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Oxidation of Sterically Hindered Phenols

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The homolytic oxidation of sterically hindered phenols has been reviewed. The possible criteria of the reactivity of phenolic compounds, the properties of phenoxy-radicals–the primary products of oxidation by bound oxygen in non-polar media, and the kinetics of the reactions of phenoxy-radicals in the presence and absence of oxidants, have been discussed. Particular attention has been devoted to the oxidation of sterically hindered phenols in polar media by molecular oxygen, which exhibits a number of characteristic features. The bibliography comprises 84 references.

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I. INTRODUCTION

In recent years there has been an exceptionally vigorous development of the chemistry of sterically hindered phenols. To a high degree, this is due to practical requirements, the phenols being used to suppress undesirable free-radical (chain) processes. Various sterically hindered phenols are widely employed as effective antioxidants for the stabilisation of polymers, for the inhibition of the oxidation processes of fats used as food, etc.[1,2]

Considerable interest attaches to the chemistry of phenols from the standpoint of their role in biochemical processes[3]. In this connection the study of the mechanism of the oxidation processes of sterically hindered phenols assumes special importance. The present review deals with the homolytic oxidation of sterically hindered phenols. Reactions of type (1) and (2) take place under the influence of homolytic oxidants:

$$R_2R'H_2C_6O{-}H \rightarrow R_2R'H_2C_6O\cdot + \cdot H\ , \qquad (1)$$

$$(R_2R'H_2C_6O{:})^- \rightarrow R_2R'H_2C_6O\cdot + e \qquad (2)$$

Processes of the first type include reactions of phenols with peroxy-radicals[4,5], diphenylpicrylhydrazyl (DPPH)[6,8], and tri-t-butylphenoxy-radicals[9,10]. One-electron processes of type (2) take place under the action of oxidants such as potassium hexacyanoferrate(VI)[11-14], potassium permanganate[15], cerium sulphate[16], and molecular oxygen in alkaline media[16,17]. The products of reactions (1) and (2) are phenoxy-radicals. Most of the work on the oxidation of sterically hindered phenols has been devoted to the identification of the phenoxy-radicals, the study of their properties, the reactions with oxidants, and the identification of the final oxidation products. On the other hand, the studies on the kinetic features of the behaviour of phenoxy-radicals are relatively few. In the examination of the available data on the oxidation of sterically hindered phenols particular attention will be given to the kinetics and mechanism of oxidation.

II. CRITERIA OF THE REACTIVITY OF PHENOLIC COMPOUNDS

The ease of the homolytic dissociation of the O–H bond in phenol is due to the dissociation energy of this bond. Accurate values of bond dissociation energies have been

determined mainly for simple organic molecules[18]. Accurate bond energies have been obtained only quite recently for several sterically hindered phenols[19]. To a first approximation, the dissociation energy of the PhO–H bond ($D_{O...H}$) may be regarded as the energy of the highest occupied molecular orbital (E_{HOMO}).[20-22] Consequently the change in the overall π-electron density at the oxygen atom (q_0) on going from one phenol to another, differing in the substituents, determines the differences in the dissociation energies of the O–H bonds in these phenols[23] and hence also the different capacities of the phenols to undergo oxidation. The effect of substituents is shown to the greatest extent when the substituent and the OH group are in the same conjugation system, i.e. are located in the *ortho*- or *para*-positions relative to one another[24,25]. The influence of the substituent in the *meta*-position is due solely to the inductive effect, since the conjugation effect of the *meta*-substituent is zero. Since the inductive effect decreases rapidly with distance[26], in the studies of the relative reactivities of sterically hindered phenols appreciable differences in reactivity may be expected in phenols having different substituents in the *para*-position.

Electron-donor substituents in the *para*-position increase the overall π-electron density at the oxygen atom[22], while electron-acceptor substituents decrease it. To characterise the capacity of the phenol for participation in a reaction involving the dissociation of the O–H bond, q_0 and E_{HOMO} will be used as the parameters of reactivity. Quantum-mechanical study of the activity of phenolic compounds as inhibitors of oxidation processes established a satisfactory correlation between the inhibiting activity of phenolic compounds and q_0 and E_{HOMO}.

Earlier it was established empirically that the activities of phenols as oxidation inhibitors are proportional to their redox potentials (v_0).[26,27] For certain stable phenol–phenoxy-radical systems, v_0 may be determined directly[27,29]; however, most of such systems are unstable under the conditions necessary for the determination of the potential. Fieser[30] proposed a method for the determination of v_0 of unstable redox systems, which consists in the determination of the potential of a stable redox system in the presence of the unstable system. In such cases one measures the minimum potential at which the rate of electron transfer from the phenol to the reference oxidant reaches a minimum value. This potential is called the "critical potential" v_c. For monohydric phenols, $v_c = v_0 - 0.136$ V, i.e. the critical potentials of the systems indeed characterise their redox potentials.

Calculations show the presence of a linear relation between the experimental criterion v_c of the capacity of phenols to be oxidised and the calculated reactivity parameter q_0 [20] and E_{HOMO}.[21] Hush[20] showed that $v_c = 3.0\,(q_0 - 1) - 0.55$ V. The highest occupied molecular orbital of the phenoxide ion is a non-bonding molecular orbital (NBMO), whose energy can be calculated from the formula

$$E_{HOMO} = \alpha + (c_{nx})^2 k_x \beta\,, \qquad (3)$$

where α and β are the coulombic integrals of the carbon atom and the resonance integral of the C=C double bond respectively, c_{nx} is the coefficient of the NBMO of the oxygen atom, and k_x the coulombic parameter of the oxygen atom. Fueno et al.[21] calculated $(c_{nx})^2$ for 200 phenols by the NBMO method. Comparison of the known values of v_c with $(c_{nx})^2$ revealed a linear relation between the two quantities (Fig. 1), which can be described by the equation:

$$v_c = 2.807\,(c_{nx})^2 - 0.459\,. \qquad (4)$$

Since β is negative and k_x is positive, it is evident from a comparison of Eqns. (3) and (4) that the NBMO becomes more stable when $(c_{nx})^2$ increases and the less stable is the NBMO the greater is the ease of oxidation of the phenol. Thus the capacity of the phenol to be oxidised can be estimated from the value of $(c_{nx})^2$, which is linearly related to v_c. Using this relation, the authors calculated v_c for about 180 phenols. In addition it has been shown that for phenols $D_{O...H} = v_c + 57$ kcal mole^{-1}, which made it possible to estimate the dissociation energies of O–H bonds for certain phenols[20].

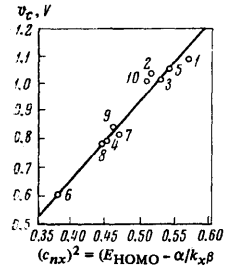
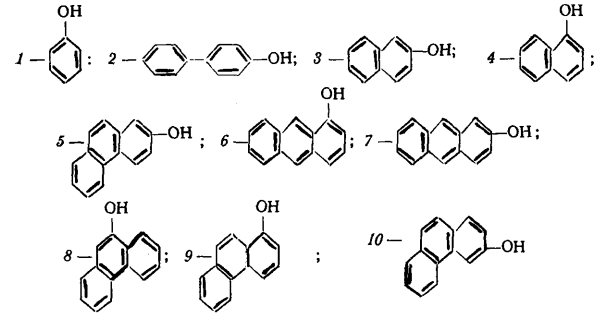


Figure 1. Variation of critical redox potentials of phenolic compounds with the energy of the highest occupied molecular orbital:

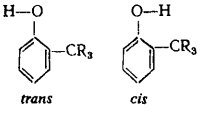


Another physicochemical quantity in which the dissociation energies of the bonds ruptured and formed in molecules of reactants and final products play a major role is the activation energy E_A. However, there is no exact correlation between E_A and bond dissociation energies, particularly in solutions, since effects associated with the electrostatic interaction between ions or dipoles and effects due to changes in solvation during the reaction are important for reactions in solution[31]. For this reason, the activation energies E_A cannot be used to estimate the relative reactivities. The determination of E_A is important for the study of the process mechanism (for example, in the determination of the rate-limiting stage or the changes in the mode of a complex process).

