Reviews

Mechanisms for the formation of ester compounds in the liquid-phase oxidation of cyclohexane

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The channels of formation of ester compounds in the liquid-phase oxidation of cyclohexane are reviewed. At least 99.8% cyclohexyl esters of mono- and dicarboxylic acids are formed as a result of cyclohexanol acylation with mixed anhydrides including residues of all compounds with carboxyl groups present in the oxidized cyclohexane. The formation of mixed anhydrides is related to the fast reacylation of adipic anhydride with carboxylic acids. Alcoholysis of mixed anhydrides containing the formic acid residue with cyclohexanol leads mainly to cyclohexyl formate. The formation of ε-caprolactone during cyclohexane oxidation is the result of the Baeyer—Villiger oxidation of cyclohexanone with peroxy acids through α-hydroxy-α-hydroperoxy ester. A decrease in the yield of ε-caprolactone is reached under the conditions of decomposition or reduction of peroxy acids in the presence the compounds of variable valency metals or sulfur-containing reagents, respectively. The cobalt(II) and manganese(II) compounds stimulate the homolytic decomposition of α-hydroxy-α-hydroperoxy ester during which no lactone is formed. The cyclization of 5-hydroxypentanoic acid, which was formed by the oxidative transformations of cyclohexanone, leads to δ-valerolactone. The compounds of variable valency metals slightly affect the yield of δ-valerolactone. The mechanism of ester formation associated with the acylation of oxiranes formed by the radical chain oxidation of carbonyl compounds at the β-CH bonds was proposed.

Key words: cyclohexane, cyclohexanol, cyclohexanone, 2-hydroxycyclohexanone, adipic acid, adipic anhydride, ε-caprolactone, δ-valerolactone, cyclohexyl esters, liquid-phase oxidation, mechanism.

Introduction

Liquid-phase oxidation of cyclohexane with molecular oxygen catalyzed by the cobalt(II) salts is used in two large-scale industrial processes: syntheses of caprolactam[1,2] and adipic acid.[2—4] Caprolactam manufacturing gives cyclohexyl hydroperoxide, cyclohexanol, and cyclohexanone as the target products, and others (bifunctional, carboxylic

Published in Russian in *Izvestiya Akademii Nauk. Seriya Khimicheskaya,* No. 10, pp. 1803—1820, October, 2019.
1066-5285/19/6810-1803

acids, and esters) are the side products.[1,2,5–8] In this production, the conversion of cyclohexane rarely exceeds 5—7%, since the target products can be involved in radical chain and nonradical transformations.[5] When manufacturing adipic acid, the liquid-phase oxidation of cyclohexane at the first step is conducted until the substrate conversion equal to 8—10% is reached. At the second step, after the main portion of cyclohexane was distilled off, the bottom residue is oxidized with nitric acid.[2,3] In this case, low conversions of cyclohexane are associated with deviations from the α-mechanism during oxidative destruction of the major and side products, which result in decreasing yield of adipic acid.[9,10]

The ester compounds of oxidized cyclohexane (mainly mono- and dicarboxylic acid esters, ε-caprolactone, and δ-valerolactone) are attributed to the major side products of cyclohexane oxidation.[1,7,10–19] Although it is usually assumed that ester compounds are the final products of cyclohexane oxidation,[1,9] they can be involved in further radical chain transformations.[9,20–22] The problems of the mechanism, kinetics, catalysis, and inhibition of ε-caprolactone formation during the oxidation of cyclohexane and its oxygen-containing derivatives were considered in the reviews.[10,11,16,17] The data on the mechanisms of formation of cyclohexyl esters of mono- and dicarboxylic acids were generalized in several works.[10,11] After publication of these works,[10,11] a number of new results concerning ester formation during cyclohexane oxidation was obtained. The quantitative data on the kinetics of the esterification of carboxylic acids with cyclohexanol[14] and acylation of cyclohexanol with carboxylic acid anhydrides[15,23] made it possible to estimate the significance of two channels of formation of cyclohexanol esters in the industrial process and to elucidate the role of formic acid in these reactions.[13,14]

The study of the composition of the products of radical chain oxidation of the carbonyl compounds (ketones,[24,25] esters,[26,27] and carboxylic acids[27–29]) at the β-CH bonds allowed researchers to propose new mechanisms of their oxidation leading to α,β-epoxy and α,β-unsaturated compounds. The possibility of formation of esters due to the acylation of epoxy groups with carboxylic acids was substantiated.[28]

This review is the continuation of our earlier[5–7] efforts to summarize the key problems of the liquid-phase oxidation of cyclohexane. The data concerning the main channels and mechanisms of formation of the compounds with ester functional groups under the conditions close to those used in industrial liquid-phase cyclohexane oxidation were systematized and discussed.

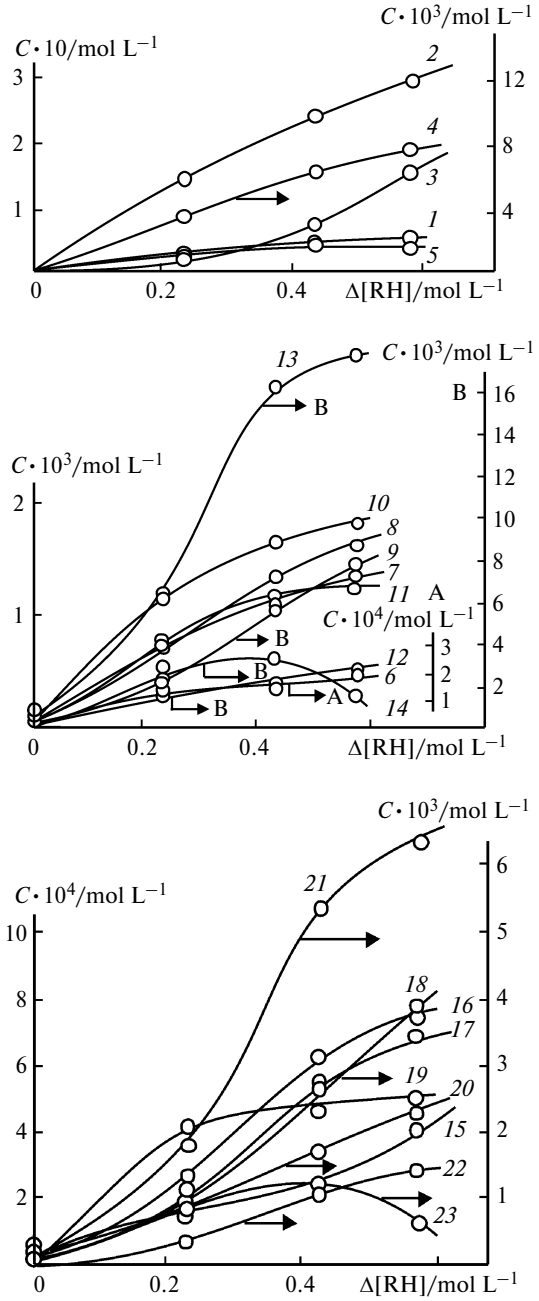
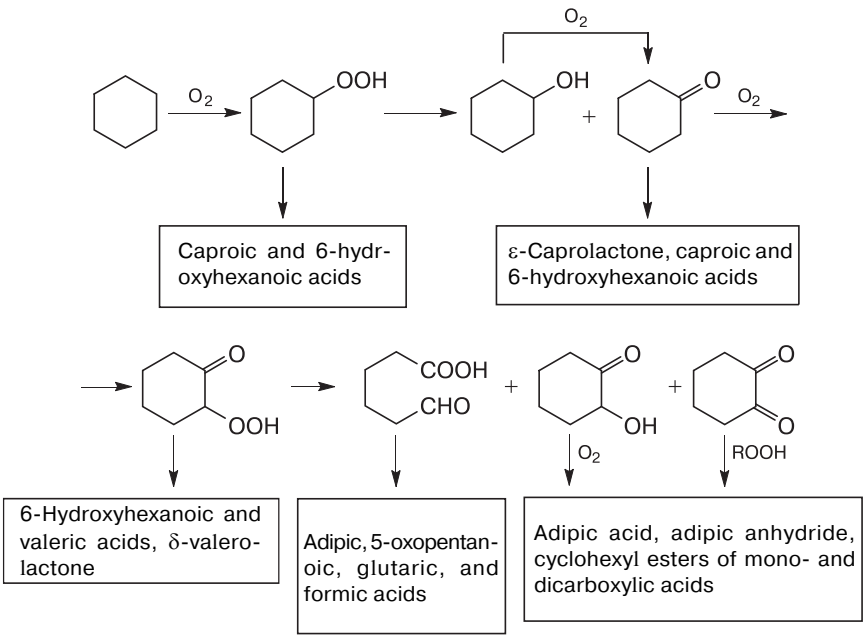


Fig. 1. Effect of the oxidation depth (Δ[RH]) on the content of products of cyclohexane oxidation (423—428 K, 0.04% cobalt naphthenate, pressure 0.8 MPa): peroxide compounds (*1*), cyclohexanol (*2*), cyclohexanone (*3*), mixed carboxylic acid anhydrides (*4*), water *(5)*, formic acid (*6*), butyric acid (*7*), valeric acid (*8*), caproic acid (*9*), succinic acid (*10*), glutaric acid (*11*), 5-oxopentanoic acid (*12*), adipic acid (*13*), 6-oxohexanoic acid (*14*), cyclohexyl formate (*15*), cyclohexyl butyrate (*16*), cyclohexyl valerate (*17*), cyclohexyl capronoate (*18*), cyclohexyl succinate (*19*), cyclohexyl glutarate (*20*), cyclohexyl adipinate (*21*), dicyclohexyl adipinate (*22*), and cyclohexyl 6-oxohexanoate (*23*).

