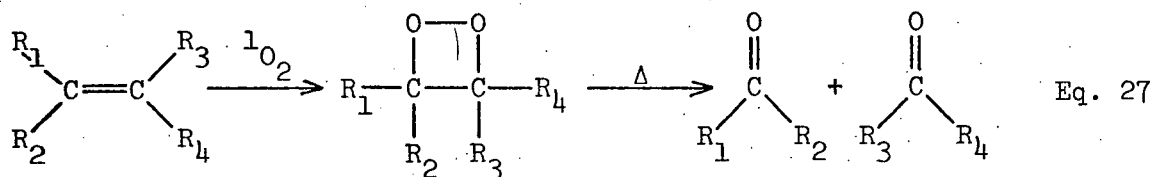
This reaction normally requires special activation of the double bond (e.g. alkoxy substituents) or the absence of an active allylic hydrogen. Indene, when photooxygenated in the presence of sodium azide, gave an azido hydroperoxide after reduction instead of the normal oxygenation product, homophthalaldehyde (Eq. 28).[73] The intermediate, presumably a dioxetane, is

$$\text{Eq. 28}$$
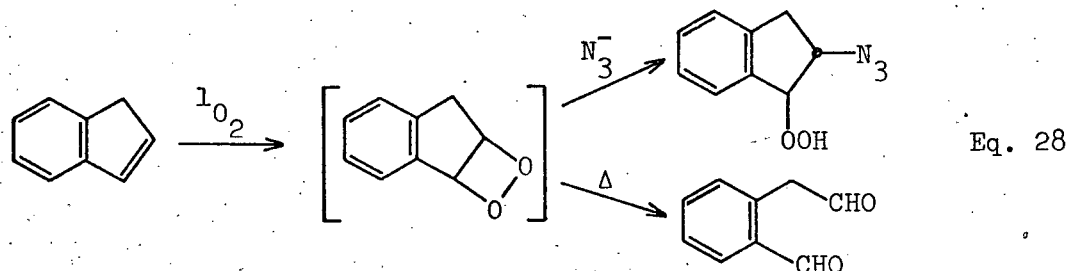
intercepted by the nucleophilic azide ion. Dioxetanes which have been synthesized by chemical methods or by photosensitized oxygenation at low temperatures all undergo thermal decomposition to give only carbonyl fragments.[74-77] Molecular orbital and state correlations for dioxetane formation predict that $(2_s + 2_a)$ addition is allowed,[74] but that $(2_s + 2_s)$ addition may be forbidden unless the olefin has a low π-ionization potential.[36] A stepwise ionic mechanism is also conceivable.[74]

The oxygenation of enamines also gives carbonyl fragments,[78-80] but no intermediate dioxetane has yet been isolated or detected in these

reactions. In fact, the results of temperature dependent nmr studies were inconsistent with a dioxetane intermediate.[78] Dimeric or polymeric peroxides were suggested as possible intermediates.

III.   LABORATORY SOURCES OF SINGLET OXYGEN

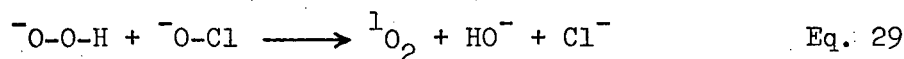   A. Sensitized Photooxygenation

   Sensitized photooxygenation is the oldest, the most practical, and still the most widely utilized technique for reacting singlet oxygen with suitable acceptors.[4-8]   In general, the technique consists of irradiating suitable sensitizer-acceptor mixtures in solution with low energy visible light in the presence of oxygen.   The most efficient sensitizers are those which give long-lived triplets in high quantum yields, since oxygenation generally proceeds via the triplet state of the sensitizer.[81]   Some common-ly used sensitizers are rose bengal, methylene blue, hematoporphyrine, and tryptaflavine.   In order to minimize photochemical side reactions of the acceptor, products, or sensitizer, a monochromator or color filter is often used to selectively populate only the desired excited state of the sensi-tizer.

   The key step in the mechanism of the sensitized photooxygenation reaction (Eq. 7-10) is the transfer of energy from triplet sensitizer to triplet oxygen to give singlet oxygen.   Initial photoexcitation of the sensitizer followed by intersystem crossing to the triplet state gives the triplet sensitizer.   Subsequent energy-transfer from triplet sensitizer to triplet oxygen to give singlet sensitizer and singlet oxygen is a spin-allowed process.

   B.   Chemical Oxygenation

      1) Heterolytic Decomposition of Hydrogen Peroxide

   Hydrogen peroxide in alkaline solution is heterolytically decomposed by hypochlorite ion or bromine to give singlet molecular oxygen (Eq. 29 and 30).