One of the important physicochemical characteristics of phenols dependent on the total π-electron density at the oxygen atom is the characteristic vibration frequency of the free hydroxyl ν_{OH}, which may be regarded as a measure of the polarity of the O–H bond[32]. The total π-electron density which has been increased, for example, by the introduction of electron-donor substituents in the *para*-position reduces the electronegativity of the oxygen atom and renders the coulombic integral of the σ-orbitals of oxygen more positive. This change in the coulombic integral then induces a change in the σ-electron structure of the phenol, particularly in the O–H bond[22], reducing the polarity of the latter[33]. Electron-acceptor substituents increase the

polarity of the O–H bond. The vibration frequency ν_{OH} increases with increasing bond polarity. However, experiments have shown[5,34,35] that the frequencies for phenols containing tertiary alkyl groups in the *ortho*-position are too high to be accounted for solely by their electron-donor properties. Thus, for *ortho*-substituted phenols, the average ν_{OH} is 3610 ± 2 cm^{-1}, for *ortho*-disubstituted phenols which do not contain two tertiary alkyl groups it is 3620 ± 2 cm^{-1}, and for phenols which do contain two such groups it is 3642 ± cm^{-1}.[35] Such powerful influence of tertiary alkyl groups in the *ortho*-position on ν_{OH} is due to two effects of these groups on the polarity of the O–H bond: in the first place the electron-donor effect and in the second the steric interaction of the tertiary alkyl groups with the hydroxyl, the O–H bond being coplanar with the benzene ring or nearly so[34,35]. Ingold's study of the infrared spectra of *o*-alkyl, *o*-t-alkyl-, and *o*-di-t-alkyl-phenols[34,35] showed that also other *o*-alkyl groups interact sterically with the hydroxyl, but this is restricted to the case where the OH group is oriented in the direction of the *ortho*-substituent.

According to Ingold[35,36], *o*-t-alkyl and *o*-alkyl-phenols exist in the form of two isomers corresponding to the *cis*- and *trans*-orientation of the hydroxyl relative to the *ortho*-substituent. Two bands have been observed in the infrared spectra of *o*-t-alkylphenols: the more intense band at the lower frequency corresponds to the *trans*-isomer and the less intense band at the higher frequency to the *cis*-isomer. These isomers have different properties. Thus, when the polarity of the solvent is varied, the *trans*-isomer behaves like phenol (with increasing polarity of the medium, ν_{OH} decreases appreciably), while the behaviour of the *cis*-isomer is similar to that of the corresponding 2,6-di-t-alkylphenol, which exhibits steric hindrance of the effect of the solvent[36,37].



Analysis of the half-width $\Delta\nu_{1/2}$ of the *o*-alkylphenol infrared band shows that the latter consists of two unresolved components. The fraction of the *cis*-isomer is determined by the bulk of the substituent in the *ortho*-position and also by the substituents in positions 5 and 6. In the *cis*-isomer there is steric repulsion between the phenolic hydrogen and the *ortho*-alkyl substituent, leading to an increase of frequency; in 2,6-di-t-alkylphenols there is a possibility of the interaction of the hydroxyl with the second t-alkyl group, reflected in the attraction of the unshared electron pairs of oxygen, which leads to a displacement of the absorption band towards longer wavelengths. These problems have been discussed in detail in Ingold's papers[35,36].

Attempts to use ν_{OH} as a criterion of reactivity were made in studies of the inhibiting activity of phenolic compounds. This criterion is based on the fact that the greater is the polarity of the O–H bond the greater is the displacement of the O–H band in the spectrum towards lower frequencies and the greater is the energy necessary for its homolytic dissociation and conversely. On this basis, it was to be expected that the inhibiting activity of a particular phenol can be assessed from the position of the free hydroxyl vibration band. Indeed comparison of the antioxidant activities and O–H bond polarities showed that the activity of monosubstituted phenol with different substituents in the *para*-position, expressed in terms of the ratio k_7/k_2 of the rate constants for the reactions

$$RO_2^{\cdot} + RH \xrightarrow{k_2} RO_2H + R^{\cdot},$$

$$RO_2^{\cdot} + C_6H_5OH \xrightarrow{k_7} RO_2H + C_6H_5O^{\cdot},$$

increases with ν_{OH}.[2] A rigorous linear relation between k_7/k_2 and ν_{OH} has been established[5] for phenols with substituents in the *ortho*-position, i.e. there is a proportional change in k_7/k_2 as ν_{OH} varies. However, for di- and trisubstituted phenols sterically hindered to different extents, there is a different relation. The efficiency of the inhibiting effect of phenols decreases with increasing ν_{OH} (Fig. 2). However, for phenols sterically hindered to the same extent there is again a possibility of a linear relation between k_7/k_2 and ν_{OH}.[5,35] Thus the use of ν_{OH} to estimate the relative reactivities is possible only within a series of phenols having similar steric structures. This is consistent with the results of the comparison of the inhibiting activities of phenols with the energies of the highest occupied molecular orbital[5]: the correlation curves for two groups of phenols (*o*-t-alkyl phenols and phenols without t-alkyl groups in the *ortho*-position) have different slopes.

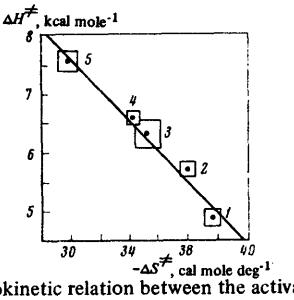


Figure 2. The isokinetic relation between the activation parameters: *1*) cyclohexane; *2*) benzene; *3*) chlorobenzene; *4*) anisole; *5*) benzonitrile.

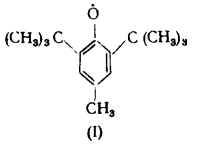
Table 1. Reactions of 2,6-di-t-butyl-4-R-phenols with peroxy-radicals.

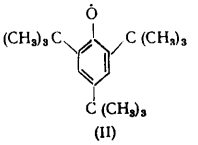
R	k_7, litre $mole^{-1}$ s^{-1} (styrylperoxy-radical) (Ref.39)	k_7/k_2 (tetralkyl-peroxy-radical) (Ref.5)	ν_{OH}, cm^{-1} (Ref.5)	ν_{OH}, cm^{-1} (Ref.38)	σ (Ref.24)
H	$2.35 \cdot 10^3$	967	3640	3648	0
CH_3	$7.95 \cdot 10^3$	1990	3643	3651	−0.17
t-C_4H_9	$7.3 \cdot 10^3$	1430	3642	3650	−0.20
OCH_3	$31.2 \cdot 10^3$		3652	3652	−0.27

However, within a series of phenols with the same steric hindrance, the changes in frequency are small. Thus, for a series of *para*-substituted phenols, the difference in frequency between the extreme members, with *p*-NO_2 (σ = +0.78) and *p*-OH (σ = −0.46) groups, amounts to 23 cm^{-1}, the resolution being 2–3 cm^{-1}.[5] The introduction of an alkyl substituent in the *para*-position of 2,6-di-t-butylphenol increases the inhibiting activity by a factor of more than two, while the change in frequency amounts to 2–3 cm^{-1} (Table 1). All this restricts the use of ν_{OH} as a reactivity index.

III. PROPERTIES OF PHENOXY-RADICALS—PRIMARY PHENOL OXIDATION PRODUCTS

Phenoxy-radicals are fairly stable. Their lifetimes depend on the structure of the radical, the polarity of the medium, and the presence of an oxidant in the system. In polar media the lifetimes of sterically hindered phenoxy-radicals are measured in fractions of a second[39], and therefore the ESR spectra of radicals generated in the oxidation of phenols in polar media, obtained by the usual steady-state technique, refer to secondary radicals[18,40,41]. On the other hand, in non-polar solvents the lifetimes of primary phenoxy-radicals are measured in minutes and even hours[42]. In the presence of an oxidant the primary phenoxy-radicals are converted into more stable secondary radicals[43]. If, for example, after the preparation of the radical (PbO_2 oxidant in an organic solvent) the excess PbO_2 is separated and the solvent is distilled off, the radical remains stable for several months[43]. The stability of sterically hindered phenols is determined by the steric hindrance and delocalisation of the unpaired electron over the benzene ring. The delocalisation of the unpaired electron is reflected in the infrared spectra of phenols. The 2.7 μm band associated with the O–H bond vibrations vanishes from the infrared spectra and a double bond, with frequencies similar to those of the vibrations of the C=O double bond conjugated with a C=C double bond appears in the region 6.0–6.4 μm.[44,45]. The delocalisation of the unpaired electron is confirmed by the analysis of the ESR spectra of phenoxy-radicals. The ESR spectrum of the free electron should have $g = 2.0013$ and comprise a single resonance line. The ESR spectra of phenoxy-radicals have a hyperfine structure (HFS), reflecting the distribution of the unpaired electron over the π-electron system of the phenoxy-radical. For example, the spectrum of 2,6-di-t-butyl-4-methylphenoxy-radical (I) consists of four triplets with the intensity ratios 1 : 3 : 1, the intensity ratios within each triplet being 1 : 2 : 1; the spectrum of 2,4,6-tri-t-butyl-phenoxy-radical (II) consists of a triplet with the intensity ratios 1 : 2 : 1.[42,44]


(I)


(II)

The appearance of four lines in the spectrum of compound (I) is due to the interaction of the unpaired electron with the three equivalent protons of the CH_3 group and the splitting of each line into three components by the interaction with the two equivalent protons in the *meta*-positions of the ring. The degree of interaction of the unpaired electron with β-protons is low, since the effect associated with the hyperconjugation overlapping of the orbitals falls sharply with distance and therefore usually the spectrum of compound (II) consists of a triplet due to the interaction with the metastable protons of the ring. The degree of interaction of the unpaired electron with the ring is characterised by the hyperfine splitting constant a_H, which can be calculated from the ESR spectrum. The observed splitting is proportional to the spin density ρ^π at the corresponding carbon atom. According to Mc Connel's equation, $a_H = Q\rho_C^\pi$. Assuming that Q_{CH}^H and $Q_{CCH_3}^H$ are 23.7 and 27.2 Oe respectively, Stone and Waters[39] calculated from the ESR spectra of phenoxy-radicals the distribution of electron density in the ring.