Ester products of cyclohexane oxidation

Recovered cyclohexane and cobalt(II) naphthenate as the catalyst are used in the industrial process of cyclohexane oxidation.[1–7] Under these conditions, the induction period is nearly absent and the primary molecular product of the radical chain oxidation of cyclohexane, cyclohexyl

Scheme 1



hydroperoxide, decomposes already at the initial steps of the reaction to form cyclohexanol and cyclohexanone. Since these products are substantially more reactive than cyclohexane, they react with peroxyl radicals *via* the radical chain and nonchain mechanisms. Therefore, a complicated mixture of peroxide and non-peroxide products, including compounds containing ester moieties, is formed even at the cyclohexane conversion equal to 3—5%. Figure 1 provides some insight into the composition of the products of cyclohexane oxidation in the industrial process at the Kemerovo JCP "Azot" at 423 K.[13] The main channels of formation of products of cyclohexane oxidation are presented in Scheme 1.[1—7]

According to the classifications proposed in the reviews,[10,11,30] the majority of ester compounds formed in liquid-phase oxidation can be divided into three groups. The first group consists of esters of primary alcohols formed during the oxidation of the open-chain compounds and lactones formed by cycloalkane oxidation. Esters of this group contain the same total number of carbon atoms as the oxidized compound. The products of this group are formed in the course of the Baeyer—Villiger oxidation of the corresponding carbonyl compounds with peroxy acids. When the oxidation of cyclohexane, cyclohexanol, and cyclohexanone is considered, ε-caprolactone is usually ascribed to the products of the first group. The yield of ε-caprolactone increases on going from cyclohexane oxidation[7] to cyclohexanone oxidation[18,31,32] and decreases in the presence of the cobalt(II) and mangenese(II) salts,[16—18,31,32] but the chromium(III) salts do not exert this effect[32] (Figs 2[7] and 3[18,31,32]).

The second group includes esters of secondary alcohols (with the same number of carbon atoms as in the starting compound) and acids containing the same or lower number of carbon atoms than alcohol.[10,11,30] Cyclohexyl and 2-oxocyclohexyl esters of mono- and dicarboxylic acids satisfy these requirements for the oxidation of cyclohexane (see Fig. 1),[1,7,12,13—15] cyclohexanol (Table 1),[33,34] and cyclohexanone.[12,31—33] Since the formation of esters of the second group is associated with the acylation of alcohols with mixed carboxylic acid anhydrides, this reaction can involve not only cyclohexanol and 2-hydroxycyclohexanone but also any compounds with hydroxy groups.

Finally, the third group of the products includes γ- and δ-lactones.[10,11,30] Their formation is explained by a ready

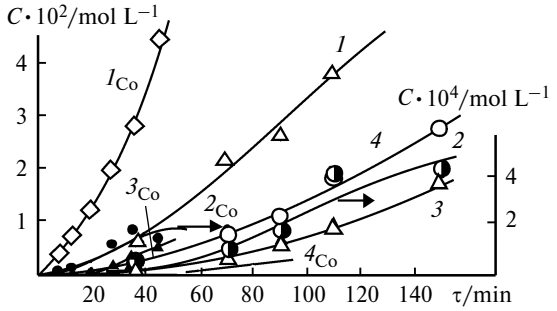


Fig. 2. Kinetic curves of accumulation of products of cyclohexane oxidation in the absence (*1—4*) and in the presence of the cobalt naphthenate catalyst (1_{Co}—4_{Co}) ($8.5 \cdot 10^{-4}$ mol L^{-1}) at 423 K.[7] Designations: *C* is the concentration of the products, τ is the reaction time; *1*, adipic acid; *2*, adipic anhydride; *3*, monocyclohexyl adipinate; and *4*, ε-caprolactone.

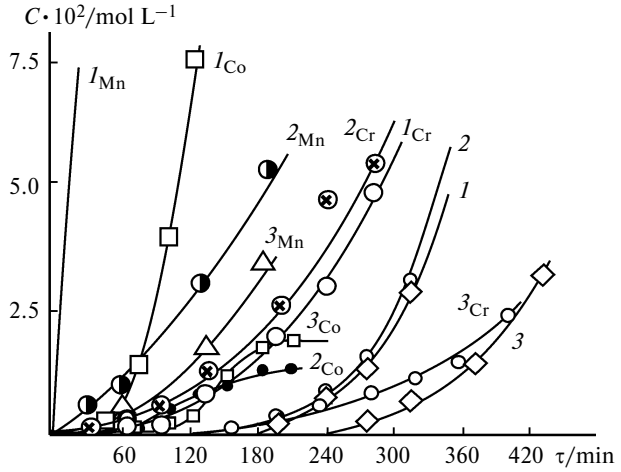


Fig. 3. Kinetic curves of accumulation of products of cyclohexanone oxidation in the absence[31] (*1*—*3*) and in the presence of the following catalysts: cobalt naphthenate ($1.6 \cdot 10^{-3}$ mol L^{-1}) (1_{Co}—3_{Co}),[31] chromium naphthenate ($1.6 \cdot 10^{-3}$ mol L^{-1}) ($1_{Ск}$—$3_{Ск}$)[32] at 393 K, and manganese naphthenate (0.04 mol L^{-1}) (1_{Mn}—3_{Mn})[18] at 353 K. Designations: *C* is the concentration of the products, τ is the reaction time; *1*, adipic acid; *2*, ε-caprolactone; and *3*, δ-valerolactone.

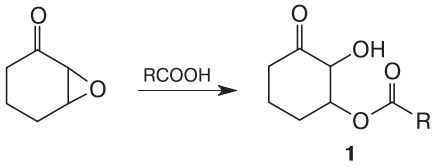
Table 1. Composition of the non-peroxide products of cyclohexanol oxidation at 393 K[33] at 30% conversion and an oxidation time of 230 min (I) and at 40% conversion and an oxidation time of 260 min (II)

Oxidation products	Content (%)	
	I	II
Cyclohexanone	84.1	65.0
Adipic acid	5.7	12.4
Glutaric acid	1.0	3.1
Caproic acid	0.8	1.8
Valeric acid	0.6	1.2
ε-Caprolactone	1.2	2.9
δ-Valerolactone	1.0	2.7
Monocyclohexyl adipinate	4.4	8.9
Dicyclohexyl adipinate	0.1	0.2
Dicyclohexyl capronate	0.4	0.9
Monocyclohexyl glutarate	0.4	1.1

intramolecular cyclization of δ- and, especially, γ-hydroxy acids.[7] δ-Valerolactone was found[7,18,31—35] among the oxidation products of cyclohexane, cyclohexanol, and cyclohexanone (see Fig. 3).

The formation of oxiranes during the oxidation of saturated carbonyl compounds at the β-CH bonds described above[24—29] paves the way for formation of esters (glycol monoesters (compound **1**)) by the reaction of oxiranes with carboxylic acids (Scheme 2). 3-Butanoyloxy-2-hydroxybutanoic acid was found among the products of butanoic acid oxidation.[27—28]

Scheme 2



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Esters formed with the participation of carboxylic acid anhydrides

The mechanism of formation of esters of secondary alcohols assigned to the second group of the products remained unclear for a long time. Assumptions about the formation of esters by the reactions of carboxylic acids with alcohols (esterification reaction) were not confirmed.[10,11] Even the most optimistic estimates showed that the contribution of esterification does not exceed 10—25% of the apparent rate of ester accumulation (see reviews[10,11] and works cited therein). This argument is in favor of the existence of another route for ester formation.

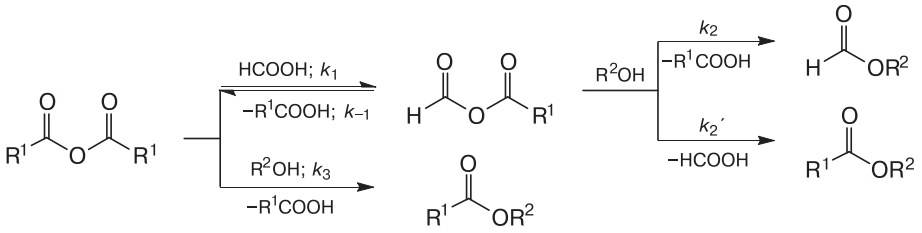
The channels of destruction of the cyclohexane ring leading to adipic anhydride were found in several works.[12,36—42] They are related to the radical chain oxidation of 2-hydroxycyclohexanone[2,36—41] and oxidation of cyclohexane-1,2-dione by hydroperoxides[42] (see Scheme 1). The kinetics of adipic acid accumulation during the liquid-phase oxidation of cyclohexane[12] and cyclohexanone[31,32] was studied using gas chromatography method dedicated to developed for the determination of low concentrations of anhydrides in complex mixtures.[12,43] On the basis of the obtained data, it was concluded that the rate of cyclohexyl formation in the reaction of cyclohexanol with adipic anhydride is significantly higher than that obtained for the reaction with adipic acid.[12]

Carboxylic acid anhydrides were found to undergo rapid reacylation with other carboxyl-containing oxidation products even at 293 K to form an equilibrium mixture of mixed anhydrides bearing acyl groups of all carboxyl compounds.[33] This results in participation of adipic anhydride in the formation of cyclohexyl esters of not only adipic but also other mono- and dicarboxylic acids (see Fig. 1, Table 1).

The ratio of the yield of cyclohexyl esters to the yield of the corresponding acids changes insignificantly during cyclohexane oxidation[13] (see Fig. 1 and Table 2). The exceptions are cyclohexyl formate and formic acid. In the case of cyclohexyl formate and formic acid, this ratio is four-fold that observed for other mono- and dicarboxylic acids and their cyclohexyl esters (see Table 2).

Using the improved GC method for the determination of anhydrides,[44] their total content in oxidized cyclohexane, cyclohexanone, and cyclohexanol was found. The obtained kinetic data[14,15,23] made it possible to compare

Scheme 3



k_1, k_{-1}, k_2, k_2', and k_3 are the rate constants of the corresponding steps.

the rates of two alternative reactions of cyclohexyl ester formation (alcoholysis of anhydrides and esterification of carboxylic acids with cyclohexanol) under the conditions of industrial cyclohexane oxidation.

