

## BIOMIMETIC ACTIVATION OF THE C-H BOND.

2.\* OXYGENATION OF HYDROCARBONS WITH O<sub>2</sub> CATALYZED  
BY PORPHYRIN COMPLEXES OF METALS IN THE PRESENCE  
OF FERROCENE AS A REDUCING AGENT

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The oxygenation of cyclohexane, ethylbenzene, and styrene by O<sub>2</sub> catalyzed by metalloporphyrin complexes in the presence of ferrocene and its derivatives as a reducing agent was studied. The oxygenation is probably accomplished by oxygen-containing radical species.

The monooxygenase enzymes, which are contained in the cells of living organisms and often have the constituent cytochrome P-450, oxygenate aromatic, saturated, and olefinic hydrocarbons at low temperatures [2-6]. The mechanism accepted at the present time assumes stages of the coordination of O<sub>2</sub> with the reduced iron ion, the formation of the oxo complex of the high-valent iron (in the oxidation state IV or V), and the transfer of the oxygen atom from the iron to the substrate. Nicotinamide dinucleotide (NADH) and nicotinamide dinucleotide phosphate (NADPH) emerge as the reducing agents in natural systems. In the purely chemical systems simulating such oxygenation (including the porphyrin complex of iron and manganese as the catalyst), ascorbic acid, sodium borohydride, thiosalicylic acid, etc., served as the reducing agents. In another type of the models of cytochrome P-450, the oxidation is performed not by O<sub>2</sub>, but by the donor oxygen atom, and a reducing agent is not required in this case. Iodosobenzene C<sub>6</sub>H<sub>5</sub>IO is most frequently utilized to provide the donor O atom. Data has recently appeared indicating that the oxygenation of alkenes by iodosobenzene is effectively catalyzed by the porphyrin complexes of not only Fe and Mn, but also those of Al and Zn, in which case the formation of oxo derivatives is not possible [7]. These results may indicate that a key stage in the oxygenation of hydrocarbons in the presence of cytochrome P-450 (and its chemical models) should optionally consist of the transfer of the oxygen atom from the complex of the metal in the high oxidation state. Therefore, it is probably impossible to consider that the mechanism of the oxygenation is definitely established. Consequently, the search for new systems, particularly those based on O<sub>2</sub> and the metalloporphyrins, which can activate the C-H bond in hydrocarbons is acquiring special significance. Systems reducing O<sub>2</sub>, and in a certain regard being models of some enzymes, may appear to be of such a type [8].

The given work first investigated the oxygenation of aromatic, saturated, and olefinic hydrocarbons by O<sub>2</sub> with the catalysis by the porphyrin complex of Co and some other metals in the presence of ferrocene and its derivatives as reducing agents, as well as other donors of hydrogen atoms.

It was recently shown that O<sub>2</sub> is reduced by ferrocene and some of its derivatives in the presence of protonic acids with the catalysis by the porphyrin complexes of Co, Fe, and Mn [9, 10]. Cobalt porphyrinate catalyzes the reduction of oxygen by 10-methyl-9,10-acridine [11]. The reduction by this compound, as well as by 1,1'-dimethylferrocene, is catalyzed by HClO<sub>4</sub> in acetonitrile or by heterogeneous catalysts (Al<sub>2</sub>O<sub>3</sub>, zeolites, ZrO<sub>2</sub>, treated with H<sub>2</sub>SO<sub>4</sub>, etc.) [12]. Finally, O<sub>2</sub> is reduced on a graphite electrode modified by the phthalocyanine complex of cobalt [13]. The corrin complexes of cobalt reduce O<sub>2</sub> to H<sub>2</sub>O in the presence of a reducing agent (ascorbic acid or ubiquinone) [14], and the adducts of O<sub>2</sub> with the phthalocyanine complex of cobalt set free the superoxide anion on treatment with cyanide

\*For previous communication, see [1].

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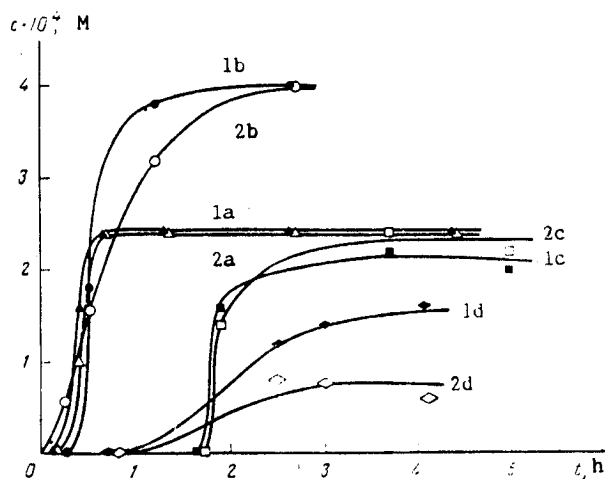


Fig. 1. Accumulation of cyclohexanol (1) and cyclohexanone (2) during the oxidation of cyclohexane (0.46 M) in the 2000:1 v/v mixture of  $\text{CH}_3\text{CN}-\text{H}_2\text{O}$  in the presence of  $10^{-2}$  M ferrocene,  $7.55 \cdot 10^{-3}$  M  $\text{HClO}_4$ , and the  $10^{-4}$  M catalyst of TPPCo (a), TPPFeOCOCH<sub>3</sub> (b), TPPH<sub>2</sub> (c), and ETPZn (d).