The data of Table 2 are in good agreement with the absolute values of ρ for the unsubstituted phenoxy-radical, quoted by Buchachenko[44]: $\rho_o = 0.29$, $\rho_m = 0.08$, $\rho_p = 0.45$. The spin densities calculated for theoretical models of these radicals differ significantly from those quoted above. The simplest model[46] represents the radical as a benzyl cation in which only five electrons are associated with the ring, the splitting constants a_{H_o} and a_{H_m} being then identical. A more complex model[47] yields $\rho_o = 0.32$, $\rho_m = 0.21$, and $\rho_p = 0.28$ for phenoxy-radicals. Taking into account the dipolar character of the C–O bond, the following distribution of spin density has been obtained for tri-t-butylphenoxy-radicals by semiempirical calculations[48]:

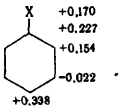


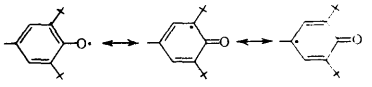
Table 2. Spin density of phenoxy-radicals[39].

Radical from	ρ_o	ρ_m	ρ_p	$\rho_p+2(\rho_o+\rho_m)$
Phenol	0,28	—0.075	0.42	0.83
p-Cresol	0.25	—0.06	0.44	0.82
2,6-Dimethylphenol	0.24	—0.07	0.40	0.74
2,4,6,-trimethylphenol	0.22	—0.06	0.44	0.76

The negative spin density in the *meta*-position implies that the direction of the spin of the unpaired electron at the *meta*-carbon atom is opposed to the direction of the spin of the radical as a whole[48,49]. Possibly the density at the C_1 atom is also negative; it has been suggested[48] that it is similar to the density at C_3 and C_5.

Despite such differences in experimental data, one can say that the major part of the unpaired electron is associated with carbon atoms C_2 and C_6, 20–25% being associated with the oxygen atom and C_1.[6,39,44,50].

Thus ESR spectroscopy of phenoxy-radicals demonstrates the existence of several reaction centres, which can be represented by three mesomeric structures in equilibrium[13]:


(5)

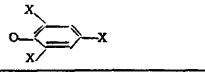
[—+ = C(CH₃)₃]

The reactivity of the reaction centres is determined by the electron density at the corresponding carbon or oxygen atom. This permits the prediction of the possible mode of oxidation reactions of phenols and of the nature and relative amounts of the products.

The introduction of substituents into the phenyl ring causes a redistribution of the electron density, which is reflected in a change of the splitting constants. Alkyl substituents reduce the splitting constants for the *ortho*- and *para*-positions, and alkoxy-substituents reduce the splitting constants for the *ortho*-position to a much greater extent than do alkyl substituents and also to a much greater extent than the constants for splitting by the *meta*-protons of the ring[39]. Probably a considerable proportion of the unpaired electron of such radicals is associated with two oxygen atoms. Table 3 presents the splitting constants for sterically hindered phenoxy-radicals[44]. The constant for splitting by *meta*-protons depends little on the alkyl substituent in the *para*-position, while the constant for splitting by the α-protons of the *para*-substituent has been

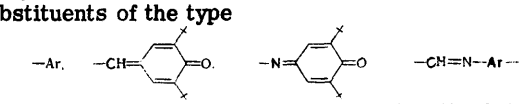
found to vary markedly with its structure. The replacement of methyl by t-butyl leads to a decrease of the constant by a factor of more than two[44]. For *para*- and *ortho*-alkyl-substituted unhindered phenoxy-radicals, the constant for splitting by α-protons decreases in the sequence $CH_3 > C_2H_5 > n\text{-}C_3H_7 \simeq C_6H_5CH_2 > iso\text{-}C_3H_7 > s\text{-}C_4H_9$.[37] A relation of this kind cannot be explained solely by a change in spin density ρ^{π}; it is probably also related to changes in the constants $Q^{H}_{C\text{-}Alk}$. The value of $Q_{C\text{-}H}$ for α-CH groups depends on the orientation of the C–H bond in relation to the electronic symmetry axis and hence also on the average conformations of CH_2R or CHR_2 in relation to the benzene ring[39,44]: the α-CH groups coplanar with the CH groups of the ring make a bigger contribution than the CH-groups oriented at a large angle with respect to the ring.

Table 3. Splitting constants of phenoxy-radicals (oersteds)[44].

	$a_H(meta)$	$a_H(para)$	Other nuclei
X=—CH_3	1.8	10.6	
—CH_2CH_3	1.8	8.7	
—$CH(CH_3)_2$	1.8	4.6	
—$CH_2C_6H_5$	1.8	—	0.37 (H in CH_3)
—$CH_2(C_6H_5)_2$*	1.6	8.7	
—$CH(C_6H_5)_2$	1.8	8.3	
—$CH(CH_3)C_6H_5$	1.8	6.6	
—CH_2OH	2.0	12.3	
—CH_2OCH_3	1.8	11.6	
—$CH_2N(CH_3)_2$	1.9	10.4	1.9(N)
—CH_2NH_2	1.8	11.0	1.8(N)
—NH_2	0.5	2.3	3.7(N)
—	2.5	—	
—	2.2	—	
—	1.9	—	
—	2.2	0.6	
—OCH_3	1.0	1.6	
—OCH_2CH_3	1.0	1.6	
—$OCH(CH_3)_2$	1.0	1.0	
—$OC(CH_3)_3$	1.0	—	
—	1.8	—	

* Error in Russian original (Ed. of Translation).

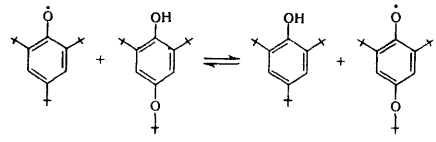
Buchachenko[44] made a thorough examination of the effect of the *para*-substituent on the splitting constants of sterically hindered phenoxy-radicals. The influence of the substituent can be explained by two factors: inductive and resonance effects. The inductive effect leads to a redistribution of the charges, which can lead to a change in spin density. The resonance effect implies the incorporation of the π-orbitals of the substituents in the general molecular orbital, resulting in a change of Q. At the same time there is a possibility of a redistribution of electron density. One can only put forward certain hypotheses concerning the effect of these factors on the splitting constants (see Table 15 in Buchachenko's book[44]). In a few cases one can speak of one or other effect predominating. Thus the increase in the stability of sterically hindered phenoxy-radicals on introduction into the *para*-position of substituents of the type



must be attributed to an increase in the length of the resonance conjugation chain, which favours greater delocalisation of the unpaired electron[43].

IV. FUNDAMENTAL REACTIONS OF PHENOXY-RADICALS: RECOMBINATION, ISOMERISATION, DISPROPORTIONATION, AND REACTION WITH OXYGEN

As already stated there are three reaction centres in phenoxy-radicals: the *ortho*- and *para*-carbon atoms and the oxygen atom. Only the *para*-carbon atom participates in the recombination reaction of sterically hindered phenoxy-radicals: the oxygen and *ortho*-carbon centres are blocked by bulky t-butyl groups. The capacity of 4-alkyl-2,6-di-t-butyl phenoxy-radicals for recombination is restricted by the bulk of the *para*-substituent: for example 2,4,6-tri-t-butylphenoxy- and 2,6-di-t-butyl-4-triphenylmethylphenoxy-radicals do not yield recombination products[44]. 4-Alkoxy-2,6-di-t-butylphenoxy-radicals exhibit higher stability in solution compared with alkyl derivatives. Direct comparison of the stabilities of 4-alkyl- and 4-alkoxy-2,6-di-t-butylphenoxy-radicals was achieved in experiments designed to investigate the equilibrium between phenoxy-radicals[9]. It was shown that the addition of a small amount of 4-butoxy-2,6-di-t-butyl phenol to a blue solution of 2,4,6-tri-t-butylphenoxy-radicals instantly results in the appearance of the red colour of 4-butoxy-2,6-di-t-butylphenoxy-radicals: on addition of a sufficient amount of 2,4,6-tri-t-butylphenol, the blue colour can be restored.



(6)

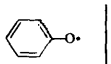
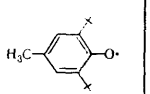
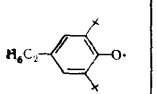
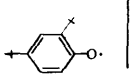
Spectrophotometric study of equilibrium (6) made it possible to estimate the equilibrium constant. The equilibrium constant for 4-butoxy-2,6-di-t-butylphenol at 25°C is 51.7 ± 4.1 and $\Delta H = -3.4 \pm 0.17$ kcal mole^{-1} and for 2,6-di-t-butyl-4-methoxyphenol $K = 210$ and $\Delta H = -5$ kcal mole^{-1}. Such a difference in the constant on going from 4-butoxy- to 4-methoxy-phenol can be accounted for by the fact that, on replacement of the methoxy-group by the butoxy-group, there is an increase in the polarity of the OH bond and therefore methoxyphenol is oxidised more rapidly. The constant for an equilibrium of this kind can be used in principle as a quantitative criterion of the capacity for oxidation but this is hindered by serious technical difficulties[9].