The kinetics of the reaction of valeric anhydride wth cyclohexanol in the presence of formic acid (*o*-dichlorobenzene, 333—373 K) corresponds to Scheme 3.[15] Note that formic acid exerts no catalytic effect on the rates of the reactions shown in Scheme 3.

The temperature dependences of the rate constants of the reactions shown in Scheme 3 and the equilibrium constants of the reversible step of formation of mixed formic acid anhydride (K) are described by Eqs (1)—(6)[15]

$$\ln k_1 = (8.9\pm0.4) - (44400\pm900)/(RT), \quad (1)$$

$$\ln k_{-1} = (-0.7\pm0.1) - (22400\pm400)/(RT), \quad (2)$$

$$\ln K = (9.6\pm0.4) - (22300\pm300)/(RT), \quad (3)$$

$$\ln k_2 = (24.3\pm1.0) - (89300\pm800)/(RT), \quad (4)$$

$$\ln k_2' = (14.6\pm2.1) - (69100\pm1200)/(RT), \quad (5)$$

Table 2. Effect of the conversion on the ratio of yield of cyclohexyl mono- and dicarboxylates to the yield of the corresponding free acids in the oxidation of cyclohexane at 423 K at the conversions 1.9 (I), 3.2 (II), and 4.8% (III)[13]

Acid	Ratio of yields		
	I	II	III
Formic	1.25	1.71	2.10
Butanoic	0.35	0.55	0.56
Valeric	0.32	0.41	0.42
Caproic	0.41	0.44	0.48
Succinic	0.35	0.28	0.27
Glutaric	0.31	0.38	0.45
6-Oxohexanoic	0.37	0.39	0.40
Adipic[a]	0.29	0.33	0.36
Monocyclohexyl adipinate[b]	0.19	0.21	0.23

[a] Ratio of the yields of monocyclohexyl adipinate and adipic acid.
[b] Ratio of the yields of dicyclohexyl adipinate and monocyclohexyl adipinate.

$$\ln k_3 = (15.2\pm1.2) - (69500\pm800)/(RT). \quad (6)$$

The study of the kinetics of alcoholysis of valeric anhydride with cyclohexanol (chlorobenzene, 333—363 K) discovered the temperature dependence of the rate constant for this reaction[23]

$$\ln k = (13.1\pm0.6) - (62\,300\pm500)/(RT). \quad (7)$$

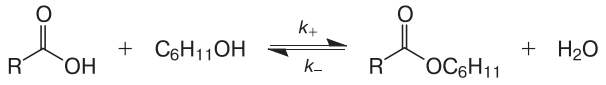
The rate constants calculated from the dependence (7) are consistent with the values of k_3 constants (Eq. (6)).

A comparison of the k_2 and k_2' constants confirmed the predominant formation of formates by alcoholysis of mixed formic acid anhydrides.

The data needed for the quantitative estimation of the role of the alternative channel for the formation of cyclohexyl esters of mono- and dicarboxylic acids, esterification reaction, were provided by the study of the kinetics of the reactions of cyclohexanol with formic, caproic, and adipic acids (*o*-dichlorobenzene, 423—463 K).[14]

The esterification of caproic and formic acids with cyclohexanol is reversible (Scheme 4).[14]

Scheme 4

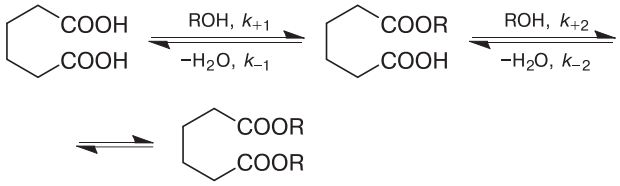


R = H, C_5H_{11}

k_+ and k_- are the rate constants of the direct and backward steps, respectively.

Dicyclohexyl adipinate is formed by the reaction of adipic acid with cyclohexanol due to two consecutive reversible steps (Scheme 5).[14]

Scheme 5



k_{+1}, k_{-1}, k_{+2}, and k_{-2} are the rate constants of the direct and backward reactions.

It is shown that formic and other acids exert no catalytic effect on the esterification rate. The temperature dependences of the rate constants of the reactions shown in Schemes 4 and 5 are described by the following equations:[14]

(1) esterification of formic acid with cyclohexanol

$$\ln k_{+} = (17.5\pm1.1) - (97\,500\pm800)/(RT), \quad (8)$$

$$\ln k_{-} = (22.2\pm1.4) - (116\,600\pm1200)/(RT); \quad (9)$$

(2) esterification of caproic acid with cyclohexanol

$$\ln k_{+} = (2.9\pm0.4) - (56\,500\pm600)/(RT), \quad (10)$$

$$\ln k_{-} = (-4.8\pm0.2) - (20\,100\pm400)/(RT); \quad (11)$$

(3) esterification of adipic acid with cyclohexanol

$$\ln k_{+1} = (5.3\pm0.3) - (61\,700\pm400)/(RT), \quad (12)$$

$$\ln k_{-1} = (8.9\pm0.4) - (66\,300\pm300)/(RT), \quad (13)$$

$$\ln k_{+2} = (2.7\pm0.4) - (55\,600\pm700)/(RT), \quad (14)$$

$$\ln k_{-2} = (0.3\pm0.1) - (37\,000\pm200)/(RT). \quad (15)$$

The rate constants for the formation of cyclohexyl esters of carboxylic acids *via* alcoholysis of the anhydrides with cyclohexanol at 423 K were obtained using Eqs (1)—(7). Based on these data and concentrations of products in the samples of cyclohexane oxidized at the same temperature (see Fig. 1), we calculated the rates of formation of cyclohexyl formate, cyclohexyl capronate, and mono- and dicyclohexyl adipinates (Table 3).[14]

The analytically determined total content of carboxylic acid anhydrides ($\Sigma[R^iC(O)OC(O)R^j]$) (Eq. (16) in oxidized cyclohexane represents the sum of concentrations of anhydrides of different reactivities formed with involvement ($\Sigma[HC(O)OC(O)R^{i,j}]$) and without involvement of formic acid ($\Sigma[R'C(O)OC(O)R']$)[14]

$$\Sigma[R^iC(O)OC(O)R^j] = \Sigma[HC(O)OC(O)R'] + \Sigma[R'C(O)OC(O)R']. \quad (16)$$

The ratio between these groups of anhydrides is determined by Eq. (17) derived for the equilibrium constant of the reversible step of formation of mixed formic acid anhydride (according to Eq. (3), $K = 26.9$ at 423 K)[14,15]

$$K = \frac{\sum[HC(O)OC(O)R'] \cdot \sum[RCOOH]_i}{\sum[R'C(O)OC(O)R'] \cdot [HCOOH]}, \quad (17)$$

where [HCOOH] is the concentration of formic acid, and $\Sigma[RCOOH]_i$ is the total content of carboxyl groups ignoring the concentration of formic acid.

Equation (18) for the calculation of the total concentration of mixed anhydrides containing the formic acid residue was obtained from Eqs (16) and (17)[14]

$$\sum[HC(O)OC(O)R'] = \frac{\sum[R^iC(O)OC(O)R^j]}{1 + \sum[RCOOH]_i/(K[HCOOH])}. \quad (18)$$

The rate of cyclohexyl formate formation (W_{cf}) was determined from Eq. (19)

$$W_{cf} = k_2 \cdot \Sigma[HC(O)OC(O)R'] \cdot [ROH], \quad (19)$$

where k_2 is the rate constant of alcoholysis of mixed formic acid anhydride to cyclohexyl formate (see Scheme 3), and [ROH] is the concentration of cyclohexanol.

It was assumed[14] that the rate of cyclohexyl capronate formation (W) is equal to the sum of the rate of alcoholysis of mixed formic-caproic anhydride to cyclohexyl capronate (W') and the rate of alcoholysis of other mixed caproic acid anhydrides (W'')

$$W = W' + W'' = k_3 \cdot [HC(O)OC(O)C_5H_{11}] \cdot [ROH] + 0.5k_2' \cdot \Sigma[R'C(O)OC(O)C_5H_{11}] \cdot [ROH], \quad (20)$$

where k_3 and k_2' are the rate constants of the reactions shown in Scheme 3, $[HC(O)OC(O)C_5H_{11}]$ is the concentration of formic-caproic anhydride, $\Sigma[R'C(O)OC(O)C_5H_{11}]$ is the total concentration of other mixed caproic acid anhydrides, and 0.5 is a coefficient. The coefficient takes into account that the alcoholysis of mixed anhydride of caproic acid and another carboxylic acid with cyclohexanol affords cyclohexyl ester of the latter with equal probability.

Equation (21) needed for the calculation of the concentrations of formic-caproic anhydride was obtained from

Table 3. Effect of the conversion on the calculated rates of formation of cyclohexyl carboxylates by alcoholysis of anhydrides with cyclohexanol during oxidation of cyclohexane at 423 K[14]

Conversion (%)	$W \cdot 10^6$/mol L^{-1} s^{-1}								
	Cyclohexyl formate	Cyclohexyl capronate			Monocyclohexyl adipinate			Dicyclohexyl adipinate		
		W'	W''	W	W'	W''	W	W'	W''	W
1.9	17.0	0.03	0.2	0.2	0.1	1.1	1.1	0.02	0.3	0.3
3.2	28.7	0.05	0.8	0.8	0.1	4.0	4.1	0.05	1.3	1.4
4.8	54.9	0.12	1.3	1.4	0.3	5.7	6.0	0.10	2.0	2.2

Eq. (18) under the assumption that the concentration of mixed carboxylic acid anhydrides is proportional to the concentration of the carboxyl groups of the acid

$$[HC(O)OCC_5H_{11}]= \frac{\sum[R^iC(O)OC(O)R^j]}{1+\sum[RCOOH]_i^2/(K[HCOOH][C_5H_{11}COOH])}. \quad (21)$$

The $\Sigma[R'C(O)OC(O)C_5H_{11}]$ value was calculated by Eq. (22)

$$\sum[R'C(O)OC(O)C_5H_{11}]= \frac{\sum[R^iC(O)OC(O)R^j]-\sum[HC(O)OC(O)R']}{\sum[RCOOH]_i}\times \times[C_5H_{11}COOH]. \quad (22)$$

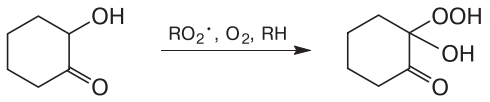
The W', W'', and W values for cyclohexyl capronate and mono- and dicyclohexyl adipinates are presented in Table 3. It follows from the data in Table 3 that at 423 K the rate of cyclohexyl formate formation *via* the reactions of alcoholysis of mixed anhydrides with cyclohexanol is substantially higher than the rates of formation of cyclohexyl capronate and mono- and dicyclohexyl adipinates at any level of cyclohexane transformation. The alcoholysis of mixed anhydrides containing the formyl group makes the main contribution to the formation of these three esters.