$$^-O\text{-}O\text{-}H + {}^-O\text{-}Cl \longrightarrow {}^1O_2 + HO^- + Cl^-$$ Eq. 29

$$^-O-O-H + Br-Br \longrightarrow {}^1O_2 + HBr + Br^-$$ Eq. 30
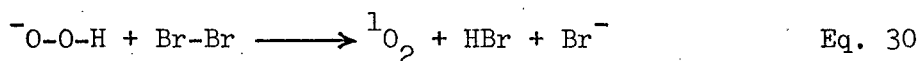
Using sodium hypochlorite as the oxidant, Foote[55a] made extensive use of this method of generating singlet oxygen for both preparative and kinetic purposes. The technique simply consists of slowly adding aqueous sodium hypochlorite below the surface of a stirred alkaline solution of acceptor and excess hydrogen peroxide in methanol, ethanol, or a mixture of methanol and t-butanol. High yields (up to 80%) were obtained with the more reactive acceptors, but with less reactive acceptors large excesses of hypochlorite were required to obtain significant yields. Because of solubility problems arising from a limited choice of suitable solvents, the oxyge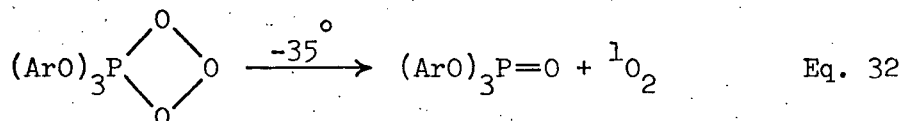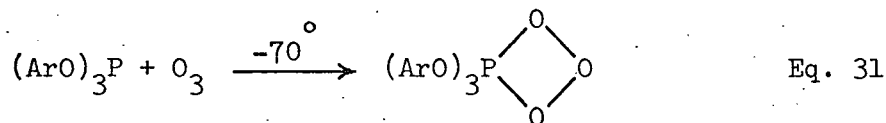nation of even some highly reactive acceptors (e.g. substituted polyacenes) was very inefficient. Solubility problems and radical side reactions seriously limit the synthetic utility of the hydrogen peroxide-hypochlorite method of generating singlet oxygen.

A two-phase system devised by McKeown and Waters[82] overcomes the solubility problem to a great extent. The acceptor is dissolved in an upper organic layer and bromine is slowly added with stirring to a lower aqueous alkaline hydrogen peroxide layer. Singlet oxygen formed in the aqueous layer rises up through the organic layer where oxygenation occurs. Bromination and other side reactions again limit the synthetic utility of this technique.

2) Thermal Decomposition of Ozone Adducts

Ozonolysis of a number of organic and inorganic substrates, including tertiary amines, phosphines, sulfides, sulfoxides, and suitably substituted 1-olefins, occurs with concomitant evolution of gaseous oxygen,[83] which has for some time been suspected to have singlet multiplicity.[56,84,85] Thompson[84] first reported in 1961 that at $-70°$ ozone and triaryl phosphites

form stable 1:1 adducts which give the corresponding phosphate and molecular oxygen upon warming (Eq. 31 and 32). Murray and Kaplan[85] demonstrated

$$(ArO)_3P + O_3 \xrightarrow{-70^\circ} (ArO)_3P\Big\langle\begin{smallmatrix} O \\ \\ O \end{smallmatrix}\Big\rangle O \qquad \qquad \text{Eq. 31}$$

$$(ArO)_3P\Big\langle\begin{smallmatrix} O \\ \\ O \end{smallmatrix}\Big\rangle O \xrightarrow{-35^\circ} (ArO)_3P=O + {}^1O_2 \qquad \text{Eq. 32}$$

that the evolved gas exhibits the characteristic gas phase reactions and epr spectrum[86] of singlet oxygen.

A synthetically useful technique for oxygenating singlet oxygen acceptors in solution with the triphenyl phosphite-ozone adduct was developed by Murray and Kaplan.[87] The adduct is formed by passing ozone into a methylene chloride solution of the phosphite at -78° followed by nitrogen purging to remove excess ozone. A cold methylene chloride solution of the acceptor is then added and the solution allowed to warm slowly to room temperature. The product is isolated and analysed by standard techniques.

The nature of the reactive intermediate in solution has not been unambiguously identified. Although the products are identical to those of singlet oxygen reactions, Bartlett and Mendenhall[88] have shown that, at least in the case of tetramethylethylene, the acceptor reacts with the ozonide at temperatures (-60° to -70°) far below that at which oxygen evolution is detectable (-35°).[85] Murray and Kaplan,[87] on the other hand, found that rubrene reacts appreciably only at higher temperatures (-35° to -25°). These results indicate that at low temperatures the triaryl phosphite adduct directly donates molecular oxygen to some acceptors but not to others. However, at higher temperatures probably all acceptors react with free singlet oxygen evolved by the decomposition of the adduct and perhaps some also react directly with the adduct.

Even some relatively unreactive substrates such as isopropyl ether and isopropyl alcohol have been observed to form ozone adducts, probably hydrotrioxides, at low temperatures $(-70°)$.[89] Decomposition of these adducts at higher temperatures $(>-10°)$ leads to evolution of gaseous oxygen or, if suitable acceptors are added, formation of typical singlet oxygen reaction products in yields up to 61%. Many other organic substrates including hydrocarbons, amines, and aldehydes also form unstable ozonolysis products or intermediates which are suspected to give singlet oxygen upon decomposition.[89]

These methods of generating singlet oxygen all suffer from several inherent disadvantages. The necessity of low temperatures gives rise to solubility problems with some substrates. The ozonide and its decomposition products may catalyze side reactions and must be removed during the final workup of products.

3) Thermal Decompositon of Polyacene Peroxides

Many substituted and unsubstituted polyacenes undergo Diels-Alder addition of singlet oxygen to give transannular peroxides.[6,7] Some of these peroxides have the interesting property of thermally decomposing to give gaseous oxygen and the original polyacene.