The recombination of 4-alkyl derivatives of phenoxy-radicals was investigated in detail by Land and Porter[51]. In the analysis of the electronic spectra of the photolysis product of phenols a characteristic group of bands (two or three) was observed in the region of 4000 Å; at longer wavelengths weak absorption was found. In their experiments involving the observation of the change in absorption at 4000 Å, Land and Porter investigated the kinetics of the decomposition of phenoxy-radicals. The results obtained are presented in Table 4.

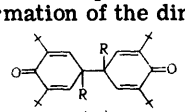
The decomposition of all the phenoxy-radicals investigated is a second-order reaction. The fact that the rate

constant is smaller by a power of ten than the calculated rate constant for a process the rate of which is controlled by diffusion suggests that the authors in fact observed dimerisation. 2,6-Di-t-butyl-4-methoxy- and 2,6-di-t-butyl-4-ethyl-phenoxy-radicals showed an interesting feature. These radicals initially disappear according to a second-order reaction and then, when the concentration of the radicals is still fairly high, the reaction deviates from the second order. Probably two processes are superimposed—rapid dimerisation [reaction (7)] and slow isomerisation.

Table 4. Rate constants for the initial decomposition of phenoxy-radicals by a second-order reaction at 20° ± 3°C. [51]

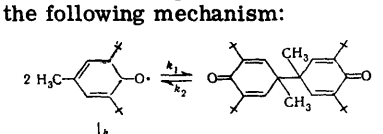
Radical	Solvent	k/ε, cm s^{-1}	k_1, litre mole^{-1} s^{-1}; ε = 1800 max	$k_{calc} = \frac{8RT}{3000\eta}$, litre mole^{-1} s^{-1}	K
	H_2O	$3\cdot10^5$	$5.4\cdot10^8$	$6.4\cdot10^9$	—
	CCl_4	$8.2\cdot10^4$	$1.5\cdot10^8$	$6.7\cdot10^9$	$7\cdot10^{-7}$
	CCl_4	$7.4\cdot10^3$	$1.3\cdot10^7$	$6.7\cdot10^9$	$1\cdot10^{-6}$
	liquid paraffin	$1.1\cdot10^4$	$2.0\cdot10^7$	$4.6\cdot10^7$	—

Neglecting the isomerisation process along the section of the curve which follows the second-order equation, one can determine the dimerisation constant k_1 and the equilibrium constant K, and the dimer dissociation constant k_2 (the final concentration of radicals was determined from the intensity of absorption and the initial concentration by extrapolation of the second-order curve to zero time). Comparison of the constants k_1 for methyl and ethylderivatives confirms the formation of the dimer (III):

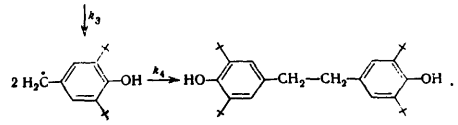


(III)

since on formation of a dimer with a different structure the *para*-substituent would have no steric effect. The slow isomerisation of the phenoxy-radical to a benzyl radical, with a rate constant k_3, is terminated by subsequent rapid dimerisation. Thus the process as a whole can be represented by the following mechanism:



(7)



(8)

Much work has been done on the isomerisation of phenoxy-radicals to benzyl radicals. The appearance of the intermediate benzyl radical makes it possible to explain the formation of 3,5,3′,5′-tetra-t-butylstilbene-4,4′-quinone (IV) in the oxidation of 2,5-di-t-butyl-4-methylphenol (V) with benzoyl peroxide [52]. The predominance (75% yield) of the stilbenequinone (IV) in the oxidation products (V) is observed also when other oxidants are employed [53,54]. Cook et al. [55] explained the formation of the benzyl radical as a result of the rearrangement of the primary phenoxy-radical and proposed the following oxidation mechanism:

$$\text{phenol} \rightarrow \text{phenoxy-radical} \xrightarrow[\text{(rearrangement)}]{} \text{benzyl radical} \xrightarrow[\text{(dimerisation)}]{} \text{final products.} \quad (9)$$

This mechanism can now be regarded as proved. The application of the ESR method in the study of the oxidation showed that the primary radical produced in the oxidation of compound (V) is 2,6-di-t-butyl-4-methylphenoxyl (I). [56] The study of the kinetics of the oxidation of sterically hindered phenols by the ESR method [57] revealed that the kinetic curve for the disappearance of radicals derived from 2,6-di-t-butyl-4-methyl- and 2,6-di-t-butyl-4-ethyl-phenols distinctly follows a first-order process, which suggests that the rate-limiting stage in the oxidation of these phenols is intramolecular rearrangement of the phenoxy-radical to a benzyl radical. Table 5 shows that in a polar solvent the isomerisation rate constant is markedly reduced. This may be due to the solvation of the phenoxy-radical. It has been noted [58,59] that solvation leads to the delocalisation of the unpaired electron over the solvent shell.

Table 5. Kinetic data on the oxidation of sterically hindered phenols in various media [57].

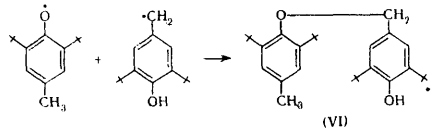
Phenol	Solvent	k, s^{-1}; t = 25°C	E, kcal mole^{-1}	k_0, s^{-1}
2,6-Di-t-butyl-4-methylphenol	benzene	$1.33\cdot10^{-2}$	11.4	$3.1\cdot10^8$
	methylcyclohexane	$1.23\cdot10^{-2}$		
		$0.35\cdot10^{-2}$		
2,6-Di-t-butyl-4-ethylphenol	benzene	$0.75\cdot10^{-2}$		

The low value of k_0 can be explained by the fact that in the intramolecular rearrangement the bulky substituent prevents the formation of a π-complex between the migrating group and the ring. However, the temperature range in which the reaction was studied has not been indicated [57].

According to the data of Brodskii and coworkers [60], the disappearance of 2,6-di-t-butyl-4-ethylphenoxy-radicals is a first-order reaction only close to room temperature. On increase of temperature, the first order is gradually replaced by the second. At room temperature the rearrangement of the phenoxy-radical to a benzyl radical in fact determines the nature of the process. The occurrence of the intramolecular rearrangement has been demonstrated directly by the oxidation with PbO_2 of 2,6-di-t-butyl-4-methylphenol deuteriated at the hydroxy-group, in solution not containing mobile protons [61]. The oxidation leads to a product the infrared spectrum of which contains a band with ν_{OH} = 3647 cm^{-1}, while ν_{OD} for the initial phenol is 2692 cm^{-1}. [62] On the other hand, the oxidation of 2,6-di-t-butyl-4-methylphenol deuteriated in the CH_3 group results in the appearance of a 2692 cm^{-1} band in the infrared spectrum of the product. The replacement of OD by OH and conversely is possible only when the

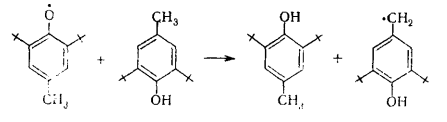
phenoxy-radical rearranges to a benzyl radical. On increase of temperature, the disproportionation reaction begins to make a significant contribution.

On the basis of the above mechanism, it would appear that the product of the cross recombination of the phenoxy- and benzyl radicals should be expected in the reaction products:



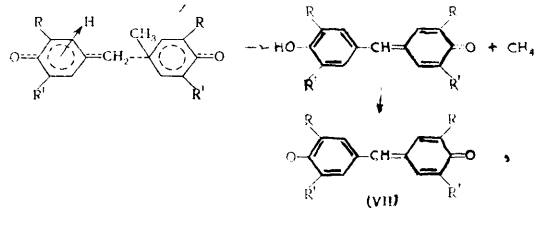
(VI) (10)

However, compound(VI) was not detected. Bennett[57] explained the absence of the product of cross recombination of the phenoxy- and benzyl radicals by the low rate of interaction of phenoxy-radicals with other free radicals[63]. One can add to this that the reaction at the oxygen atom is in general not characteristic of sterically hindered phenoxy-radicals, with the exception of the proton transfer reaction (the reaction with hydrocarbons[64,65], with another molecule of the same compound[66], and with oximes and hydroperoxides[67]). In the reaction between the phenoxyl and another radical the addition takes place as a rule in the *ortho*- or *para*-position. The benzyl radical may be regarded as a variety of alkyl radicals which are known to add to phenoxy-radicals (in the inhibition of the polymerisation of styrene for example) in accordance with the general rule, the addition to the oxygen atom with formation of an ether occurring only partially[44,45]. Apparently the absence of the cross recombination product cannot be regarded as a criterion in the assessment of the oxidation mechanism, as was suggested earlier[40]. The formation of the benzyl radical by reaction (11) is also unlikely[40]:

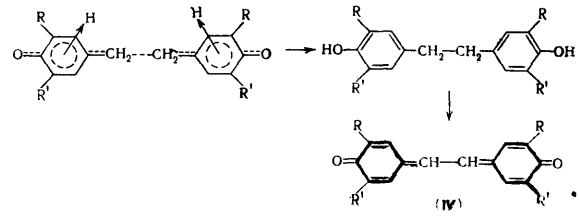


(11)

since the reaction of 2,4,6-tri-t-butylphenoxy-radicals with toluene, which has a similar mechanism, takes place at a low rate, the activation energy for such a reaction amounting to 23 kcal mole^{-1} and $k_0 = 9.7 \times 10^{-13}$ cm^3 s^{-1}.[65] In this case the independence of the rate constant of the initial phenol concentration may be regarded as direct proof. However, in the literature there are only Bennett's data[57], which show that the initial concentration varied within a 5% range. The range of variation of concentration is in this case too narrow to conclude that the rate constant for the disappearance of 2,6-di-t-butyl-4-methylphenoxy-radicals is independent of the concentration of phenol. Becconsall et al.[40] put forward the following mechanism to account for the appearance of compound (VII) among the reaction products:

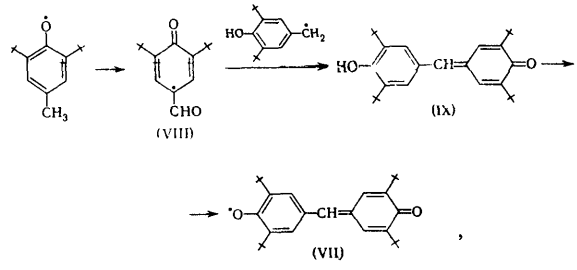


(VII) (12)



(IV)

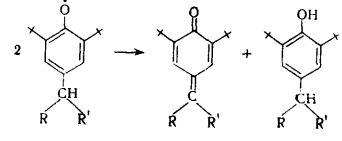
This mechanism does indeed account for the formation of compound (VII), which was detected by Coppinger[68], but it is difficult to accept it since it contradicts the first-order of the radical disappearance reaction, which has been firmly established[57,59]. It can be supposed that the formation of radicals (VII) is preceded by the oxidation of the phenoxy-radical, for example with formation of compound (VIII). The subsequent removal of the *para*-substituent as a result of the interaction of compound (VIII) with the benzyl radical,



(VIII) (IX) (VII) (13)

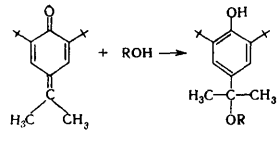
leads to the phenol (IX), whose further oxidation results in the formation of the radical (VII).

A characteristic reaction in the absence of oxygen of sterically hindered phenoxy-radicals with a *para*-substituent containing a tertiary α-hydrogen atom is disproportionation with formation of the corresponding quinone methide and the initial phenol[45,69]:



(14)

A detailed study has been made of the properties of 2,6-di-t-butyl-4-isopropylidene-2,5-cyclohexadien-1-one the reduction of which with lithium aluminium hydride results in the regeneration of the initial phenol and its reduction with zinc in acetic acid leads to the dimeric product 1,2-bis-(3,5-di-t-butyl-4-hydroxyphenyl)-1,1′,2,2′-tetramethylethane. In the presence of an alcohol the acid-catalysed reaction (15) takes place:

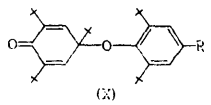


(15)

The phenols formed give rise to radicals, the stability of which is similar to that of the 2,4,6-tri-t-butylphenoxy-radical.

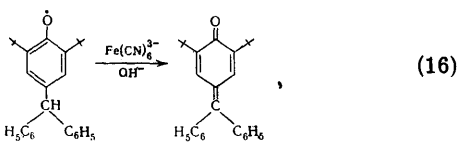
The disproportionation reaction of 2,4,6-tri-t-butylphenoxy-radicals exhibits certain characteristic features[70]. The products of this reaction are 2,4,6-tri-t-butylphenol and at least two dimeric products. Elemental analysis

and the ultraviolet and infrared spectra of one of these dimers suggest the structure (X):

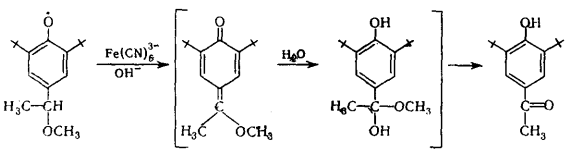


(X)

The behaviour of phenoxy-radicals containing $(C_6H_5)_2CH$ or $CH(CH_3)OCH_3$ groups in the *para*-position is interesting; the oxidation of the initial phenols is accompanied by disproportionation or, in the presence of an excess of alkaline hexacyanoferrate(III), by decomposition according to reactions (16) and (17) respectively:



(16)



(17)

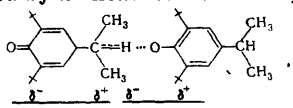
The kinetics of the disproportionation reaction were investigated for a series of sterically hindered phenoxy-radicals differing in the *para*-substituent[71]. The disappearance of the radicals was followed from the decrease of the optical density at 630 nm (phenoxy-radicals absorb in the visible region). Analysis of the kinetic curve shows that the reaction is of second order with respect to the radicals. Comparative studies of a number of phenoxy-radicals demonstrated that the rate of disproportionation decreases for the following series of substituents: $CH_3 > C_2H_5 >$ iso-C_3H_7 > cyclohexyl > s-C_4H_9 (this might have been expected bearing in mind the increasing bulk of the substituent in this series). The activation energy for the reaction increases in the sequence iso-C_3H_7 < s-C_4H_9 < cyclohexyl. The activation parameters were calculated from the results (Table 6).

Table 6 shows that the disproportionation rate constant for the 2,6-di-t-butyl-4-isopropylphenoxy-radical changes little on going from one solvent to another. However, this is not due to the absence of interaction with the solvent

Table 6. Rate constants and activation parameters for the disproportionation reaction[71].

Radical	Solvent	k, litre mole^{-1} s^{-1}; 25°C	E, kcal mole^{-1}	$\Delta H^{\neq}$, kcal mole^{-1} 25°C	$\Delta S^{\neq}$, kcal mole^{-1} deg^{-1}
2,6-Di-t-butyl-4-isopropyl-phenoxyl	benzene	2.17±0.01	6.23±0.15	5.74±0.14	−37.80±0.50
	cyclohexane	3.82±0.09	5.50±0.18	4.91±0.16	−39.46±0.59
	anisole	3.20±0.03	7.20±0.14	6.61±0.13	−34.12±0.46
	benzonitrile	5.64±0.3	8.16±0.19	7.57±0.19	−29.26±0.63
	bromobenzene		7.25±0.11	6.76±0 10	
	chlorobenzene	3.08±0.08	6.94±0.25	6.35±0.23	−35.06±0.82
	carbon tetrachloride		5.80±0.09	5.21±0.08	
4-s-Butyl-2,6-di-t-butyl-phenoxyl	benzene	0.618±0.015	7.04±0.11	6.45±0.10	
2,6-Di-t-butyl-4-cyclohexyl-phenoxyl	benzene	1.28±0.029	7.93±0.14	7.34±0.13	
	cyclohexane		7.45±0 11	6.83±0.10	

but to the presence of a compensation effect with an isokinetic temperature of −9°C, as shown by the linear relation between $\Delta H^{\neq}$ and $\Delta S^{\neq}$ for various solvents (Fig. 2). The authors explain this effect by the different degrees of solvation of the reaction and transition states; the latter can be represented by a "head-to-tail" complex:



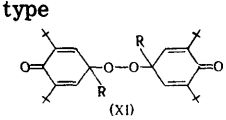
The formation of the transition state is accompanied by desolvation. Close to the isokinetic temperature, a linear relation between the rate constant (and hence also the free energy of activation) and the dielectric constant of the solvent cannot be observed. At temperatures differing significantly from the isokinetic temperature, the difference in the dipole neutralisation energy in the "head-to-tail" orientation in two media with different dielectric constants D_1 and D_2 is defined by the formula

$$\Delta E = \frac{28.9\mu_A \mu_B \Delta D}{D_1 D_2 r^2},$$

where μ_A and μ_B are the dipole moments of the two dipoles and r is the difference between them. Near the isokinetic temperature a not entirely rigorous (large scatter) linear relation between $\Delta H^{\neq}$ and $(D-1)/D$ is observed in this case, in agreement with the results of Leffler and Alder[72]. Thus the results indicate the possibility of a polar factor in radical reactions.

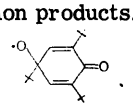
As already stated for 2,6-di-t-butyl-4-methylphenol, in the presence of an oxidant the spectrum of the primary radical varies in time. Table 7 presents the parameters of the spectra of primary and secondary phenoxy-radicals obtained in the oxidation of a number of phenols with PbO_2 in cyclohexane in the absence of oxygen[42]. The primary radical derived from compounds having an α-methylene group is replaced by a more stable secondary radical, which is formed from the primary radical as a result of the oxidation of the *para*-substituent. The spectrum of such a secondary radical consists of a triplet with a_H = 1.2 Oe, which suggests that the splitting is due to the equivalent *meta*-protons.