Similar data on the rates of formation of the above mentioned cyclohexyl esters *via* the reactions of carboxylic acids with cyclohexanol are presented in Table 4. A comparison of the data presented in Tables 3 and 4 shows that the formation rates of all cyclohexyl esters in the esterification reactions (W_{est}) are much lower than the rates of formation of the same esters by alcoholysis of mixed anhydrides. For example, for cyclohexyl formate the rate of formation is more than 25 000 times lower than the rate of its formation by the alcoholysis of mixed formic acid anhydrides.[14] For the formation of mono- and dicyclohexyl adipinates, the contribution of the esterification rection is somewhat higher than that for cyclohexyl formate formation, but it does not exceed 0.2% in this case as well.[14] Since the esterification is reversible, under certain conditions this reaction can decrease the content of cyclohexyl esters formed in the irreversible alcoholysis of carboxylic acid anhydrides with alcohols.[14]

As already noted, the formation of side cyclohexyl esters of mono- and dicarboxylic acids is undesirable for the industrial oxidation of cyclohexane.[1,8,10] These reactions transform cyclohexanol into poorly oxidizable esters[5,7,45] and thus decrease the selectivity of oxidation to the target products. The following factors should lead to decrease in the yield of cyclohexyl esters: a decline in the yield of adipic anhydride during oxidative destruction of cyclohexane, a reduction of cyclohexanol concentration, and the appearance of competitive interactions of anhydrides with other hydroxyl-containing compounds, for example, hydroperoxides and water present in the system.[10]

The main precursor of adipic anhydride in cyclohexane oxidation is 2-hydroperoxy-2-hydroxycyclohexanone (**2**) formed by the radical chain oxidation of 2-hydroxycyclohexanone (Scheme 6).[6,7,10,12,36–41]

Scheme 6



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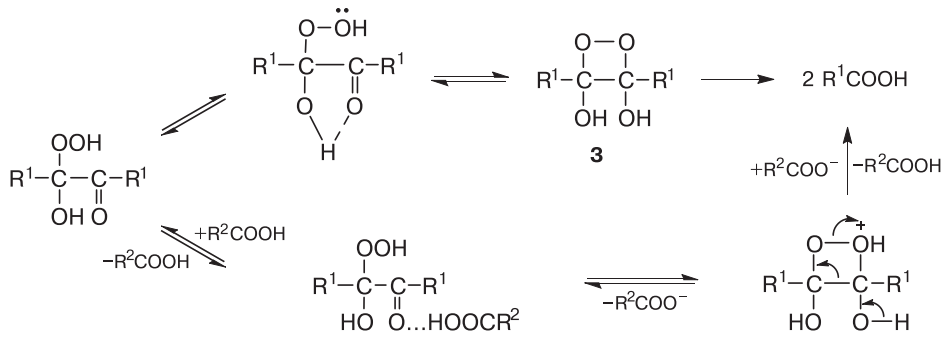
Three main routes of the transformation of hydroxyhydroperoxide **2** with carbon chain destruction are possible along with the transformation of compound **2** without carbon chain destruction into cyclohexane-1,2-dione[6,7,10,41,46]: pericyclic rearrangements *via* the dioxetane (**3**) (Scheme 7) and oxirane (**4**) (Scheme 8) intermediates and homolytic decomposition (Scheme 9).[6,7,10,41,46,47]

The transformation of peroxide **2** *via* Scheme 7 affords adipic acid, while that *via* Scheme 8 gives adipic anhydride. A homolytic decomposition of compound **2** proceeds *via* oxyl radical **5** to give monoperoxyadipic acid **6** (see Scheme 9) and then adipic acid. In this case, no adipic anhydride is formed.[10,41,46,47] The variation in the temperature of oxidation of 2-hydroxycyclohexanone and its concentration and the change of the inert solvent (chlorobenzene) to ethylbenzene exert vanishingly small effect on the ratio of yields of adipic acids and anhydride.[38] A decrease in the significance of the channel of peroxide **2** transformation into adipic anhydride can be attained by the stimulation of its homolytic decomposition,[6,7,10,41,46,47]

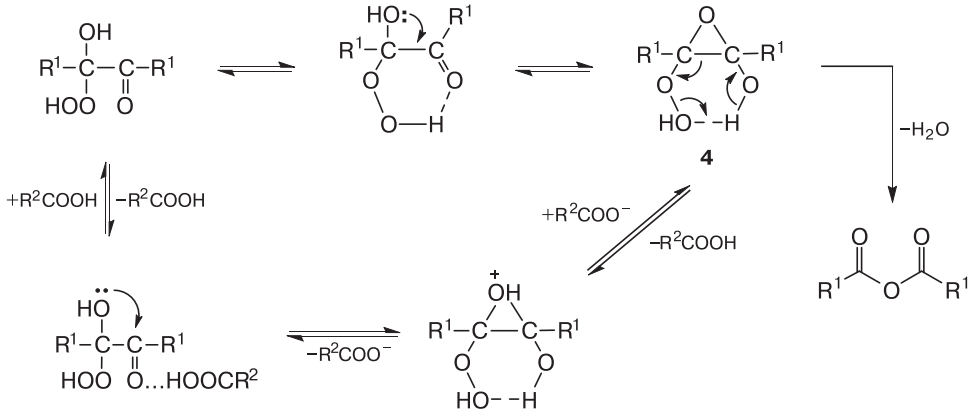
Table 4. Effect of the conversion on the calculated rates of formation of cyclohexyl carboxylates *via* esterification reactions by cyclohexanol in the oxidation of cyclohexane at 423 K[14]

Conversion (%)	$W_{est} \cdot 10^9$/mol L^{-1} s^{-1}			
	Cyclohexyl formate	Cyclohexyl capronate	Monocyclohexyl adipinate	Dicyclohexyl adipinate
1.9	0.6	0.01	2.2	0.3
3.2	1.1	–0.6	6.6	0.9
4.8	2.0	0.3	11.7	1.8

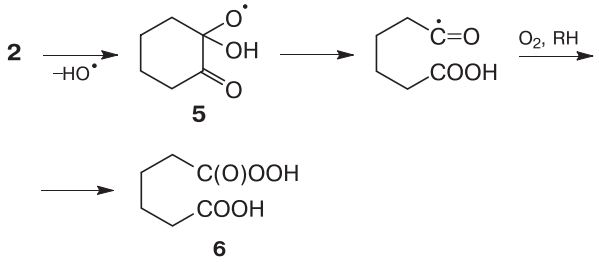
Scheme 7



Scheme 8

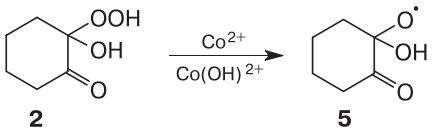


Scheme 9



for example, by the addition to the reaction mixture of the compounds of variable valency metals (Scheme 10).[48]

Scheme 10



Now we can address the data emerged from the study of the effect of a series of naphthenates of variable valency metals on the composition of the major oxidation products of 2-hydroxycyclohexanone and decomposition of the products of this reaction (Table 5).[49] A substantial decrease in the yield of adipic anhydride in the presence of cobalt(II) and manganese(II) naphthenates can be inferred. These results correspond to the data on a decrease in the yields of adipic anhydride and monocyclohexyl adipinate observed on going from the catalyst-free oxidation of cyclohexane to the cobalt(II) naphthenate-catalyzed oxidation (see Fig. 2).

In the presence of the acid catalysts, the transformations presented in Schemes 7 and 8 involve the steps of intramolecular nucleophilic addition of hydroxy and hydroperoxy groups to the carbonyl group.[6,7,10,41]

It is known that the patterns of dependence of the rate constants of hydroperoxide addition to the carbonyl group on the concentration of the polar solvent are complicated when the solvents are capable of forming the hydrogen bonds.[50] Therefore, in studies of reactions of mutarotation of monosaccharides, DMF was used as the solvent, since it suppresses addition of hydroxy groups to the carbonyl group.[51] The data on the kinetics of product accumulation observed in the oxidation of a solution of 2-hydroxycyclohexanone with

Table 5. Effect of the homogeneous catalysts on the composition of the main products of oxidation of 2-hydroxycyclohexanone and decomposition of the peroxide products of this reaction

Catalyst	Content of products (mol.%)		
	adipic acid	adipic anhydride	cyclohexane-1,2-dione
	Oxidation[a]		
Cobalt(II) naphthenate	63.0	15.9	21.1
Chromium(III) naphthenate	54.0	43.0	3.0
Nickel(II) naphthenate	68.0	32.0	Traces
Iron(III) naphthenate	63.5	32.7	3.8
Without catalyst	44.0	44.0	12.0
	Decomposition[b] (mol.% based on converted peroxide)		
Cobalt(II) naphthenate	47.0	9.9	29.4
Chromium(III) naphthenate	70.5	15.7	6.2
Iron(III) naphthenate	47.0	4.8	4.9
Copper(II) naphthenate	84.0	7.8	9.7
Manganese(II) naphthenate	65.7	7.5	8.7
Without catalyst	69.0	27.4	7.8

[a] Conditions: 323 K, chlorobenzene, initial concentration of 2-hydroxycyclohexanone 1.4 mol L^{-1}, [catalyst] = $= 1.6 \cdot 10^{-3}$ mol L^{-1}.
[b] Conditions: 323 K, argon, [catalyst] = $1.6 \cdot 10^{-3}$ mol L^{-1}.

a concentration of 1.4 mol L^{-1} in DMF at 343 K are presented in Fig. 4.[41] The oxidation rate of 2-hydroxycyclohexanone in DMF is lower than that in chlorobenzene. A significant decrease in the ratio of the yields of adipic anhydride to adipic acid is also observed (Fig. 4). Evidently, in this case adipic acid is formed *via* Scheme 9, whereas the rate of hydroxyhydroperoxide **2** transformation *via* Schemes 7 and 8 in DMF decreases considerably.