Wasserman and Scheffer[90] demonstrated that the thermal decomposition of 9,10-diphenylanthracene peroxide provides a convenient source of singlet oxygen subject to temperature control (Eq. 33). Mixtures of peroxide


Eq. 33
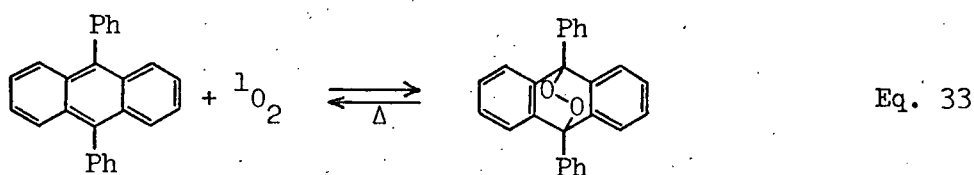
and acceptor in benzene or chloroform were refluxed for two to four days to give products in yields up to 95%. The reactive intermediate is probab-

ly singlet oxygen, but direct transfer of oxygen from peroxide to substrate has not been rigorously ruled out. The necessity of elevated temperatures limits this method to oxygenations involving thermally stable compounds. Removal of 9,10-diphenylanthracene during workup sometimes provides a major inconvenience.

C. Electric Discharge

The external generation of singlet oxygen in an electric discharge is probably the least ambiguous method known for generating singlet oxygen, but also the most complicated technologically. A microwave or radiofrequency generator and an efficient fast-flow system are the major requirements. A stream of gaseous oxygen at reduced pressures (<5 mm) is passed through an electric discharge which produces oxygen atoms and electronically excited oxygen molecules. The addition of an inert gas such as helium enables the discharge to operate at a higher total pressure without decreasing the yield of singlet oxygen.

This method, first reported by Foner and Hudson[45] in 1956, is capable of continuously converting about 10% of the ground state oxygen in a gas stream into $O_2(^1\Delta_g)$.[49,50,91] Oxygen atoms, which are produced in about 5% yield, are easily removed by recombination on a mercuric oxide coating immediately after the discharge without decreasing the concentration of $O_2(^1\Delta_g)$.[92,93] The gas stream also contains a minor but steady concentration of $O_2(^1\Sigma_g^+)$ (about 0.1%) produced by a bimolecular reaction between two $O_2(^1\Delta_g)$ (Eq. 34).[50] The lifetimes of both $O_2(^1\Delta_g)$ and $O_2(^1\Sigma_g^+)$ are

$$2O_2(^1\Delta_g) \longrightarrow O_2(^3\Sigma_g^-) + O_2(^1\Sigma_g^+) \qquad \text{Eq. 34}$$
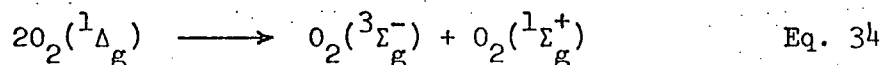
determined mainly by wall deactivation under the usual conditions of the discharge system (<5 mm).[50,94] Since the rate of collisional deactivation of $O_2(^1\Sigma_g^+)$ is much faster than that of $O_2(^1\Delta_g)$, the steady concentration

of $O_2(^1\Sigma_g^+)$ is expected to be much less than that of $O_2(^1\Delta_g)$.

The concentration of $O_2(^1\Delta_g)$ can be conveniently determined from the intensities of the 6340 $\overset{o}{A}$ and 7030 $\overset{o}{A}$ bands corresponding to the simultaneous deactivation of two $O_2(^1\Delta_g)$ (Eq. 35).[49-51] The intensities are proportional to the square of the $O_2(^1\Delta_g)$ concentration.
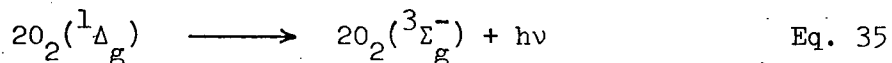
$$2O_2(^1\Delta_g) \longrightarrow 2O_2(^3\Sigma_g^-) + h\nu \qquad \text{Eq. 35}$$

Use of the electric discharge method of generating singlet oxygen has been almost completely restricted to gas phase reactions. Previous to our investigations[95] the only reported application of this method to the liquid phase was due to Corey and Taylor[56] in 1964. A stream of oxygen gas enriched in singlet oxygen after being subjected to an electric discharge was bubbled through a solution of the acceptor in various organic solvents. Unfortunately their system proved to be particularly inefficient. The yields were very poor, reaction times inconveniently long, and the number of reactive substrates limited. A more efficient system was clearly desirable.

IV. RESEARCH OBJECTIVES

A convenient and effective laboratory method of generating the meta-stable $^1\Delta_g$ state of oxygen has been rendered highly desirable by the recent renaissance of interest in the physical and chemical properties of singlet oxygen. However, no ideal source of singlet oxygen has yet been discovered; each known source has its own particular disadvantages.

Sensitized photooxygenation requires light and sensitizer, both of which may interact directly with the substrate or products. Sensitizer bleaching, usually the result of oxygenation, is also encountered. The limitation of useful solvents to those sufficiently polar to dissolve adequate amounts of sensitizer can be disadvantageous in some cases. For example, solubility problems of non-polar substrates and solvent addition reactions can occur more readily in polar solvents. Removal of sensitizer during workup provides an additional inconvenience.

