REACTION OF OXIRANES AND OXETANES WITH CARBONYL COMPOUNDS.

SYNTHESIS OF 1,3-DIOXACYCLOALKANES (REVIEW)

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Data on the reaction of oxiranes and oxetanes with carbonyl compounds are correlated. The effect of the nature of the catalyst and the structure of the starting reagents on the selectivity of the reaction and the kinetics, stereochemistry, and mechanism of the reaction are discussed.

1,3-Dioxacycloalkanes are convenient subjects for the solution of problems of theoretical organic chemistry and conformational analysis. In addition, compounds of this class have the properties of solvents, plasticizers, corrosion inhibitors, biologically active substances, and medicinals. The acetal functional group can be readily converted to alcohol, carboxy, ester, carbonyl, and other functional groups [1].

Of the methods for the preparation of 1,3-dioxacycloalkanes, the most detailed study has been devoted to the Prins and Salmi reactions, which have been described in reviews and monographs [1-4].

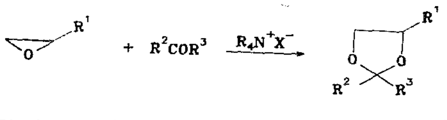
A number of reports of the reaction of oxetanes and oxiranes with carbonyl compounds, which leads to the formation of 1,3-dioxacycloalkanes, have been published in recent years. Owing to its universality, the simplicity with which it is realized, and its high selectivity, this reaction is attracting increasing attention. A peculiarity of the synthesis of 1,3-dioxacycloalkanes from epoxy compounds is the possibility of carrying it out in a closed system, since, in contrast to acetalization [1], water is not liberated during the reaction. At the same time, generalizations regarding the synthesis of 1,3-dioxolanes from oxiranes have reduced primarily to a description of the methods and the products that can be obtained in this reaction [5, 6].

1. SYNTHETIC ASPECTS OF THE REACTION OF OXIRANES AND OXETANES WITH CARBONYL COMPOUNDS

1.1. Acid-Catalyzed Reaction of Oxiranes and Oxetanes with Carbonyl Compounds

Acidic catalysts are used in the overwhelming majority of cases to obtain 1, 3-dioxacycloalkanes from oxiranes or oxetanes and carbonyl compounds. The results of the reaction depend to a considerable extent on the structures of the starting reagents, the nature of the catalyst, and the conditions under which the synthesis is carried out.

1.1.1. Effect of the Nature of the Acidic Catalyst on the Yields of 1,3-Dioxacycloalkanes. Both protic acids (sulfuric, p-toluenesulfonic, and formic acids) [7, 8] and Lewis acids [$BF_3 \cdot O(C_2H_5)_2$, $SnCl_4$, $FeCl_3$, $AlCl_3$, and $CuSO_4$] [7, 9-14] have been tested as catalysts for this reaction. p-Toluenesulfonic acid and KU-2 cation-exchange resin have low catalytic activity [7]. 1,3-Dioxacycloalkanes have been obtained in high yields from oxiranes and oxetanes in the presence of catalysts such as H_2SO_4 [7, 15], $BF_3 \cdot O(C_2H_5)_2$ [7, 14, 16], and $SnCl_4$ [11, 12]; boron trifluoride etherate catalyzes the condensation of 1,2- and 1,3-epoxy

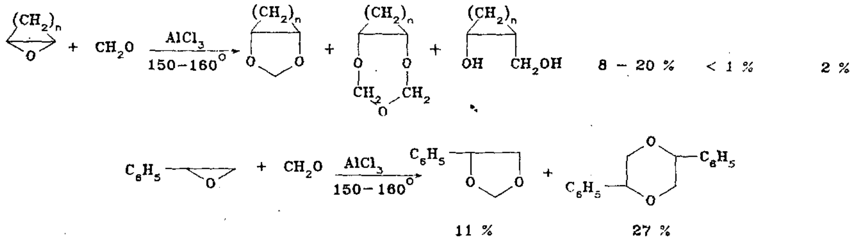


$R=C_2H_5$, C_4H_9; X=Cl, Br, I; $R^1=H$, CH_3; $R^2=H$; $R^3=$**sec-alkyl** , C_6H_5; $R^2=C_6H_5$, $R^3=CHCl_2$

Ufa Petroleum Institute, Ufa 450062. Translated from Khimiya Geterotsiklicheskikh Soedinenii, No. 3, pp. 291-306, March, 1984. Original article submitted October 26, 1982.

compounds with ketones and is less active in the reaction with aldehydes. The yields of ketals in the presence of $BF_3 \cdot O(C_2H_5)_2$ are 10-15% higher than in the presence of H_2SO_4 [7]. Tetraalkylammonium halides can be used as catalysts in the synthesis of 1,3-dioxanes from oxiranes and carbonyl compounds (at 125-220°C for 1-24 h) [17, 18].