The presence of oxygen leads as a rule to the formation of peroxides of the type



(XI)

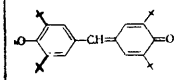
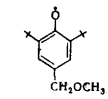
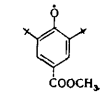
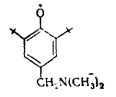
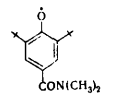
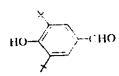
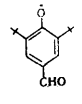
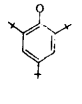
where R = alkyl, alkoxy-group, C_6H_5, C_6H_5CO, etc.[40,44,45,73] The study of the properties of quinolide peroxides showed that the peroxide derived from the 2,4,6-tri-t-butylphenoxy-radical decomposes, at 100–120°C for example, with formation of unstable radicals[40,44], the spectra of which consist of a triplet with a_H = 1.2 Oe. It is believed that the breakdown of the peroxide takes place at the O–O bond with formation of a radical with structure (XII); 2,6-di-t-butylbenzoquinone and isobutene have been detected in the decomposition products.



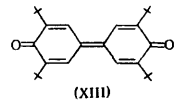
(XII)

A comparative study of the reaction of phenoxy-radicals with oxygen has been made for a series of radicals obtained by the oxidation of the corresponding phenols with alkaline potassium hexacyanoferrate(III).[70] The reaction rate was estimated from the disappearance of the colour of the radical. It was shown that the rate of disappearance of the

Table 7. ESR spectra of phenols undergoing oxidation[42] (oxidant—PbO_2 in cyclohexane).

Phenol	Description of spectrum	Time of observation	Splitting constants, Oe					Radical
			o-methylene group	m-methylene group	p-methylene group	ring H	others	
	(a) quartet of triplets	immediately	—	—	10.7	1.8	—	
	(b) triplet	after 10 min	—	—	—	1.3	—	
	(c) doublet of quintets	after several days	—	—	—	1.4	5.9	
	(a) triplet of triplets	immediately	—	—	9.0	1.8	—	
	(b) triplet		—	—	—	1.2	—	
	(a) triplet of triplets	immediately	—	—	12.3	2.0	—	
	(b) triplet		—	—	—	1.25	—	
	(a) triplet of triplets	immediately	—	—	11.6	1.8	—	
	(b) triplet		—	—	—	1.2	—	
	(a) triplet of quintets	immediately	—	—	10.4	1.9	1.9	
	(b) triplet		—	—	—	1.2	—	
	(a) triplet	immediately	—	—	—	1.3	—	
	(a) triplet	immediately	—	—	—	1.8	—	

colour decreases in the following series of *para*-substituents: $t\text{-}C_4H_9 > C_6H_5 > (C_6H_5)_3C > C_6H_5CO > CN$. On going from C_6H_5 to CN, the rate decreases by a factor of ten, while on going from C_6H_5 to $t\text{-}C_4H_9$ it increases by a factor of ten. Such reduction of sensitivity with respect to oxygen can be due to enhanced resonance stabilisation or partial lowering of electron density at the *p*-carbon atom. Analysis of the oxidation products revealed an appreciable yield of biscyclohexadienone peroxides when the groups C_6H_5 and C_6H_5CO are located in the *para*-position. The oxidation of 2,6-di-t-butyl-4-nitrophenol and 3,5-di-t-butyl-4-hydroxybenzoic acid leads to the formation of the dimeric product (XIII), which is characteristic of the oxidation of 2,6-di-t-butylphenol[17].

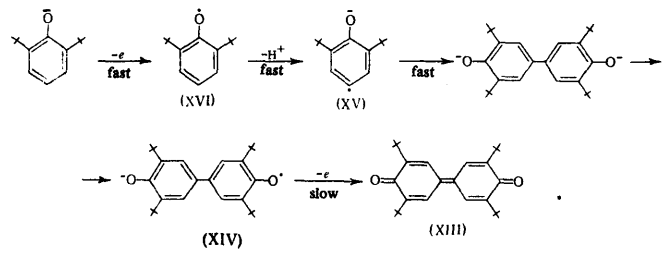


(XIII)

V. OXIDATION OF STERICALLY HINDERED PHENOLS BY MOLECULAR OXYGEN IN POLAR MEDIA

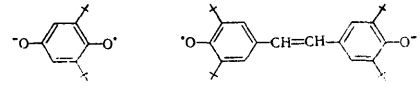
So far we have discussed the reactions of phenoxy-radicals obtained by the homolytic oxidation of phenols in the absence of oxygen. The oxidation of phenols with molecular oxygen in an alkaline medium shows certain characteristics features. In the first place the study of the oxidation by the ESR method revealed the presence of radicals of the semiquinone type and in the second place the kinetic oxygen absorption curve is of an autocatalytic type. Finally, analysis of the molecular oxidation products showed the presence of hydroperoxides and their decomposition products (quinols).

We shall consider the ESR study of the oxidation of the simplest representative of sterically hindered phenols—2,6-di-t-butylphenol[17]. Its oxidation product in an alkaline medium is dibenzoquinone (XIII). If alcoholic potassium hydroxide is added to a tube containing an alcoholic solution of phenol saturated with air and the tube is closed to prevent further diffusion of oxygen and placed in the resonator of a radiospectrometer, the ESR spectrum of this system shows in the first minutes a broad singlet with increasing intensity, which is subsequently split into a quintet with intensity ratios of 1 : 4 : 6 : 4 : 1 and a splitting constant of 0.6 Oe; the 5-line spectrum then disappears and a triplet remains with intensity ratios of 1 : 2 : 1 and a_H = 1.5 Oe. The triplet spectrum persists for several hours. The broad singlet line is probably due to the 2,6-di-t-butylphenoxy-radical (a 6-line spectrum with intensity ratios of 1 : 1 : 2 : 2 : 1 : 1 is expected) and almost simultaneously a radical forms which gives rise to a quintet. The quintet spectrum can be attributed to the radical-ion (XIV), since an identical spectrum arises in the reduction of dibenzoquinone (XIII). The triplet spectrum can be attributed to 2,6-di-t-butyl-4-benzosemiquinone. A radical of this kind can form from the intermediate hydroperoxide. The triplet splitting may be due also to the radicals (XV), which form from the phenoxy-radicals when the number of protons available is insufficient. The existence of the (XVI)–(XV) stage can be postulated also on the basis of the fact that in the oxidation of phenol with neutral potassium permanganate in acetone there appears initially a broad singlet line, which then splits into a quintet. Analysis of the spectrum suggests the following mechanism for the oxidation:



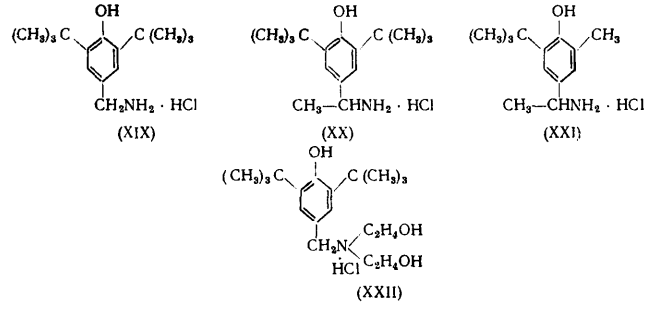
(XVI) (XV) (XIV) (XIII)

In the oxidation of 2,6-di-t-butyl-4-methylphenol (ionol) with air in alkaline acetone a radical forms whose ESR spectrum consists of eight lines[18]. In the presence of a deficiency of oxygen the 8-line spectrum disappears and is replaced by a triplet with a splitting of 1.3 Oe and intensity ratios of 1 : 2 : 1. This spectrum may be due either to the radical (XVII) or to the radical (XVIII)[40]. A triplet of this kind was observed after three days in the oxidation of ionol in alkaline methanol; the initial spectrum consists of fifteen lines and appears to result from the superposition of the spectra of several radicals[40]. The present authors'[41] study of the oxidation of four 4-aminoalkyl-2,6-di-t-butylphenols (XIX)–(XXII) in alkaline aqueous alcoholic (1 : 1) solution saturated with oxygen showed that, for all four phenols, which differ in the *para*-substituent, the reaction mixture has a yellow-green colour and even in the first minute gives rise to an ESR signal in the form of a triplet with a splitting of 1.4 Oe and intensity ratios of 1 : 2 : 1.[42] The structure of this spectrum persists for tens of minutes at 45–67 °C. The kinetic curve of the radical with a triplet ESR spectrum passes through a maximum, the descending branch representing the disappearance of the radicals. Most of the curve can be formally described by the equation for first-order kinetics.



(XVII), a_H = 1.5 Oe (XVIII), a_H = 1.6 Oe

The radicals generated in the oxidation of phenols (XIX), (XX), (XXI), and (XXII) disappear with the same activation energy (23 kcal mole^{-1}).