The presence of extraneous chemical species in the chemical methods gives rise to competitive side reactions which can complicate analysis of the reaction and significantly decrease the yield of oxygenation products. Free radical oxidation becomes significant when large excesses of hypo-chlorite are required to oxygenate unreactive acceptors. Base induced side reactions can readily occur under the highly alkaline conditions of hydrogen peroxide decomposition. When bromine is used as the oxidant, bromination of olefinic substrates and products can also readily occur. Direct interaction of the triaryl phosphite-ozone adduct with some acceptors has complicated the analysis of the mechanism of oxygenation by this method. The necessity of low temperatures ($<-70^{\circ}$) to form the triaryl phosphite-ozone adducts results in solubility problems and the necessity of high temperatures ($>60^{\circ}$) to decompose 9,10-diphenylanthracene peroxide results in the enhancement of undesirable side reactions,

especially if either reactants or products are not particularly stable thermally. Aqueous workup in the hydrogen peroxide-hypochlorite method and removal of side products (9,10-diphenylanthracene and triphenyl phosphate) in other chemical methods can be major inconveniences.

The electric discharge method of generating singlet oxygen, used mainly by spectroscopists and kineticists for gas phase reactions, is potentially the mildest and the most direct method of reacting singlet oxygen with suitable acceptors. The relatively crude system used by Corey and Taylor[56] to oxygenate several known singlet oxygen acceptors has since been considerably improved by Ogryzlo and coworkers.[49,50] By this method, a stream of oxygen gas enriched in singlet oxygen [about 10% $O_2(^1\Delta_g)$ and 0.1% $O_2(^1\Sigma_g^+)$] can be directly reacted with suitable acceptors without the interference of extraneous chemicals, light, or extremes of temperature.

The first objective of this research was to determine the synthetic applicability of the electric discharge method of generating singlet oxygen. Neither the original solution experiments by Corey and Taylor nor later gas phase experiments[96-98] conveniently produced synthetically useful amounts of oxygenated products. Hence, we felt it highly desirable to design and test an electric discharge system which could be conveniently utilized for preparative scale oxygenations of suitable acceptors.

The second objective was the investigation of singlet oxygen reactions with acceptors adsorbed onto solid surfaces. With the exception of Kautsky's original experiments, in which the substrate and sensitizer were adsorbed onto physically separate particles of silica gel or alumina, and two more recent extensions of these experiments, all reported singlet oxygen reactions have been carried out with the acceptor dissolved in solution or in the gas phase. The sensitized oxygenation of acceptors adsorbed onto solid supports has never been shown to be a useful technique
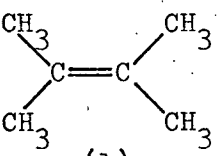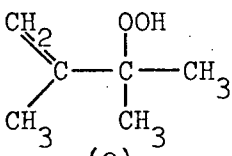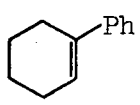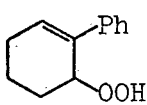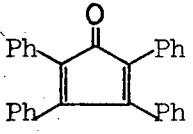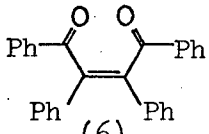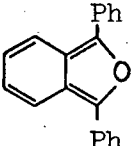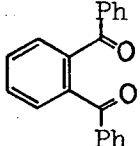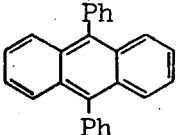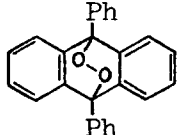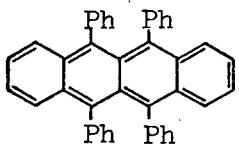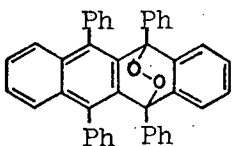
for preparative scale reactions. We wished to demonstrate that this adsorption technique, when used in conjunction with discharge-generated singlet oxygen, could in fact be successfully utilized for preparative scale oxygenations. In addition, we wished to investigate the differences, if any, in the oxygenation reactions of acceptors adsorbed onto solid surfaces as compared to those in solution or in the gas phase.

The third and last objective was an exploratory search for previously undiscovered singlet oxygen acceptors containing functional groups other than the usual 1,3-diene or olefinic groups.

V. RESULTS

The oxygenation apparatus is that of Ogryzlo[95,99] and is described in the experimental section. The substrates, products, and yields of the successful oxygenation reactions are summarized below (Table 1).

Table 1 - Oxygenation Results

Substrate	Product	Yield		
		A	B	C
(1)	(2)	14%	-	-
(3)	(4)	NA	33%	NA
(5)	(6)	76%	76%	86%
(7)	(8)	82%	91%	NA
(9)	(10)	64%	79%	60%
(11)	(12)	NA	73%	NA

(A) in solution
(B) on microcrystalline cellulose adsorbent
(C) on silica gel adsorbent
(NA) not attempted

The solution phase reactions were all carried out at -78° in toluene with the exception of tetramethylethylene (1), which was oxygenated in methanol. The oxygenation reactions on solid supports were all carried out at room temperature on microcrystalline cellulose or silica gel adsorbents. All products were identified by comparison of spectral and physical data with those of authentic samples or with those reported in the literature. Additional comparisons were made after sodium borohydride reduction of the hydroperoxides (2) and (4) to the corresponding alcohols. All yields were based on unrecovered starting material. Control experiments without the electric discharge operating showed no detectable reaction of substrates with ground state oxygen.

A. Oxygenation of Tetramethylethylene (TME)

A methanolic solution of tetramethylethylene (1) was exposed to discharge-generated singlet oxygen at -78°. Removal of solvent and distillation of the product in vacuo gave a 14% yield of the hydroperoxide (2), but no attempt was made to recover unreacted TME. Reduction of the hydroperoxide with excess sodium borohydride gave the corresponding alcohol. The nmr and ir spectra of the hydroperoxide and the alcohol were in good agreement with those reported.[55a] Photosensitized[100] and chemical[55a] oxygenations of TME are reported to give 82% and 65% yields respectively.