The choice of catalyst determines the temperature conditions of the condensation. Whereas heating at 110°C is required for the synthesis of 1,3-dioxacycloalkanes from oxiranes and oxetanes in the presence of sulfuric acid [7], condensation with $SnCl_4$ as the catalyst takes place at 27-70°C [11, 12, 19]. The use of $BF_3 \cdot O(C_2H_5)_2$ makes it possible to carry out the reaction at room temperature [7, 9, 14, 16] and even at 0°C [20, 21]. 1,3-Dioxalanes were obtained in yields that did not exceed 20% from 1,2-epoxycycloalkanes and paraformaldehyde in the presence of $AlCl_3$ by heating in an autoclave at 150-160°C for 5 h [22]. The reaction in this case was complicated by side processes, viz., the formation of 1,3,5-trioxabicycloalkanes and hydroxymethylhydroxycycloalkanes or dimerization of the oxirane [22]:

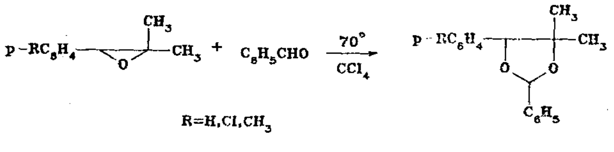


The solvent used in the reaction is also determined by the type of catalyst. Thus condensation with $SnCl_4$ as the catalyst is usually carried out in carbon tetrachloride [19, 23] or in methylene chloride [11, 12], whereas condensation with H_2SO_4 as the catalyst is usually carried out in carbon tetrachloride [19, 23] or in methylene chloride [11, 12], whereas condensation with H_2SO_4 as the catalyst is usually carried out in toluene [7, 15, 24]. The starting ketone in a twofold to tenfold excess relative to the oxide is used as the solvent in reactions catalyzed by $BF_3 \cdot O(C_2H_5)_2$ [7, 9, 14, 20, 21].

1.1.2. Effect of the Structure of the Epoxy Compound on the Yields of 1,3-Dioxacycloalkanes. Both 1,2- and 1,3-epoxy compounds with the most diverse structures undergo condensation with carbonyl compounds. Satisfactory results when the simplext oxiranes (ethylene oxide and propylene oxide) are used can be obtained only under conditions of a significant excess of the carbonyl component. Thus, for example, 2,2-dimethyl-1,3-dioxolane was obtained in 12% yield from ethylene oxide and acetone in the presence of boron trifluoride at up to 40°C by feeding small portions of the oxirane into a mixture of the ketone with the catalyst [25].

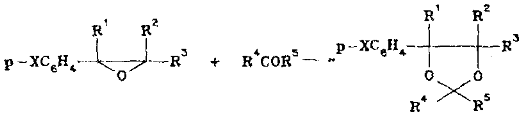
Aliphatic epoxyalkanes undergo 20-95% conversion in the reaction with acetone in the presence of copper sulfate; 2,3-dialkyl-2,3-epoxyalkanes are less active by a factor of two to four times than 2,2,3-trialkyl-3,4-epoxyalkanes [13]. 2-Monosubstituted oxiranes react with carbonyl compounds only when the temperature is raised to 60°C. It is assumed that the reactivities of aliphatic oxiranes are determined by the stability of the carbonium ion formed from the epoxyalkane as a result of reaction with the Lewis acid [13].

The yields of 4-aryl-1,3-dioxolanes from aryloxiranes usually reach 40-70%. Thus, for example, 4,4-dimethyl-2-phenyl-5-aryl-1,3-dioxolanes were obtained in 51-68% yields in the reaction of 2,2-dimethyl-3-aryloxirane with benzaldehyde in the presence of $SnCl_4$ in a molar ratio of 2:4:1 (respectively) [19]:



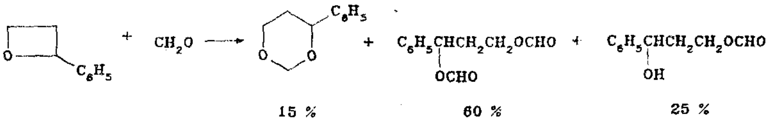
The reactivities of 2-aryloxiranes in the reaction with acetone in the presence of anhydrous $CuSO_4$ increases in the following order with respect to the 4'-R substituents: Br < Cl < H < CH_3 [13].

2-Alkoxy-2-aryl- and 2-acyl-3-aryloxiranes form products of condensation with carbonyl compounds in 40-85% yields [9, 26-29]:

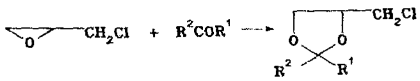


X=H, Cl, CH_3, OCH_3; $R^1=OCH_3$, $R^2=R^3=CH_3$, $R^4=H$, R^5=aryl ; $R^1=R^2=H$, $R^3=COR^6$,
R^4, $R^5=CH_3$, C_6H_5, $-(CH_2)_5-$

The reaction of 2-phenyl- and 2-phenyl-2-methoxetanes with formaldehyde in the petroleum ether–formic acid heterophase system has been realized [8]. Whereas 4-methyl-4-phenyl-1,3-dioxane is formed in 61% yield from 2-phenyl-2-methyloxetane and formaldehyde, 1-phenyl-1,3-propanediol mono- and diformates were obtained as the principal products from 2-phenyloxetane:

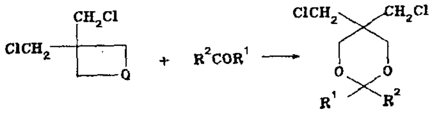


(Halomethyl)oxiranes have been used extensively in condensation with carbonyl compounds. This primarily applies to 1-chloro-2,3-epoxypropane [11, 12, 30, 31]:

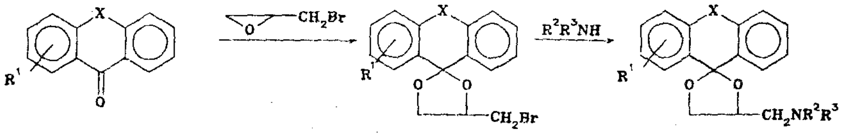


High yields of 4-chloromethyl-1,3-dioxolanes have been obtained with various catalysts including H_2SO_4, $BF_3 \cdot O(C_2H_5)_2$ [7, 15, 31], and $SnCl_4$ [11, 12].