Esters formed in the Baeyer—Villiger reaction. To this group of ester compounds encountered in cyclohexane oxidation[1,10,11,16,17,52] ε-caprolactone and formic acid esters formed from the compounds with aldehyde functional groups can be attributed.[53—55]

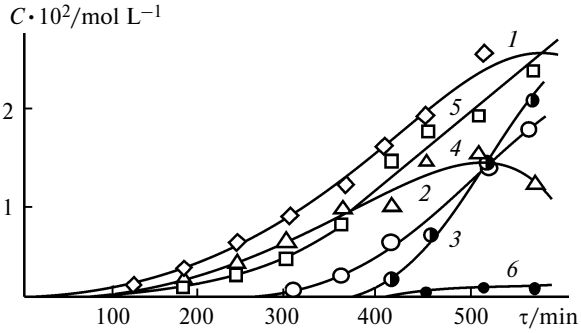


Fig. 4. Kinetic curves of accumulation of products of 2-hydroxycyclohexanone (1.4 mol L^{-1}) in a DMF solution at 343 K.[41] Designations: *C* is the concentration of the products, τ is the reaction time; *1*, 2-hydroperoxy-2-hydroxycyclohexanone and cyclohexane-1,2-dione; *2*, peroxy acid; *3*, hydrogen peroxide; *4*, 6-oxohexanoic acid; *5*, adipic acid; and *6*, adipic anhydride.

ε-Caprolactone is one of important side products of oxidation of cyclohexane[7,52] (see Fig. 2) and cyclohexanol (see Table 1).[33,34] For the catalyst-free[9,19,31] and chromium(III) naphthenate-catalyzed[32] oxidation of cyclohexanone, the yield of ε-caprolactone exceeds that of adipic acid. However, in the presence of the cobalt(II)[9,31] and manganese(II)[18] salts, the yield of ε-caprolactone decreases substantially (see Fig. 3). It was assumed that ε-caprolactone was formed due to the oxidation of cyclohexanone with peroxy acids,[1,56] hydroperoxides,[10] and peroxyl radicals.[8,9] The kinetics of peroxy acid accumulation during cyclohexanone oxidation[19] was studied using gas chromatography determining the total content of peroxy acids.[57] To estimate the contribution of the channel of ε-caprolactone formation involving peroxy acids, the "subtraction" method was used,[19,58—61] which is based on the selective reduction of peroxy acids with the sulfur-containing reagents directly during radical chain oxidation.

The formation of lactone was terminated completely when diphenyl sulfide, reagent reducing peroxy acids *via* Scheme 11, was introduced into oxidized cyclohexanone, and it was resumed only after the most parts of sulfide and sulfoxide were consumed.[58]

Scheme 11

$$RCOOOH + Ph_2S \longrightarrow RCOOH + Ph_2SO$$

$$RCOOOH + Ph_2SO \longrightarrow RCOOH + Ph_2SO_2$$

Similar results were obtained for the co-oxidation of cyclohexanone with additives of diphenyl sulfide and

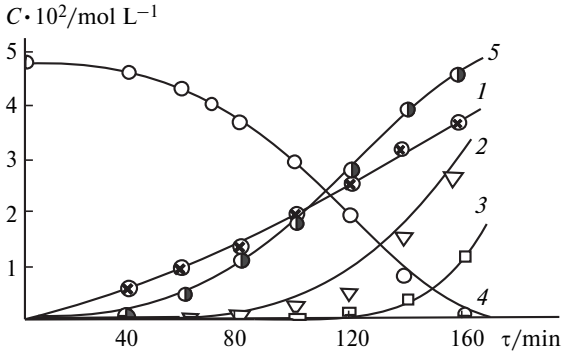
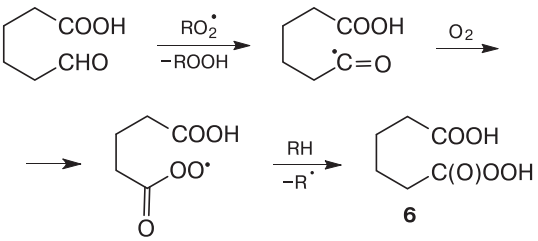


Fig. 5. Kinetic curves of accumulation of products and consumption of diphenyl sulfoxide during the oxidation of cyclohexanone (393 K, 4.0 *M*, chlorobenzene) in the presence of diphenyl sulfoxide (0.048 mol L^{-1}). Designations: *C* is the concentration of the products, τ is the reaction time; *1*, peroxide compounds; *2*, adipic acid; *3*, ε- caprolactone; *4*, diphenyl sulfoxide; and *5*, diphenylsulfone.

diphenyl sulfoxide (Fig. 5).[19] The accumulation of hydroperoxides and adipic acid in the presence of sulfide or sulfoxide additives confirms the occurrence of the radical chain process (see Fig. 5). Thus, the termination of ε-caprolactone formation in the experiments with sulfone or sulfoxide additives indicates that under the conditions of cyclohexanone oxidation an alternative mechanisms of lactone formations *via* the oxidation of ketone with hydrogen peroxide, hydroperoxides, or peroxyl radicals are not operative to a noticeable extent.[19,58]

It was accepted[56] that ε-caprolactone forms *via* monoperoxyadipic acid (**6**), the product of the radical chain oxidation of 6-oxohexanoic acid (Scheme 12).

Scheme 12



The more probable channel of formation of peroxy acid **6** is related, most likely, to the homolytic decomposition of 2-hydroxy-2-hydroperoxycyclohexanone[7] (see Scheme 9).

An enhanced (over adipic acid) yield of ε-caprolactone in the noncatalytic oxidation of cyclohexanone cannot be provided by monoperoxyadipic acid transformations only, since ε-caprolactone and adipic acid are formed in equimolar amounts in the oxidation of cyclohexanone by peroxy acid **6**.[19] It was assumed[19] that two peroxyacid groups can be formed in the homolytic decomposition of one molecule of 2-hydroperoxycyclohexanone (Scheme 13).

The homolytic decomposition of 2-hydroperoxycyclohexanone *via* ketone formation or *via* the reaction of the type shown in Scheme 13 affords 2-oxocyclohexyloxy radical **7**, which is transformed into 2-hydroxycyclohexanone, or undergoes destruction to form 1,6-dioxohexyl radical **8**. The latter can transform into 6-oxoperoxyhexanoic acid (**9**) and then into diperoxy acid **10** in a medium of oxidized cyclohexane. The formation of peroxy acids is possible when hydrogen peroxide is acylated with carboxylic acids or anhydrides.[10,16,17] Hydrogen peroxide is formed by the oxidation of both cyclohexanol[1,5–7,9,10] and carbonyl compounds at the β-CH bonds.[29,62]

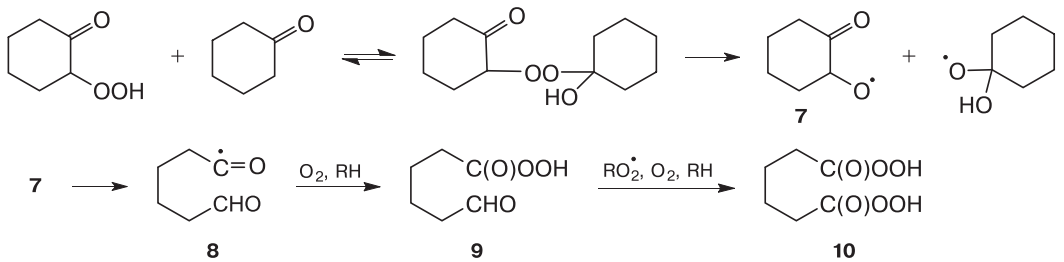
The kinetics of cyclohexanone oxidation with peroxy acids was studied using its reaction with peroxylauric acid[63–66] as an example with the data analyzed in the review.[17]

The results emerged from the study of the kinetics of the Baeyer—Villiger reaction[63–66] and the selective determination of peroxy acid and α-hydroxyperoxy ester[67] indicated the main steps of this transformation. These are the formation of 1-hydroxy-1-acylperoxycyclohexane (**11**) (Criegee intermediate) and its rearrangement to ε-caprolactone or the homolytic decomposition without formation of lactone (Scheme 14). The effective rate constants k_1^{eff}, k_{-1}^{eff}, k_2^{eff}, and k_3^{eff} of the steps shown in Scheme 14 depend linearly on the concentration of lauric acid ([RCOOH]), including that formed from peroxy acid.[17,63–66]

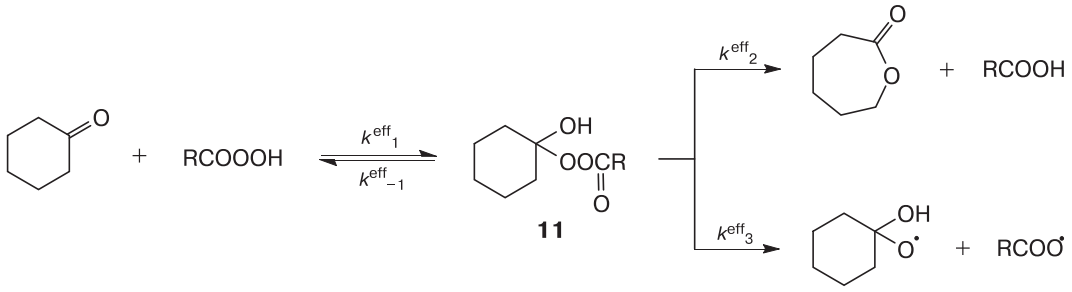
The transformation of the Criegee intermediate into lactone is the nucleophilic rearrangement at the electron-deficient center. The synchronous mechanism[17,68–70] is preferable (Scheme 15).