Attempts to oxygenate TME adsorbed onto microcrystalline cellulose or silica gel were unsuccessful. The substrate was highly volatile, even as a solid at -78°, and was quickly carried off by the gas stream.

B. Oxygenation of 1-Phenylcyclohexene

Oxygenation of 1-phenylcyclohexene (3) on cellulose by discharge-generated singlet oxygen gave, in addition to a mixture of uncharacterized products, a 33% yield of crude 3-hydroperoxy-2-phenylcyclohexene (4) after chromatography. The nmr spectrum was consistent with the assigned structure.

Reduction of the hydroperoxide (4) with excess sodium borohydride gave the corresponding alcohol. The nmr and ir spectra were consistent with the assigned structure and the melting point of the phenylurethane was in good agreement with that reported.[101]

C. Oxygenation of Tetraphenylcyclopentadienone

Tetraphenylcyclopentadienone (5), when oxygenated by discharge-generated singlet oxygen, gave cis-dibenzoylstilbene (6). The yields were 76% in toluene solution and 76% and 86% on cellulose and silica gel respectively. The melting points and ir spectra were in good agreement with those reported.[55a,62] Photosensitized[62] and chemical[55a] oxygenations of (5) are reported to give (6) in 65% and 50% yields respectively.

D. Oxygenation of 1,3-Diphenylisobenzofuran

Photooxygenation of 1,3-diphenylisobenzofuran (7) is reported to give a high yield of o-dibenzoylbenzene (8).[63] The reaction was repeated in carbon disulfide to give a 17% yield of (8). The melting point of the product was in good agreement with that reported[64] and the nmr and ir spectra were consistent with the assigned structure.

Oxygenation of (7) by discharge-generated singlet oxygen gave (8) in 82% yield in toluene solution and 91% yield on cellulose. The melting point and the nmr and ir spectra were in good agreement with those of the photoproduct.

E. Oxygenation of 9,10-Diphenylanthracene

The photooxygenation of 9,10-diphenylanthracene (9) is reported to give the endoperoxide (10) in 81% yield.[66] Repetition of the photooxygenation in carbon disulfide gave a 50% yield of (10), which decomposed with evolution of gas when heated. The melting point of the product was similar to that reported[66] and the ir spectrum was consistent with the assigned structure.

Oxygenation of (9) by discharge-generated singlet oxygen gave (10) in yields of 64% in toluene solution and 79% and 60% on cellulose and silica gel respectively. The melting points and ir spectra of the products corresponded to those of the photoproduct.

F. Oxygenation of Rubrene

The photooxygenation of rubrene (11) is reported to give the endo-peroxide (12) in 80% yield.[16,102] The reaction was repeated in carbon disulfide to give an 81% yield of the endoperoxide (12), which decomposed with evolution of gas when heated. The melting point closely corresponded to that reported[16] and the ir spectrum was consistent with the assigned structure.

Oxygenation of (11) on cellulose by discharge-generated singlet oxygen gave a 73% yield of (12). The melting point and ir spectrum corresponded to those of the photoproduct.

G. Miscellaneous Unsuccessful Oxygenation Reactions

A number of compounds which were adsorbed onto cellulose and subjected to discharge-generated singlet oxygen were found to be unsuitable substrates under the experimental conditions for various reasons. Cholesterol, a known singlet oxygen acceptor,[68,69] was only very slightly oxygenated even after prolonged exposure. Norbornadiene and cyclohexene oxide were too volatile even at -78° and dimethyl norbornadien-1,2-dicarboxylate and tolan were too unreactive. Hexamethyl (Dewar benzene) and 9,10-epoxy-1,4,5,8,-tetrahydronaphthalene were both reactive but gave only intractable tars.

VI.   DISCUSSION

The experimental results show that the electric discharge method of generating singlet oxygen can be utilized for oxygenations on a scale useful to synthetic organic chemists. Suitable acceptors can be efficiently oxygenated both in solution and on solid surfaces, but the latter method is generally preferred. The experimental setup is definitely a great improvement over that used by Corey and Taylor[56] and can serve as a useful alternative to other methods of oxygenation.

The major advantages of the substrate adsorption technique arise from its inherent simplicity; the acceptor is exposed only to a stream of oxygen gas enriched in singlet oxygen. Extraneous chemicals which can lead to undesirable side reactions are all eliminated. Oxygenations on solid surfaces can be run at any desired temperature, whereas those in solution generally require low temperatures to prevent excessive solvent evaporation. Solubility problems which are inevitable in the solution reactions are eliminated by adsorbing substrates on solid surfaces. The workup procedure is greatly simplified, since the products can be isolated directly from the solution or eluted from the solid support without the necessity of removing extraneous chemicals and side products.

On the other hand, the major disadvantages of the method are the relatively high initial cost of the apparatus and the necessity of reduced pressures within the system. Because of the latter restriction, solution phase reactions must be run at sufficiently low temperatures to prevent excessive solvent and/or substrate evaporation. Although the adsorption technique eliminates the problem of solvent evaporation, the substrate itself must be relatively non-volatile. For example, tetramethylethylene proved to be too volatile even at $-78°$ to be oxygenated by this method.