Data on the synthesis of 5,5-bis(chloromethyl)-1,3-dioxanes from 3,3-bis(chloromethyl)-oxetane have been published in recent years [7, 24, 31]:

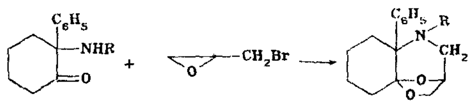


A large number of amino-substituted 1,3-dioxolanes that have various pharmaceutical properties have been synthesized from 1-bromo-2,3-epoxypropane in two steps [32, 33]:



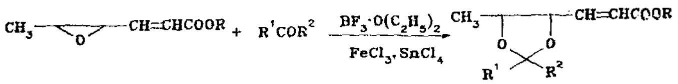
X=$-OCH_2-$, $-CH_2CH_2-$, $-CH=CH-$;
R^1=H, Cl, OCH_3

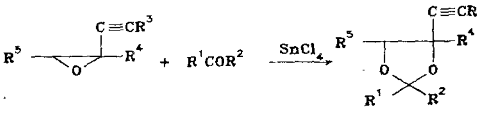
A method for the preparation of anesthetizing agents in which both steps are combined has been patented [34]:



R=H, CH_3, C_4H_9

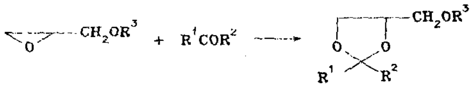
Oxiranes that contain multiple bonds in the side chain react smoothly with carbonyl compounds. Alkenyl- [10, 23] and alkynyl-1,3-dioxolanes [35] are obtained:





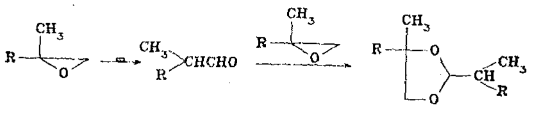
$R=C_2H_5$; C_3H_7, i-C_3H_7, C_4H_9; R^1, $R^2=CH_3$, C_2H_5, $-(CH_2)_5C_6H_5$; R^3=H, $C(OH)(CH_3)_2$,
R^4, R^5=H, CH_3

A large number of 1,3-dioxolanes have been synthesized from glycidic esters [16, 37, 37]:

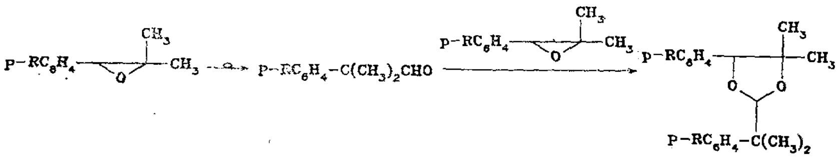


R^1=H,CH_3; R^2=CH_3,C_3H_7,C_6H_5
R^1-R^2=-$(CH_2)_5$-

In acidic media oxiranes are capable of undergoing isomerization to carbonyl compounds [5, 38]; substituted 1,3-dioxolanes can therefore be obtained in some cases using only one reagent, viz., the oxirane [39]:



The ability to undergo isomerization determines the possibility of the competitive realization of two processes, viz., dimerization of the oxide and reaction with the starting carbonyl compound. The probability of the primary occurrence of one or the other process depends on the structure of the starting oxide and the reaction conditions. Whereas, as indicated above, the corresponding dioxolanes are formed in good yields in the reaction of 2,2-dimethyl-3-aryloxiranes with benzaldehyde in the presence of $SnCl_4$ at a molar ratio of 2:4:1 (respectively), benzaldehyde does not undergo condensation at an oxirane:benzaldehyde:$SnCl_4$, molar ratio, since a stable complex with composition $SnCl_4 \cdot 2C_6H_5CHO$ is formed, and 4,4-dimethyl-2-(1-methyl-1-arylethyl)-5-aryl-1,3-dioxolanes are isolated as the principal products in 37-67% yields [19]:



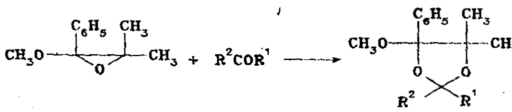
The formation of significant amounts of a ketone that is isomeric with respect to the oxirane has been reported in the case of 2,3-dimethyl-1,4-dibromo-2,3-epoxybutanes [40]:

R=H,CH_3

However, derivatives of the ketones, viz., the corresponding 1,3-dioxolanes, have not been detected.

1.1.3. Effect of the Structure of the Carbonyl Compound on the Yields of 1,3-Dioxacycloalkanes. The structure of the carbonyl compound has a smaller effect on the results of the reaction than the structure of the oxirane and the nature of the acidic catalyst (Table 1).

2-Alkoxy-3,3-dimethyl-2-phenyloxiranes do not react with aliphatic aldehydes; at the same time, the corresponding 1,3-dioxolanes were obtained in 20-65% yields by condensation with aromatic aldehydes [26, 29] and in 60-70% yields by condensation with ketones [28]:



R^1, R^2= alkyl, aryl; R^1= aryl, R^2=H

In the synthesis of 1,3-dioxolanes from oxiranes in the presence of tetraalkylammonium halides the yields of reaction products depend substantially on the structure of the starting carbonyl compounds and reach their maximum values (55-81%) in the case of aromatic and aliphatic aldehydes with branched structures [17]. The reaction of oxiranes with aldehydes

TABLE 1. Conditions and Results of the Reaction of Oxiranes and Oxetanes with Carbonyl Compounds on Various Catalysts