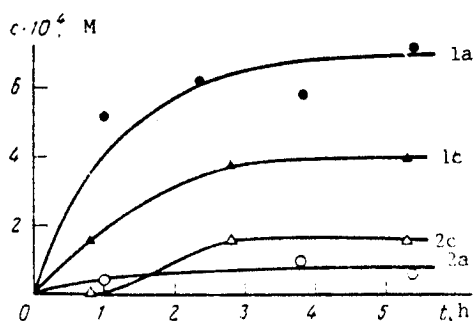


Fig. 2. Oxidation of cyclohexane in the presence of benzylferrocene ( $10^{-2}$  M). The conditions and designations are as in Fig. 1.

[15]. We will note here that the formation of oxygen-containing radicals is observed during the reduction of  $\text{O}_2$  by systems containing cytochrome P-450 [16].

#### EXPERIMENTAL

Experiments were performed in air with the periodic stirring with a magnetic stirrer at  $\sim 20^\circ\text{C}$  with protection from the light. Samples removed at certain intervals of time were analyzed by the method of GLC on the LKhM-80-6 chromatograph with the sorbent INERTON AW-HMDS, 0.2-0.315 mm, saturated with 5% Carbowax 1500; the length of the columns was 2 m, the gas carrier was argon.

#### RESULTS AND DISCUSSION

The formation of the products of the hydroxylation of the hydrocarbon occurs when the solution of cyclohexane in aqueous acetonitrile is stirred in air in the presence of ferrocene, perchloric acid, and catalytic amounts of the porphyrin complexes of metals. The kinetic curves are presented in Fig. 1. It can be seen that the accumulation of the oxygenation products proceeds at the same initial rates (after a small induction period) in the case of the tetraphenylporphyrinate (TPP) complexes of Co(II) and Fe(III), although the total yield is somewhat higher in the second case. When the etioporphyrinate (ETP) complex of zinc is utilized, the induction period on the kinetic curves is much longer, and the yield of the products is lower. The formation of the oxygenation products of cyclohexane proceeds very

TABLE 1. Parameters of Selectivity for the Joint Oxygenation of Ethylbenzene and Cyclohexane by Oxygen of the Air in the Mixture of  $\text{CH}_3\text{CN}-\text{H}_2\text{O}$  in the Presence of a Reducing Agent and a Catalyst (the time of reaction 1 day)

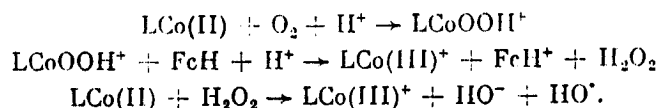
Reducing agent	Catalyst	Molar ratio of the reaction products				$\Psi$
		1-phenyl-ethanol	acetophenone	cyclohexanol	cyclohexanone	
$\text{C}_5\text{H}_5\text{FeC}_5\text{H}_4\text{CH}_2\text{C}_6\text{H}_5 + \text{H}^+$	TPPCo	0.5		5.0		15.7
	TPPF <sub>e</sub> OCOCH <sub>3</sub>	0.5		1.0		15.5
$1,2-\text{C}_6\text{H}_4(\text{CH}_2\text{C}_6\text{H}_5)_2\text{FeC}_5\text{H}_4\text{CH}_2\text{C}_6\text{H}_5 + \text{H}^+$	TPPCo	2.2		5.9		7.6
	TPPF <sub>e</sub> OCOCH <sub>3</sub>	1.2		1.3		8.0
	ETPZn	1.7		1.6		7.3
	TPPH <sub>2</sub>	1.3		0.8		8.3
$[\text{C}_5\text{H}_4\text{CH}(\text{OH})\text{C}_6\text{H}_5]_2\text{Fe}$	TPPCo	1.1		2.2		7.6
	TPPH <sub>2</sub>	0.8		0.6		8.8
Ascorbic acid	TPPCo	0.2		2.5		4.9
	TPPF <sub>e</sub> OCOCH <sub>3</sub>	0.4		2.2		4.8
	ETPZn	0.9		7.6		2.5
	TPPH <sub>2</sub>	0.5		5.7		3.6

characteristically if tetraphenylporphyrin (TPPH<sub>2</sub>) not containing metal is utilized as the catalyst; rapid oxidation is observed after a prolonged induction period. When ferrocene is substituted by benzylferrocene, the yield of the products of the oxygenation of cyclohexane increases, the induction period is shortened, and cyclohexanol begins to predominate in the mixture of products (Fig. 2).