(XIX) (XX) (XXI)

(XXII)

All these findings confirm that we are dealing with the same radical in all four cases and that this radical is not a primary phenoxyl. The spectra of primary phenoxy-radicals derived from these phenols should show significant differences. Thus the primary phenoxy-radical from 4-aminomethyl-2,6-di-t-butylphenol (XIX) obtained in the oxidation of this phenol with PbO_2 in benzene has an ESR spectrum in the form of a triplet of quintets with a splitting of 10.4 Oe in the triplet and 1.9 Oe in the quintet[43], while

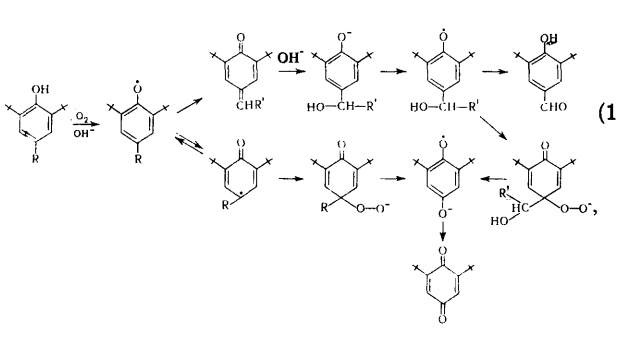
the spectrum of the phenoxy-radical from 4-aminoethyl-2,6-di-t-butylphenol (XX) should consist of a doublet of quintets with a splitting of about 8.5 Oe in the doublet and 1.8–1.9 Oe in the quintet.

The spectrum obtained by the authors can be attributed to 2,6-di-t-butyl-1,4-benzosemiquinone (XVII). The absence of splitting by *ortho*-substituents under these conditions leads to identical spectra of the semiquinone radical-ions derived from 4-aminoethyl-6-t-butyl-2-methylphenol (XXI) and phenols containing two t-C_4H_9 groups in the *ortho*-positions.

The radical detected by Adams et al.[17] and Becconsall et al.[40] in the oxidation of ionol in a polar medium, which has a triplet spectrum with a splitting 0.1 Oe, is also 2,6-di-t-butyl-1,4-benzosemiquinone (XVII). We have shown[74] that the formation of 2,6-di-t-butyl-1,4-benzosemiquinone is characteristic of the oxidation with molecular oxygen in alkaline aqueous alcoholic solution of 2,6-di-t-butylphenols containing electron-donor substituents in the *para*-position. The oxidation of alkylphenols with oxygen in alkaline aqueous alcoholic solution probably begins with the stage involving the formation of the corresponding phenoxy-radicals, which are extremely unstable under the experimental conditions and can either disproportionate to the corresponding methylenequinones or interact with oxygen to form 2,6-di-t-butyl-1,4-benzosemiquinone, which leads as a rule to the removal of the *para*-substituent regardless of the structure of the initial 4-substituted 2,6-di-t-butylphenol.

In our experiments on the oxidation of certain 4-substituted phenols, quinone methides stable in an alkaline aqueous alcoholic solution were also isolated. Such methides are 2,6-di-t-butyl-4-*NN*-dimethylaminomethylenecyclohexa-2,5-dien-1-one and 2,6-di-t-butyl-4-methoxymethylenecyclohexa-2,5-dien-1-one, which are converted under the action of acid into 3,5-di-t-butyl-4-hydroxybenzaldehyde (XXIII). This benzaldehyde was also detected in the oxidation products of 2,6-di-t-butyl-4-(β-hydroxyethyl)aminophenol (XXII) on addition of concentrated hydrochloric acid to the reaction mixture. The formation of quinone methides in the reaction is confirmed also by the ultraviolet spectra of the reaction mixture. The absorption by the reaction mixture obtained from 2,6-di-t-butyl-4-dimethylaminomethylphenol in the region of 340 nm is due to aminomethylenequinone[75]; 2,6-di-t-butyl-4-methoxymethylenecyclohexa-2,5-dien-1-one gives rise to an absorption band with a maximum at 325 nm.

2,6-Di-t-butyl-1,4-benzosemiquinone (XXII) is formed from an intermediate hydroperoxide with a *para*-quinolide structure. On the basis of the results of Strigun et al.[41,74] and other literature data, the oxidation with molecular oxygen in polar media of alkylphenols with electron-donor substituents in the *para*-position can be represented by the following mechanism:

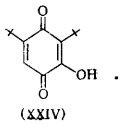


(18)

where R = CH_3, C_2H_5, $CH(CH_3)_2$, CH_2OCH_3, $CH_2OC_2H_5$, CH_2NH_2, $CH_2N(CH_3)_2$, $CH_3-CH(CH_2)$, or $CH_2N(CH_2CH_2OH)_2$.

The relative amounts of reaction products depend on reaction conditions. 3,5-t-Butyl-4-hydroxybenzaldehyde formed during the reaction is not oxidised by oxygen under the experimental conditions and does not interact with any of the other reaction products and therefore the mode of the disproportionation reaction of the phenoxy-radical can be assessed from the amount of the hydroxy-aldehyde. When the concentration of oxygen in the system is sufficiently high, the phenoxy-radicals are rapidly converted into semiquinone radical-ions. As a result, the oxidation process is determined by the characteristics of the oxidation of the semiquinone. According to the above mechanism, semiquinone radicals disappear in the disproportionation reaction, which leads to the formation of quinone in the system. At advanced stages of the reaction the quinone accumulated in the system is reduced. The formation of semiquinone by the reduction of the quinone in the alkaline medium[76,77] is superimposed on the disproportionation process, as a result of which the kinetic curve describing the disappearance of the radicals is of a complex form and cannot be fully described by simple equations.

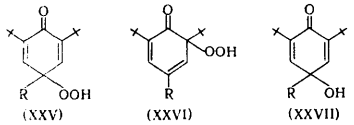
The hydroxy-quinone with the structure (XXIV) has been detected in the oxidation products of the phenol (XXII)[74], its structure having been demonstrated by infrared, ESR, and NMR spectra. It has been shown that this hydroxy-quinone is formed on direct interaction between 2,6-di-t-butyl-1,4-benzoquinone and alkali. All these findings indicate that, at advanced stages of the reaction, the system containing a phenol undergoing oxidation obeys the general laws governing the reduction of quinones[74,76,77].



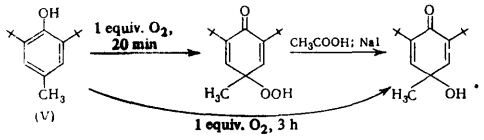
(XXIV)

Hydroperoxides with structures (XXV) and (XXVI) are characteristic products of the oxidation with molecular oxygen of sterically hindered phenols[78–80]. In an alkaline solution they isomerise and decompose into the quinols (XXVII) or the initial phenol.

The absorption of one equivalent of oxygen by a solution of ionol (V) in alkaline ethanol leads to the formation of the hydroperoxide (XXV) with a yield of 86%.[78] Slow absorption (restricted access of the gas) of the same amount of oxygen results in the formation of the corresponding quinol[19]:



(19)



The oxidation of 2,4,6-tri-t-butylphenol under similar conditions yields the *o*-hydroperoxide as the main product together with a small amount of *p*-hydroperoxide. The properties of these hydroperoxides are interesting[79]. The reduction of *p*-hydroperoxides with hydrogen iodide leads to the corresponding quinols. When the *p*-hydroperoxide (XXV, R = C_4H_9) is heated for 2 h at 40°C and pH 14 in

alcohol in the presence of oxygen, the isomeric *o*-hydroperoxide (XXVI, R = C_4H_9) and the corresponding quinol (XXVII, R = C_4H_9) are formed. Under the same conditions the *o*-isomer gives rise to the *p*-hydroperoxide and the corresponding quinol but the relative amounts of the two products are different (Table 8).

Table 8. Isomerisation of hydroperoxides (XXV) and (XXVI) (R = t-C_4H_9.[75]

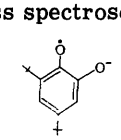
Hydroperoxide	% formed on heating		isomer / quinol
	of isomer	of quinol	
p-Hydroperoxide	19.5	30.5	0.64
o-Hydroperoxide	21	29	0.72

Table 8 shows that the isomerisation is accompanied by the decomposition of the hydroperoxide. It has been shown that when the *p*-hydroperoxide (XXV, R = CH_3) is heated under the above conditions for 4 h, it is decomposed to the extent of 80%, the main product being the quinol (XXVII, R = CH_3); heating in nitrogen leads to the decomposition of the peroxide to the extent of 90%, the reaction products—quinol (XXVII) and ionol—being formed in proportions of 2 : 3. On decomposition in a stream of nitrogen, the yield of the phenol and oxygen can reach 70%. The study of this reaction in 50% aqueous t-butyl alcohol[80], with potassium cyanide added to bind heavy metal ions which catalyse the decomposition of the peroxide, showed that the decomposition is a first-order reaction and depends on the pH of the medium. This suggested that the reaction proceeds as follows:

$$ROO^- \rightarrow R^- + O_2 \,. \qquad (20)$$

The *p*-hydroperoxide (XXV, R = C_4H_9) undergoes a similar reaction, but the yield in this case is lower.