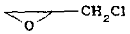
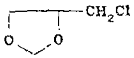
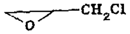
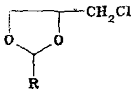
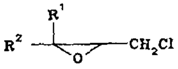
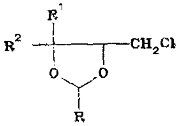
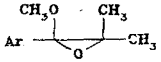
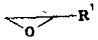
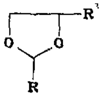
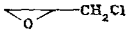
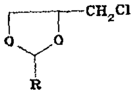
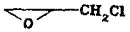
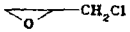
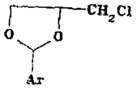
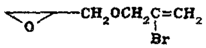
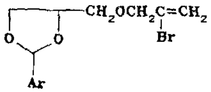
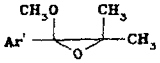
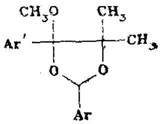
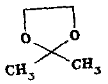
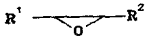
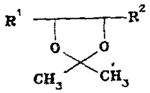
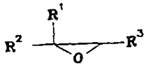
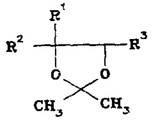
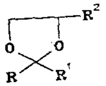
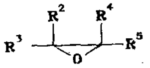
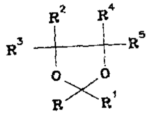
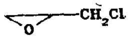
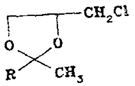
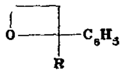
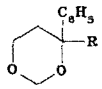
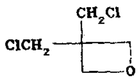
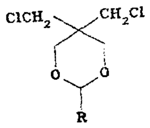
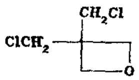
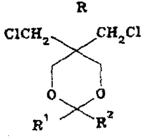
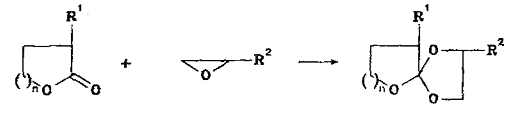
Carbonyl compound	Oxirane	Reaction conditions				1,3-Dioxacycloalkane obtained	Yield, %	Literature
		catalyst	temp., °C	time, h	solvent			
1	2	3	4	5	6	7	8	9
CH_2O		H_2SO_4	100—110	4—5	Toluene		60	[7]
RCHO (R= alkyl)		H_2SO_4	90—100	4—5	Toluene		65—75 68—87	[12] [17]
RCHO (R= alkyl)	 $R^1, R^2 = H, CH_3$	$SnCl_4$	Up to 40	10	CH_2Cl_2		51—65	[7]
RCHO (R=alkyl)		$SnCl_4$	Room	—	CCl_4	—	—	[7]
RCHO (R=sec-alkyl)	 $R^1 = H, CH_3$	$(C_2H_5)_4\overset{+}{N}\overset{-}{Br}$	125—220	2—4	—		12—81	[28]
RCHO (R=H, i-C_4H_9)		KU-2	100	6	Toluene		3	[30]
RCHO (R=H, i-C_4H_9)		p-$CH_3C_6H_4SO_3H$	100	6	Toluene	—	—	[7]
ArCHO		H_2SO_4	100—110	4—5	Toluene		70	[7]
ArCHO		$BF_3 \cdot O(C_2H_5)_2$	Room	24	—		86	[16]
ArCHO		$SnCl_4$	Room	—	CCl_4		60—65	[29]

TABLE 1 (continued)

1	2	3	4	5	6	7	8	9
CH_3COCH_3		$SnCl_4$	—	—	—		30	[45]
CH_3COCH_3	 $R^1, R^2 = H, CH_3$	$BF_3 \cdot O(C_2H_5)_2$	Room 55	6 0,5	Three- to fivefold excess of acetone		12—35	[25]
CH_3COCH_3		$CuSO_4$	Room	6—24	Excess acetone		20—95	[13]
R^2COR^1 (R, R^1= alkyl)	 $R^3 = CH_2Cl, CH_2OCH_2CBr{=}CH_2$	$BF_3 \cdot O(C_2H_5)_2$	Room	8 24 6—8	Excess ketone		62—89 76—89 51—70	[7] [16] [14]
$RCOR^1$ (R^1= alkyl) R^2= alkyl, aryl, 2-furyl	 $R^2 = H, CH_3, CH_3O$ $R^3 = H, CH_3, Ar$ $R^4 = CH_3, CH_2Cl, CH_2Br$ $R^5 = H, CH_3$	$SnCl_4$	27—31 Up to 40 Room	3—4 10 —	CH_2Cl_2 CH_2Cl_2 CCl_4		48—93 60—86 60—70	[11] [12] [28, 29]
$RCOCH_3$ (R= alkyl)		$FeCl_3$ $AlCl_3 \cdot O(C_2H_5)_2$	Room	6—8	Excess ketone		6—20	[14]
CH_2O		HCOOH	Refluxing	—	Petroleum ether, formic acid		16—61	[8]
RCHO (R=H, alkyl)		H_2SO_4	100—110	4—5	Toluene		62—70	[7]
R^1COR^2		$BF_3 \cdot O(C_2H_5)_2$	20	8	Excess ketone		70—78	[7]

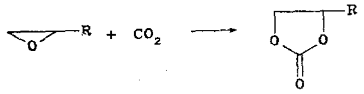
that contain two hydrogen atoms in the α position is complicated by crotonic condensation [17].