Ethylbenzene and styrene are also oxidized under these conditions. Ethylbenzene forms 1-phenylethanol and acetophenone; styrene gives benzaldehyde as the main product, as well as a small amount of acetophenone. The kinetic curves for the accumulation of benzaldehyde are presented in Fig. 3. It can be seen that the accumulation proceeds with a marked induction period when TPPH<sub>2</sub> and its complex with a non-transition metal (zinc) are utilized as catalysts. Moreover, the formation of benzaldehyde proceeds without an induction period in the presence of the porphyrinate complexes of transition metals (Fe, Co, Mn), although the rate of its accumulation depends strongly on the nature of the metal and even the fifth ligand in the complex.

The competitive oxidation of ethylbenzene and cyclohexane was carried out. The parameters of selectivity, showing the ratio of the resulting alcohol and ketone, as well as the relative reactivity of one C-H bond in the CH<sub>2</sub> groups of ethylbenzene and cyclohexane (the factor  $\Psi$  [1]), are presented in Table 1. It follows from the data of Table 1 that the ratio alcohol/ketone < 1 for the reduction by different substituted ferrocenes with the catalysis by TPPH<sub>2</sub>. The value of  $\Psi$  for one and the same catalyst changes markedly in the transition from one reducing agent to another. In all cases, this value approximates to the value of  $\Psi$  characteristic of the hydroxylation by HO· radicals (2.9-3.6), practically agreeing with the value for the oxidation catalyzed by TPPH<sub>2</sub> in the presence of ascorbic acid. In the majority of the other reactions, the value of  $\Psi$  is higher than the characteristic value for the oxidation by the hydroxyl radicals.

As was shown in [10, 12, 14], the reduction of O<sub>2</sub> catalyzed by porphyrin (or corrin) complexes proceeds with the intermediate formation of peroxide derivatives of the metal, superoxide and hydroxyl radicals, and hydrogen peroxide:



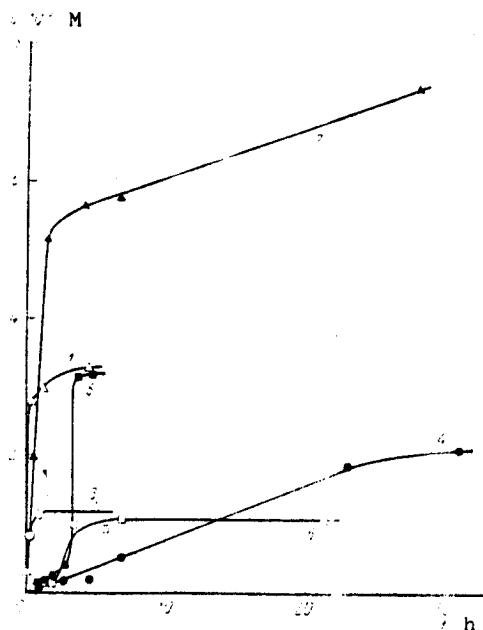


Fig. 3. Accumulation of benzaldehyde in the oxidation of styrene (0.46 M) in the 2000:1 v/v mixture of  $\text{CH}_3\text{CN}-\text{H}_2\text{O}$  in the presence of  $10^{-2}$  M ferrocene,  $7.55 \cdot 10^{-3}$  M  $\text{HClO}_4$ , and  $10^{-4}$  M of the catalyst TPPCo (1),  $\text{TPPFeOCOCH}_3$  (2),  $\text{TPPFeCl}$  (3),  $\text{TPPMnCl}$  (4),  $\text{TPPH}_2$  (5), and  $\text{ETPZn}$  (6).

The oxygen-containing radicals are probably the species which hydroxylate the hydrocarbon substrate occurring in the solution. Moreover, a study of the parameters of the selectivity of the process allows the proposition that the free hydroxyl radicals do not accomplish the attack on the hydrocarbon. Such species probably form adducts with metal ions in the porphyrin complex. The formation of the peroxide complex  $\text{OEPFe}(\text{OH})(\text{OOH})$ , where OEP is the octaethylporphyrinate ligand, by the reduction of the adduct  $\text{OEPFe}(\text{Py})\text{O}_2$  with sodium ascorbate was described in [17]. The iron atom in the ferrocene may also influence the reactivity of the hydroxylating species. In fact, the value of  $\Psi$  is especially high in the case of benzylferrocene, the iron atom in which is the least sterically shielded. The value of the parameter  $\Psi$  is the closest to the value for the hydroxylation by the system which does not contain a metal (ascorbic acid- $\text{TPPH}_2$ ). Here, it is possible that the polyunsaturated porphyrin ring has the role of the flavine or pteridine fragment in the flavine- or pteridine-dependent monooxygenases not containing a metal atom [18, 19]. The  $\text{HO}^\cdot$  radicals thereby formed cannot be coordinated with the complexes of the metals, and immediately attack the hydrocarbon.

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