Substrates adsorbed onto solid surfaces showed no difference in

reactivity towards singlet oxygen as compared to those in solution. The same products were isolated in comparable yields in all cases. Although quenching studies[103] indicate that silica gel quenches singlet oxygen much more efficiently than cellulose, little difference was observed in the yield or duration of oxygenation reactions on the two adsorbents. The only significant effect of the solid support was to enhance the rate of oxygenation by increasing the area of contact between the substrate and singlet oxygen.

Exploratory oxygenations of 1,4-dienes and epoxides adsorbed onto cellulose were all unsuccessful. Some substrates were completely unreactive and others gave only intractable tars. This area of research definitely requires further investigation.

VII. EXPERIMENTAL

Discharge Apparatus and Operation

The experimental setup (Figure 1) is that of Ogryzlo.[95,99]
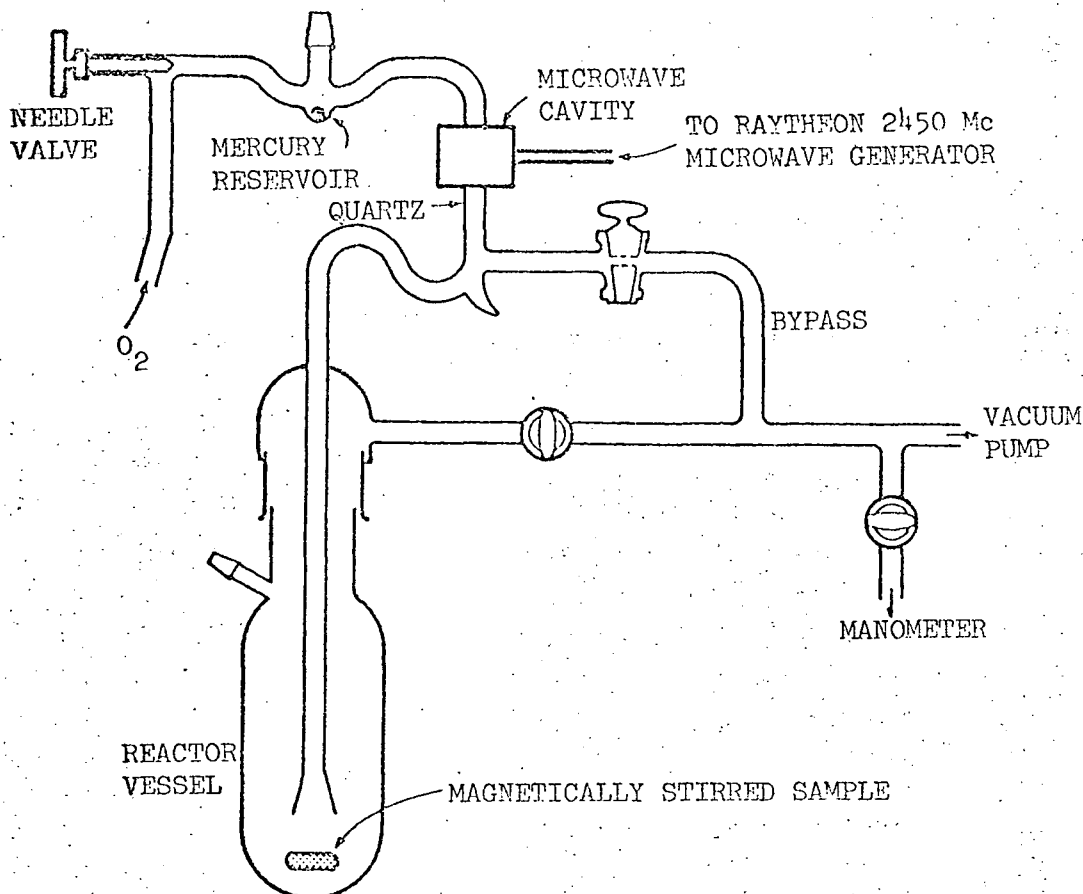
FIG.1.- OXYGENATION APPARATUS.

A pyrex fast-flow system was equipped with a vacuum pump (Precision Scientific Co., Model 75) and a needle valve to maintain a continuous flow rate of about 0.2 mmol/sec and a pressure of about 5 mm Hg within the flow system. The microwave cavity was a foreshortened 1/4 wave coaxial type with a coupling adjustment. With the gas flow restricted to the bypass, the microwave discharge was initiated with a Tesla coil and maintained in a short (about 10 cm) section of air-cooled 9 mm OD quartz-glass tubing by a Raytheon 2450 Mc, 100 W generator operating at 70-80 W. In order to remove oxygen atoms from the gas flow, a film of mercuric oxide was coated

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onto the inside wall of the tubing immediately after the discharge by distilling a small amount of mercury through the discharge. The gas flow was finally diverted through the reactor vessel for the duration of the oxygenation reaction. The mercuric oxide coating was renewed occasionally (about every 15 min) by distilling additional mercury through the discharge.

General

Oxygen was from Canadian Liquid Air, Ltd.; cellulose powder was W. & R. Balston, Ltd. standard grade; activated silica gel for oxygenations was Davison Chemical commercial grade (100-200 mesh); and activated silica gel for chromatography was from E. Merck Ag. Darmstadt (<0.08 mm).

Infrared (ir) spectra were recorded on a Perkin-Elmer Model 137 spectrophotometer. Nuclear magnetic resonance (nmr) spectra were recorded on a Varian A-60 or Varian T-60 spectrometer. Melting points were determined on a Fisher-Johns melting point block and are all uncorrected. Gas-liquid partition chromatography (glpc) was carried out on a Varian Aerograph Model 90-P instrument. All yields were based on unrecovered starting material.