The use of esters instead of carbonyl compounds makes it possible to obtain cyclic orthoesters [41-44]. Thus a number of 1,4,7-trioxaspiroalkanes have been synthesized from γ and δ-lactones and oxiranes in the presence of Lewis acids [$BF_3 \cdot O(C_2H_5)_2$, $SnCl_4$]:



n=1—3; R^1=H, Cl; R^2=H, CH_3, CH_2Cl, $CH_2OC_6H_5$

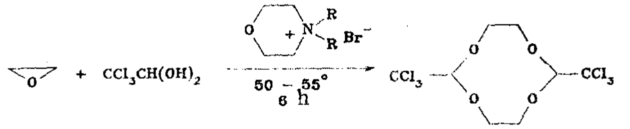
Cyclic carbonates were obtained in high yields from oxiranes and carbon dioxide either in the presence of transition metal (Cr, Mn, Ru, Rh, and Cd) halides at low temperatures [46] or under a pressure of up to 60 atm and at 150-180°C [47]:



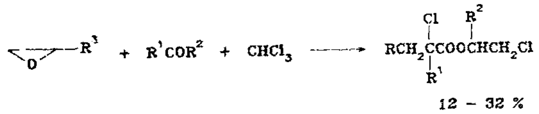
R=H, CH_3, *cyclo*-C_6H_{11}, —$CH{=}CH_2$, C_6H_5, $CH_2O(CH_2)_nOCH{=}CH_2$

1.2. Other Methods for the Synthesis of 1,3-Dioxacycloalkanes from Oxiranes and Oxetanes

1.2.1. Condensation of Oxiranes with Carbonyl Compounds in Neutral and Alkaline Media. The reaction of ethylene oxide with chloral hydrate in chloroform and in the presence of catalytic amounts of a dialkylmorpholine bromide, which leads to a macrocyclic diacetal in 90% yield, has been reported [48]:



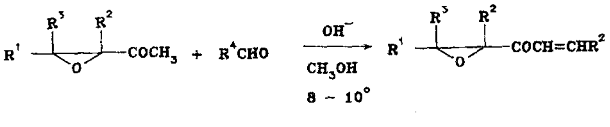
In the presence of diethylmorpholine bromide in chloroform oxiranes undergo condensation with aldehydes and ketones to give acyclic products, viz., chlorine-containing carboxylic acid esters [49]:



R^1=H, CH_3; R^2=CH_3, C_2H_5, *i*-C_3H_7; R^2—R^1=—$(CH_2)_6$—

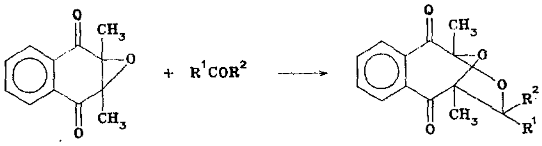
In alkaline media oxiranes react with carbonyl compounds that contain a hydroxy or amino group to give monoethers of the corresponding glycol or amino alcohol, the cyclization of which to 1,3-dioxolanes is impossible [50-54].

α,β-Epoxy ketones react with aromatic and heterocyclic aldehydes in alkaline media with retention of the oxirane ring; products of crotonic condensation, viz., monoepoxides of arylaliphatic divinyl ketones, were obtained in 35-93% yields [55]:



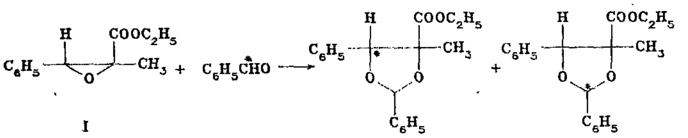
R^1, R^2, R^3=H, CH_3, C_6H_5; R^4=C_6H_5, 4-BrC_6H_4, 2-$CH_3OC_6H_4$, 4-ClC_6H_4, 4-FC_6H_4, 2- furyl
2- thienyl

1.2.2. Photochemical Condensation of Oxiranes with Carbonyl Compounds. Oxiranes undergo thermal [56] and photochemical [57, 58] 1,3-cycloaddition reactions with aldehydes and ketones to give 1,3-dioxolanes in 12-85% yields:



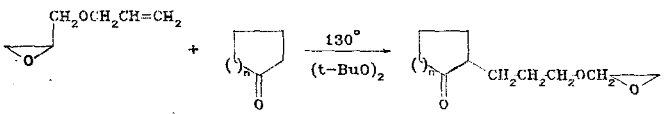
$R^1=H$, $R^2=$alkyl, $p\text{-}NO_2C_6H_4$; R^1, $R^2=$alkyl; $R^1—R^2=—(CH_2)_4—$, $—(CH_2)_5—$

On the basis of the results of the reaction of 2-methyl-2-ethoxycarbonyl-3-phenyloxirane (I) with ^{14}C-labeled benzaldehyde in benzene initiated with light with λ 254 nm it was shown [57] that cleavage of the C—O and C—C bonds in oxirane I is realized in a ratio of 6:1:



I

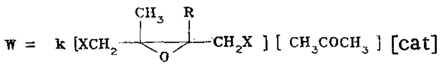
Photolysis of oxirane I in the presence of acetaldehyde or formaldehyde leads to the formation of 1,3-dioxolanes in 40 and 70% yields, respectively, as a result of cleavage of only the C—C bond of oxirane I. The thermolysis of a mixture of oxirane I and benzaldehyde proceeds with cleavage of exclusively the C—C bond of the oxirane [56]. Unsaturated epoxides react with aldehydes and ketones in the presence of tert-butyl peroxide with retention of the α-oxide ring [59-61]:



2. KINETICS, STEREOCHEMISTRY, AND MECHANISM OF THE REACTION OF OXIRANES AND OXETANES WITH CARBONYL COMPOUNDS

Only a few papers devoted to the study of the kinetics and mechanism of the reaction of oxiranes with carbonyl compounds are available, and they do not make it possible to describe the reaction mechanism in general form. The published data pertain primarily to the solution of special problems of the kinetics and mechanism, viz., to the elucidation of the kinetic equations of the reactions for a limited number of 1,2- and 1,3-epoxyalkanes, carbonyl compounds, and catalysts, and also to the determination of the qualitative and quantitative dependences of the reactivities of the starting reagents on their structures. Nevertheless, a comparison is possible in individual cases, since the conditions under which the kinetic experiments were carried out are similar.