The ESR study[78] of the decomposition of the *p*-hydroperoxide (XXV, R = CH_3) in an alkaline medium showed that after heating for 4 h in the system gives rise to the characteristic spectrum of the catechol semiquinone (XXVIII); the presence of isobutene was demonstrated by gas–liquid chromatography and mass spectroscopy.



(XXVIII)

When equimolar amounts of solutions of the *p*-hydroperoxide (XXV, R = CH_3) and ionol or of cumenyl hydroperoxide and the quinol (XXVII, R = CH_3) are mixed, this type of spectrum appears instantly. The characteristics of the spectra of these semiquinones are presented in Table 9.

Gersmann and Bickel[80,81] suggested that the *o*-quinone or *o*-semiquinone radical-ions formed in the decomposition of *o*-hydroperoxides can catalyse the oxidation of phenols. The data of Conradi and McLaren[82] demonstrate that the *o*-quinone is definitely formed in the oxidation of phenols. Gersmann and Bickel made a detailed study of the kinetics of the oxidation of sterically hindered phenols in polar media[80,81]. The kinetic oxygen absorption curve is of an autocatalytic type. The authors explained the autocatalysis of the oxidation of sterically hindered phenols by the catalytic effect of the *o*-hydroperoxide (Fig. 3); *p*-hydroperoxides do not exhibit a catalytic effect. The catalytic effect of the *o*-hydroperoxide is in all probability associated with its decomposition accompanied by the formation of the active catalyst: *o*-quinone or a radical. The attempts to show that the auto-oxidation of sterically hindered phenols in polar media with molecular oxygen is a radical chain process proved unsuccessful: the addition of hydrogen donors (9,10-dihydroanthracene) and initiators ($\alpha\alpha$-azobisisobutyronitrile) did not show a definite effect on the rate of oxidation; the addition of free-radical reaction inhibitors (quinones and aromatic polynitro-compounds) accelerates the oxidation. This favourable catalytic effect will be discussed in detail below.

Table 9. Properties of the ESR spectra of *o*-semiquinones observed in the oxidation of 2,6-di-t-butyl-4-R-phenols.

R	Intensity ratio	Splitting constants	
		a_1	a_2
CH_3	1:1:3:3:3:3:1:1	5.2	2.5
Benzyl	1:1:2:2:1:1	4.1	2.5
iso-C_3H_7	1:2:1	2.4	2.4
t-C_4H_9	1:1		2.5

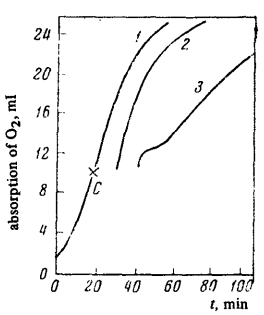


Figure 3. Auto-oxidation of 2,4,6-tri-t-butylphenol: *1*) phenol alone, initial concentration 4 x 10^{-2} M; *2*) phenol mixed with the *o*-hydroperoxide in proportions corresponding to the content of both components in the reaction mixture at point *C*; *3*) phenol alone, initial concentration equal to the concentration of the phenol in the reaction mixture at point *C*.

Comparative study of the auto-oxidation of sterically hindered phenols in various solvents showed that oxidation in the 1 : 1 mixture of t-butyl alcohol and 1,2-dimethoxyethane containing potassium butoxide is much faster than in 90% ethanol; the kinetic [oxygen] absorption curve does not show an induction period in this case, but the yield of hydroperoxide in ethanol is higher. The reaction remains of first order with respect to the phenoxide ion up to 80% conversion; at the same concentration of alkali the reaction is of first order with respect to oxygen pressure. Table 10 presents data on the oxidation of ionol.

The much higher rate of oxidation in the presence of potassium t-butoxide in the t-butyl alcohol–1,2-dimethoxyethane mixture is due to the fact that in this solution the phenol is evidently completely ionised while in 90% ethanol

at pH 13 ionol is dissociated only to the extent of 20%. Furthermore, the difference in solvation may play a significant role. The formation of hydrogen bonds is in this case difficult due to steric hindrance. The importance of the size of solvent molecules can be seen from the low rate of oxidation in 100% methanol containing potassium methoxide.

Table 10. Auto-oxidation of ionol (0.5 - 1.0 mole/30 ml).[81]

№	Molarity of base	Solvent*	p_{O_2}, mmHg	t, °C	k, min^{-1}
1	0.10	A	76	25	0.92
2	0.10	A	76	0	0.12
3	0.25	A	76	0	0.12
4	0.25	A	53	0	0.075
5	0.25	A	34	0	0.052
6	0.10	A	76	0	0.644
7	0.10	A	76	0	0.253
8	0.10	90% C_2H_5OH	76	0	0.0024
9	0.10	100% CH_3OH	76	0	0.0005

* A represents a 1 : 1 mixture of t-butyl alcohol and 1,2-dimethoxyethane; in experiment No. 6 20 mg of 2,6-di-t-butylbenzoquinone and in experiments Nos. 7 and 8 20 mg of *m*-dinitrobenzene were added.

As stated above, 2,6-di-t-butylbenzoquinone, duroquinone, and *m*-dinitrobenzene proved to be effective catalysts of the oxidation of sterically hindered phenols (Table 11). The study of the kinetics of the catalysis by quinones and polynitrobenzenes showed differences which the authors attributed to differences in the mechanism of the catalysis. Thus the oxidation catalysed by *m*-dinitrobenzene depends on the concentration of the catalyst, is of first order with respect to the phenol (as shown by the analysis of the kinetic oxygen absorption curves) and is independent of oxygen pressure in the range between 0.5 and 1 atm which Gersmann and Bickel believe[81] to indicate the usual catalytic mechanism involving the formation of a catalyst–substrate complex.

Table 11. Activation energy for the catalysed oxidation of 2,6-di-t-butyl-4-methylphenol in 90% ethanol.[80]

Catalyst	E, cal mole^{-1}
2,6-Di-t-butylbenzoquinone	12000
m-Dinitrobenzene (20 ml/mole)	8900
m-Dinitrobenzene (50 ml/mole)	9400
No catalyst	20000

In the catalysis by quinones the rate of reaction is independent of quinone concentration in the range of the latter investigated and is proportional to oxygen pressure. In the catalytic oxidation of polyphenols such a phenomenon is called saturation of quinone catalysis[83,84]. The independence of the catalytic effect of the concentration of the quinone is due to the formation of a complex[80] between the phenol and the quinone, the interaction with another quinone molecule becoming unlikely.

However, with duroquinone, the catalytic effect does vary with catalyst concentration somewhat. It has been shown[80] that *m*-dinitrobenzene and quinones catalyse the decomposition of *p*-hydroperoxides. Since the decomposition is accompanied by isomerisation, then, on the basis of the data presented, one can probably postulate that the catalytic effect of both nitrobenzenes and quinones is not direct. It is due to the catalytic effect of these compounds on the decomposition of the hydroperoxide.

Since the catalytic effect of *m*-dinitrobenzene on the decomposition of *p*-hydroperoxides is weaker than the effect due to 2,6-di-t-butylbenzoquinone, in the oxidation of phenol higher concentrations of *m*-dinitrobenzene than of the quinone are required for catalysis. It may be supposed that further increase in the amount of catalyst would result in the independence of the reaction rate constant of the concentration of *m*-dinitrobenzene. The possible saturation of the catalytic effect of *m*-dinitrobenzene in the oxidation of trialkylphenols is indicated by the comparison of the activation energies for processes catalysed by different amounts of *m*-dinitrobenzene (Table 11). Table 11 shows that, on going from 20 to 50 ml of *m*-dinitrobenzene per mole, the activation energy is virtually constant, but the rate constant increases almost by a factor of two.

In our experiments the addition of benzoquinone at the beginning of the oxidation with molecular oxygen of 4-aminoalkyl-2,6-di-t-butylphenols in a 1 : 1 alkaline aqueous alcoholic medium leads to an increase of the induction period on the kinetic curve for the consumption of the phenol. The addition of 2,6-di-t-butyl-1,4-benzoquinone at the beginning of the oxidation of 4-aminoethyl-2,6-di-t-butylphenol (XX) does not affect the induction period, but after the induction period the rate of consumption of the phenol (XX) is much lower in experiments with the addition of this quinone than without it. Probably the observed effect is associated with the reduction of the phenoxy-radicals under the influence of the benzoquinone to the initial phenol, while in the presence of 2,6-di-t-butyl-1,4-benzoquinone the phenoxy-radicals are not reduced. The effect of 2,6-di-t-butyl-1,4-benzoquinone begins when a sufficient amount of hydroperoxides accumulates in the system, their decomposition to the initial phenol and the quinone being catalysed by 2,6-di-t-butyl-1,4-benzoquinone. As a result, the *o*-quinone does not accumulate in the system in amounts necessary for an autocatalytic process.

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