Oxygenation of Tetramethylethylene in Solution

A solution of 5.00 g (59.4 mmol) of tetramethylethylene (1) (Chemical Samples Co.) in 200 ml of methanol was cooled to -78° and exposed to singlet oxygen with continuous stirring for 1 hr. The solution was concentrated and distilled to give 0.923 g (7.93 mmol, 14%) of hydroperoxide (2), bp 24° (5 mm) [lit.[55a] 53-55° (12 mm)]. The ir spectrum (neat) and nmr spectrum (CCl_4) were in good agreement with those reported.[55a]

Reduction of Hydroperoxide (2)

Hydroperoxide (2), 0.40 g (3.3 mmol), was reduced by dropwise addition with continuous stirring of a solution of 0.52 g (13.7 mmol) of sodium borohydride in 15 ml of ethanol over a period of about 2 min. Purification

of the crude product by glpc gave the corresponding alcohol. The ir

spectrum (CCl_4) and nmr spectrum (CCl_4) were in good agreement with those

reported.[55a]

Oxygenation of 1-Phenylcyclohexene on Cellulose

1-Phenylcyclohexene (3) (Aldrich Chemical Co., Inc.), 2.00 g (12.6

mmol), was adsorbed onto 5 g of cellulose powder and exposed to singlet

oxygen with continuous stirring for 3 hr. The powder was extracted with

200 ml of ether in 20 ml portions, the solvent evaporated, and the liquid

residue chromatographed on activated silica gel with hexane-ether (1:1)

to give, in addition to 1.13 g of a mixture of uncharacterized products,

0.700 g (3.68 mmol, 33%) of crude hydroperoxide (4): nmr (CCl_4) τ 0.76

(s, 1, OOH), 2.79 (m, 5, Ph), 3.80 (t, 1, C=CH), 5.25 (m, 1, CH), 7.30-

9.00 (m, 6, CH_2).

Reduction of Hydroperoxide (4)

A solution of 0.600 g (3.15 mmol) of hydroperoxide (4) in 5 ml of

methanol at $0°$ was reduced by the addition of 0.109 g (2.88 mmol) of

sodium borohydride in small portions with continuous stirring over a period

of 5 min. Purification of the crude product by glpc gave the corresponding

alcohol: ir (neat) 2.69 (m), 2.98 (s), 3.30 (m), 3.42 (s), 6.07 (w),

6.23 (m), 6.69 (m), 6.93 (m), 7.20 (m), 7.41 (m), 7.50 (m), 7.85 (m),

7.97 (m), 8.45 (w), 8.62 (m), 9.23 (m), 9.43 (s), 9.64 (m), 10.00 (m),

10.27 (s), 10.61 (m), 10.86 (m), 10.97 (m), 11.38 (w), 11.78 (w), 12.20 (w),

12.93 (m), 13.18 (s), 13.50 (m) μ; nmr ($CDCl_3$) τ 2.70 (m, 5, Ph), 3.92

(t, 1, C=CH), 5.48 (m, 1, CH), 7.49 (s, 1, OH), 7.60-8.70 (m, 6, CH_2);

phenylurethane mp 153.5-155$°$ (lit.[101] 152-153$°$).

Oxygenation of Tetraphenylcyclopentadienone in Solution

A solution of 2.00 g (5.15 mmol) of tetraphenylcyclopentadienone (5)

(Aldrich Chemical Co., Inc.) in 300 ml of toluene was cooled to -78$°$ and

exposed to singlet oxygen with continuous stirring for 4.5 hr. Ethanol, 200 ml, was added to the pale purple solution and the total solution concentrated to about 100 ml and cooled to 0° to give 1.55 g (3.95 mmol, 76%) of cis-dibenzoylstilbene (6), mp 214.5-216° (lit.[62] 215-216°). The ir spectrum (KBr) was in good agreement with that reported (Nujol).[55a]

Oxygenation of the Dienone (5) on Cellulose and on Silica Gel

The dienone (5), 0.200 g (0.515 mmol), was adsorbed onto 5 g of cellulose powder and exposed to singlet oxygen with continuous stirring for 3 hr. The powder was extracted with 200 ml of chloroform in 20 ml portions, the solvent evaporated, and the solid residue chromatographed on silica gel with benzene to give 0.092 g of starting material and 0.083 g (0.214 mmol, 76%) of (6), mp 211-214°. The ir spectrum was identical to that of the solution product.

The dienone (5), 0.200 g (0.515 mmol), was adsorbed onto 5 g of activated silica gel and treated in the same manner as above to give 0.137 g of starting material and 0.055 g (0.141 mmol, 86%) of (6), mp 214-216°. The ir spectrum was identical to that of the solution product.

Photooxygenation of 1,3-Diphenylisobenzofuran

A solution of 0.100 g (0.370 mmol) of 1,3-diphenylisobenzofuran (7) (Aldrich Chemical Co., Inc.) in 40 ml of carbon disulfide was vigorously stirred in an open pyrex flask and irradiated with a G.E. 275 W Sunlamp from a distance of 1 ft for 6 hr. The solvent was evaporated and the solid residue recrystallized three times from methanol to give 0.018 g (0.063 mmol, 17%) of o-dibenzoylbenzene (8): mp 144-146° (lit.[64] 145°); ir (KBr) 3.30 (m), 6.02 (s), 6.26 (m), 6.35 (m), 6.91 (m), 7.63 (m), 7.89 (s), 8.48 (m), 8.66 (m), 9.10 (w), 9.33 (w), 9.74 (w), 9.98 (w), 10.22 (w), 10.35 (w), 10.66 (s), 10.80 (m), 11.74 (w), 12.43 (w), 12.87 (s), 13.00 (m), 13.48 (m) μ; nmr (CDCl$_3$) τ 2.15-2.95 (aromatic protons only).