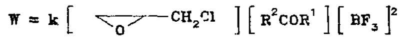
The condensation of acetone with chloro- and bromomethyloxiranes in the presence of stannic chloride or boron trifluoride etherate in CCl_4 at 10-40°C is described by a third-order equation [40]:



$$W = k\,[XCH_2C(CH_3)(O)C(R)CH_2X]\,[CH_3COCH_3]\,[\text{cat}]$$

$X=Cl$, Br; $R=H$, CH_3

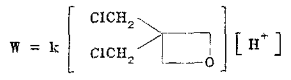
Overall second order in the oxirane and catalyst was established in the case of the reaction of 2,3-bis(halomethyl)oxiranes with acetone in carbon tetrachloride in the presence of $SnCl_4$ at 10-40°C [40]. The condensation of 1-chloro-2,3-epoxypropane with aliphatic ketones in the presence of boron trifluoride etherate obeys a fourth-order equation [62]:



$$W = k\,[\,C_2H_3O\text{—}CH_2Cl\,]\,[\,R^2COR^1\,]\,[\,BF_3\,]^2$$

It is assumed that the second order in the catalyst is determined by reaction of complexes of the starting reagents with the catalyst in the rate-determining step [62]. This assumption is confirmed by the data in [63], in which low-temperature PMR spectroscopy was used to study the behavior of aliphatic oxiranes in the presence of Lewis acids and carbonyl compounds.

The reaction of 3,3-disubstituted oxetanes with aliphatic and aromatic aldehydes in toluene in the presence of sulfuric acid at 25-85°C is described by a third-order expression [62, 64-66]. At the same time, the rate of the reaction of 3,3-bis(chloromethyl)oxetane with cyclohexanone under the same conditions depends on the cyclohexanone concentration [67]:



Thus the reaction rates in all of the investigated cases are proportional to the oxirane or oxetane concentration; the catalyst concentration enters into the kinetic equation to the first or second power. The concentration of the carbonyl compound is also included in the kinetic equation to the first power in most cases, although there are cases in which the reaction rate is independent of the ketone concentration.

The quantitative dependence of the reactivities of carbonyl compounds on their structures was studied in [40, 62, 64]. It was shown that the size of the hydrocarbon groups in series of aliphatic and alicylic ketones has little effect on their reactivities in reactions with oxiranes [62]. Thus, for example, diethyl ketone is less active than acetone by a factor of only 1.3 in the reaction with 2,3-bis(bromomethyl)oxirane in the presence of $SnCl_4$ [40]. A cyclic ketone, viz., cyclohexanone, displays increased activity as compared with alicyclic ketones [62]. The reactivities of aliphatic aldehydes in reactions with 3,3-bis(chloromethyl)oxetane change only slightly [64].

The activity of the epoxy compound is determined by its structure. Replacement of a chlorine atom by an alkoxy group in a 3,3-disubstituted oxetane, even when it is remote from the reaction center of the molecule, increases the reactivity extremely significantly. 3-propoxy-3-chloromethyloxetane is more active than 3,3-bis(chloromethyl)oxetane by a factor of 1.7 and less active than 3,3-bis(propoxymethyl)oxetane by a factor of 5.0 (Table 2) [62].

The authors assume that such a significant difference in the reactivities of chloromethyl- and alkoxymethyl-substituted oxetanes in condensation with benzaldehyde is due either to different inductive effects of the substituents or to the possibility of delocalization of the positive charge that develops during cleavage of the oxetane ring on the carbon atom through the unshared electron pairs of the oxygen atom in the alkoxy group [62].

The rate constants for 1,4-dibromo-2,3-epoxybutanes in reactions with acetone increase somewhat when the hydrogen atom attached to the $C_{(2)}$ atom is replaced by a methyl group and decrease sharply when yet another methyl substituent is introduced (Table 3) [40].

According to the assumption made by Dryuk and co-workers [40], the reason for the increased reactivity of the oxirane is an increase in the nucleophilicity of the oxygen atom when a methyl substituent is introduced into the oxirane ring or when chlorine is replaced by bromine in the halomethyl group; two methyl substituents increase the steric strain in the transition state, which results in a decrease in the reactivity of the oxirane.

The kinetic parameters of the reactions of oxetanes and oxiranes with carbonyl compounds were determined in [40, 62, 64, 67]. The energy of activation of the reaction of 1-chloro-2,3-epoxypropane with cyclohexanone in the presence of the aprotic BF_3 catalyst is 53.5 ± 1.3 kJ/mole [62], as compared with 49.3 ± 1.8 kJ/mole for the reaction of 3,3-bis(chloromethyl)oxetane with cyclohexanone catalyzed by sulfuric acid [67]. The energy barrier is higher for the reaction of 3,3-disubstituted oxetanes with aldehydes in toluene in the presence of sulfuric acid and ranges from 94.9 to 136.4 kJ/mole [62, 64]. On the basis of the small $\Delta H^{\neq}$ values (41.0-65.6 kJ/mole) and the significant negative $\Delta S^{\neq}$ values (—104.5 to —167.2 J/mole·deg) a multicenter mechanism was proposed for the reaction of 1,4-dihalo-substituted 2,3-epoxybutanes with ketones in the presence of $SnCl_4$ [40]:

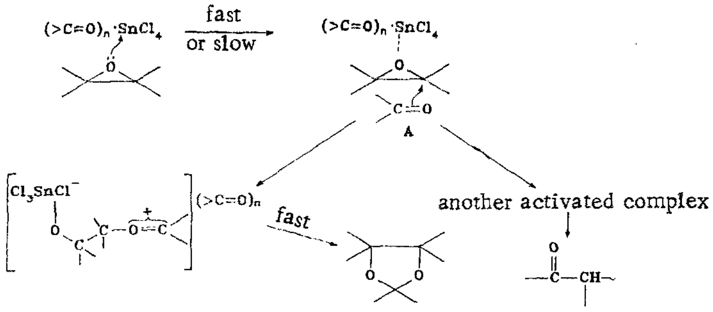
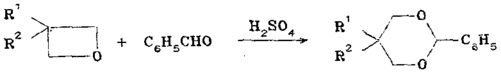


TABLE 2. Rate Constants and Energies of Activation in the Reaction of Substituted Oxetanes with Benzaldehyde (T = 353°C) [62]



R^1	R^2	$k \cdot 10^4$, liters/mole-sec	E, kJ/mole
Cl	Cl	8,7	110,9
OCH_3	OCH_3	78,6	94,9
OC_3H_7	OC_3H_7	73,6	95,3
Cl	OC_3H_7	14,6	—

The key step in the scheme is the reaction of the oxirane with the Lewis acid complex of the ketone, which leads to donor-acceptor complex A. The conversion of this complex to the activated form includes attack by a molecule of the ketone from the solvate shell of the complex via a "push-pull" mechanism. The formation of complex A may be the rate-determining step in some cases [40].

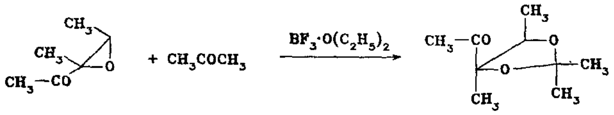
The solution of the problem of primary protonation is of great importance for the selection of a possible mechanism of the reaction in the presence of protic acids.

The behavior of 3,3-disubstituted oxetanes in superacid media was investigated by PMR spectroscopy in order to ascertain the structure of the intermediate particles formed from oxetanes by protonation. It was established that at –70°C in HSO_3F 3,3-bis(chloromethyl)- and 3,3-bis(alkoxymethyl)oxetanes form oxonium ions that are stable at –10 to 5°C:

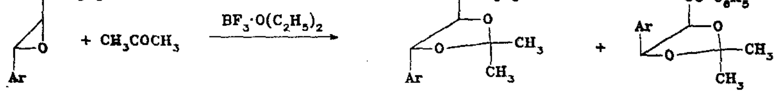
R = Cl, OCH_3, OC_2H_5

When the temperature is raised, the ring is opened to give, in all likelihood, monofluorosulfates of the corresponding diols. The formation of carbonium ions is not observed. These results constitute evidence that the formation of oxonium ions and subsequent opening of the latter under the influence of nucleophiles occur in acid-catalyzed reactions of oxetanes.

The use of individual stereoisomers of oxiranes has made it possible in a limited number of cases to establish that the condensation of aliphatic oxiranes with ketones takes place stereospecifically and is accompanied by inversion of the configuration of one of the carbon atoms of the three-membered ring [68]:



Specially designed experiments showed that stereoisomeric alkyl-substituted 4-acyl-1,3-dioxolanes do not undergo epimerization in the presence of boron trifluoride etherate [9]. On the other hand, 4-aryl-5-acyl-1,3-dioxolanes undergo isomerization under these conditions to give mixtures of cis and trans isomers with a certain preponderance of the latter in most cases [9, 21]:



2,3-Epoxyoctane reacts stereospecifically with acetone in the presence of anhydrous copper sulfate [13]:

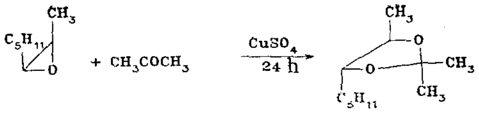
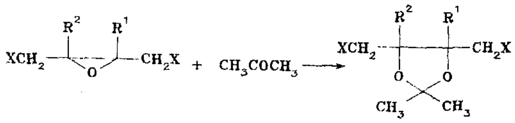
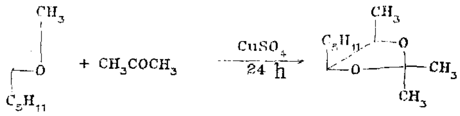


TABLE 3. Rate Constants for the Reaction of 1,4-Dihalo-2,3-epoxybutanes with Acetone in Carbon Tetrachloride ($SnCl_4$, T = 303°C) [40]

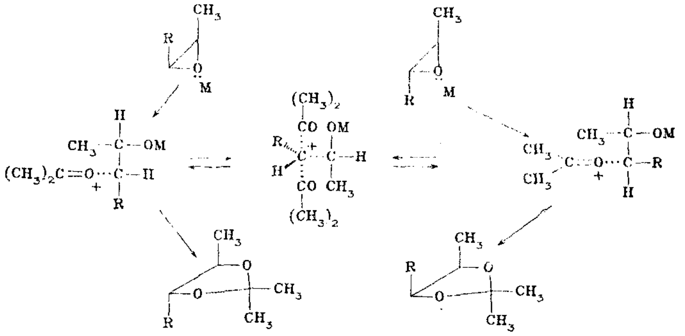


X	R¹	R²	k·10⁴, liters/ mole-sec
Br	H	H	7,00
Br	CH_3	H	7,77
Br	CH_3	CH_3	0,91
Cl	H	H	5,89
Br	H	H	1,38*

*With $BF_3 \cdot O(C_2H_5)_2$ as the catalyst.