A comparison of the values of constants k_2^{eff} and k_3^{eff} showed that the contribution of the rate of the homolytic

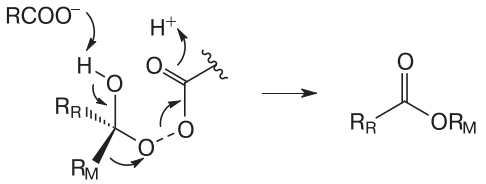
Scheme 13



Scheme 14



Scheme 15



R_M and R_R are the migrating and nonmigrating group, respectively.

channel of decomposition of Criegee intermediate **11** to the rate of the heterolytic rearrangement under the studied conditions (chlorobenzene, 291 K), did not exceed 1—2%.[17,67,68]

Noticeable differences between the calculated and experimental data were observed when the kinetic model (see Scheme 14) was used. These differences were eliminated when the assumption was made that the second intermediate occurs that is formed in the irreversible reaction and decomposed with a higher rate than the Criegee intermediate.[17,66]

It is assumed that dioxirane (1,2-dioxaspiro[2,5]octane (**12**)) can be this intermediate (Scheme 16). Dioxirane **12** is known as an intermediate product of cyclohexanone oxidation with peroxysulfuric acid under the basic catalysis conditions.[71—73]

For the oxidation of cyclohexanone with peroxylauric acid (chlorobenzene, 291 K), the dependences of the effective rate constants of the reactions shown in Scheme 16 on the concentration of lauric acid are described by Eqs (23)—(28)[17,66]

$$k_1^{eff} = 9.7 \cdot 10^{-6} + 1.2 \cdot 10^{-4} \cdot [RCOOH], \quad L\ mol^{-1}\ s^{-1}; \qquad (23)$$

$$k_{-1}^{eff} = (0.9 \pm 0.1) \cdot 10^{-4} + (7.0 \pm 0.9) \cdot 10^{-4} \cdot [RCOOH], \quad s^{-1}; \qquad (24)$$

$$k_2^{eff} = (0.75 \pm 0.03) \cdot 10^{-4} + (1.30 \pm 0.03) \cdot 10^{-3} \cdot [RCOOH], \quad s^{-1}; \qquad (25)$$

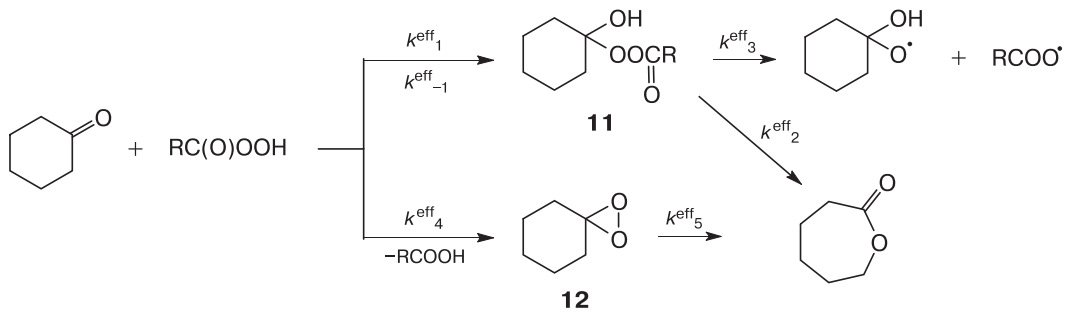
$$k_3^{eff} = (1.7 \pm 0.3) \cdot 10^{-6} + (7.1 \pm 0.4) \cdot 10^{-5} \cdot [RCOOH], \quad s^{-1}; \qquad (26)$$

$$k_4^{eff} = 2.8 \cdot 10^{-7}, \quad L\ mol^{-1}\ s^{-1}; \qquad (27)$$

$$k_5^{eff} = 2.8 \cdot 10^{-2}, \quad s^{-1}. \qquad (28)$$

Zero values of the coefficients at [RCOOH] for k_4^{eff} and k_5^{eff} indicate that the presence of lauric acid affects neither the step of formation, nor the step of dioxirane decomposition to lactone. A higher value of k_1^{eff} over k_4^{eff} shows that the reaction proceeds predominantly *via* Criegee intermediate.[17,66] Although the rate constant of

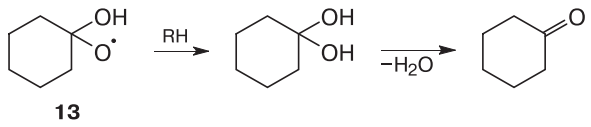
Scheme 16



decomposition of dioxirane **12** to lactone (k_5^{eff}) is substantially higher than the rate constant of decomposition of α-hydroxyperoxy ester (k_2^{eff}), the contribution of this route is determined by the step of formation of compound **12**. Under experimental conditions, about 5% of ε-caprolactone are formed *via* dioxirane **12**.[17,66]

As already mentioned, the fraction of the radical decomposition of Criegee intermediate **11** is low when cyclohexanone is oxidized with peroxy acid. The 1-hydroxycyclohexylperoxy radical (**13**) formed in this reaction is transformed into cyclohexanone at temperatures lower than 353 K (Scheme 17).

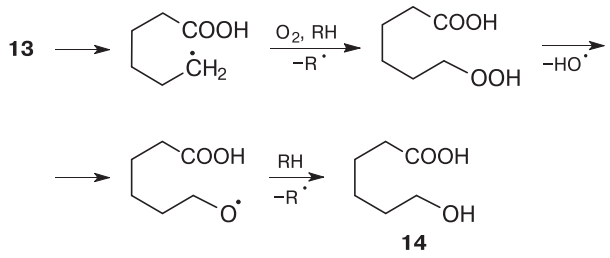
Scheme 17



13

The destructive decomposition of radical **13** is possible at a higher temperature (Scheme 18). This decomposition can lead to ε-hydroxycaproic acid (**14**) (see Scheme 18) but its cyclization to lactone is hardly possible.[10,17,52,74] It is for this reason that cyclohexanone is not oxidized to ε-caprolactone in the absence of peroxy acids (see Fig. 5). Hydrogen peroxide and hydroperoxides can be used for the preparation of ε-caprolactone only in the presence of strong acids or Lewis acids favoring the heterolytic cleavage of the O—O bond.[10,17,75]

Scheme 18



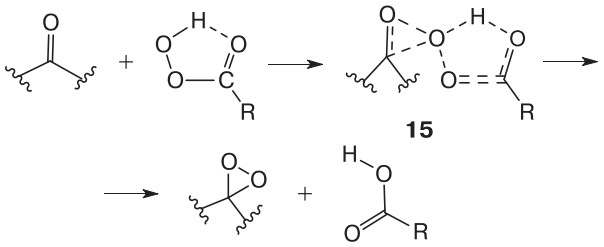
14

The mechanisms of formation and transformation of compound **12** in acidic or neutral media using peroxycarboxylic acid as an oxidant remain insufficiently clear. The concerted mechanism[17] with the transition state of type **15** known for the Prilezhaev reaction,[76,77] which does not require acid catalysis (Scheme 19), was proposed for the formation of oxirane **12**.

The radical mechanism with the intermediate formation of the biradical of type **16**[72,73] (Scheme 20) became very popular for the explanation of the transformation of oxirane **12** into lactone.

The problems of catalysis and inhibition of all steps of the Baeyer—Villiger reaction (see Schemes 14 and 16) by

Scheme 19



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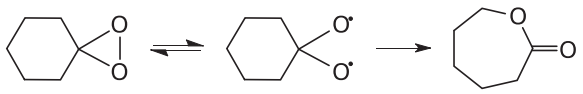
Scheme 20

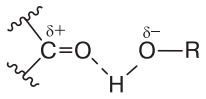


12 **16**

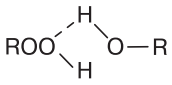
carboxylic acids and the compounds of variable valency metals under the conditions of liquid-phase oxidation were discussed in the recent reviews.[16,17] The steps of reversible addition of peroxy acid to the carbonyl compound, rearrangement, and homolytic decomposition of α-hydroxyperoxy ester are accelerated *via* the generalized mechanism of acid catalysis.[16,17,68,69]

The effect of cobalt(II), manganese(II), nickel(II), copper(II), iron(III), chromium(III), vanadium(III), and cerium(IV) naphthenates on the yield of ε-caprolactone in the reaction of cyclohexanone with peroxylauric acid at 293 K was studied.[78] It was shown that the cobalt, manganese, and vanadium salts strongly suppressed the formation of lactone, the effect of naphthenates of chromium and cerium was less evident, while the iron, nickel, and copper compounds exert a low effect on the yield of lactone.[17,78] Cobalt, manganese, nickel, and iron naphthenates were found[78,79] to accelerate the step of reversible addition of peroxy acid to ketone (see Scheme 14). The activity of naphthenates in this reaction decreases in the order Fe > Ni > Mn > Co. Cobalt, manganese, and nickel naphthenates exert almost no effect on the rate of heterolytic rearrangement of α-hydroxyperoxy ester to lactone, whereas the iron salts accelerate this reaction to the most extent. Manganese naphthenates and, to a lower extent, iron naphthenates increase the contribution of homolytic decomposition of α-hydroxyperoxy ester, whereas nickel naphthenate nearly does not affect the role of this reaction.[78,79] A substantial decrease in the yield of lactone in the presence of cobalt naphthenate is caused by both the decomposition of free peroxy acid and the homolytic transformation of α-hydroxyperoxy ester, which, as mentioned above, does not afford lactone. In the presence of manganese naphthenate, a decrease in the yield of lactone is mainly related to the catalytic decomposition of peroxy acid.[17]