Oxygenation of 1,3-Diphenylisobenzofuran in Solution

A solution of 0.200 g (0.740 mmol) of (7) in 150 ml of toluene was cooled to -78° and exposed to singlet oxygen with continuous stirring for 3 hr. The solvent was evaporated and the solid residue chromatographed on activated silica gel with benzene-ether mixtures to give 0.026 g of starting material and 0.151 g (0.527 mmol, 82%) of (8), mp 142-145°. The ir and nmr spectra were identical to those of the photoproduct.

Oxygenation of 1,2-Diphenylisobenzofuran on Cellulose Powder

The furan (7), 0.200 g (0.740 mmol), was adsorbed onto 5 g of cellulose powder and exposed to singlet oxygen with continuous stirring for 3 hr. The powder was extracted with 200 ml of chloroform in 20 ml portions, the solvent evaporated, and the solid residue chromatographed to give 0.096 g of starting material and 0.100 g (0.349 mmol, 91%) of (8), mp 142-145.5°. The ir and nmr spectra were identical to those of the photoproduct.

Photooxygenation of 9,10-Diphenylanthracene

Dry air was bubbled into a solution of 3.00 g (9.09 mmol) of 9,10-diphenylanthracene (9) (Aldrich Chemical Co., Inc.) in 1 l. of carbon disulfide via a fritted glass dispersion tube and irradiated for 48 hr with continuous stirring. The solution was concentrated to about 100 ml, added to 350 ml of hexane, and concentrated to 250 ml. After standing overnight, the white crystalline product was collected and recrystallized from carbon disulfide to give 1.63 g (4.50 mmol, 50%) of the peroxide (10), mp 162-167° dec. (lit.[66] dec. at 180° under vacuum). The ir spectrum (CDCl$_3$) had principal bands at 3.32 (m), 6.23 (m), 6.71 (m), 6.88 (s), 7.60 (m), 8.01 (w), 9.68 (w), 10.15 (m), 10.90 (m), 11.05 (m), 11.21 (m) μ.

Oxygenation of 9,10-Diphenylanthracene in Solution

A solution of 1.00 g (3.03 mmol) of (9) in 350 ml of toluene was cooled to -78° and exposed to singlet oxygen with continuous stirring for

11 hr. The solvent was evaporated and the solid residue chromatographed on activated silica gel with benzene-hexane mixtures to give, in addition to 0.645 g of starting material, 0.249 g (0.687 mmol, 64%) of (10), mp 167-172° dec. The ir spectrum was identical to that of the photoproduct.

Oxygenation of 9,10-Diphenylanthracene on Cellulose and Silica Gel

9,10-Diphenylanthracene (9), 0.200 g (0.606 mmol), was adsorbed onto 5 g of cellulose powder and exposed to singlet oxygen with continuous stirring for 3 hr. The powder was extracted with 200 ml of chloroform in 20 ml portions, the solvent evaporated, and the solid residue chromatographed on activated silica gel with benzene-hexane (1:1) to give 0.146 g of starting material and 0.047 g (0.130 mmol, 79%) of (10), mp 166-168° dec. The ir spectrum was identical to that of the photoproduct.

9,10-Diphenylanthracene (9), 0.200 g (0.606 mmol), was adsorbed onto 5 g of activated silica gel and treated in the same manner as above to give 0.146 g of starting material and 0.042 g (0.116 mmol, 60%) of (10), mp 167-169° dec. The ir spectrum was identical to that of the photoproduct.

Photooxygenation of Rubrene

A solution of 1.00 g (1.88 mmol) of rubrene (11) (Aldrich Chemical Co., Inc.) in 500 ml of carbon disulfide in an open flask was allowed to stand in sunlight for 2 days. The solvent was evaporated and the solid recrystallized from carbon disulfide to give 0.86 g (1.52 mmol, 81%) of rubrene peroxide (12), mp 161-171° dec. (lit.[16] rapid dec. at 150° under vacuum). The ir spectrum (KBr) had principal bands at 3.27 (m), 5.10 (w), 6.24 (w), 6.67 (s), 6.80 (m), 6.93 (s), 7.17 (w), 7.38 (m), 7.69 (w), 7.95 (w), 8.40 (w), 8.63 (w), 9.31 (w), 9.54 (w), 9.72 (m), 9.95 (w), 10.26 (m), 10.42 (w), 10.98 (m), 12.84 (s), 13.04 (s), 13.77 (s) μ.

Oxygenation of Rubrene on Cellulose Powder

Rubrene, 0.100 g (0.188 mmol), was adsorbed onto 5 g of cellulose

powder and exposed to singlet oxygen with continuous stirring for 3 hr. The powder was extracted with 200 ml of chloroform in 20 ml portions, the solvent evaporated, and the solid residue chromatographed on activated silica gel with benzene-hexane (1:1) to give 0.053 g of starting material and 0.038 g (0.067 mmol, 73%) of rubrene peroxide (12), mp 155-162° dec. The ir spectrum was identical to that of the photoproduct.

VIII.   BIBLIOGRAPHY

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