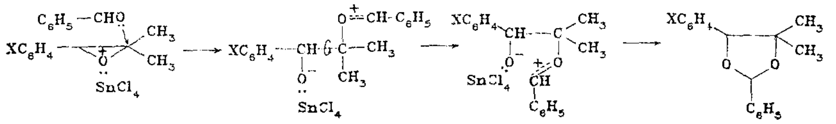


Neither 1,3-dioxolanes nor oxides undergo isomerization in the presence of $CuSO_4$ under these conditions. Both the cis- and trans-epoxide of β-methylstyrene react with acetone in the presence of $CuSO_4$ to give the same mixture of 4-methyl-5-phenyl-1,3-dioxolane stereoisomers with preponderance of the trans isomer (66:34). In the case of (4-R-phenyl)oxiranes (R = Br, Cl, H, CH_3) it was shown that $\rho = -2.63$ in the Hammett correlation equation, which constitutes evidence for a mechanism with a carbonium ion intermediate. The authors propose the following mechanism:

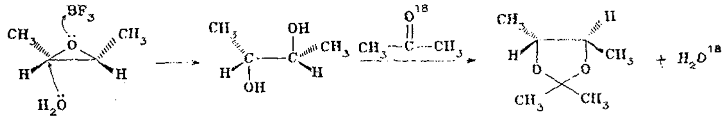


With a substituent that is capable of stabilizing the carbonium center the reaction proceeds through an intermediate that is common to each of the stereoisomers of the epoxide. If the carbonium ion formed from the oxirane is less stable, it undergoes rapid cyclization to give a 1,3-dioxolane with an inverted configuration of one of the ring carbon atoms as comparec with the oxirane.

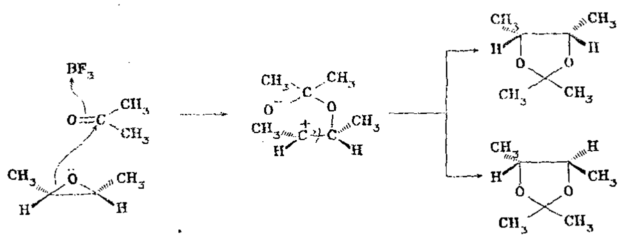
A similar scheme was previously proposed to explain the mechanism of the reaction of aryl-substituted oxiranes with benzaldehydes [26], which includes attack from the rear of the carbon atom of the oxirane ring coordinated with the catalyst with subsequent rotation about the C–C bond and ring formation.



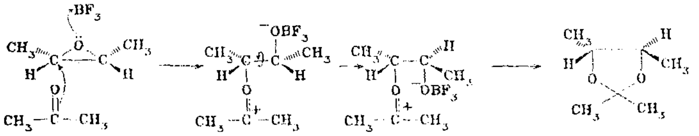
It was proved by means of labeled molecules, particularly ^{18}O-enriched acetone, that water impurities do not play a substantial role and that a diol is not an intermediate in the cyclization [20]:



The absence of oxygen-18 enrichment of the water constituted evidence in favor of this. Initial coordination of the catalyst with either the oxide or the carbonyl reagent is possible, in principle. The catalytic complex is then attacked by the reagent. It is difficult to distinguish these mechanisms kinetically. At the same time, the observed stereoselectivity of the reaction [20] cannot be explained on the basis of an ion-pair interaction, since in this case inversion of the configuration should not occur:



The following mechanism is therefore considered to be the most likely pathway [20]:



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POLYFURYL(ARYL)ALKANES AND THEIR DERIVATIVES.

4.* SYNTHESIS OF FURYLDIARYLMETHANE DERIVATIVES

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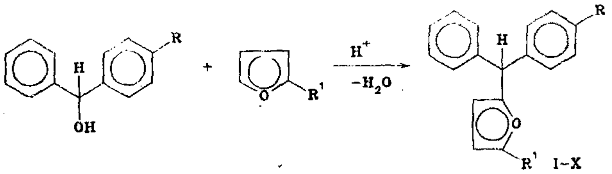
UDC 547.727.07:542.953

A number of substituted furyldiarylmethanes were obtained by the reaction of furan derivatives with secondary aromatic alcohols.

Very little information on furyldiarylmethane derivatives is available. Only the preparation for furylbis(N,N-dimethylaminophenyl)methane by the reaction of furfural with dimethylaniline has been described [2]. An alternative method for their synthesis is the reaction of furans with substituted benzhydrols.

We have established that alkylfurans, as well as ethyl furoate, react with benzhydrol derivatives in benzene in the presence of catalytic amounts of perchloric acid to give the corresponding furyldiarylmethanes (I-X) in up to 96% yields (Table 1):



I–V R=H; I $R^1=CH_3$; II $R^1=C_4H_9$; III $R^1=C_5H_{11}$; IV $R^1=C_6H_{13}$; V $R^1=C_7H_{15}$; VI, VII $R^1=CH_3$; VI R=Br; VII $R=OCH_3$; VIII–X $R^1=COOC_2H_5$; VIII R=Cl; IX R=Br; X $R=OCH_3$

The product of the reaction of unsubstituted benzhydrol with ethyl furoate is not the expected (5-carbethoxy-2-furyl)diphenylmethane but rather 1,1,1',1'-tetraphenyldimethyl ether, which is obtained as a result of self-etherification of benzhydrol. The formation of this product in the reaction of benzhydrol with phenol was previously reported [3].

The presence of several groups of resonance peaks is characteristic for the PMR spectra of furyldiarylmethanes I-X: signals of aryl protons at 6.87-7.1 ppm, double doublets of furan β protons of the compounds that contain an alkyl group in the 5 position at 5.7-5.8 (3H) and 5.5-5.6 ppm (4H), and double doublets of furan β protons of the compounds that contain an ester group in the 5 position at 5.8-5.9 (3H) and 6.9-7.0 ppm (4H).

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*See [1] for Communication 3.

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