The data in Table 1 show that the average ratio of the yields of ε-caprolactone and adipic acid (0.22) observed in the noncatalytic oxidation of cyclohexanol at 393 K is substantially lower than that found in the noncatalytic oxidation of cyclohexanone under similar conditions (>1) (see Fig. 3). This difference cannot be related to a lower concentration of cyclohexanone, since the data in Table 1 refer to high conversions of cyclohexanol transformation. The oxidation of cyclohexanol is characterized by the presence of a substrate capable of forming hydrogen bonds. As mentioned above, this results in the complicated dependences of the rate constants of reversible addition of hydroperoxides to the carbonyl group on the polar solvent concentration.[50] For the reaction of cyclohexanone with *tert*-butyl hydroperoxide in CCl_4 at 293 K, an increase in the concentration of the *n*-hexanol additive from 0 to 1 mol L^{-1} results in a considerable increase in the rate constants of hydroperoxide addition to ketone and hydroxyperoxide dissociation.[50] The rate constants decrease with the further increase in the alcohol concentration.[50] The increase in the rate constant of hydroperoxide addition to cyclohexanone under catalysis with alcohol is obviously explained by the activation of the carbonyl group prior to the nucleophilic attack in the complex with the hydrogen bond of type **17**, while the decrease is due to the deactivation of the nucleophile (complex **18**).[80]



17



18

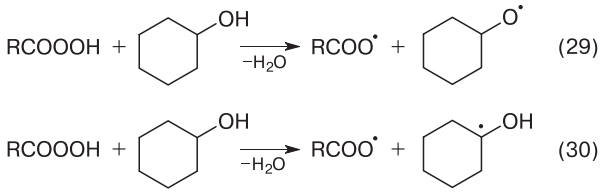
In addition, alcohols significantly accelerate the decomposition of peroxy acids.[50,81,82] At 352 K, the effective rate constants of peroxybenzoic acid decomposition in cyclohexane and cyclohexanone are ($k \cdot 10^4$, s^{-1}) 0.37 and ~40, respectively.[50,82]

The acceleration of peroxy acid decomposition under catalysis with cyclohexanol can be associated with the known reactions shown in Scheme 21.[20] The carbonyl compounds found in the products of decomposition of peroxybenzoic acid in alcohols[82] provide the evidence in favor of reaction (30).

The presence of the compounds with aldehyde functional groups (for example, 6-oxohexanoic acid) in the products of cyclohexane oxidation and the channels of peroxy acid formation (see above) assume the possibility of oxidation of the former with the latter *via* the Baeyer—Villiger reaction (Scheme 22).

Criegee intermediate **19** formed according to Scheme 22 can be rearranged to either two acid molecules (route *a*), or carboxylic acid and formic acid ester (route *b*).[16,17,53—55] The ratio of two routes of transformation of compound **19** is affected by the solvent nature and the structure of the substituent bound to the aldehyde group.[53] The contribution of route *b* increases if the secondary hydrocarbon substituent is bound to the aldehyde group (as, for example, in 2-ethylhexanal). Since no formation of butyl formate was found for the oxidation of valeric aldehyde,[53] route *b* cannot play an appreciable role in the oxidation of cyclohexane.

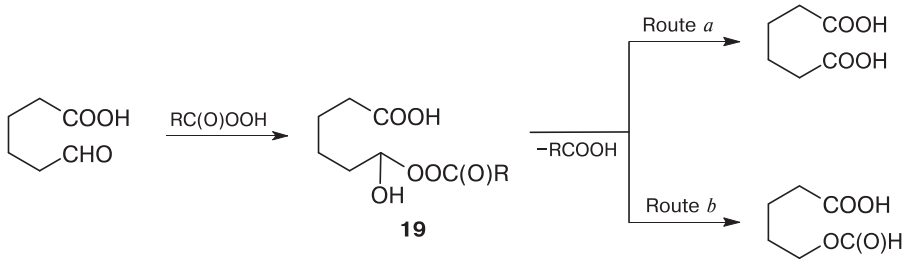
Scheme 21



δ-Valerolactone

δ-Valerolactone is formed along with ε-caprolactone in the oxidation of cyclohexane and its oxygen-containing derivatives.[7,18,31,32—35] The yield of δ-valerolactone produced by noncatalytic oxidation of cyclohexanone is approximately three times lower than the yield of ε-caprolactone[31] (see Fig. 3), while the yields of these lactones are close for the noncatalytic oxidation of cyclohexanol[33,34] (see Table 1). On oxidizing cyclohexanone, the cobalt(II),[31,32] manganese(II),[18] and chromium(III)[32] compounds hardly affect the yield of δ-valerolactone over the yield of adipic acid (see Fig. 3). The yield of δ-valerolactone does not exceed 0.22% based on the converted cyclohexane in the cobalt(II) octanoate-catalyzed oxi-

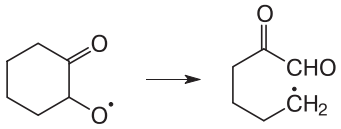
Scheme 22



dation of cyclohexane at 431 K.[35] It is shown by the oxidation of ^{14}C-labeled cyclohexane with the addition of nonlabeled cyclohexanol and cyclohexanone that 78% δ-valerolactone are formed from cyclohexanone during cyclohexane oxidation.[35]

δ-Valerolactone **20** is formed, most probably, from 5-hydroxypentanoic acid (**21**), which readily undergoes cyclization.[7] The channels of formation of acid **21** during cyclohexane oxidation were reviewed in detail.[7] The major precursor of 5-hydroxypentanoic acid is 2-oxocyclohexyloxyl radical **7** formed by the homolytic decomposition of 2-hydroperoxycyclohexanone, for example, *via* Scheme 13. The destructive decomposition of radical **7** is possible *via* two routes to form either 1,6-dioxohexyl radical **8** (see Scheme 13), or 5,6-dioxohexyl radical **22** (Scheme 23).

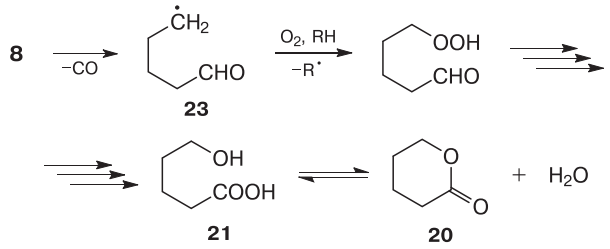
Scheme 23



7 **22**

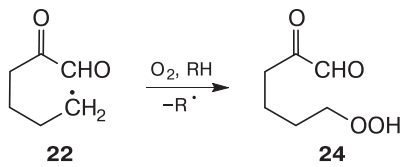
The decarbonylation of radical **8** and subsequent multistep transformations of 5-oxopentyl radical **23** can result in 5-hydroxypentanoic acid and then in δ-valerolactone (Scheme 24).

Scheme 24



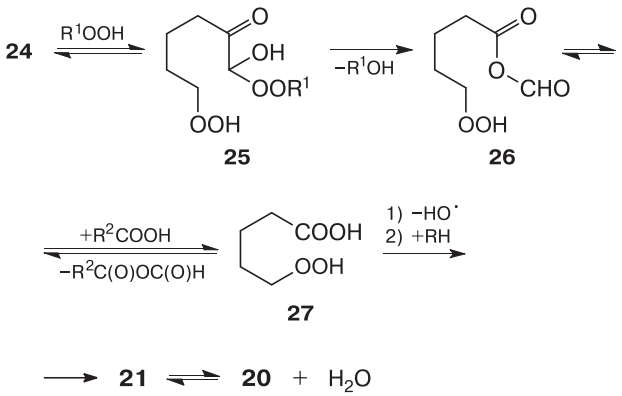
5,6-Dioxohexyl radical **22** can also successively react with oxygen and substrate to transform into 6-hydroperoxy-2-oxohexanal (**24**) (Scheme 25).

Scheme 25



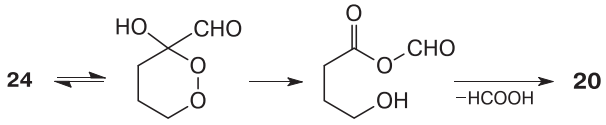
Further transformations of compound **24** (as α-dicarbonyl compound) can be related to the reactions with hydroperoxides, H_2O_2, and peroxy acids (see above). The oxidation of compound **24** affords α-hydroxy-α-peroxy ketone **25**, which decomposes *via* the pericyclic mechanism (see Scheme 8) to mixed anhydride of formic and 5-hydroperoxypentanoic acids **26**. The reacylation of the latter with carboxylic acids leads to 5-hydroperoxypentanoic acid (**27**) and then to δ-valerolactone (through acid **21**) (Scheme 26).

Scheme 26



Along with the intermolecular reaction (see Scheme 26), the intramolecular version of hydroperoxide group addition is possible for compound **24** (Scheme 27).

Scheme 27



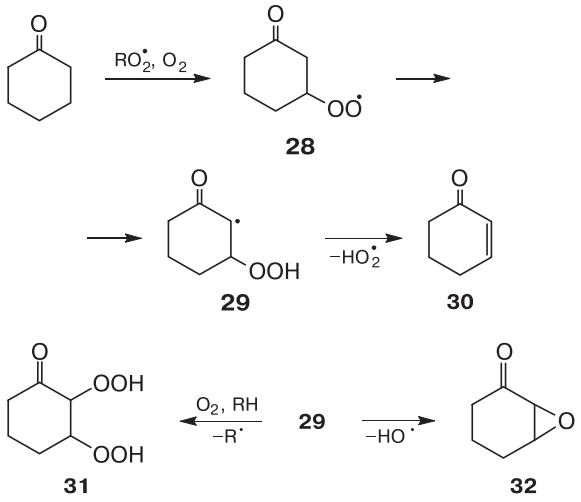
The mechanisms proposed for the formation of δ-valerolactone are related to the homolytic transformations of the hydroperoxide intermediates (see Schemes 13 and 24). It is known that the cobalt(II) and manganese(II) compounds stimulate the homolytic decomposition.[41] Therefore, it is not entirely clear why these catalysts poorly affect the relative yield of δ-valerolactone during the oxidation of cyclohexanone (see Fig. 3). This is possibly explained by the fact that the cobalt(II) and manganese(II) compounds catalyze the reactions shown in Schemes 13 and 24 and also simultaneously decompose the hydroperoxide groups involved in the transformations shown in Schemes 26 and 27.

Esters formed by the acylation of oxiranes

The oxidation of cyclohexanone at the β-CH bonds (positions 3 and 5) does not lead, as it was accepted previ-

ously, to 3-hydroperoxycyclohexanone. 5-Hydroperoxy-2-oxocyclohexyl radical **29**, which is formed due to the intramolecular isomerization of 3-oxocyclohexylperoxy radical **28**, is transformed into cyclohex-2-en-1-one (**30**), 2,3-dihydroperoxycyclohexan-1-one (**31**), and 2,3-epoxycyclohexan-1-one (**32**) (Scheme 28)[6,7,24,25] (Fig. 6).[24]

Scheme 28



In addition, under the conditions of cyclohexane oxidation, epoxy ketone **32** can be formed upon the oxidation of ketone **30** with both peroxy acids (Prilezhaev reaction)[76,77] and peracyl radicals[61] (Scheme 29).

Now we can address the data available[5,24,45,83] on the relative reactivity of the CH bonds of the oxygen-containing cyclohexane derivatives in the reaction with *tert*-butylperoxy radicals at 333 K (Fig. 7). These data calculated

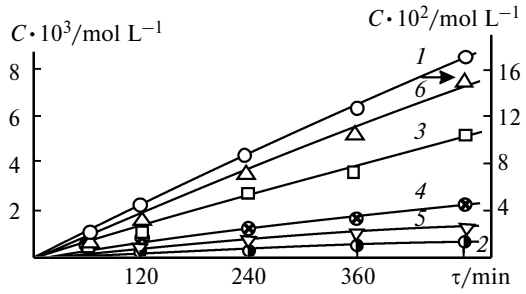


Fig. 6. Kinetic curves of accumulation of products of the azodiizobutyronitrile (AIBN)-initiated oxidation of cyclohexanone in the presence of *tert*-butyl hydroperoxide (TBHP) (333 K, 3.2 *M*, chlorobenzene, [AIBN] = 0.01 mol L^{-1}, [TBHP] = 0.5 mol L^{-1}).[24] Designations: *C* is the concentration of the products, τ is the reaction time; *1*, 2-hydroperoxycyclohexanone and 2-hydroxycyclohexanone; *2*, cyclohexane-1,2-dione; *3*, cyclohex-2-en-1-one; *4*, 2,3-epoxycyclohexan-1-one; *5*, 2,3-dihydroperoxycyclohexanone and 2,3-dihydroxycyclohexanone; and *6*, 4-hydroperoxycyclohexanone and 4-hydroxycyclohexanone.

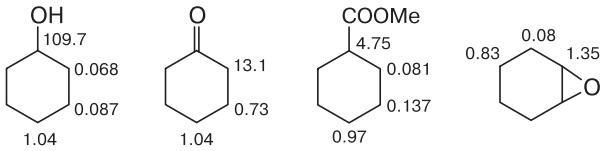
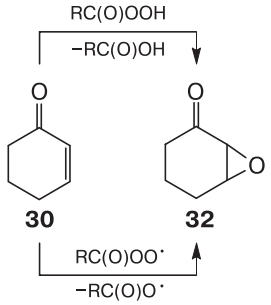


Fig. 7. Relative reactivity of the C—H bonds of cyclohexanone, cyclohexyl acetate, and epoxycyclohexane (at 333 K) in the reactions with *tert*-butylperoxy radicals compared to the reactivity of the C—H bonds of cyclohexane.

Scheme 29



in relation to the CH bonds in cyclohexane indicate a low oxidizability of the CH bonds of the oxirane ring in the reaction with peroxyl radicals.

It can be assumed that the reactions with oxygen-containing nucleophiles, *i.e.*, water, alcohols, and carboxylic acids, can be important channels of transformations of oxiranes of type **32**. The reactions with carboxylic acids lead to glycol monoesters (see Scheme 2). As described above, 3-butanoyloxy-2-hydroxybutanoic acid was found among the oxidation products of butanoic acid.[27—28]

It is known[84,85] that the reactions of oxiranes with the oxygen-containing nucleophiles proceed *via* the mechanism of nucleophilic substitution at the aliphatic carbon

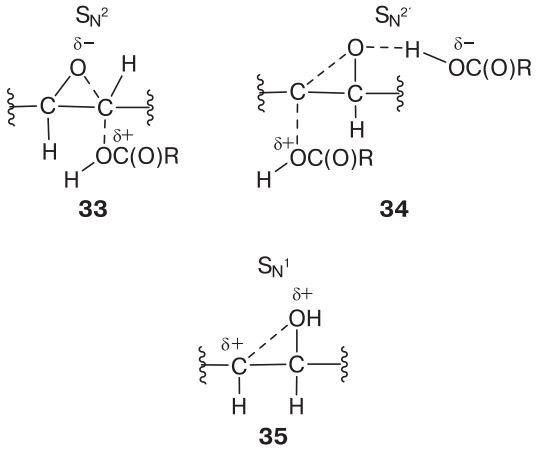


Fig. 8. Possible transition states in the reactions of oxiranes with the oxygen-containing nucleophiles.

atom. The theoretical model with the transition state **33** of the S_N2 mechanism is preferable for the noncatalytic reaction (Fig. 8).[84,85] This model is consistent with the known kinetic features of oxirane ring opening and explains the Walden inversion of the structure of the reaction center characteristic of this reaction. Probably, the oxirane ring opening *via* the S_N2' mechanism is possible for the liquid-phase oxidation of cyclohexane, which occurs during the general acid catalysis by carboxylic acids with the transition state of type **34** (see Fig. 8). Under the acid catalysis conditions, the S_N2' mechanism with the transition state **35** is preferrable[85] over the S_N1 mechanism.

Conclusion

A wide range of ester compounds is formed during the liquid-phase oxidation of cyclohexane and its oxygen-containing derivatives. These ester compounds can be divided into three main groups on the basis of their structures and mechanisms of formation.

The first group is mainly presented by cyclohexyl esters of mono- and dicarboxylic acids. These esters are nearly completely resulted from acylation of cyclohexanol with mixed anhydrides containing acyl groups of all compounds with free carboxyl groups that are present in oxidized cyclohexane. Mixed anhydrides are formed by the reacylation of the initially formed anhydrides (predominantly adipic anhydride) with carboxylic acids. The sources of adipic anhydride are the radical chain oxidation of 2-hydroxycyclohexanone and oxidation of cyclohexane-1,2-dione with hydroperoxides, H_2O_2, and peroxy acids. Anhydrides can also be formed from other α-dicarbonyl compounds but in substantially lower amounts. Alcoholysis of mixed formic acid anhydrides with cyclohexanol results in the predominant formation of cyclohexyl formate. Under the conditions of industrial cyclohexane oxidation, the ratio of the yields of cyclohexyl formate and formic acid increases fourfold than the analogous values for other mono- and dicarboxylic acids. In the case of cyclohexane oxidation, this channel can lead to esters of both cyclohexanol and 2-hydroxycyclohexanone, as well as of other compounds with free hydroxy groups. The contribution of an alternative source of esters of this group, esterification of free carboxylic acids with alcohols, does not exceed 0.2% under the industrial conditions. Since esterification is reversible, it can reduce, under certain conditions, the content of cyclohexyl esters formed in the irreversible alcoholysis of carboxylic acid anhydrides with alcohols.

The main representative of the second group of ester compounds of oxidized cyclohexane is ε-caprolactone. Upon in the liquid-phase oxidation of cyclohexane, this compound is formed *via* the Baeyer—Villiger oxidation of cyclohexanone with peroxy acids predominantly through α-hydroxy-α-hydroperoxy ester. Alternative channels for ε-caprolactone formation *via* the reactions involving hydroperoxides, H_2O_2, and peroxyl radicals do not occur to an appreciable extent. α-Hydroxy-α-hydroperoxy ester is transformed into lactone due to the nucleophilic rearrangement. The homolytic channel of the transformation of α-hydroxy-α-hydroperoxy ester does not result in lactone. Carboxylic acids and the compounds of variable valency metals accelerates the steps of formation and transformation of α-hydroxy-α-hydroperoxy ester. The yield of ε-caprolactone decreases due to the decomposition or reduction of peroxy acids catalyzed by the compounds of variable valency metals or sulfur-containing reagents, respectively. In addition, the yield of ε-caprolactone decreases when the homolytic decomposition of α-hydroxy-α-hydroperoxy ester is stimulated by the cobalt(II) and manganese(II) compounds. The formation of formic acid esters by the Baeyer—Villiger oxidation of aldehyde groups with peroxy acids is not substantial in cyclohexane oxidation.

Lactones formed due to the cyclization of γ- and δ-hydroxy acids were assigned to the third group of ester compounds. The oxidation products of cyclohexane contain δ-valerolactone formed predominantly at the steps followed cyclohexanone oxidation. It is assumed that the main channel of formation of the δ-valerolactone precursor, 5-hydroxypentanoic acid, is related to the homolytic decomposition of 2-hydroperoxycyclohexanol and subsequent oxidative transformations of the 5,6-dioxohexyl radical. The compounds of variable valency metals exert a slight effect on the yield of δ-valerolactone.

Since oxiranes were found in the oxidation products of the carbonyl-containing compounds at the β-CH bonds, it can be assumed that glycol esters are resulted from the acylation of oxiranes with carboxylic acids *via* the mechanisms of nucleophilic substitution at the aliphatic carbon atom.

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Received April 12, 2019;
in revised form May 20, 2019;
accepted June 3, 2019